NBS SPECIAL PUBLICATION 459

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Performance Evaluation of Programmable Robots and Manipulators

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress March 3, 1901. The Bureau's overall goal is to strengthen and advance the Nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research and provides: (1) a basis for the Nation's physical measurement system, (2) scientific and technological services for industry and government, (3) a technical basis for equity in trade, and (4) technical services to promote public safety. The Bureau consists of the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Institute for Computer Sciences and Technology, and the Office for Information Programs.

THE INSTITUTE FOR BASIC STANDARDS provides the central basis within the United States of a complete and consistent system of physical measurement; coordinates that system with measurement systems of other nations; and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. The Institute consists of the Office of Measurement Services, the Office of Radiation Measurement and the following Center and divisions:

Applied Mathematics — Electricity — Mechanics — Heat — Optical Physics — Center for Radiation Research: Nuclear Sciences; Applied Radiation — Laboratory Astrophysics[2] — Cryogenics[2] — Electromagnetics[2] — Time and Frequency[2].

THE INSTITUTE FOR MATERIALS RESEARCH conducts materials research leading to improved methods of measurement, standards, and data on the properties of well-characterized materials needed by industry, commerce, educational institutions, and Government; provides advisory and research services to other Government agencies; and develops, produces, and distributes standard reference materials. The Institute consists of the Office of Standard Reference Materials, the Office of Air and Water Measurement, and the following divisions:

Analytical Chemistry — Polymers — Metallurgy — Inorganic Materials — Reactor Radiation — Physical Chemistry.

THE INSTITUTE FOR APPLIED TECHNOLOGY provides technical services to promote the use of available technology and to facilitate technological innovation in industry and Government; cooperates with public and private organizations leading to the development of technological standards (including mandatory safety standards), codes and methods of test; and provides technical advice and services to Government agencies upon request. The Institute consists of the following divisions and Centers:

Standards Application and Analysis — Electronic Technology — Center for Consumer Product Technology: Product Systems Analysis; Product Engineering — Center for Building Technology: Structures, Materials, and Life Safety; Building Environment; Technical Evaluation and Application — Center for Fire Research: Fire Science; Fire Safety Engineering.

THE INSTITUTE FOR COMPUTER SCIENCES AND TECHNOLOGY conducts research and provides technical services designed to aid Government agencies in improving cost effectiveness in the conduct of their programs through the selection, acquisition, and effective utilization of automatic data processing equipment; and serves as the principal focus within the executive branch for the development of Federal standards for automatic data processing equipment, techniques, and computer languages. The Institute consists of the following divisions:

Computer Services — Systems and Software — Computer Systems Engineering — Information Technology.

THE OFFICE FOR INFORMATION PROGRAMS promotes optimum dissemination and accessibility of scientific information generated within NBS and other agencies of the Federal Government; promotes the development of the National Standard Reference Data System and a system of information analysis centers dealing with the broader aspects of the National Measurement System; provides appropriate services to ensure that the NBS staff has optimum accessibility to the scientific information of the world. The Office consists of the following organizational units:

Office of Standard Reference Data — Office of Information Activities — Office of Technical Publications — Library — Office of International Relations — Office of International Standards.

---

[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.

[2] Located at Boulder, Colorado 80302.

Performance Evaluation of Programmable Robots and Manipulators

Report of a Workshop held at
Annapolis, Maryland
October 23-25, 1975

Edited by

Thomas B. Sheridan
Thomas B. Sheridan and Associates
32 Sewall Street
West Newton, MA 02165

U.S. DEPARTMENT OF COMMERCE, Elliot L. Richardson, *Secretary*

Edward O. Vetter, *Under Secretary*

Dr. Betsy Ancker-Johnson, *Assistant Secretary for Science and Technology*

U.S. NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director*

Issued October 1976

Library of Congress Catalog Card Number: 76-600057

National Bureau of Standards Special Publication 459
Nat. Bur. Stand. (U.S.), Spec. Publ. 459, 213 pages (Oct. 1976)
CODEN: XNBSAV

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1976

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D. C. 20402
(Order by SD Catalog No. C13.10:459). Stock No. 003-003- Price $3.40
(Add 25 percent additional for other than U.S. mailing).

ABSTRACT

The Workshop brought together representatives of industry, academic institutions and government agencies, including the potential designers, suppliers and users of a new generation of manipulators and robots which include varying degrees of control by both people and computers. The Conference was motivated by the lack of common bases for comparing one such device with another in terms of performance, or one task with another in terms of how well a given device will perform it.

The Workshop concluded that there is a need for (1) common definitions of many terms which now are the source of pervasive confusion, (2) common test codes, (3) checklists, guidelines, and specifications to help users and suppliers better communicate with one another, and (4) common tests for demonstration and exhibition of new research and development in this field. Conference participants emphasized that once these needs were met to allow communication in the field, actual performance testing should be left to the user and supplier in the free marketplace.

KEY WORDS: Guidelines; industrial robots; manipulator; performance evaluation; programmable robots; and specifications.

PREFACE

During the past few decades, robot systems have advanced from the imagination of science fiction writers to the reality of industrial robots and remote control manipulators at work by the thousands in industry and in Government facilities today.

This new technology of computer controlled automatic manipulators is characterized by its generality. The same industrial robot that is found loading red hot steel ingots into forging presses in one industry is found spot welding automobile bodies in another.

The combination of complexity and generality of such systems poses a problem to the potential user. How should he specify the design or performance of such a device for procurement? Too detailed a specification will result in an expensive, custom designed system. On the other hand, too loose a description may result in a system that doesn't perform adequately.

Government agencies face an even more difficult problem in the development of advanced systems for handling radioactive materials, exploring other planets, mining offshore drilling and undersea exploration, and handling explosives and other dangerous materials.

Today's marketplace for robots and programmable manipulators is characterized by a lack of quantitative performance measures and even the lack of a basic common vocabulary for specifying performance.

To address these problems, the Office of Developmental Automation and Control Technology of the Institute for Computer Sciences and Technology of the National Bureau of Standards contracted with Thomas B. Sheridan and Associates to organize a workshop that would bring together selected experts from Government, industry, and academic research groups. Prepared papers were solicited to address specific aspects of the problem, and a two day workshop was held to discuss the papers and identify specific problems to be solved.

The papers in this proceedings do not represent the viewpoint or official position of the National Bureau of Standards. They are the personal opinions of experts in the field that identify specific needs in developing a common vocabulary, guidelines and performance measures that will improve the communication in the marketplace for robot systems and programmable manipulators.

The Office of Developmental Automation and Control Technology develops guidelines, standards, and performance measures that will assist other Government agencies and industry in specifying, procuring, and using computer based automation systems, including robot and programmable manipulators. We believe that these proceedings, which are one of the ways in which we endeavor to provide this assistance, will be useful to Government, to industry, and to the research community in improving their ability to discuss the performance capabilities of robot and programmable manipulators.

John M. Evans, Jr.
Acting Manager
Office of Developmental Automation
and Control Technology
Institute for Computer Sciences
and Technology
National Bureau of Standards

TABLE OF CONTENTS

APPENDICES

1. INTRODUCTION

The designer or supplier of a general purpose programmable robot or manually controlled remote manipulator (teleoperator) has a difficult problem. He would like his device to fit a great variety of applications, for its very versatility to adapt to whatever specific job the user may have is what makes it economically viable. Yet he knows each particular job is different. Beyond the general desire for ever greater speed, accuracy, strength and reliability he lacks precise specification of an objective function or performance criterion. He is largely dependent on the programming and operating skills of his customer in order for his product to succeed.

Similarly, the purchaser of a programmable robot or manipulator has a problem. He is not clear on how to decide which available system is best for him, for he doesn't know how best to specify what he needs. If he specifies required performance in terms of the most recent or the present task, it is not likely that the robot will be adaptable to other tasks in the future, not that it will perform well with respect to aspects of today's task which he does not understand well enough to specify. Alternatively, the purchaser can specify for procurement in terms of some "worst anticipated case", e.g. "pick-up the (heaviest) object in the (most arbitrary) location and orientation, move it (in the least time) and make the (tightest tolerance) assembly to another object (whose position is poorly known)." However, requiring that the robot be designed as though it is to work regularly at this rare simultaneous extremum of all the performance variables is likely to be naive economically. In those rare cases of an extreme in terms of one variable (weight or speed, etc.) some other variable may well be able to give, and the greatest pay-off is likely to come with a system designed primarily for the kinds of jobs it faces most often. Finally the purchaser can defer judgement until after he has purchased a robot or manipulator system and had a chance to try it out.

Programmable robots and manipulators are relatively <u>general purpose tools</u>, intended to be adapted to a <u>variety of future tasks</u> in ways limited primarily by ingenuity of their programmers and human operators. This fact, however, only aggravates the problem of specifying performance of devices yet to be built or of evaluating performance of those already built. It only complicates the process by which supplier and user can make agreements to which they can be held accountable.

How should performance be measured? In terms of the physical attributes of the <u>tools</u>, such as geometry, speed, load, controlability, reliability, cost? Or in terms of various <u>tasks</u> to be accomplished, perhaps "real" demonstration tasks, consisting of integrated sequences of component subtasks - or perhaps a battery of discrete component tasks, each of which can be calibrated and scored separately (for accuracy, time, etc.), a sort of "aptitude test" or "I.Q. test" for robots? Should robot capabilities be specified in terms of a "resume" of accomplishments, much as a human job applicant?

Different governmental or industrial programs already have produced ad-hoc performance evaluations of a great many specific systems, and there is considerable experience already gained in terms of types of measures and criteria employed, types of decision problems faced, etc. Yet there remains little or no consensus on performance measurements and evaluation across sectors of industry and government in the U.S. (though national "standardization" efforts have begun in some other countries, e.g. Japan).

The National Bureau of Standards, Department of Commerce (Office of Developmental Automation and Control Technology) recognizes a need to develop a better understanding of problems of measurement and evaluation of performance of programmable robots and manipulators. This should include work to secure agreement on common yardsticks and language in addressing these problems across relevant research, development, manufacturing and using communities, including: manufacturing (materials processing, parts handling and assembly, inspection, warehousing); service industries (trash collection, vehicle loading, building maintenance and construction); hazardous environment operations (deep ocean oil drilling, work in high temperature or chemically toxic environments, nuclear "hot lab" operations, space operations in earth orbit or on the planets); "remoted" micro-surgery; mining and many others.

Clearly the development of conventional "standards" for use by government or industry would be premature at this point. The need at this time is rather to define and understand the problems, and for a sharing of measurement techniques and evaluation experience among interested parties.

To this end a Workshop on Performance Evaluation of Programmable Robots and Manipulators was sponsored by the Office of Developmental Automation and Control Technology, Institute for Computer Sciences and Technology, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C. 20234. Through Contract No. 5-35922, Thomas B. Sheridan and Associates, 32 Sewall St., W. Newton, MA 02165, served as organizer. Dr. John M. Evans, Jr. was contract monitor. The Workshop was held Oct. 23-25, 1975 at Annapolis, Maryland.

Attendeees at the Workshop (full titles and addresses given in the appendix) were:

James Albus	National Bureau of Standards
Anthony Barberra	National Bureau of Standards
Antal Bejczy	Jet Propulsion Laboratory
Alan Case	General Electric Co.
Jos. F. Engelberger	Unimation, Inc.
John M. Evans	National Bureau of Standards
Jack G. Grundmann	Oak Ridge National Laboratory
William Hamel	Oak Ridge National Laboratory
Dennis Hanify	ITT Research Institute
Richard E. Hohn	Cincinnati Milacron Co.
Demetrius G. Jelatis	Central Research Laboratory
P. Michael Lynch	Charles Stark Draper Laboratory
Gerald Malecki	Office of Naval Research
Douglas A. Morlock	Picatinny Arsenal, U.S. Army
Richard L. Paul	Stanford Research Institute
Alan J. Pesch	Eclectech Associates
Andreas Rechnitzer	Office of the Oceanographer, U.S. Navy
Bernard Roth	Stanford University
Bernard M. Sallot	Society of Manufacturing Engineers
Thomas B. Sheridan	T.B. Sheridan Associates
Nicholas Shields, Jr.	Essex Corporation
William L. Verplank	Stanford University
Jean Vertut	Atomic Energy Commission of France
Charles D. Wicker	Oak Ridge National Laboratory

The following individuals contributed written statements (which are printed in Section 5 along with the other papers):

Y. Hasegawa	Waseda University
I. Masaki	Kawasaki Heavy Industries, Ltd.
M. Iwasawa	Oki Electric Industry Co. Ltd.
A.E. Kobrinski	Academy of Sciences, U.S.S.R.
M.S. Konstantinov	Central Laboratory of Manipulators and Robots, Bulgaria
M. Vukobratovic	Mihailo Pupin Institute, Yugoslavia

The contributions of Ms. Helen Stottlemeyer, Ms. Marie-France Pierre and Ms. Toni Heller in administrative assistance and typing are gratefully acknowledged.

2. SUMMARY OF WORKSHOP

2.1 Objectives

The objectives of the workshop were:

1. to motivate the preparation of position papers on robot and manipulator performance evaluation by key persons representing industry, government and university, as well as both supplier and user in major application areas;

2. to provide an opportunity for the above persons to discuss each others' viewpoints and come to a better mutual understanding of current practices and problems in robot/manipulator performance evaluation;

3. to collect written responses of individuals and small working groups on theme questions (responses presented in Section 4):

   Question 1: How can the specification of performance of relatively general purpose robots and manipulators be improved (so that the supplier can specify his product's capabilities and the user can specify his task requirements and each can be held accountable?)

   Question 2: What terms, tests and indices used for performance measurement and evaluation can be common across the various types of devices and fields of application (e.g. manufacturing, mining, space, undersea, nuclear labs)? Which ones, if any, must be different for different applications?

   Question 3: Should evaluative procedures for new developments and experiments be different from those for competitive procurement in already proven application areas? How?

   Question 4: What institutional arrangements should be made to achieve equitable evaluation and communication of results? Who should do the testing (producer, consumer, government, independent testing agency or consultant, other)?

4. to identify specific terms and performance measures which have been used successfully or unsuccessfully, and why;

5. to prepare a report on the results of the workshop, including recommendations for further action.

2.2 Program

The program is given in Appendix 2. The presentations were grouped according to application area; these are reviewed in Section 3, along with salient points of discussion. Time was allowed for discussion in small groups, where participants were evenly divided by application area and type of institution into three groups, X, Y, Z, to discuss the theme questions cited above and prepare written responses (Section 4). The full papers are in Section 5.

2.3 Conclusions and Recommendations

The following conclusions and recommendations were drafted by the editor, as being representative of consensus by workshop participants, and edited by the participants.

2.3.1 Need to agree on definitions of terms

There is a need for agreement across the robot/manipulator community on common definitions of terms. Too often terms such as "friction", "stiction", "hysteresis", "backlash", "damping", "stiffness", "strength", "active", "passive", "load carrying capacity", "speed", "block-to-block time", "degrees of freedom", "naturalness", "controllability", "reliability", "maintainability", "programming ease", "specification", "standard", and "robot" are not understood (by people reluctant to admit it), or misunderstood (by people who understand a different meaning). One or more efforts should be mounted to compile a glossary or thesaurus while at the same time gaining agreement and acceptance of terms across the technical community.

2.3.2 Need to establish common test codes

There is a need to establish commonly accepted test codes or procedures according to which measures of elemental motions or mechanical, electrical or chemical properties of manipulators or robots derive meaning and are understood by all parties to mean the same thing. These test codes complement and extend the verbal definitions called for in the previous paragraph, giving more precise definition to "backlash", "positioning accuracy", "load carrying capacity", "deflection under load", etc. Common test codes are particularly essential for dynamic performance specification.

2.3.3 Need for checklists and guidelines

There is a need to develop checklists (for thinking about) and guidelines (for writing) specifications, to help individual users specify clearly what tasks they need done, to help suppliers provide unambiguous exposition of what capabilities their tools provide, and to help each ask the right questions of the other. It is up to the user to describe his specific jobs, work-place environments, acceptance tests, etc. but his use of a more or less standard format (likely to be different for different industries and areas of application) may be helpful to the supplier. It is up to the supplier to describe his product by means of performance measurements, resume of accomplishments, or whatever, but his use of a standardized guidelines and formats which have potential for semi-standardization should be tested out with cooperation by user and supplier groups.

2.3.4 Need for common demonstration tests

There is a need to develop certain kinds of tests for demonstration and exhibition, primarily in research and development activities. These should be described and compiled along with other similar tests already developed, such that these same tests may be performed at the discretion of users and suppliers and the measures of performance of the tests will have a commonly understood meaning. Examples of such tests are drilling holes, inserting bolts, threading a needle, striking a match, building a stack of blocks. Measures of performance can include task completion time, classes of errors, etc.

2.3.5 Performance and design standards inappropriate for now

It is believed inappropriate and premature at this time, and even inhibiting to research and development in the field, to generate specific pass-fail standards for performance (speed, accuracy, etc.) on basic design features of robots, or manipulators (kinematic configuration, power transmissions, control systems, workplace compatability, environmental vulnerability). Standards for certain attributes such as safety are of course being motivated by special federal regulatory agencies (though criteria for such attributes may be included in checklists and guidelines).

2.3.6 Appropriate institutional roles

Appropriate roles for professional societies, trade organizations, universities and government agencies are in:

a) educating the public and potential users as to the advantages and disadvantages in various applications of robots and disseminating information about recent advances in the field;

b) implementing 2.3.1., 2.3.2., 2.3.3., and 2.3.4. above;

c) considering other areas of standardization such as software for robots and robot teaching procedures.

Actual performance testing should be left for now to the supplier and user, the operating parties in the free marketplace.

3. REVIEW OF PRESENTATIONS AND DISCUSSIONS

J.M. Evans opened the Workshop on behalf of NBS. He asserted that the interest of NBS was to help government procurement and the U.S. economy in general, and that NBS does not wish to force premature standardization. However, quantitative specifications of products can, in general, improve a competitive marketplace by allowing better communication between buyer and seller. Voluntary standards, he claimed, are encouraged by economic pressures. In the discussion which followed it was questioned whether or not it is acceptable to wait and evaluate manipulators "on-the-job". Many believed it was. Some felt there are always lots of surprises when the real application begins.

T.B. Sheridan gave an overview paper to introduce three kinds of ideas: the first included some axioms about evaluation generally (that value functions are scalar, ultimately subjective, that they may be non-ordinal, that they must be publically accepted and understood, that completely "fair" social choice on standards is impossible, that perfect simulation of the future is impossible, that the cost of evaluation must be considered). He also discriminated between manipulator tasks and manipulator tools. Finally he suggested a taxonomy scheme for evaluating robots and manipulators.

D.G. Jelatis, having many years of experience in developing master-slave manipulators, suggested that over the years many manipulator systems failed to survive because they were not the "fittest" - were not rugged enough and were used for tasks for which they were not designed. He proclaimed the importance of "naturalness", and called for some better agreement on terms and measures for "obtrusiveness", "friction", "elastic deflection". There were questions raised as to whether in the development of master-slave manipulators specifying of standards was helpful. It was pointed out in response that often government procurement specifications become standards. There was additional concern about specifying things which aren't needed, but one government representative cited a case of not having a proper spec and being rewarded by $70K worth of stripped gears. The concluding discussion called for standardization primarily of terms and guidelines, where too much standardization of devices themselves may be stultifying.

B. Roth then presented a systematic way of considering kinematic criteria. He described how displacement of the free end is the most important variable, that coupling of rotation and translation depends upon type of joints used, why the number of ways a manipulator can reach a position is important. He went on to characterize solvability - the ability to find all possible joint angles for a given endpoint position. He said it is difficult to design to a prespecified work envelope. Finally, he discussed approach angles, and why the larger the range of approach angle the better. Discussion concluded on the note that some things do not have to be rigidly specified.

J. Vertut presented his recent work on evaluating master-slave manipulators. He showed how exact spatial correspondence between master and slave is not important so long as force feedback or "feel" is good. The evaluation tasks he used included: 1) putting a peg in a hole or a block on a peg, etc; 2) making a wall from lead bricks; using two arms to lift what you can't lift with one. He showed how different manipulators (different control schemes) are characterized by significantly different profiles of log completion times over the various tasks. He asserted that to some extent certain specifications, such as compliance, must be relative to specific tasks.

J.F. Engleberger made the first presentation in the area of industrial applications. He expressed skepticism about whether the field is ready for standards and whether standards would not be too restrictive, that invention is the higher order activity. He worried that man has been too much the standard, that the object is to replace man and do better than he does. He also cited the importance of dynamics in evaluation (which some of the earlier efforts to standardize tests have neglected). In considering performance descriptors he cited as important: space intrusion and the necessary modification of the workplace; programming ease and time consumed in teaching; reliability and the interdependence of the robot with other parts of the process. He suggested that robots have "resumes" of performance qualifications and achievements, much as human job applicants.

R.L. Paul liked the idea that performance of robots and manipulators be evaluated relative to that of human workers, at least in order to understand what the numbers mean. He cited key differences in actuators, sensors, mass and strength-to-weight ratio. He emphasized the functional distinction between hands and arms and differences between compliance and control. Finally, he made some comments regarding evaluation of software (core requirement, execution time, precomputation, automatic reprogramming, cleverness at branching as a function of success). In response to a question about discovering whether hardware or software is at fault, he suggested the best way is to get the people together. There were further questions about the advisability of using the human arm as a model; Paul asserted that our understanding of the function of the human arm-hand complex is primitive and there's lots to learn.

A. Case said that when he talks to manufacturing engineers about industrial robot application they are apt to ask three questions: 1) will it do the job?; 2) will it be cost effective, considering that labor may be available but capital scarce, and considering the whole system and not just the robot alone?; 3) who will service and support the robot in the factory? He went on to say that the manufacturing engineer doesn't want to spend time doing kinematic and dynamic analysis, but needs help in breaking assembly and other robot tasks down into their parametric elements.

P.M. Lynch spoke next. He outlined the Draper Laboratory approach to the evaluation of programmable assembly systems for industrial applications. The important criterion is the cost of assembly per unit of product as a function of execution time, task failure and system cost. The assembly process can be further broken down into subtasks and subcosts, all of which bear some allocation of the purchase price of the system. By changing the assembly task sequences and/or system configuration of the robot a different lower bound on task time results and a corresponding differential cost. There was discussion about the inappropriateness of a 2 year payoff of robot capitalization because of the universality. The assertion was made that 8 years would make more sense.

A. Bejczy reviewed the various studies which he has conducted at JPL on requirements for deep space applications. He cited the definite need for computer-programmed control, but at the same time the need for man in the control loop as a supervisor, even in the case of long time delay. He spoke of the importance of local sensory feedback from the wrist or hand (wrist force, touch contact, proximity) and the terminal device design. Performance measures include "success" or "failure" for effectiveness of control, accuracy and time for quantity of control, and consumption of resources for quality of control. He concluded that more systematic work is needed on task description and analysis, that a "slight" change in the task may be a trap. He also said that the quality of the breadboard is important, and the hand sensor has a significant effect.

N.L. Shields described the test program and procedures currently being used to evaluate manipulator system concepts for teleoperators. A system can be viewed as an intersection along three orthogonal scales: human operator control, through fully automated control; fixed purpose, through general purpose manipulator/tool; general, through specific tasks and task sites. A test program of ordered manipulator system tests can be utilized to evaluate a wide range of different types of manipulator systems, where the test order involves going from control of a single degree-of-freedom, through a hierarchy of tests to the control of multi-degree-of-freedom task situations. By eliminating specific candidate manipulator systems which fail to comply with system requirements at the lower end of the hierarchy, considerable resource savings can be realized (by eliminating tests on all possible combinations of manipulators and tasks).
(Editor's note: This is equivalent to coping with the "curse of dimensionality" in optimization theory.)

A.B. Rechnitzer then reviewed applications of manipulators to undersea problems and in association with test vehicles such as Alvin, Beaver, and the Deep Sea Rescue Vehicle. He emphasized the specific engineering functions which are specified (cutting of cables, attaching hooks). His colleague, G. Malacki, emphasized that in final end item procurement the evaluation is essentially "will it do the job?", whereas in research the performance testing can be more appropriately elaborated into parametric studies and interactions.

A. Pesch also discussed undersea applications, including object recovery, salvage (chain and hook applications, cable cutting), scientific operations (coring, collecting samples) and commercial applications (inspection, cable laying, equipment repair). He called for better definitions of design and system response variables and widely applicable measurement schemes, using as illustrations definitions and tests he has developed. He advocated task analysis as a means of developing performance measures which can discriminate between various manipulator designs on both a whole and part-task basis.

J.G. Grundmann opened the session on nuclear applications. He described the necessity for fuel recycling plants in the 1980's to supply fuel for nuclear reactors. To operate and repair production equipment in large hot-cells of such fuel recycle plants, a new generation of production manipulators must be developed (as contrasted to earlier manipulators used for experimental work in small hot-cells). He emphasized two types of manipulator specifications unique to nuclear applications:

1. All nuclear manipulators must have extremely high reliability because repairs must be done remotely and this is much slower and expensive than direct (hands on) maintenance.

2. Materials utilized for nuclear manipulators must be specified to ensure proper radiation tolerance. (This is necessary because some common materials deteriorate when placed in a radioactive environment.)

W.R. Hamel concurred on the future importance of manipulators for nuclear fuel recycle. He also described the complexity of the production equipment which the manipulator would maintain and hence the desirability of an advanced computer aided manipulator to handle intricate maintenance tasks quickly. A need for development work was indicated, since a suitable computer-aided nuclear manipulator is not now commercially available.

C. Wicker spoke next, emphasizing again the need for reliability in nuclear operations and for ease of maintenance of the manipulators themselves - especially difficult because of the inaccessibility and long time delays before they "cool". He implored the designers to "keep 'em simple."

W. Verplank's presentation shifted the focus back to theoretical aspects of performance measurements. He described the research of himself, D. McGovern and G. Starr of Stanford, using the NASA Ames manipulator arm under computer-augmented manual control. His results systematically related task completion time of different manipulators to an information measure of required tolerance as well as a measure of distance travelled. From these results he inferred standard time measures (like MTM) and methods of predicting the effect of automating a portion of the task. Current research with Starr is comparing rate with position control under time delay and/or with automated subroutines. There was the suggestion that rate control may be preferable under these conditions. Verplank also suggested the utility of predictor displays in time-delay teleoperator situations.

B. Sallot gave the next presentation. He described the efforts of the new Robot Institute of America to define a robot and provide a medium for exchange of information on how to use it. He commented that in spite of their high technology no strong manufacturing base for robots now exists, and that applications-oriented educational programs are in order. He concluded with the thought that rigid standards would be too restrictive at this time, but that both standard definitions and evaluation guidelines are certainly needed.

R. Hohn then gave a presentation, citing the prospects for broader application of robots in industry, especially in new factories or in conjunction with new products. He believed that "specification" should be a communication vehicle by which potential users can assess whether a particular robot meets their needs. He reiterated the notion that "specs" which become too detailed may hinder more than help. There followed some comments from the floor on the dangers of the robot community talking only to itself.

D. Morelock described the application of robots in a new automated munitions manufacturing facility to be built, then put in "lay-away" for future potential use. He discussed the problems of justifying new equipment to management, and suggested that within each category of robot application a list of benefits should be drawn up. He warned not to "tarnish the sophistication of robots, but don't make people think they'll replace human thinking". He precipitated some discussion among the participants on social effects of robots. Some thought the idea of a "robot" makes people feel anxious. There was a concern expressed about whether the robot could help in the very fundamental problems of achieving more equitable income distribution. There was a reminder that the robot creates wealth, which is the starting point (everyone wants to share in someone else's wealth). There was a warning of the dangers of too much "bottom line thinking" - and the need, for example, for people to find fulfilling jobs in any case.

The final individual presentation was given by J. Albus. He described NBS research on robot loading and unloading of a machine tool, using trajectory calculation and LED proximity sensors to control the robot's grasping phase. He also remarked about the concern people expressed over the term "standard", that invention should not be impeded thereby. His belief was that invention is problem solving, which includes selecting and defining the problem, and that a "problem well defined is a problem half solved". He felt that properly selected, a set of standard tests can be enhancing and not impeding, to channel and order the efforts of the designer. And he reiterated the need for better definition of terms.

The discussion closed with agreement that we should not standardize too many things - for example a kinematic configuration, while it would be helpful to standardize on ways to talk about kinematics. It was also agreed that we should work toward common formats for specifications, common guidelines, and tests, and common language for programming robots. But we are not yet ready to write them down; there is much work yet to be done.

Then the three small task groups, X, Y, and Z, gave their reports, primarily in response to the four theme questions cited above. Their responses are presented in Section 4.

4. QUOTED RESPONSES OF GROUPS AND INDIVIDUALS TO THEME QUESTIONS

4.1 Question 1

How can the specification of performance of relatively general purpose robots and manipulators be improved (so that the supplier can specify his product's capabilities and the user can specify his task requirements and each can be held accountable)?

4.1.1-

First, there was definite agreement on the need to clarify and standardize terminology:

• An accepted set of definitions of different terms or measures is probably the most important immediate goal we could undertake (e.g. backlash, function, load capacity, tip orientation, accuracy, statistical variation, etc.). A dictionary or thesaurus is needed (Group X).

• Technical terms should be standardized, e.g. with respect to geometry and coordinate system, control techniques (the Japanese Industrial Robot Society has begun this effort). (Group Y)

• There is need to achieve general acceptance of definitions, e.g. of "compliance", "accommodation", "accuracy", "repeatability", "resolution", "backlash", "hysteresis", "lost motion", "stiction", "breakaway", "reversal torque", "ruggedness", "maintainability". Maybe the terminology standards exist and these only need to be applied to robotics. Perhaps the robot field needs a standards committee (Group Z).

• A common language must be established including a glossary of terms (e.g. accuracy, repeatability, resolution, point-to-point control, continuous path control, etc.) before we can have any specifications on performance. This is not necessarily a difficult task since many of the terms are defined in the literature. What is required is to extract this information and modify it to be applicable to manipulators/robots. (anonymous)

• Improve the uniformity or standardization of definition of terms - perhaps a standard glossary of terms could be compiled. (anon.)

• The vendors must standardize terminology pertaining to their systems. Terms such as accuracy, geometry, load capacity, etc. must be common to the robot manufacturing industry. All users with similar manufacturing processes must standardize user terminology for their type of application. Cross communication of vendors and users is obviously appropriate during the standardization efforts above. (Grundmann)

• Consider the development of standard terms. Define the vocabulary. Limited examples exist in several areas such as: the NASA Corliss and Johnsen books; JRI; Numerical control society; IEEE; Bertsche/Pesch reports on force feedback variable definitions. Needed is a standard method of describing the work envelopes of systems in regard to: range, ability to square up to various task surfaces, degrees of freedom remaining at points in the work envelope, standard kinematics, e.g. Roth's or some coordinate system. (Pesch)

• I feel that the greatest contribution that could be made in this area is the definition of terms. While I don't think we are talking apples and oranges, we are definitely talking oranges and tangerines. For instance, should "degrees of freedom" reflect three rotations and three translations (a total of six max), the number of joints in the arm (I've seen arms with nine joints), or the arm motions plus mobility capabilities? Speed specifications should be specified at some known percentage of rated load (and arm extension for rotations). Accelerations/decelerations with a known load should also be specified so that block times can be estimated. Torque capacities at the joints should be specified as well as load capabilities. Position accuracies and repeatability should be specified as a function of load, speed, arm extension and deceleration. Drift due to changes in the ambient should also be specified if significant. I'm sure I could fill up another two pages but I think you get my point; each manufacturer interprets and publishes data to optimize the unit he is selling. (Hanify)

4.1.2-

The discussants reminded us that basic problems of definition of robot and teleoperator persist and must be dealt with:

• Group X felt that the differences between robots and teleoperators are potentially larger and more significant than the differences between applications of general purpose robots or teleoperators.

• Group Z pointed out that there will remain those who will claim, with regard to defining robots, "I don't need to define one, I know it when I see it."

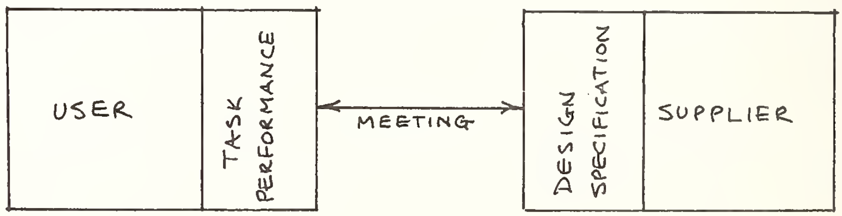
• J. Vertut feels that this difference is small in that teaching a robot is similar to operating a teleoperator.

4.1.3-

Some of the comments were to distinguish the different but complimentary roles which should be played by the user and the supplier in specifying, respectively, the task and alternative tools for achieving the task.

• The user is to supply function and task requirements and define, as explicitly as possible, the capabilities needed, including the ranges, task parameters and tolerances and the environmental conditions in the work area. (This highlights the need for good job-task analysis early in a program.) The supplier should be encouraged to offer alternative technical approaches for accomplishing the functions or tasks, including equipment design options and procedures. It is then the user's job to evaluate the merits of alternative approaches and to make a decision on the basis of performance versus cost. The users should not specify how the system should be designed - that is the responsibility of the producer. It is important not to constrain the producer, but to allow for creativity and inventiveness. (Group Y)

• Group Z suggested drawing which looked like this:



• It is necessary to separate tool and task (to the extent man is in the loop for control or programming) control specifications; all are orthogonal. We need better experiments experimental data from labs on all 3. We also need better task analysis from users and tests and demonstrations of the same tasks by different manufacturers. The "resume concept" (see below) is very good. (anon.)

• There should be separate specification of TASK and TOOL. For example, the materials and dimensions are TOOL specifications; reach and strength are TASK specifications. This will encourage flexibility of TOOL specification (leave room for invention). The problem of specifying "general purpose" remains; the only solution seems to be to specify a range of representative TASKS. (Verplank)

4.1.4.

There were a number of expressions on the desirability of some standardized format or "guideline" or checklist to be employed by user or supplier or both:

• (Devise a) checklist set of guidelines of important characteristics to be defined in the specification. These should be in hierarchical arrangement, in order from most general to most specific, e.g. task environment, load capability, operating volumes, mechanical impedance, or transfer function. The guidelines would reinforce the commonality of technical language, and the basis for user-generated "job descriptions" or "task specifications" and supplier-generated "robot resumes". As part of the format for conveying information perhaps there should be a standard kinematic drawing to specify the shape of the manipulator. (Group Z)

• A format guideline for manipulator/robot specifications would be a valuable tool. (anon.)

• A large checklist or questionnaire could be developed. This could be structured so that suppliers would have to reveal what their manipulators cannot do (as well as what they can do), and users can focus on the trade-offs between different systems. If this list were broad enough a typical sheet would have many "null" entries (e.g. "does not apply", "do not know"), and this would be a way of giving both supplier and user information that is usually missing, or not asked for until it is too late. Also, this would be a way for "experts" (i.e. people with a little experience) to help each other, as well as new users and suppliers, focus on what actually needs to be specified. In addition, this should include a resume of the type distributed by J. Engleberger. Especially important is the section on task performance. The user should be told exactly what type of tasks the manipulator has performed; and the user should be forced to specify exactly what type of tasks are minimum requirements. (Roth)

• Improved specifications of Performance - a series of guidelines/manuals should be developed to aid the communication between users and suppliers. These manuals would be used by potential users of these systems to determine and define the scope their tasks and document their functional requirements (tasks) using standardized terms and formats to provide efficient technical communication of those tasks to suppliers in procurement specifications. Upon receipt of proposals from suppliers, the user can then evaluate, using standardized data and procedures, the various proposals received and determine the best unit/system for his job.

- standardized definition of terms for robots/manipulators
- standardized manipulator/robot classifications (families by characteristics)
- performance tradeoff characteristics
- guidelines for determining applications for robots/manipulators
- guidelines for writing procurement specifications (user)
- guidelines for writing equipment specifications (supplier)

- standardized format for procurement specification

- standardized format for equipment specifications

4.1.5.

One way suggested for dealing with this question was to look at specific examples of specifications and try to improve them, for example as suggested by Wicker:

• Consider the procurement specifications used by ORNL for master-slave manipulator standard duty specification XSP-239 (reprinted in Appendix 3) and Electro-mechanical manipulator specification 10017-N-111-X.

4.1.6.

Many of the responses to this question were directed toward suggesting particular tasks or tests for evaluating manipulators or robots (note that these also begin to answer the next question, No. 2):

• Perhaps evaluation tasks should be graded with respect to dexterity, speed, load capacity, sensory communication. Perhaps there should be a standard set of exhibition stunts: writing, applying lipstick, threading a needle, striking a match, laying bricks. Perhaps one kind of task should be a survival test. (anon.)

• The specification of manipulators should be in terms of primary functions, i.e. link specifications (motion limits, strength, acceleration, type of actuator, servos, input and output, backlash, friction and inertia) such that suitability for a specific task can be evaluated. A resume of tasks that have been accomplished should be provided. In terms of software, each module should be defined as to its capability, the language used and the appropriate computer in order to evaluate its suitability for incorporation into other operating systems and programs. Software should be as modular as possible. (Paul)

• Devise standard tests, which need not be comprehensive, but might include measures of backlash, stiffness, friction, pick-and-place speed, simple assembly, complex assembly. These might also include tradeoffs of torque vs. speed, etc. (Albus)

• First limit tasks to those that have been demonstrated to be performable. Tasks that have not been demonstrated imply new development. Then list the specifications that measure the performance of general purpose robots in this range of tasks. It would be nice to develop a set of evaluation tasks the performing of which could be extrapolated to real-world jobs. Conceivably the user could merely describe the job to be done and the vendor describe (and prove) capability for doing it, i.e. "robot resume". Weighting of performance specifications might be useful. (Block to block speed is more important than machine weight.)

Typical Task-Performance

task	performance
die casting	speed (block to block)
welding	accuracy
paint spraying	manipulative power
pass	space intrusion
palletizing	reliability
plastic molding	memory capacity programming case cost

Note that the specification of performance becomes easier if the product class is limited to "general purpose robots". If all simple "pick and place" arms are included then all automation is being examined. As robot sophistication advances, the resume becomes more and more legitimate as a selection tool. The validity of the resume is tested by references and by the battery of generic skill measuring tests that users slowly evolve. (Engelberger)

• There should be developed a series of mutually acceptable and representative tasks to be completed under strictly controlled conditions, the results of which are specified in mutually acceptable terms. If we agree that "temperature" is desired measure then we need to specify on which of the available scales we are going to record temperature and we have to specify the measurement instruments - mercurial, alcohol or electrical. Methods and apparatus room need to be standardized also. (anon.)

• Instead of specifying only torque, resolution, and other parameters specific to a particular manipulator design, also specify manipulator/robot performance on a set of standard tasks. This is not to replace basic hardware specs but is to be in addition to them. This gives the user the chance to concentrate on the problem of task definition for his process and the designer the freedom to design something to accomplish the specified tasks. The designer can explore what physical properties the manipulator/robot must have to accomplish the tasks. In the case of programmable assembly, there could be a set of standard tasks which could be used to infer the performance of an assembler robot for a range of assembly specifications. For example, if execution time averages for the following tasks - gross motion (stop to stop), fine motion, grasp and release - were available, then the potential user might be able to form some estimate (albeit rough) of the assembly time for his product. Refining the estimate further would require a more detailed study. Such data on standard tasks should be treated in a way similar to the treatment of EPA highway and city driving mileage figures - rough estimates of what can be expected in different situations, and a way to compare robot performance. In any event, such performance figures would be most useful in the preliminary evaluations. (Lynch)

• As far as the measuring performance of robots and manipulators, I think the factors which always appear to be missing in any activity which I engage in concerning industrial robots is a definition of over-shoot and general positional performance. Most robotic devices depend on the system discrimination and there is not a great deal of attempt made to measure the actual performance, either the transient dynamic performance or any precise and reliable estimate of the final position or accuracy. Such factors as drift seem to be taken for granted. All these factors are very important in specifying the performance of a first generation industrial robot which is dependent on its precision and accuracy for its final functioning. The performance and relative performance of various types of actuation does not appear to be too well known, and also what is the limit to the axis speed which one can attain with different types of actuation, i.e., electrical, hydraulic, pneumatic, etc. (Heginbotham)

Editor's Note: Professor W.B. Heginbotham of the University of Nottingham did not attend the Workshop but submitted this response to our theme question by letter.

4.2 Question 2

What terms, tests and indices used for performance measurement and evaluation can be common across the various types of devices and fields of application (e.g. manufacturing, mining, space, undersea, nuclear labs)? Which ones, if any, must be different for different applications?

4.2.1.

There were many suggestions for tests which can be generic, or common across applications. There was also some agreement on what these should be:

- In defining a "tool", the following generic measures were listed:

  1) speed (block-to-block time)
  2) accuracy
  3) kinematics
  4) space intrusion
  5) reliability
  6) number of program steps
  7) programming ease

These measures were proposed for robots, but are generally applicable to teleoperators as well, particularly if a computer is assisting man in the control loop.

Task specifications are needed for non-proven applications, for example, coping with misplaced or misaligned objects. A battery of aptitude tests might be developed. A test for human aptitude for assembly work of picking up and moving an object with tweezers was given as a simple example. There are existing tests, such as water pump assembly or pin-in-a-hole tests, but they have not been generally applied. There was one member of the group that disagreed with this. The tweezer test was cited as a test of the hand, not a task aptitude test. Also, this member felt that more attention should be paid to tool design, such as link strength, length, design, backload, etc. for various application areas. (Group X)

- Standardized performance measurement and evaluation can be done in the areas of reliability (MTBF), availability, and maintainability:

  - Specify engineering integrity of the manipulator for the size and weight of the load to be handled throughout all of the motions of the task, i.e. require sufficient overdesign of stress points.

  - Test the load capacity for all orientations, power requirements of the arm and its actuators, workspace envelope, orientation of end effector within workspace, reproducibility in returning to the same point in space, accuracy, and performance correlates (what does it take to obtain that performance level in terms of cost in money, ease of maintenance, man fatigue, etc.). (Group Y)

- We recommend three different kinds of tests:

  a) acceptance tests for individual systems
  b) general tests to compare systems, including positioning accuracy and time to move between points
  c) supplier demos to show individual excellence of a product. (Group Z)

• I believe certain measures and tests are application invariant. The weight attached to each measure will vary from field to field and even between applications in the same field. My list of important tests, terms, and indices include:

1. degrees of freedom of positioning end
2. zones of operation of end effector
3. zones of operation of each link
4. load capacities (static and dynamic)
5. accuracy, backlash, deflection under load
6. control data under specific standardized test conditions
7. reliability
8. type of joints (Roth)

• Tests and indices which appear to be common to all devices are:

a. diagnostic techniques
b. reliability methods
c. load test (capacity)
d. cycle time (speed) test
e. working envelope
f. accuracy (Grundmann)

• Manipulators/robots perform tasks in any domain - space, undersea, industry, and hot lab - even though the manipulator/robot mechanisms and scale may be quite different. Therefore, performance tests based on tasks are potentially applicable across various types of devices and fields of application. To the extent that tasks are similar in different fields of application, common task based performance measures might be used, as possible. (Lynch)

• At least in the case of a robot, its primary function is positioning. Tests related to this function should be used for performance measurement. These tests could include accuracy, repeatability, stiffness, etc. What must be developed is a test code which would describe the measurement means, machine setup, and measuring techniques to establish these performance specifications. Also, testing for time to move between programmed points is important. A simple statement of maximum velocity is not useful in determining the time to move between points. (anon.)

• We should establish a set of standard test formats to measure the various aspects of remote system performance. This refers to standard means of measuring rise time, force fidelity, position accuracy, dead band, force to move, speed of movement, positioned accuracy/repeatability, etc. We have developed some tests for force feedback. These may be used as an indication of what may be generally useful. Examples of some tests currently being applied to define force feedback are in a recent ONR supervised report by Bertsche and Pesch. Also, consider developing a few standard tasks made up of basic movement elements, as found in time and motion studies, to serve as "bench mark" performance tests. There are many pitfalls to this approach since it could drive design to better perform the standard tasks rather than increase the flexibility of robot or manipulators in general. However, on the positive side, some of the evidence presented at the conference (e.g. Verplank's data) suggests that basic time and motion task analysis seems to hold across a variety of hardware and task applications. (Pesch)

• Our experience in undersea testing has been that most tasks can be divided into a surprisingly small number of elements or groups. The two tables in my paper show a rather high level grouping of elements which accounted for 95% of the behavior found in the eight applied tasks. Similar work in process, evaluating the effectiveness of the Navy's Work System Package, is using this technique to advantage. The prime advantage as I see it is the specification of standard tasks for "bench mark" evaluation of various systems. A great deal of care must be exercised over the development of the tasks. Task analysis of real manufacturing tasks, military tasks, hot labs, etc. should be followed by the creation of a sample data pool of basic task elements. These require validation and an estimate of variance prior to issue or use in assembly of new tasks. An advantage is some standardization of basic movement categories of robots and a task reference for time and accuracy measures. (Pesch)

• My paper makes some relevant points regarding "zoning classification". (Vertut)

4.2.2

Not all tests can be common across applications. For various reasons some must be different :

• Some tests will be different in as much as they relate to the peculiarities of the environmental conditions of the different fields of application, as well as the utilities (values) associated with the several criteria that pertain to the system functions. (Group Y)

• Indices which are not common to all devices. Three obvious bases for differences are:

a) classification of devices as robots or manipulators

b) robot material specifications for unusual applications

c) interlock and interface equipment

(Grundmann)

• To the extent that an application field has a problem non-existent in an other field, tests relating to this problem will be unique to that field. (Lynch)

• Different fields of application normally apply constraints on types of mechanisms used, i.e. no hydraulics for nuclear applications. These should be summarized for each field of application. In turn then manipulator specifications could state for which field of application the manipulator was suitable. (Paul)

• In one sense all, and in another sense no terms, tests and indices should be common. Certainly, definition of terms should be common across all fields of application. However, some specs which are critical for some applications will be irrelevant to others. Certainly standard tests are by definition task-specific. Each field should devise its own relevant set of performance tests and each manufacturer expecting to sell manipulators for that application should demonstrate the performance of his product under those tests. (Albus)

4.2.3.

There were other comments made in response to this question to emphasize (i) the need to consider dynamics, (ii) the need to keep tasks and tools separated, and (iii) the need to organize terms, tests and measures on a scale from general to specific.

• Current robot manipulator specifications tend to be static. Lumped parameter static specifications are satisfactory for master/slave manipulators because of the slow speed of operation but robot and some remote control operations demand rapid response and thus depend upon dynamic performance criteria. Simple slew rates and maximum loads are not adequate dynamic specifications (e.g. Engelberger), but acceleration and deceleration factors possibly combined with slew rate and block-to-block time and inertia and torque factors are needed even for simple transfer applications of robots. We need some sample tasks to agree on (e.g. Pesch vs. Vertut vs. MIT) to be able to compare dynamic task data, e.g. transfer, simple assembly vs. complex assembly. Interactions must be considered (e.g. Vertut's data on hands, degree of force feedback). (anon.)

- Again, performance should (as much as possible) be measured in terms of TASK. That is, which tasks are to be (or can be) accomplished and what are the relevant measures which describe the task and performance on the task. For example, TASK: loads, dimensions, tolerances, variabilities; PERFORMANCE: time, energy, cost, ... (Verplank)

- One should define from the common to the unique rather than emphasize differences. They each have to be so developed to exclude "area specific forms" even if what we are forced into doing is developing a thesaurus which lumps closely associated terms. If you start out proving (manipulators) have to be different you buy problems you don't need. If things are truly different and unique, they should be the leftovers and the "not elsewhere classifiable". (anon.)

4.3 Question 3

Should evaluative procedures for new developments and experiments be different from those for competitive procurement in already proven application areas? How?

4.3.1.
Some respondents said yes, feeling quite different criteria should apply to new developments vs. proven applications:

- Our group felt that it was important to distinguish between new development and proven applications. In the context of proven applications it is up to the user to specify the task and up to the supplier to prove that his tool can perform that task. In this context, the "resume" concept was generally agreed to be a very useful concept. This could be a checklist of capabilities or a list of questions to answer or a list of successful proven applications and possibly appropriate references.

It was generally agreed that for proven applications tight tool specifications were useful (leaving open cost, service, delivery, etc.) but that for development work task specifications should dominate, leaving avenues for invention open to the tool developer. (Group X)

- Yes, ordinarily, there are differences in evaluation procedures as a consequence of the distinctly different goals and technical approaches. The test and evaluation of systems that embody proven technologies can rely upon established engineering practices and measurement techniques together with quality control methods employed in manufacturing processes. The guidelines for these procedures would be expected to be contained in the work statement for the competitive procurement. R & D programs, on the other hand, employ a different set of tools and techniques, particularly those concerned with the advancement of theory and/or the extension of a technological base. Work in this arena tends to be characterized by the formulation of concepts, hypotheses and models, development of experimental designs and conduct of experiments, the derivation of lawful relationships between variables under study, and, in some cases, the development of prototype hardware (or software). The products of R & D are generally evaluated on the basis of scientific and technological merit (new knowledge, understanding of phenomena and relationships, new technologies). Of course, in the progression from fundamental research to applications the methods of science and engineering will merge and overlap. (Group Y)

• Research projects always seem to have different requirements and objectives than commercial systems and equipment. Hence, there is no reason to expect any similarity in evaluation procedures. (Lynch)

• For new developments evaluation should foster ingenuity. For proven areas specifications can be tight, leaving cost, delivery, service, etc. as variables. In frontier work, the cleverness of proposals, reputation of investigators, background knowledge should outweigh cost in evaluation. (Engelberger)

• Yes. In development work, task specifications are primary. In proven applications, tool and control specs are probably more appropriate. In the latter case, a demonstration of the tool for a specific task will often be needed. (anon.)

• Yes. Prior to the establishment of an experience data base sufficiently large to be suitable statistical tool, other methods must be employed to assure the user he is going to realize his stated functional requirements. (Morelock)

• For well-developed robot applications, the evaluation of the device can be made by demonstration in an actual manufacturing environment. For new developmental equipment the specification of equipment design must be in terms of task need; and design must be proven by final task performance. The user must be intimately involved in design work, and must communicate with the vendor in terms of detail design parameters. Cooperative preliminary design work is necessary to reach consensus on whether the development is worth the risk. (Grundmann)

• Now we <u>are</u> talking apples and oranges. New development areas will nearly always require a different set of evaluation criteria. First time user guidelines, if established, should therefore be kept general enough to allow for variation in the specific requirements of a particular application, even within the same area of use (i.e. die casting or spot welding, etc.). (Hanify)

• New developments need not meet application constraints if evidence exists to suggest that simple proven changes will enable the manipulator to meet applications area needs. (Paul)

• Yes and no. Wherever possible, it would be good to use common tests, but new developments may make some tests obsolete. (Albus)

4.3.2. Other respondents said "no" to this question or qualified their answers by discussing how new developments shade into proven applications.

• No. (Wicker)

• I don't believe they should. Hopefully the list developed for item 1 would be broad enough to cover all such conditions. Certainly users would require their own evaluative procedures in any event. (Roth)

• My basic reaction is to consider extending whatever methodology we currently have to new applications as they appear. Perhaps some basic research should be extended into the area of measuring "smart" robots" which will be alogical future development. I'd rather see the funds expended on the technology vs. measurement. The converse is somewhat a case of putting the "cart before the horse". (Pesch)

• Eventually new developments must come under the same scrutiny as off-the-shelf items or tried-and-true items in order to make decisions on comparable data. One difficulty which may occur is in deciding the time when new developments become of age and will be considered and evaluated by the proven item set of criteria. (anon.)

• There is a continuum of tasks from research to application to specification to procurement acceptance tests. This is probably the order in which they will develop (i.e. the capability is first demonstrated by researcher and finally prescribed by user). This seems a natural evolution (noting that the researcher/designer will also be looking to the user for candidate tasks). As tasks accomplished are used to illustrate the particular capabilities of various designs, they become the appropriate description of that tool, i.e. appropriate to the user for specification:

Suggested Continuum of Tasks for Performance Evaluation of Robots/Manipulators

(Task specification should be independent of manipulator or robot type/design. Task performance is the proper evaluation of the design.

Example: TASK: move object held in end effector to all possible positions and orientations.

PERFORMANCE: those positions and orientations depicted in appropriate (standard?) form, e.g. maps of positions reached and solid angle of orientations at each point (figure of merit, a la Kobrinski)

1. (RESEARCH) DEMONSTRATION TASKS (a la Paul, Engelberger's RESUME)
   -assemble water pump, turn crank, solve "Instant Insanity"...

2. COMPLEX TASKS (a la Vertut, Mullen, Pesch, Ferrell)
   -pick and place, stack, follow straight line, etc. (used in comparing competitive TOOLS)

3. ELEMENTAL MOTIONS (a la Engleberger, Lynch, McGovern, Pesch)
   -reach, position, grasp, etc. (used in predicting performance on more complex tasks)

4. MECHANICAL CHARACTERISTICS (see example above)
   -speed, accuracy, work envelope, backlash (these should all be stated in terms of specific tasks, i.e. standard tests, and NBS could create such a set of standard tasks. (Verplank)

4.4 Question 4

What institutional arrangements should be made to achieve equitable evaluation and communication of results? Who should do the testing (producer, consumer, government, independent testing agency or consultant, other)?

4.4.1.
Most respondents felt that the free marketplace had perhaps the most important institutional arrangement to effect the desired result, but that the government and professional societies had special roles to play which could certainly help:

• The implementation of testing of manipulators should primarily be governed by the forces in the free marketplace. The definitions and test methods may be developed by universities, government agencies, or other third parties, but implementation (of these tests) is between the user and the supplier in the marketplace. (Group X)

• Much of the evaluation will be user-task dependent and will require a joint responsibility of supplier and user in evaluating the ability of the machine to accomplish the particular user-related tasks. There is a role for government or an independent agency to supply some standardization of the terminology and a set of guidelines, or a checklist, so that a prospective user will have knowledge, safety factors and other important variables involved. User can either ignore or specify them in some detail according to how important they are in relationship to accomplishing his particular set of tasks. (Group Y)

- Society of Manufacturing Engineers, Robot Institute of America, Committees within professional societies, perhaps with NBS (or other government) funding. (Group Z)

- The most suitable professional societies should become aware of the needs discussed here and be provided a suitable incentive to do something about the initial groundwork and guidelines which are needed. Upon a sufficient development of these guidelines, more formal adoption of them may or may not be desirable and efficient and probably should not be decided at the present time. (Morlock)

- Probably the supplier and user should both do the testing, although some independent source, such as NBS, industry association, or even ASME-type organization could create a uniformly-accepted set of definitions that participants could agree on and use for legal precision in contract writing. This could even include some standard task definitions, such as the EPA mileage tests. (Lynch)

- A group such as the workshop participants and the NBS could develop a list of the type referred to in item 1. It would also be worthwhile to develop some standard test tasks. These then could be used by manufacturers as well as users to rate their own machines. Government agencies may be most useful where the interests of third parties are at stake, and where diverse groups of users must be considered. (Roth)

- It's too early to establish standards. Terminology and guidelines could be established by the government for government use but I would strongly recommend the involvement of non-government groups interested in the area such as the Robot Institute of America and the Robot Subdivision of the Society of Manufacturing Engineers, both of which are strongly supported by industries and other agencies (IITRI included). Specific work tasks too big to handle by committee would have to be funded by someone (NBS?) to gather data, formulate strategies and recommend alternate courses of action. (Hanify)

4.4.2.

A few individuals were skeptical that government or special agencies could accomplish much of anything by way of standardized testing:

- I see no need for institutional arrangements that do not arise naturally. It is fine if a testing agency can justify itself to industrial client. Fine, if a government agency can provide a respected service to client agencies; for example, NBS under the Brooks Act serves the government through the output of this workshop. Producers are already motivated to provide test data in order to sell their products. Users who perceive a possible benefit from using robots are disposed to evaluation testing. Unfortunately, they are not motivated to disseminate results. (Engleberger)

- Not only is performance difficult to discuss but the government or independent testing agency would make this process even more remote. (Anon.)

- I believe the marketplace will basically determine this issue. For proven applications, the producer will give the data; for development, the consumer will carry out acceptance testing. (anon.)

- Apart from a need to define terms used in manipulator specification (backlash, friction, etc) current institutional arrangements are fine. (Paul)

• This is really up to the consumer at this stage until the field studies indicate that the consumer requires protection. (Pesch)

• My immediate and personal view, being a consultant on such programs, is that you just let me keep on truckin'. (anon.)

• This question is answered in question 1 - in the attached specifications used by ORNL for purchase of remote handling equipment. (Wicker)

4.5 Other Issues

There were a few additional written comments not in response to the above four questions. Two other issues were raised:

• 1. Safety. This may be a valid problem that would generate third party instrusion in the marketplace by government or labor unions. Possibly some group such as this workshop should consider developing safety criteria before they are formulated and implemented by non-technically competent parties. (anon.)

• 2. Desired improvements in robot or teleoperator capabilities. A list of realistic engineering advances could be formulated by such a group as this to spur and guide future development efforts. (Group X)

• While not on the agenda, one could suggest that it is a higher order activity to invent than it is to specify or evaluate. The workshop participants could have taken on the assignment of cataloguing inventions needed - such catalog disciplined by an understanding of the state of impinging technology. (Cybernetics article, by way of example, will be submitted.) (Engelberger)

EVALUATION OF TOOLS AND TASKS: REFLECTIONS ON THE PROBLEM OF SPECIFYING ROBOT/MANIPULATOR PERFORMANCE

Thomas B. Sheridan

Massachusetts Institute of Technology

Cambridge, MA 02139

This paper examines some basic questions of evaluation of programmable general purpose machines performing complex tasks. It begins with some assertions about evaluating anything. It continues with some views on why evaluating manually operated manipulators and programmable general purpose robotic machines is particularly difficult, mostly because of a confusion over the differences between "tasks" and "tools". It goes on to suggest ways of breaking this performance evaluation problem down, and dealing with it both in pieces and together.

I. What is Evaluation?

Evaluation is assigning value, i.e. degree of goodness (badness) to things or events. It is appropriate to ask what specifically is assumed when we talk about evaluation. Below are some axioms I proffer in this regard.

(1) Scalar "objective function"

Value is a scalar function of all relevant variables within the system being valued. For example, one can assign value to either manipulator speed or accuracy independently, and quit here. But if speed and accuracy are to be valued in the same terms, one necessarily must have a single dependent value function of the two variables. Such an objective function then yields sets of indifference curves or compromise functions. On a plot of two independent variables (e.g. speed vs. accuracy) these are lines of constant value. For three independent variables a constant value magnitude is a surface. I used to know a colonel who insisted that he wanted the maximum performance at the minimum cost. If I hadn't been a lieutenant at the time, I would have told him he was talking nonsense. We hear it all the time, however: "the greatest good for the greatest number", etc.

(2) Subjectivity of value assessment

Ultimately, the assignment of goodness or badness is the subjective judgement of a person. There can be an algorithm or an objective function, and in back of that another objective procedure, and so on, but ultimately it all must be predicated on a subjective order of preferences, or an internal or ratio scale of goodnesses. Number of products, man-hours, dollars, etc. must ultimately be transformed to a subjectively produced utility scale which has no physical dimensions. That is, "objective function" is subjective.

(3) Ordinality or non-ordinality of transformation

An objective function, a transformation from a physical dimension to a utility dimension, can be ordinal or non-ordinal. For example, more manipulator accuracy and more strength can always be better, all other things being equal; this is an ordinal transformation. But larger size can be better up to a point, then progressively worse beyond that point. The latter non-ordinal transformation is called a "folded-scale" by psycho-physicist Clyde Coombs. It makes analyses more difficult.

(4) Operationality of choice process to permit comparison

The evaluation of music, sex and some other things may be private affairs, judgements of individuals which are of no business to other persons (beauty is in the eye of the beholder, etc.). But when an evaluation is the proper business of a community of people, and where it is desirable to have common agreement (social choice) on the relative worth of certain things and events, the procedure and/or reasons leading up to one person's subjective judgement should be as operational as possible. That is, there should be some basis for explaining how one arrived at his judgement which is open and understandable to other persons in the community so that they can have discourse, test their assumptions against one another, and perhaps come to a consensus.

(5) Impossibility of social choice which is both equitable and reliably transitive

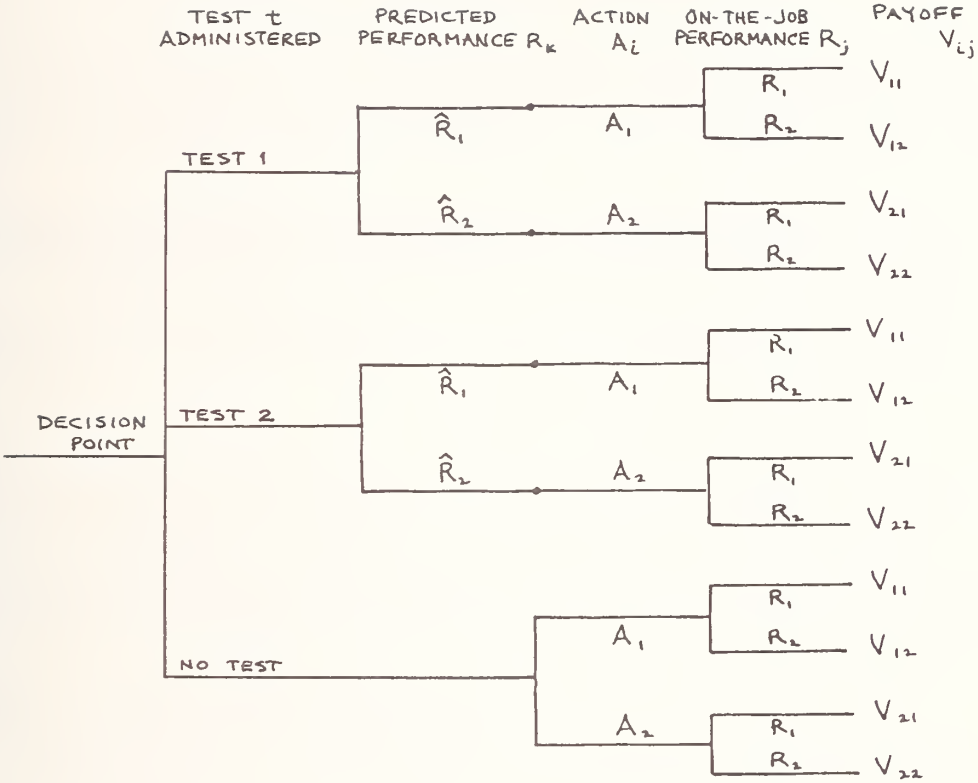
Let three machines - A, B, and C - be preference ordered by three judges. Judge 1 orders them A, B, C. Judge 2 orders them B, C, A. Judge 3 orders them C, A, B. Applying majority rule, the social choice is $A > B$, $B > C$, and $C > A$, which is inconsistent (intransitive). This is but one example of the problem characterized by Arrow's impossibility theorem, which formally proves that given some reasonable assumptions of fairness in judging preference order, there is no procedure which yields a fair social choice without intransitivity some of the time. If one considers worth assessment on a continuous (cardinal utility) scale, there are other theories about the impossibility of insuring that one person's scale is commensurate with another person's scale. Thus, given that in a democracy we feel obliged to come to some social choices, there are times when either we allow partial intransitivity or disagreement, or we allow arbitrary means to be employed to resolve intransitivity or disagreement.

(6) Imperfect simulation of a future context

Usually the purpose of making an evaluation of past (present) performance is to predict performance in the future. However, the circumstances of the future are likely to be different from those under which the evaluative data were measured. This is especially true if what is being evaluated has not yet been put in its "real working environment". In this case it is typical that the eventual "real working environment" is simulated. But simulator tests are usually deficient both because it is too expensive or impossible to include all the relevant variables in the simulation and because some of the most significant future conditions cannot be anticipated. Thus, when a design for a machine is optimized based upon performance in a simulator, it is often suboptimal relative to its performance in the "real world". For this reason factors of safety and benefit/cost discount factors have become common practice in the interpretation of evaluations of prototypes in laboratory tests.

(7) Economic compromises in doing evaluation

Evaluation, like all other activity, has its cost. So there is always the question of how much effort should be expended to make an evaluation, at what point the marginal benefit is less than the marginal cost. There is a way of deducing the relative benefit of evaluation activity itself if one can specify approximately: the costs of making different kinds of performance tests C_t in simulated conditions; the probabilities of $p(\hat{R}_k|R_j)$ of getting different results $\hat{R}_k$, given the eventual on-the-job performance R_j; the costs of various actions which one might take C_i; the probabilities of different levels of performance on the job $p(R_j)$; and the eventual benefits or payoffs of having certain performance under various conditions of deployment, V_{ij}. Figure 1 illustrates the decision tree for manipulator evaluation in a simple case of deciding whether to do no test and evaluation before deployment action, do a simple performance test, or do a more complex performance test. For simplicity of illustration, there are only two test outcomes, two alternatives for action which depend upon test outcomes, and two levels of eventual performance in the real world. The calculation of the information value preposteriori (i.e. what is the test worth before I know the test results) is



EXPECTED BENEFIT WHEN USE TEST t $= \sum_K \left\{ \max_i \left(\sum_j p(\hat{R}_k | R_j)\ p(R_j)\ V_{ij} - C_i \right) \right\} - C_t$

EXPECTED BENEFIT WHEN USE NO TEST $= \max_i \left(\sum_j p(R_j)\ V_{ij} - C_i \right)$

THE DIFFERENCE BETWEEN THE TWO EXPRESSIONS IS THE DIFFERENTIAL PAYOFF OF THE TEST ITSELF

Figure 1. Calculating the expected benefit of alternative tests or no test at all

given in the figure. This "evaluation of the evaluation" gives a rational basis for deciding which test to make, if any.

II. Special Problems of Evaluating Programmable Robots and Telemanipulators

The ultimate evaluation of a robot or manipulator is not the marketplace, but the subjective judgement of history. In the somewhat shorter run, however, the marketplace, whether in terms of commercial sales or government project approval, is the prime evaluation.

In the development of complex expensive technical systems of any kind, there are various stages of test and evaluation which necessarily precede the market test. One may say these are for the purpose of predicting both market performance and judgement of history.

The following are three problems which make evaluating robots and manipulators especially difficult at these early stages:

(1) The problem of evaluating something which is "general purpose"

The designer or manufacturer of a programmable robot or manipulator asks the question, "What, specifically, should it be designed to do?" The answer may be a wry smile, an evasive "we don't know yet" or a not-so-helpful generality such as "everything the human worker can do, only faster and with greater precision". The designer is left frustrated, since rational design tradeoffs demand precise specification of the objective function or performance criterion.

Similarly, the purchaser or user of a programmable robot or manipulator has a problem. He is not clear on how to decide which available system is best for him, for he doesn't know how best to specify what he needs. If he specifies required performance in terms of the most recent or the present task as he understands it, and the robot is designed specifically for that task, it is not likely that the robot will be adaptable to other tasks in the future, nor that it will perform well with respect to aspects of the task he does not presently understand well enough to specify. Alternatively, the purchaser can specify for procurement in terms of some "worst anticipated case", e.g. "pick-up the (heaviest) object in the (most arbitrary) location and orientation, move it (in the least time) and make the (tightest tolerance) assembly to another object (whose position is poorly known)." However, requiring that the robot be designed as though it is to work regularly at this rare simultaneous extremum of all the performance variables is likely to be naive economically. In those rare cases of an extreme in terms of one variable (weight or speed, etc.) some other variable may well be able to give, and the greatest pay-off is likely to come with a system designed primarily for the kinds of jobs it faces most often.

What the purchaser/user and the designer/supplier need is a more explicit basis for communicating, some better framework in terms of which the one can say what he needs and the other can say what he can provide and both can be held accountable for what they said.

(2) The problem of evaluating the machine without the man

Programmable robots and manipulators are relatively general purpose tools, intended to be adapted to a variety of future tasks in ways limited primarily by ingenuity of their programmers and human operators. This dependence upon programmers or human operators aggravates the problem of specifying performance of devices yet to be built or of evaluating performance of those already built.

Can the devices be evaluated apart from their programmers/users? The answer must be a partial yes and a partial no. The problem is not unlike that of evaluating the performance of an aircraft apart from its pilot.

The aircraft can, for sure, be evaluated independently in terms of the limits or envelope of its performance when "properly operated" - speed, altitude, climb, gross turn and stall characteristics. But then there are other characteristics which have meaning only in terms of a closely coupled man-machine control loop. That is, the control or "handling quality" (for flying nominal maneuvers with random disturbances) can only be solved if the pilot is characterized quantitatively in terms of the same variables as are used for the aircraft. There has been considerable progress in this direction, and quite satisfactory mathematical models now exist, differential-difference equations in few variables.

Of course, these "objective" performance equations are only part of the story. Methods for determining pilots' subjective ratings of handling qualities as a function of the aircraft's control system parameters are now relatively refined and often used.

Perhaps the same approach should be taken with robots and manipulators, evaluation in terms of: 1) gross performance parameters of the machine only, operated/programmed by experts or under ideal conditions; 2) combined man-machine performance based upon nominal-task simulator tests or in-situ tests using ordinary operators in the hot lab or mine, shop-floor reprogramming, or actual working conditions; 3) subjective ratings by users correlated with system parameters.

(3) The problem of confusion between "tasks" and "tools" in specifying and evaluating

Perhaps the most important "special problem" concerns what may be called the "task-tool problem", and has to do with whether one's viewpoint is of what needs to be done (task) or what is needed to do it (tool or instrument). It is the difference between predicate and subject. It may even have roots in the classical mind-body and yin-yang dichotomies. The point is that you need both tool and task, tool to do and task to be done, to make sense. Viewing from one side alone gives only part of the picture. In order to deal properly with evaluation, one first has to specify what is the task and/or what is the tool.

Specifying the task alone. On the task side (Figure 2) one starts with a product specification, a description of physical configuration which one wants to achieve. The product specification is of the desired central tendency as well as the variability (tolerances), perhaps with differential value given for products whose dimensions or performance or reliability approaches the ideal.

There may be many different ways to produce the product. They will probably involve the steps of: 1) storage/transport; 2) materials processing; 3) assembly; 4) test/inspect. These are the gross necessities of the task. Considering, for example, an industrial assembly task, it is clear that for specification of the initial condition (as assembly begins) size, shape, position and orientation (and other attributes) of the two or more parts to be assembled must be characterized probabilistically. The same is true of the specification of the final conditions - what the subassembly must end up to be - but with hopefully a lot tighter relationship between parts.

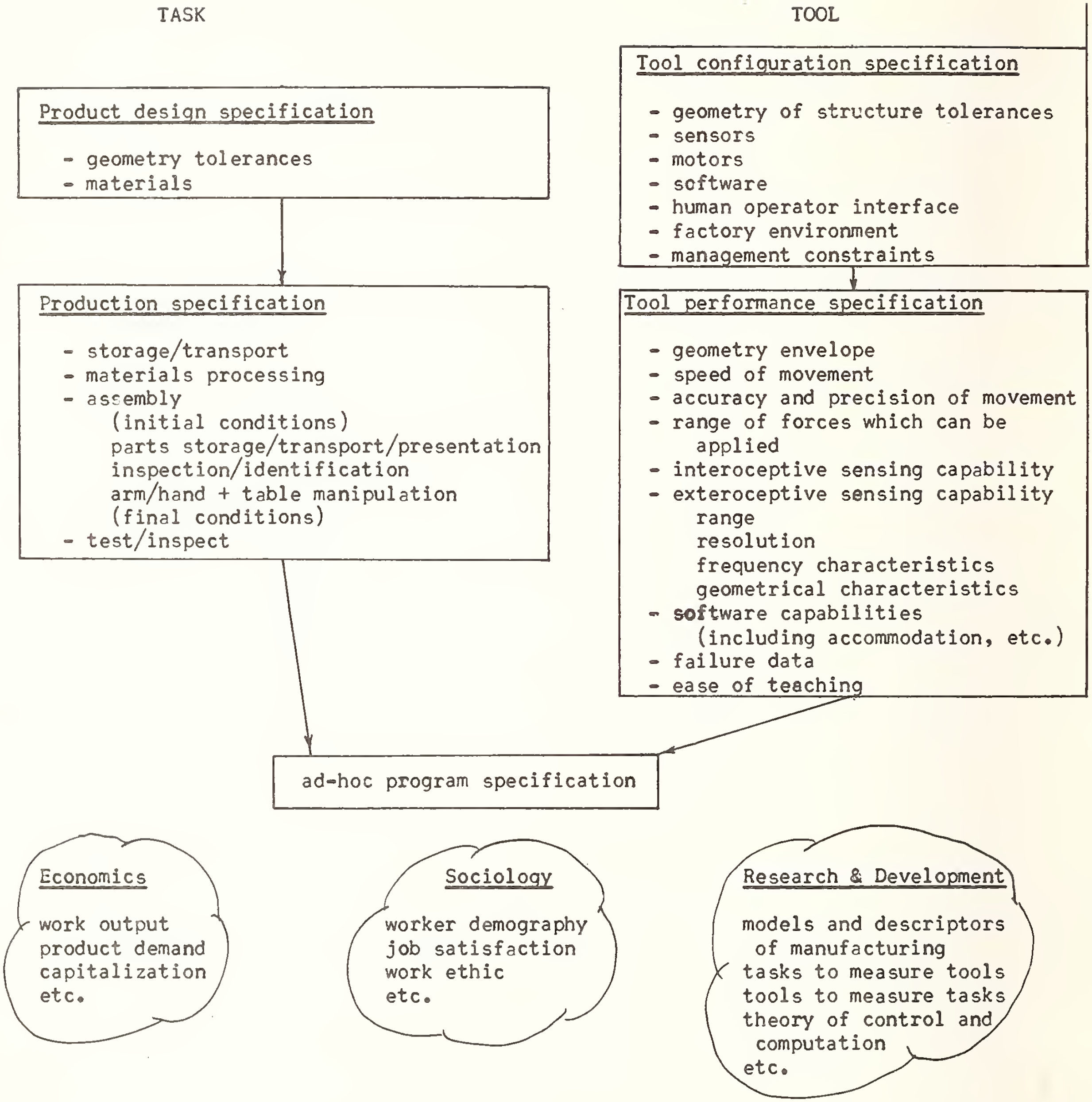


Figure 2. Relationships between task and tool

Between the initial and final conditions of a particular subassembly task lie the assembly task operations required. All the steps here more or less fall into one of three categories: 1) parts storage/transport/presentation; 2) inspection/identification; 3) manipulation of one part relative to others (not necessarily in order). Constraints on 1) and 2) may be determined by a given factory environment, or there may be very few constraints.

One could make a finer breakdown of elements (not shown in Figure 2) into envelopes, or rates through state-space of gross and fine positioning movements and application of force between parts. These are trajectories of the possible ways to put the parts together as constrained only by the geometry and materials of the product design.

Notice we have not yet made anything depend upon the tools (subjects). We have only dealt with tasks (predicates) - what we need done.

<u>Specifying the tool alone</u>. Now let us jump to the other side of the ledger - tools. A robot tool consists of a hardware configuration and a software configuration (and possibly constraints due to factory environment, human operator interface and management or union rules, safety standards, etc.). The hardware consists of sensors, motors, electronics, power transmission mechanisms, supporting linkages, bearings and frame. This is specified in much the same way the product is (materials and geometry) except for the software.

Akin to the hierarchy of required steps (and trajectory envelopes) for manufacture of the product is a similar hierarchy of performance specification of the tool - what it can do (not as before what must be done to it).

Motor performance can be specified by envelopes of possible speed and accuracy (and precision, which is different from accuracy) and load and geometry. Interoceptive sensing (of positions and forces within the arm and joints) can be specified separately, but usually is considered part of motor performance.

Exteroceptive sensing (of positions and orientations of external objects and patterns of externally applied force) similarly can be specified in terms of performance envelopes: dynamic range and resolution in magnitude and time and space. Touch sensors (on the surface of the hand) are always exteroceptors; wrist force sensors usually are if what is being learned is primarily about what is outside and what to do about it.

Specification of software as programs is easy enough, but "performance capabilities" of software must be specified in terms of program limitations (memory, word length, speed for certain standard executions, etc.). Specification of reliability is awkward here except in terms of large categories of failure events.

Accommodation, whether active or passive, is a tool property, though the manipulator may apply and sense forces through a grasped object. It is an integrated and high level activity involving stored program, exteroceptive sensing and interoceptive feedback control of position to proceed in some direction while backing away to relieve forces in other directions. So too are other control strategies which close the loop through exteroceptive sensing: edge following, techniques to center and align a peg with a hole, techniques to align jaws over an object, or to insure that both jaws contact the object simultaneously when grasping, etc.

But, so far in specifying the performance limitations on the tool, we have not had to be concerned with how best to do any particular task.

Selecting and further specifying a tool for a task: ad hoc programming. Both task and tool are usually constrained only to a degree, leaving wide latitude for exactly how the parts are moved or the tool is controlled. Life gets interesting when matching tool to the task or vice versa.

One can have several objectives or motivations in effecting this match. Examples are:

1. Select and augment a given tool (by ad-hoc software) so that it will accomplish a given task.

2. Find the least sophisticated tool to do a given task.

3. Find a most sophisticated task to show off the capabilities of a given tool or software.

4. Change the task so that a given tool will suffice (through product redesign or production technique)

Objective 1 above is expected to be most common. It starts by confirming that the tool is capable of accomplishing the task, i.e. that the set of potential tool capabilities and task requirements overlap in a Boolean sense. Then, one further specifies the tool by programming to implement that potential.

If one has a choice about tool, considering only the given task, one wishes to minimize cost by choosing that tool for which initial cost plus additional programming is minimized (Objective 2).

Objective 3 is to be expected when research and marketing of tools is the goal.

And, finally, objective 4 is where the whole field should eventually be spending much more effort.

Tasks and tools as measures of each other. An obvious point is that one measure of a task is the performance specification of the tool required to accomplish that task. And similarly a measure of a tool is a task. In each case, as occurs in science frequently, the measuring instrument is applied from outside the system. Thus, one might conceive of a standardized battery of tasks by which assembly tools may be graded and compared with one another, or a standardized battery of tools by which tasks may be compared.

III. A Suggested Taxonomy For Specifying/Evaluating Robots and Manipulators

In this section, a taxonomy is suggested for viewing the specification/evaluation problem - a way of organizing the components of "tool" and keeping these separate from "task", and of sorting out the "man" from the "machine", as well as the generality of purpose of the various aspects of evaluation discussed earlier.

Figure 3 shows at left a converging tree of system attributes of "performance to be specified/evaluated" which combine to form (progressively left to right in six stages) larger integral attributes and finally produce the attribute called here "total performance". There is no assertion intended that this is the only set of terms and combinations. It does intend to assert that one might usefully keep in view how, at

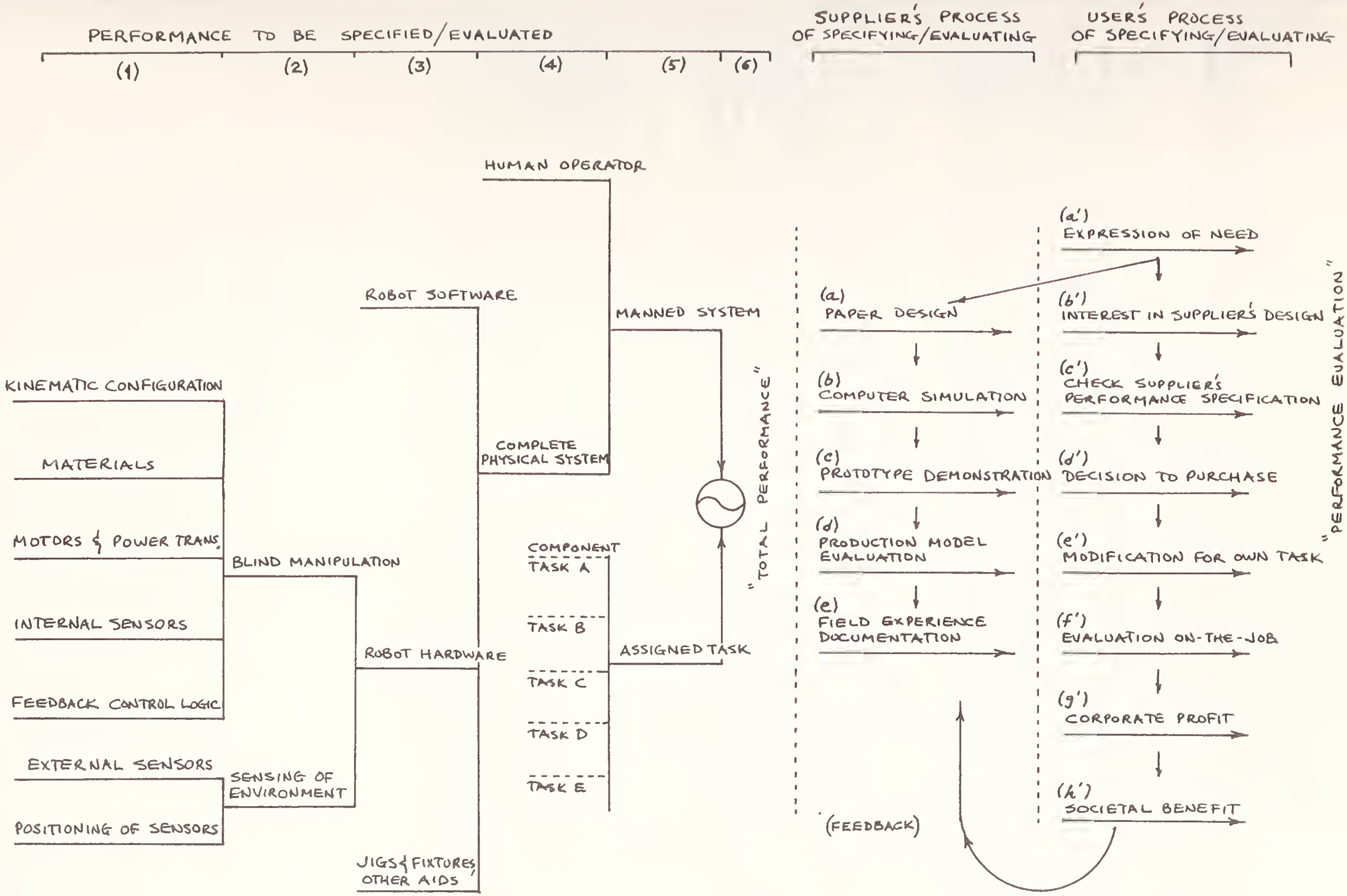


Figure 3. Taxonomy of evaluation of robots/manipulators

each stage (environmental sensing combining with manipulator, robot-manipulator hardware combining with software and environmental aids, complete hardware combining with human operator, and manned system or "complete tool" combining with task) there must be a new objective function for evaluating the combination in terms of the component attribute parameters.

As indicated at the right of Figure 3, there are two processes by which components of performance or total performance (i.e. pieces or all of the attribute tree at left) become specified/evaluated. One process is that of the supplier of the robot/manipulator, and the other that of the user. Each consists of a temporal sequence of steps. The first step (expression of need) by the user sometimes triggers the first step by the supplier, sometimes not. Typically, at any one time the supplier has advanced further with the specification/evaluation steps than the user. The supplier is usually quite interested in learning the results at various user steps, for these tend to change the supplier's specification/evaluation. This is suggested by the feedback loop.

At any given lettered stage of either supplier or user, specification/evaluation of any combination of attributes of the attribute tree can be characterized by a number and letter. Some examples are given in Table 1. Some of these are specifications or tests of raw limits on performance (of materials strength, torque output on motors). Others might be relatively simple calibration tasks where several hardware subsystems cooperate but without software or human operator. Still others might require the complete programmed or human operated system performing a battery of "robot I.Q. tests". Some might concern early stages of design and development. Others might make sense only at the last stages. Others may be tools designed to measure the difficulty of tasks.

There are additional questions which are concommitant with developing satisfactory means for specification/evaluation of tools and tasks within a particular application area. The first is whether a test in that one application area can be generalized to the others, perhaps to all robot/manipulator applications. The answer to that question will best be answered by experience and consensus after some further effort. The second question is what kind of institutional arrangement is most appropriate for promoting improved and perhaps standardized procedures for communicating results to the interested community, and possibly even for administering tests. Should there be a government agency, a not-for-profit agency analogous, to the Educational Testing Service) or no agency at all - leaving the problem primarily to negotiations between supplier and user? Hopefully, the resolution of this question can come out of our Workshop.

Table 1. Example of Tests

1 a, b'	capability limits (e.g. structural strength of a member, no load angular velocity of a joint, maximum stall torque of a joint, minimum or differential threshold of a sensor, effective stiffness coefficient, gross movement envelope)
2 d	calibration task (e.g. hold end effector position constant against varying force, move end point in arbitrary straight line, move as quickly as possible and hold within end point tolerance)
5 c, d'	general "I.Q." test (e.g. stack blocks as rapidly as possible, assemble certain size peg and hole, follow surface and maintain contact with maximum speed)
6 d	perform some real undersea, hot-lab, or industrial task
4 g	satisfy fail-safe criteria (e.g. shut off and hold when servo error suddenly gets large, avoid destructive collision with suddenly appearing obstacle)
1 f	assess promise of new transducer concept (subjective assessment of usefulness in various design applications)
5 a a'	difficulty of task (e.g. capability of a given robot to perform task as more and more degrees of freedom are locked out, accuracy of position sensor or servo gain required to complete assembly)

PERFORMANCE EVALUATION OF MANIPULATORS FROM A KINEMATIC VIEWPOINT

by

Bernard Roth

Department of Mechanical Engineering

Stanford University

Stanford, CA 94305

ABSTRACT

The number of links and joints, as well as their types and sequence, determine the kinematic geometry of a manipulator. In this paper it is shown that it is possible to predict aspects of manipulator performance from this geometry. The effect of manipulator geometry on each of the following is discussed: displacement of the free end, coupling of position and orientation, number of ways to reach a given position, solvability, working spaces, and approach angles.

I. Introduction

The purpose of this paper is to summarize the kinematic theory of mechanisms as it is applied to manipulators. The question kept in mind throughout the writing of the work was: what should the manipulator designer know about kinematics in order to produce the best kinematic configuration? Of course those interested in evaluating a manipulator or enunciating standards of good design would require the same knowledge. This work represents a first attempt to bring together material which ranges in age from two days to two hundred years. Much is known, and yet throughout this writing I was aware of many still unanswered questions. Kinematics is today a rather active field, so I ask the reader to keep in mind that what was unknown on August 17, 1975 may no longer be so when this work is read.

The term kinematics as used herein is in reality geometrical kinematics, i.e., we are interested in those properties of the manipulator motion which depend only on the geometry of its construction. We do not deal with properties which depend upon the time duration of its movement; such properties are properly treated from the view-points of manipulator dynamics and control. No mention is made of force (although static forces and moments are closely related to geometrical kinematics, and perhaps should have been included).

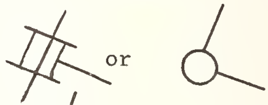
II. Kinematic Notation

From the kinematic point of view, notation is very important. Manipulators are commonly described by names (e.g., Unimate, Scheinman Arm) which carry no kinematic information. Even such descriptions as elbow flexion and wrist rotation are often ambiguous and sometimes meaningless. The same criticism can even be leveled at such "scientific" standbys as pitch and yaw. What we seek is a standard notation which does not rely on a manipulator being analogous to the human arm, or its free end moving along special directions, or any restrictions other than those imposed by the design itself. With this in mind, a meaningful kinematic notation for manipulators is the one commonly employed by spatial mechanisms.

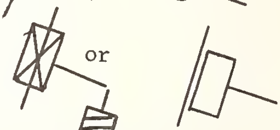
The kinematic notation gives the following information about the linkage: the type of joint between each link, and the order in which the joints are connected. Associated with this notation is a set of parameters which give the kinematic dimensions of each link.

The notation is based on a single capital letter representing each joint. The following are more-or-less standard:

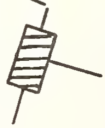
R - for revolute joint, symbolically



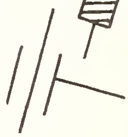
P - for prismatic joint, symbolically



H - for helical, symbolically



C - for cylindrical, symbolically



S - for spherical (or G - for globoidal), symbolically

F - for flat planar, symbolically

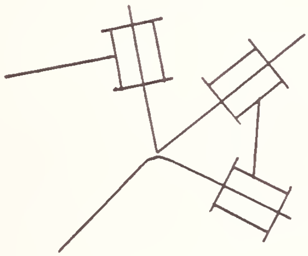
These joints are used to join rigid bodies, called links, in such a way as to allow relative motion between the members at the joint. The R joint is a simple hinge. The only possible relative motion between the paired members is a rotation about the joint axis. This is the most commonly used joint in manipulators. All members joined in this way can easily be driven by any type of rotary actuator (motors, vane type, gear type). Also pulleys and gears work naturally with R joints. The joint is formed basically from one (or two) cylindrical holes and a matching cylindrical rod (usually bushings or bearings, and end retainers are also used but these do not affect the (ideal) kinematic behavior).

The second most commonly used manipulator joint is the P joint. This is a simple sliding joint in which no relative rotation occurs between the jointed members. The only relative motion is a pure (rectalinear) translation along the slide direction. This joint is useful in connection with linear actuators, since no conversion to rotation is necessary. The name prismatic comes from the cross-sectional shape of the joint which usually has a prismatic shape in order to prevent rotation. A common shape is a rectangular tongue-and-groove arrangement.

The other types of joints are rarely used in manipulators because they are difficult to power. However their effects can be obtained by special combinations of R and P joints. The H joint acts like a screw-and-nut arrangement. It can be substituted for by a coaxial R and P joint with a constant ratio of rotational to translational displacement, but even in this form it is not generally used in manipulators.

The C joint is in effect a revolute without the end constraints, i.e., sliding takes place along the revolute axis. This joint can be formed by a coaxial R and P joint, and it is in this form that it generally exists in manipulators. The R and P are independently powered and controlled. We will use the symbol $\widehat{RP}$ (or $\widehat{PR}$) to denote that the joints are coaxial and function therefore as a C joint.

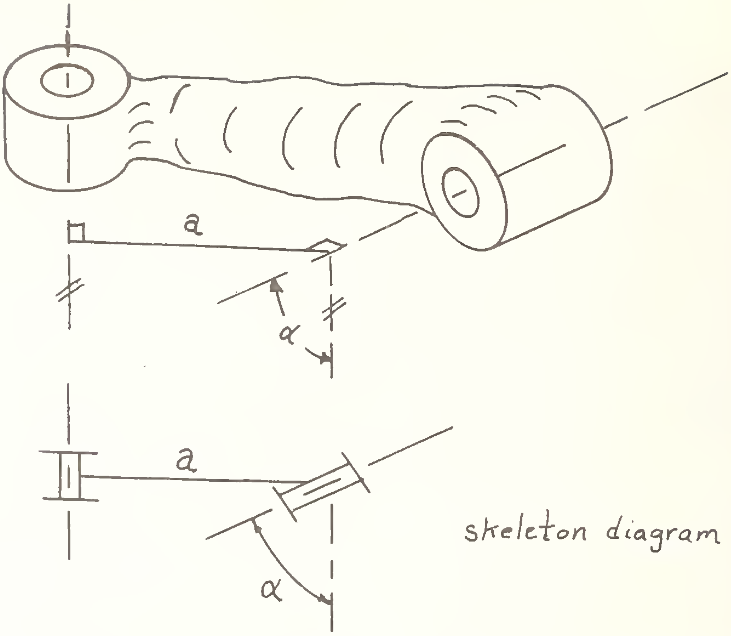
The S joint can be formed by a spherical ball-and-socket arrangement. The relative motion is spherical which means that all joints remain at a fixed distance from the center point of the joint. In manipulators the effect of this joint is obtained by three non-coplanar independently powered R joints. These joints are each connected to one of the others and are aligned so that their axes always intersect at the point which is to act as the center of the S joint. We will use $\widehat{RRR}$ or the symbol $\widehat{3R}$ to denote such an arrangement. Symbolically we will show it as:



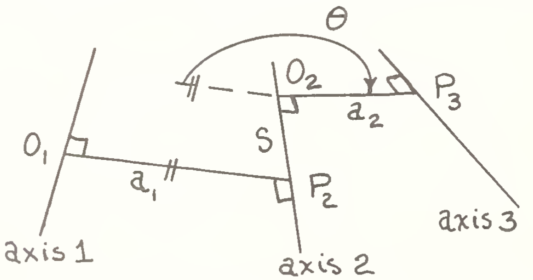
The F joint can be thought of as two flat planes sliding and turning on each other. For manipulator purposes it can be constructed as two non-parallel P joints and an R joint perpendicular to the directions of both P joints.

There are other possible joints, but those above are the most important. In this paper we will treat configurations with R, P, $\widehat{RP}$, and $\widehat{3R}$ joints.

The only significance of links (i.e., rigid bodies), from a kinematic perspective, is that they maintain fixed configurations between their joints (and also their other points and lines). In manipulator work we are usually only interested in the joints. Hence, the dimensions of a link with, for example, two revolute joints are kinematically significant only in so far as they fix the relative positions of the two revolute axes. The important idea here is that regardless of the actual location, shape, or size of the physical link it may be completely represented by the skeleton diagram shown below. Its only two significant (kinematic) dimensions are, a , the shortest distance between the R axes, and, α , the angle between the axes in a plane perpendicular to a. It is customary to call a "the length" and α "the twist" of the link.



Generally two links are connected at each joint axis. This axis will have two perpendiculars to it: one for each of the links. The relative positions of two such connected links is given by their distance, S, along the common axis, and their angle, θ , measured in a plane normal to this axis. S and θ, are called respectively the distance and angle between adjacent links. The sketch illustrates these ideas.

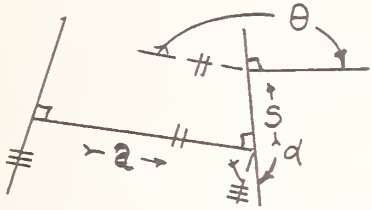


Here there are two links. Link 1 has axes 1 and 2, and link 2 has axes 2 and 3. Their lengths are a_1 and a_2 respectively.
The distance between link 1 and 2 is S, it is the directed distance P_2O_2.

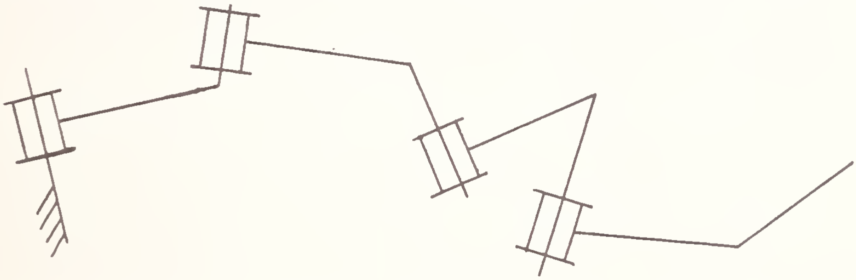
The directed angle from P_2O_1, to direction O_2P_3 is θ. It is customary to use a single subscript to associate S and θ with a given axis; we have in this sketch S_2, θ_2, both measuring the position of link 2 relative to link 1.

The symbol of the joint type (as well as the actual physical actuators) can be placed anywhere along the axis. It is redundant to use more than one joint of the same type to connect the same two links, hence the joint symbol for axis 2 will usually be placed at either point O_2 or P_2. With this in mind if joint 2 is a R-pair then S_2 is called the off-set (or the bend, or the kink) in link 1, and θ_2 is called the rotation in the joint. If joint 2 is a P joint then S_2 is called the displacement in joint 2. In R joints, θ varies during motion but S is fixed by the construction; for P joints the opposite is true.

The result of all this is that there are four parameters, a, α , S , θ associated with each manipulator link. If we provide a sign convention for each of these we have a (minimal) set of parameters which is sufficient to completely and uniquely determine the kinematic configuration of a manipulator. It should be kept in mind that the parameters come in pairs: two (a, α) determine the structure of the link, and two (S, θ) determine the relative position of a neighboring link.



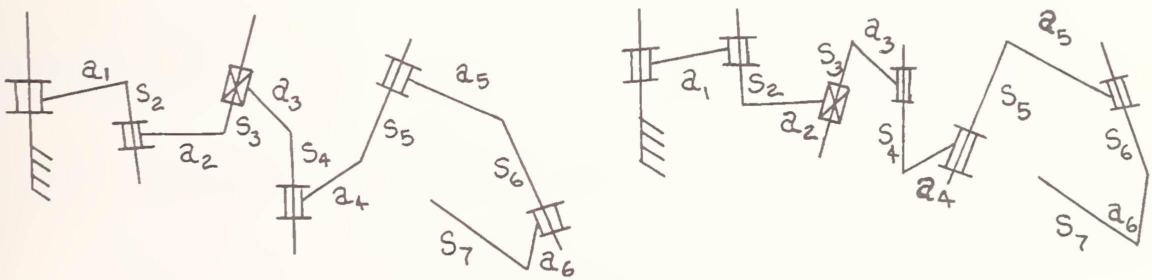
If we add the further conventions that: we list first the manipulator axis fixed to the frame, and then, moving from left to right in our listing, add neighboring joints until we come to the end-effector, we have the basic tools to classify a manipulator's structure. For example, the manipulator shown in the sketch has four moving links, and four revolute joints. Such a manipulator is of type 4R.



All 4R manipulators have roughly the same general capabilities from a kinematic point of view. If their values of α_i, a_i, S_i (i = 1, 2, 3, 4) are identical, they are kinematically identical regardless of their actual constructional details. However, if special values are assigned to some of these parameters (e.g., $\alpha = 0$ or π, or a = 0, or S = 0), some properties of the general type 4R are usually lost. The motion parameters for the 4R are θ_i, i = 1, 2, 3, 4.

As another example, consider a manipulator with a revolute joint between its first moving link and the frame, followed in order by a revolute, a prismatic, and then three revolute joints. The sketch shows this manipulator drawn in two forms which are kinematically identical; its type is 2RP3R, and its structure depends upon

$_1$, a_1, S_2; $_2$, a_2, θ_3; $_3$, a_3, S_4; α_4, a_4, S_5; $_5$, a_5, S_6; $_6$, a_6, S_7.



The motion parameters for this sytem are θ_1, θ_2, S_3, θ_4, θ_5, θ_6.

We have then a notation which allows us to identify and compare different designs from their geometric-kinematic structure. In terms of evaluation two rules will be shown to follow; all other things being equal:

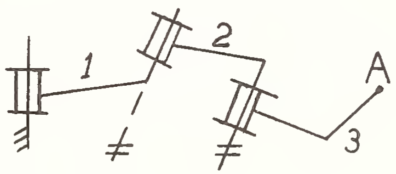
1. The greater the number of joints of a given type the more versatile the manipulator (since it has more freedoms).

2. The greater the number of non-zero parameters, the greater and the more general) the number of possible link and end-effector positions.

The most general six degree-of-freedom systems, with either all revolutes (i.e., the 6R) or with three or more revolutes and the rest prismatic, has 18 kinematic design parameters (for the 6R: a_i, α_i, S_i + 1; i = 1, ..., 6). Most manipulators have six (or less) degrees-of-freedom, and so the study of kinematic manipulator-design-and-evaluation is essentially the study of what happens when we assign specific values to these 18 parameters. For additional freedoms, we gain three design parameters, and one motion parameter, with each freedom. For less than six, we lose three design parameters with each freedom. Basically, for f freedoms we have 3f design parameters, and f motion parameters. In the following sections we discuss the effect on performance due to specialized values of the design parameters.

III. The effect of $\alpha = 0$ (or π)

When $\alpha = 0$ (or π) the link has no twist. Hence, if the two joints are revolutes, the relative motions between its neighboring links must be so-called coplanar motions. This means they always move in parallel planes. In the sketch, link 2 has two parallel R joints.



Holding link 1 fixed, it is clear that all joints in link 3 generate planar trajectories in planes perpendicular to the two parallel R axes. If the two R axes were skew (i.e., $\alpha_2 \neq 0$ or π) then instead of a point such as A being confined to a flat plane its locus relative to link 1 would be a 4th order surface called a scew (or general) torus -- this will be discussed in more detail later. From the point of view of simply maintaining a point of link 3 in a special plane relative to link 1, the use of two parallel R joints is wasteful. Either of the joints is sufficient to give, for example, point A a trajectory in the plane. However, with two parallel joints the point does have the freedom to be anywhere (within a given range) on the plane, while if the axes are skew it can only lie on certain curves (two circles) in the plane.

If one of the parallel joints is prismatic, the relative motion of link 3 to 1 is exactly the same as if the R joint is replaced by a RP (i.e., a C) joint. The trajectories of points on link 3 relative to link 1 are all on right circular cylinders with the R joint as axis. The location of the parallel-axis P-joint is totally irrelevant (from kinematic criteria). If instead of 0 or π, $\alpha_2 = \frac{\pi}{2}$ or $\frac{3\pi}{2}$ then the effective displacement is exactly the same as for two parallel R joints.

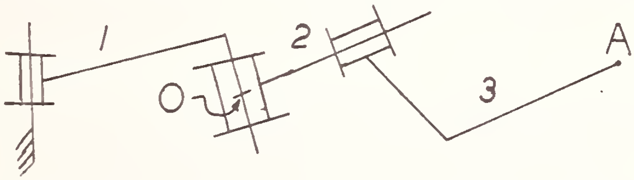
If the two parallel joints are both prismatic, the relative motion of link 3 to link 1 is exactly the same as with one P joint. Hence using two parallel P joints is generally wasteful.

As a general conclusion: Unless special reasons exists (such as limited actuator motion, or special workspace shapes), manipulators should not be designed with no-twist links or with a 90° twist for RP (or PR) links. The result of such designs is simplified and less general relative motion possibilities between the links connected to the parallel joints.

IV. The effect of $a = 0$

If $a = 0$ in addition to $\alpha = 0$ (or π) the two joints coincide, and the link can be considered a null link. Its effect is the same as if we directly join its two neighbors together with a single joint having the same freedom as the original two (now coinciding) joints. In this way we can consider an $\widehat{RP}$ joint as a null link with two one-degree-of-freedom joints, or as a single two-degree-of-freedom C joint.

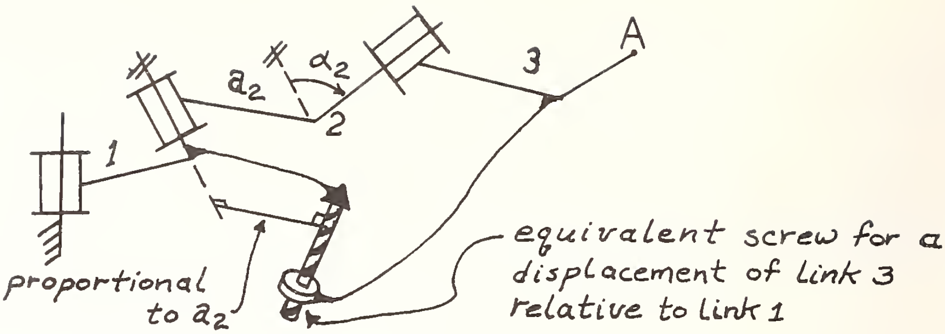
If $a = 0$ and $\alpha \neq 0$ or π, we do have a link; it has the special property of having no kinematic length. If the intersecting joints are revolutes the relative motion is called spherical. This term is used because, as can easily be seen from the sketch, all points on link 3 move so that, relative to link 1, they lie on concentric spheres centered at O, the intersection point of the axes. Also, the relative positions of link 3 are limited to those which can be reached by pure rotations about axes through point O.



For a prismatic axis, $a = 0$ has no special meaning. In fact, a has no kinematic significance when measured to or from a P axis: any P joint moved to any parallel position gives exactly the same kinematic constraints! The same straight line trajectories exist regardless of where the axis is physically located, all that matters is its direction.

V. The general screw displacement

When $\alpha \neq 0$ (or π) and $a \neq 0$, the link is considered to be general. The reason is that with its two revolute joints along skew axes, link 2 can produce a general relative displacement (within the range of its motion) between links 3 and 1. By general, we mean what is usually called a screw displacement. So, any displacement of 3 relative to 1 can be obtained by rotating it about an axis fixed to link 1 (not generally of link 1's joint axes) and translating it along this same axis. (When the revolutes intersect or are parallel this translation is absent, and the rotation axis always passes through the same point.) This axis, along which the translation and about which the rotation occurs, is called the screw axis. Furthermore, the magnitude of the translation along the screw is proportional to $a_2 \sin \alpha_2$. The distance of the screw axis from axis 2 is proportional to a_2 (as shown on the sketch).



Thus, the larger a, the larger the translational displacement associated with any changes in Θ_2 and Θ_3. Clearly, when $\alpha_2 = \pi/2$ we have the greatest translational effect due to link twist.

The value of S_3 for R joints in no way changes the relative displacement for a given change in Θ_2 and Θ_3; it does, however, effect the final position of points attached to link 3.

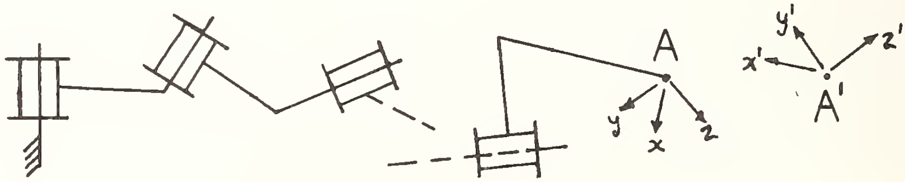
If one of the joints (of link 2) is prismatic the relative displacement will be a screw displacement, but the screw axis will always be parallel to the R joint (of link 2).

If both joints (of link 2) are prismatic, the relative displacement is a pure translation; clearly the values of Θ_2 and Θ_3 do not effect the relative displacement of link 3.

In this and the preceding two sections, we have used the relative displacement of link 3 to link 1 to illustrate how the parameters associated with the joints of a link (link 2 in this case) effect the relative displacements of the links they join. The conclusions are clearly equally valid regardless of where the three links are located in the manipulator chain.

VI. Decoupling of position and orientation

The requirement for locating the free end of a manipulator can generally be stated in terms of its position and orientation. So, as shown in the sketch, we are often confronted with the problem of bringing a point A on the last link of the manipulator into a specified position A', while the orientation of this link, given



by directions x, y, z fixed in it, changes to x', y', z'. In general three degrees of freedom are needed to bring point A into any position, and three other degrees of freedom to orient the last link. It is convenient to speak of these as though they were three translational and three rotational requirements, respectively. Most manipulators however are not constructed to yield decoupled motions. Some however are. The orientation and position do decouple when the last three R joints (toward the free end) have axes which intersect in a common point. In this case these three freedoms essentially determine the orientation and all other joints, be they R or P, essentially determine the position.

A six-degree-of-freedom manipulator with any ordering of three revolute and three prismatic joints has the orientation of its end completely decoupled from the displacement in the three P joints. Moreover, the orientation depends only on the three rotation angles, θ_i, and the directions of the R axes -- their relative locations (i.e., their a's and S's) do not effect the orientation of the last link. Hence the following are identical in regard to orienting the last link:

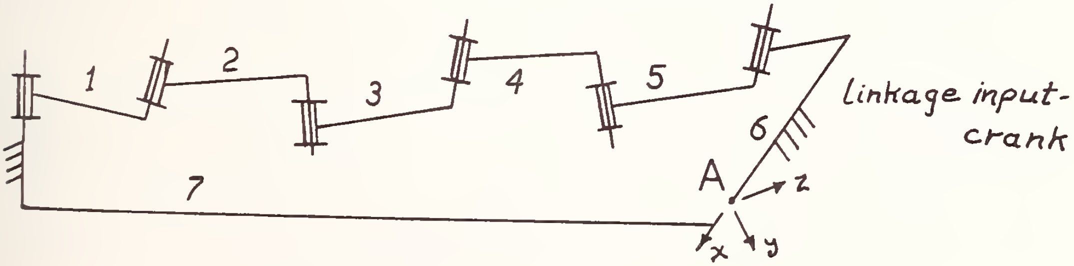
3P3R, 2PRP2R, 2P2RPR, 2P3RP, PR2P2R, PRPRPR, PRP2RP, P2R2PR, P2RPRP, P3R2P, R3P2R,

R2PRPR, R2P2RP, RPR2PR, RPRPRP, RP2R2P, 2R3PR, 2R2PRP, 2RPR2P, 3R3P.

If the first, second, and third revolute axes in each of the above are respectively parallel, the same joint rotations in any of the above yield exactly the same orientations. Also, if the P's are respectively parallel, in any order, between any of the above, the same displacements along parallel P's yield the same displacement for point A. However, unless the R axes all intersect at one point, the locations of the R axes do effect the displacements of A and so the end point trajectories will generally be different for each of the above.

VII. The manipulator as a closed loop mechanism

Knowing the position and orientation of the last link of a manipulator is equivalent to fixing its position in the coordinate system of the frame. This means that in any one position we can regard the last link as being fixed to the frame. As illustrated in the sketch for the 6R manipulator, this situation is identical to the configuration of a closed loop linkage with its input crank in a known (fixed) position relative to the fixed link.



For our present purposes we can ignore the question of what type of joint exists at A; since the position of link 6 is known the joint type is of no interest. Taking this approach we can consider a 6R manipulator, with a known end-link location, as a 7R or a 6RP, (or a 6RX, where X is any joint) mechanism with its input crank (link 6) in a known position relative to the frame (link 7).

This technique allows us to convert a manipulator system with n moving links into a n + 1 link closed-loop linkage. Furthermore, if we know the location of the last link of the manipulator, we know the input crank position (for the linkage) and the dimensions of the fixed link. Using this idea, since we know the number of ways a linkage can be assembled at a given crank position, we can immediately know how many ways a given manipulator type could be positioned so that its last link has a given location and orientation.

All other factors being equal, manipulators with more possible ways to obtain a given end position are better than manipulators with fewer ways. The general rule is that the more general the link parameters the more ways there are to reach a given position and orientation. For example, if we take a 6R manipulator we find that (all other parameters being non-zero):

if $a_1 = a_3 = a_5 = 0$ there are at most four ways

if $a_3 = a_5 = 0$ there are at most eight ways

if $a_3 = 0$ there are at most sixteen ways

if none of the parameters is zero there are - it is believed, although not entirely verified - at most 32 different ways to reach the same position and orientation.

In general using P joints instead of R joints halves the number of possible ways. So, for example, it is believed, although not yet confirmed, that the general 5RP manipulator can reach a given end link position and orientation in 16 different ways. When we go from an RP to an $\overset{\frown}{RP}$ construction, α and a go to zero, and the number of configurations also halve. Thus the 2$\overset{\frown}{RP}$2R manipulator has at most eight ways to reach a location, while the 2$\overset{\frown}{RP}$RP has only four, and the 3$\overset{\frown}{RP}$ has at most two. This halving is not a universal rule, but it is a useful qualitative (if not quantitative) measure of which changes in a design tend to make things better or worse in regard to obtaining more ways to reach a given location.

If we consider six-degree-of-freedom systems, the following list covers manipulators with at most two prismatic joints.

Maximum number of ways to reach a given position and orientation (provided the chain has no zero link-parameters)	Manipulator types
4	$\overset{\frown}{RP}$R$\overset{\frown}{RP}$R, R$\overset{\frown}{RP}$R$\overset{\frown}{RP}$
8	2$\overset{\frown}{RP}$2R, R2$\overset{\frown}{RP}$R, $\overset{\frown}{RP}$2R$\overset{\frown}{RP}$, RP2R$\overset{\frown}{RP}$, 2R$\overset{\frown}{RP}$RP, 2RPR$\overset{\frown}{RP}$, PR$\overset{\frown}{RP}$2R, $\overset{\frown}{RP}$RP2R, $\overset{\frown}{RP}$2RPR, P2R$\overset{\frown}{RP}$R, R$\overset{\frown}{RP}$P2R, 2RP$\overset{\frown}{RP}$R, P$\overset{\frown}{RP}$3R, RP$\overset{\frown}{RP}$2R, $\overset{\frown}{RP}$3RP, $\overset{\frown}{RP}$P3R, 2P4R, P3R$\overset{\frown}{RP}$, 4R2P, 3R2PR, P4RP

12	3RPRP, PRP3R, 2RPRPR, RP3RP, P3RPR
16	2RP2RP, P2RP2R, $R\widehat{RP}3R$, $2R\widehat{RP}2R$
16 (?)	3RP2R, P5R, 5RP, 4RPR
32 (?)	6R

(The question marks indicate that the last two lines contain results which are, as yet, not completely verified.)

The above numbers are for the maximum possible ways to reach a location. For any given manipulator the actual number of ways depends upon the particular location and the manipulator's parameters. Clearly for every manipulator there exist locations which cannot be reached. Hence, the actual number of ways will vary from zero, for locations outside the zones of operation, to any number up the maximum given in the above listing. Generally, the actual configurations exist in pairs, so we can expect 0, 2, 4, 6, ... ways. However, at a boundary of a zone of operation a pair amalgamates into a single configuration, and so odd numbers of actual ways are also possible.

VIII. Solvability

If the motion parameters are given the position and orientation of any manipulator link can easily be calculated. One convenient way to do this is to develop a coordinate transformation matrix for each link and then multiply these matrices to obtain the desired location measured in the coordinates of the fixed frame. In general this is a very simple procedure to execute with even a small computer. P joints are simpler than R joints, but the amount of computation is not significant even in the most general case.

On the other hand, the problem of determining the motion parameters necessary to obtain a given position and/or orientation is still not completely solved. A manipulator will be called solvable if the motion parameters can be determined by an algorithm which allows one to determine <u>all</u> the motion parameters associated with a given position and orientation. This definition implies that we know <u>all</u> possible configurations which allow the manipulator to place a given link in a given location. It seems likely that soon all systems will be solvable. However, at the moment, to be solvable a six-degree-of-freedom manipulator must have at least two prismatic joints, or a $\widehat{RP}$ joint, or two pairs of intersecting R joints. In other words the 5R, 1P combination (with the P in any position in the chain) and the 6R manipulator are not solvable unless they have certain of their parameters equal to zero.

When manipulators are not solvable they can be treated by use of one of several iterative techniques which break a displacement down into a series of small incremental displacements. Of course an iterative incremental-displacement technique can also be used with solvable designs. The major drawback of the iterative techniques is that they generally yield only one of several possible configurations associated with a given location. For certain displacements there also are difficulties in getting the iterations to converge. In addition, iterative techniques are generally more time consuming than computations using the properties of solvability; this is especially true for large displacements.

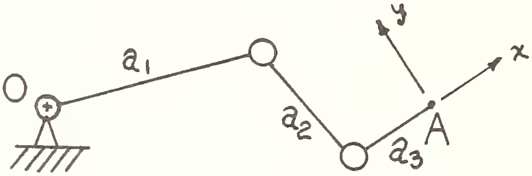
Manipulators with less than six-degrees-of-freedom may be considered as degenerate cases of six-degree-of-freedom systems and so they are all solvable. Systems with more than six freedoms can often be treated as six-degree-of-freedom systems with the "extra" motion parameters chosen either arbitrarily or according to some scheme to make the motion more efficient.

Whenever we use a solvable technique the computation time depends upon the maximum (and not the actual) number of possible ways to reach an arbitrary orientation. Hence, the listing in the preceding section is in order of increasing computation time.

IX. Working Spaces

The spaces associated with possible positions and orientations of the last link of a manipulator can be considered its working spaces or zones of operation. In determining the working spaces we ask two questions: which points can be reached?; at each point which can be reached, what orientations can be obtained? The answers to these questions give a measure of the efficiency of the design. For some designs the answers are self evident, while for others they are extremely complicated.

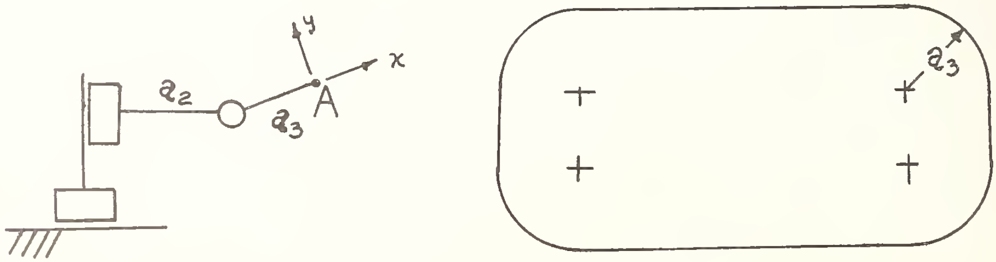
Consider first the relatively simple case of a manipulator in a plane. If we use revolutes, we need a 3R manipulator to cover all possible positional and orientational freedoms of the last link. From the sketch it is easy to see that $a_1 + a_2 + a_3$ will be the furthest distance of A from O, and that $|a_1 - (a_2 + a_3)|$



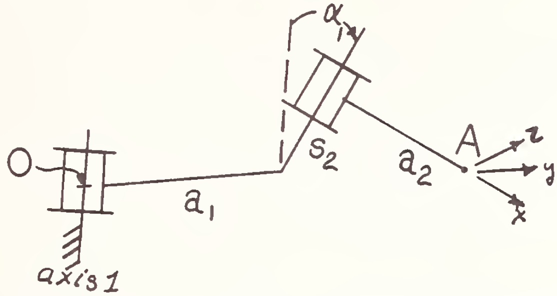
is the closest distance when $a_2 + a_3 \leq a_1$. Hence if we want the maximum possible positional working space within a distance D from O we need: $a_1 + a_2 + a_3 = D$, $a_1 - (a_2 + a_3) = 0$.

The result is that $a_1 = \frac{D}{2}$ and $a_2 + a_3 = \frac{D}{2}$. For orientation, all possible orientations of x, y are possible (but not at every position of A). The result is that we have a manipulator which position-wise totally covers a circular shaped work space, centered at point O, with diameter 2D, but does not at each position have total orientation freedom.

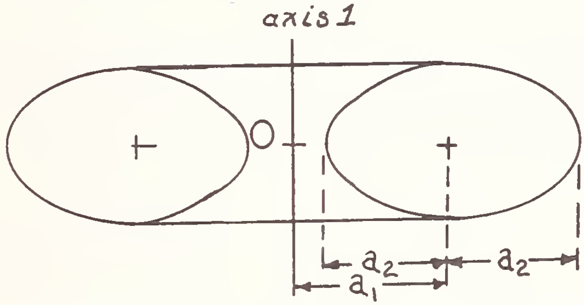
Similarly, if we use a 2PR manipulator in the plane, the workspace can be a rectangular shape with rounded ends; total orientation in parts of the space is possible, if θ_3 can vary from 0 to 2π. Planar RPR, P2R and 2RP manipulators also give combinations of circular and rectangular zones of operation.



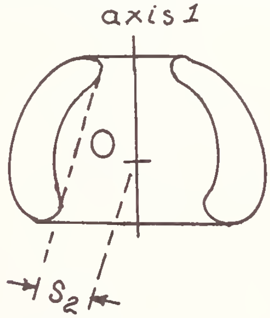
In general we require a six dimensional workspace consisting of three translational and three rotational dimensions. The structure of such a space is very complex. In studying such spaces it is best to start with the relative motion of two links connected by a RR link. For the 2R manipulator shown, A has a workspace which is a fourth order surface called a torus.



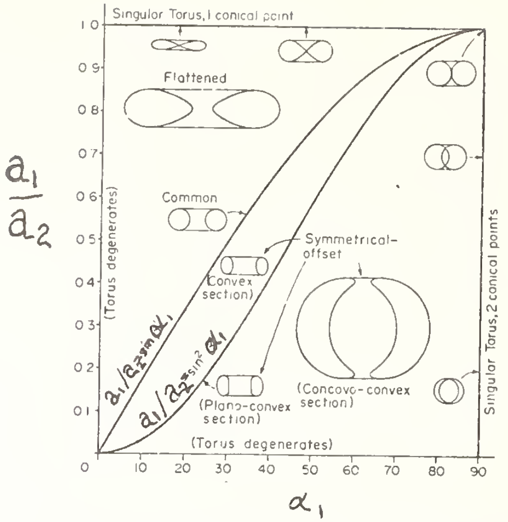
In a plane which contains axis 1 the workspace has an egg-shaped cross section if $a_2 < a_1$ and $S_2 = 0$:



When $S_2 \neq 0$, if $a_2 > a_1$, the shape becomes one with banana-shaped sections.

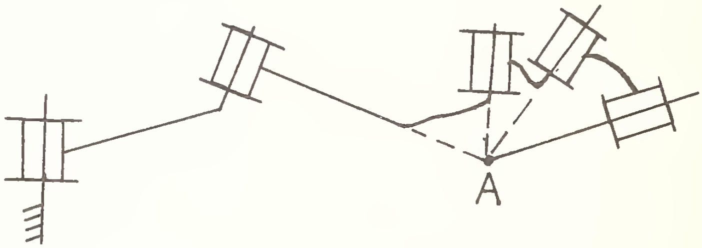


If a_2 is large enough we get overlapping regions. The effect of the various parameters on the shape of the region is shown by the following figures for the case $S_2 = 0$.



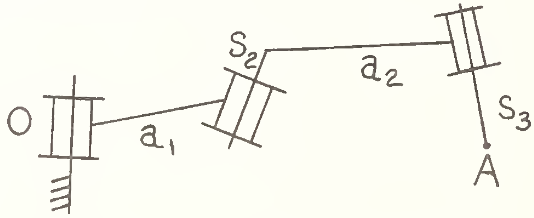
From a structural point of view, it is worth noting that the same torus can be generated, about axis 1, by four different sets of 2R manipulators each having different link parameters.

The orientation (x, y, z-axes) is completely coupled to the position of A. In order to obtain any possible orientation and a toroidal positional space, we need to add three revolute joints which all intersect at the position of A:



The distance D of A from the origin O is given by $D^2 = a_2^2 + S_2^2 + a_1^2 + 2a_1a_2\cos\theta_2$, clearly the extremes are at $\theta_2 = 0$ and π.

We can make this configuration slightly more general. This is shown with a slight change in nomenclature in the sketch. Now D is given by



$D^2 = S_3^2 + a_2^2 + S_2^2 + a_1^2 + 2a_1a_2\cos\theta_2 + 2a_1a_2\sin\alpha_2\sin\theta_2 + 2S_2S_3\cos\alpha_2$, and the extremes occur at

$$\theta_2 = \tan^{-1}\left(\frac{S_3\sin\alpha_2}{a_2}\right)$$

Substituting this value into D^2 we get the conditions on a_1, a_2, S_2, S_3, α_2 for the torus to extend a given distance from 0 and approach within a given distance to 0. If we use a_1 and S_2 to meet these conditions, α_1 and the quantity $\sqrt{a_2^2 + S_3^2 \sin^2 \alpha_2}$ may be used to adjust the toroidal shape.

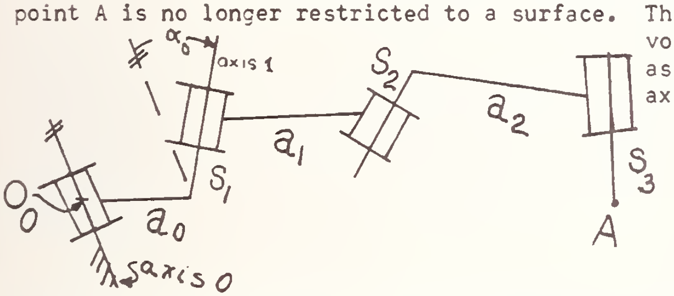
The actual coordinates of point A (with origin at 0, Z-axis along axis 1) are

$$X:\ S_3(\cos\theta_1 \sin\theta_2 \sin\alpha_2 + \sin\theta_1 \cos\theta_2 \cos\alpha_1 \cos\alpha_2 + \sin\theta_1 \sin\alpha_1 \sin\alpha_2) + a_2(\cos\theta_1 \cos\theta_2 - \sin\theta_1 \sin\theta_2 \cos\alpha_1) + a_1 \cos\theta_1 + S_2 \sin\theta_1 \sin\alpha_1$$

$$Y:\ S_3(\sin\theta_1 \sin\theta_2 \sin\alpha_2 - \cos\theta_1 \cos\theta_2 \cos\alpha_1 \sin\alpha_2 - \cos\theta_1 \sin\alpha_1 \cos\alpha_2) + a_2(\sin\theta_1 \cos\theta_2 + \cos\theta_1 \sin\theta_2 \cos\alpha_1) - S_2 \cos\theta_1 \sin\alpha_1 + a_1 \sin\theta_1$$

$$Z:\ S_3(-\cos\theta_2 \sin\alpha_1 \sin\alpha_2 + \cos\alpha_1 \cos\alpha_2) + a_2 \sin\theta_2 \sin\alpha_1 + S_2 \cos\alpha_1$$

If we add an additional link, at the frame-end (called link 0, for convenience) point A is no longer restricted to a surface. The working space of point A is the volume swept out by the foregoing torus as it is rotated about the newly added axis, axis 0.



(We have departed from the usual nomenclature in an effort to make it clear that the torus generated by holding axis 1 fixed is the one that envelopes the working volume.) Hence, by tilting the toroidal axis by α_0 and rotating about 0 we can get any point in the work space; its coordinates, in terms of X, Y, Z given before we added axis 0, and referred to a system with origin at 0_0 and z_0-axis along axis 0, are

$$x_0 = X\cos\theta_0 - Y\sin\theta_0 \cos\alpha_0 + Z\sin\theta_0 \sin\alpha_0 + a_0 \cos\theta_0$$

$$y_0 = X\sin\theta_0 + Y\cos\theta_0 \cos\alpha_0 - Z\cos\theta_0 \sin\alpha_0 + a_0 \sin\theta_0$$

$$z_0 = Y\sin\alpha_0 + Z\cos\alpha_0 + S_1$$

From these equations we can determine the shape of the working volume in terms of its limiting dimensions. For example, the distance from 0_0 to A is

$\sqrt{x_0^2 + y_0^2 + z_0^2}$, while the distance from axis 0 to A is $\sqrt{x_0^2 + y_0^2}$;

differentiating and setting the result to zero yields the extremes.

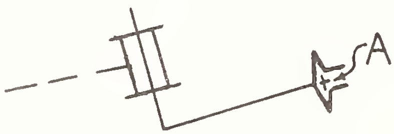
With such a configuration we can reach every point in the working volume. Adding two intersecting R joints at A allows us to reach these points with any given orientation.

As we add generality (or links) the problem of determining the work spaces becomes much more complex. For any given manipulator the results can, in time, be computed and plotted out, but this does not lead to a priori design rules or bases of comparison. The problem in all its generality has never been solved, but many useful special cases have been analyzed. The most fruitful approach has relied on geometrical arguments. Using such an approach, the following table of 120 special 6R manipulators was constructed. The manipulators are identified by their non-zero parameters. Hence, the first one which is listed as a_1S_2 has the following restrictions $a_2 = a_3 = a_4 = a_5 = a_6 = S_1 = S_3 = S_4 = S_5 = S_6 = 0$.

The remark column tells us if the configuration is: Degenerate, D, in which case in addition to being solvable it can be put into an orientation at every reachable position; and whether it has restricted orientation, R, or not, G, within its working volume. Also the letter S or N indicates if a solvable set of analysis equations exists or not.

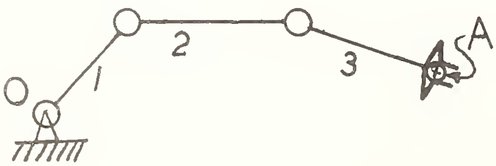
X. Approach Angles

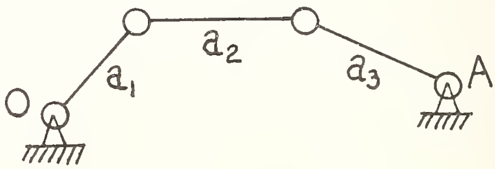
The question of orientation of the last link is intimately related to the notion of approach or working angles. If we assume a "terminal device" (which can only open and close) is rigidly attached to the last link of a manipulator, and if point A is the center of a hypothetical object to be grasped by this terminal device, it follows that the orientation of the link determines the angle at which the object is approached. Furthermore, if the object is stationary, point A can be assumed attached to the fixed frame of the manipulator.



We now return to the earlier concept of the manipulator being equivalent to a closed loop mechanism. However, now instead of the entire last link being fixed, only its endpoint, A, is fixed. There are several possibilities depending on the shape of the object to be grasped. The shape dictates what type of joint we can assume exists at A. It is usually assumed that we have a revolute joint, at A, with its axis normal to the plane of the terminal device's profile. However on occasion a spheric, cylindric, or prismatic joint might be more representative of a given service requirement.

With these concepts the range of orientation of the last link focuses on its useful aspects, namely the angles at which the terminal device can approach an object. Returning to the planar 3R configuration, and using these concepts, we see that the manipulator can be considered as a 4R closed loop linkage, provided we hold the position of A fixed. The question of link orientation then becomes one of determining the range of rotational displacement of link 3 about fixed pivot A. This range can be called





Solubility and Orientation Restrictions in 6R Manipulators

MANIPULATOR	REMARK	MANIPULATOR	REMARK	MANIPULATOR	REMARK
1 a_1s_2	D	16. a_2s_3	D	31. s_4a_4	D
2. a_1a_2	D	17. a_2a_3	S G	32. s_4s_5	D
3. a_1s_3	D	18. a_2s_4	S G	33. s_4a_5	D
4. a_1a_3	S G	19. a_2a_4	N R	34. a_4s_5	D
5. a_1s_4	S G	20. a_2s_5	S R	35. a_4a_5	D
6. a_1a_4	S G	21. a_2a_5	S R	36. s_5a_5	D
7. a_1s_5	D	22. s_3a_3	D	37. $a_1s_2a_2$	D
8. a_1a_5	D	23. s_3s_4	S G	38. $a_1s_2s_3$	D
9. s_2a_2	D	24. s_3a_4	S G	39. $a_1s_2a_3$	S G
10. s_2s_3	D	25. s_3s_5	S R	40. $a_1s_2s_4$	S G
11. s_2a_3	S G	26. s_3a_5	S R	41. $a_1s_2a_4$	S G
12. s_2s_4	S G	27. a_3s_4	D	42. $a_1s_2s_5$	D
13. s_2a_4	S G	28. a_3a_4	S G	43. $a_1s_2a_5$	D
14. s_2s_5	D	29. a_3s_5	S R	44. $a_1a_2s_3$	D
15. s_2a_5	D	30. a_3a_5	S R	45. $a_1a_2a_3$	S G

MANIPULATOR	REMARK	MANIPULATOR	REMARK	MANIPULATOR	REMARK
46. $a_1a_2s_4$	S G	63. $a_1a_4a_5$	S R	80. $s_2s_4a_4$	S G
47. $a_1a_2a_4$	N R	64. $a_1s_5a_5$	D	81. $s_2s_4s_5$	S G
48. $a_1a_2s_5$	S R	65. $s_2a_2s_3$	S G	82. $s_2s_4a_5$	S R
49. $a_1a_2a_5$	S G	66. $s_2a_2a_3$	S G	83. $s_2a_4s_5$	S G
50. $a_1s_3a_3$	S G	67. $s_2a_2s_4$	S G	84. $s_2a_4a_5$	S R
51. $a_1s_3s_4$	S G	68. $s_2a_2a_4$	N R	85. $s_2s_5a_5$	D
52. $a_1s_3a_4$	N G	69. $s_2a_2s_5$	S R	86. $a_2s_3a_3$	S G
53. $a_1s_3s_5$	S R	70. $s_2a_2a_5$	S R	87. $a_2s_3s_4$	S G
54. $a_1s_3a_5$	S R	71. $s_2s_3a_3$	S G	88. $a_2s_3a_4$	N G
55. $a_1a_3s_4$	S G	72. $s_2s_3s_4$	S G	89. $a_2s_3s_5$	S R
56. $a_1a_3a_4$	N R	73. $s_2s_3a_4$	N R	90. $a_2s_3a_5$	S R
57. $a_1a_3s_5$	N R	74. $s_2s_3s_5$	S R	91. $a_2a_3s_4$	S G
58. $a_1a_3a_5$	N R	75. $s_2s_3a_5$	S R	92. $a_2a_3a_4$	N R
59. $a_1s_4a_4$	S G	76. $s_2a_3s_4$	S G	93. $a_2a_3s_5$	N R
60. $a_1s_4s_5$	S R	77. $s_2a_3a_4$	N R	94. $a_2a_3a_5$	N R
61. $a_1s_4a_5$	S R	78. $s_2a_3s_5$	N R	95. $a_2s_4a_4$	N R
62. $a_1a_4s_5$	S R	79. $s_2a_3a_5$	N R	96. $a_2s_4s_5$	N R

MANIPULATOR	REMARK	MANIPULATOR	REMARK	MANIPULATOR	REMARK
97. $a_2s_4a_5$	N R	105. $s_3s_4a_4$	S G	113. $a_3s_4a_5$	S R
98. $a_2a_4s_5$	N R	106. $s_3s_4s_5$	S R	114. $a_3a_4s_5$	S R
99. $a_2a_4a_5$	N R	107. $s_3s_4a_5$	S R	115. $a_3a_4a_5$	S R
100. $a_2s_5a_5$	S R	108. $s_3a_4s_5$	S R	116. $a_3s_5a_5$	S R
101. $s_3a_3s_4$	S G	109. $s_3a_4a_5$	S R	117. $s_4a_4s_5$	D
102. $s_3a_3a_4$	S G	110. $s_3s_5a_5$	S R	118. $s_4a_4a_5$	D
103. $s_3a_3s_5$	S R	111. $a_3s_4a_5$	S G	119. $s_4s_5a_5$	D
104. $s_3a_3a_5$	S R	112. $a_3s_4s_5$	S R	120. $a_4s_5a_5$	D

the service angle; it is the angular range over which link 3 can approach point A in the given position. In terms of the service angle, ψ, it is possible to define a service coefficient at each point A (we use in general the total solid angle at A for ψ):

$$\theta = \psi/4\pi$$

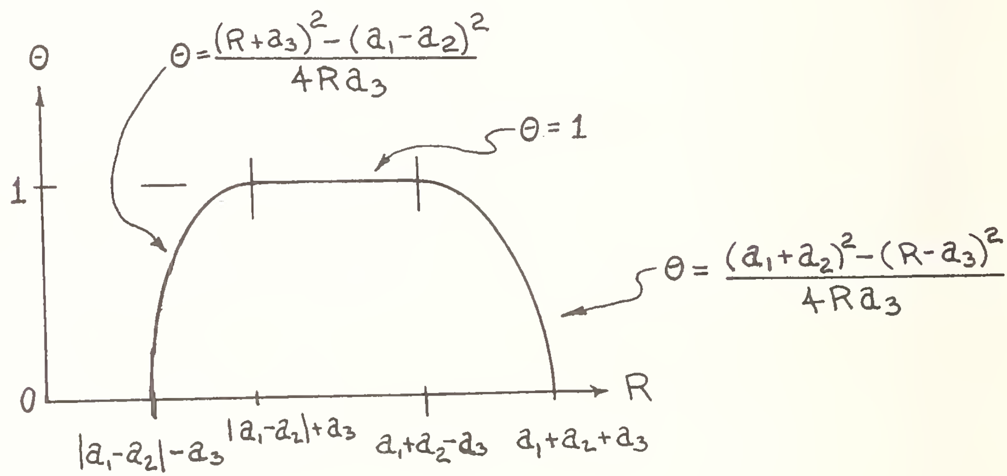
and by integrating over the entire positional space, v, of A, we can define a service coefficient for the manipulator

$$\bar{\theta} = \frac{1}{v} \int_{(v)} \theta dv$$

The service coefficient varies from 0 to 1, and is a measure of manipulator usefulness. It affords a way of evaluating different designs.

If $\overline{OA}$ is R, and if $a_1 > a_2 > a_3$, we find there are three distinct zones as we vary the length of R.

The results are:

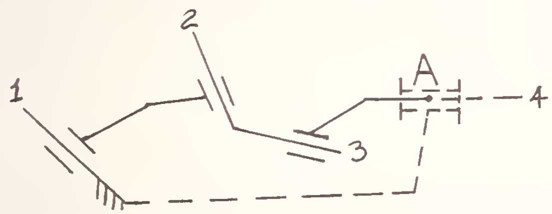


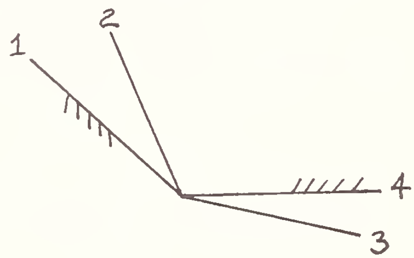
To apply these ideas in general we would like to know the effect of all the link dimensions -- not only the fixed link -- on the range of crank rotation. This is a relatively new subject and there are as yet few results to draw from. The basic result is for the planar four-bar, it is called Grashof's criteria. Phrasing it in terms of manipulators we have: If $\overline{OA}$ is less than all the lengths a, and if $\overline{OA}$ plus the largest a is less than (or equal to) the sum of the other two a's, any approach angle is possible at this position. The only other possibility for a total range in approach angles requires that a_3 be the shortest length and that its length plus the largest of $\overline{OA}$, a_1, a_2 be less than (or equal to) the sum of the other two lengths.

For this manipulator, if the variation is less than 2π(in the plane) at any A, the approach angle has two separate ranges each less than π. These arc segments are symmetrically located with respect to line OA.

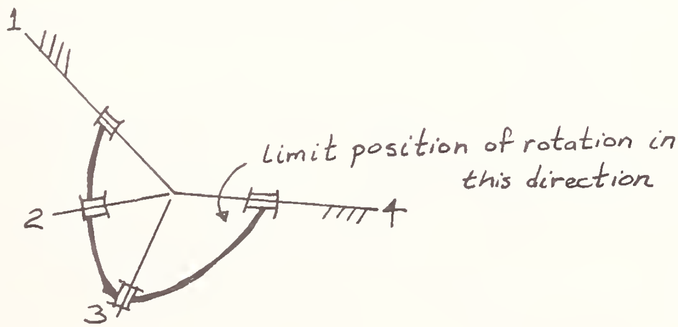
Similar, although much more complicated results are known for the RRPRRP (with $S_4 = 0$) and the RPRRPR (with $S_3 = 0$) manipulators. The spatial manipulators for which most such results exist are the RRRRRRR, the RRRRRRR, RRRRR, RRRRR, RRRRRP, PRRRRR.

Before leaving this topic, it is pointed out that the spherical <u>indicatrix</u> yields necessary conditions in regard to the angular aspects of displacements. Often it yields sufficient information for the entire analysis of approach angles. A spherical indicatrix is the figure formed by drawing images of the R axes of a manipulator, where all the axes remain parallel to their actual positions but are displaced so that they intersect in a common point. So, for example, the spherical indicatrix of the closed loop 3RPR mechanism (formed from a 3RP manipulator with its terminal device rotating about a fixed point A) is shown in the sketch together with the original system. Connecting these image-revolutes, in order, yields a spherical four-bar. By drawing this four-bar on the unit sphere we can determine the





limit positions for the third link which is the end-effector. The general rule is that if the spherical linkage formed from the indicatrix has a limit position, the actual link cannot rotate beyond that position.



REFERENCES

For Section II: The kinematic notation described herein was originated by J. Denavit and is described in the last chapter of the text by Hartenberg and Denavit (1). Its first application to manipulator seems to be due to Pieper (2), and Pieper and Roth (3).

For Sections III, IV, and V: For a modern discussion of screw displacements see Roth (4), and Tsai and Roth (5).

For Section VII: The idea of considering a manipulator as a closed kinematic chain seems to have originated with Pieper (2), and Pieper and Roth (3). The tabulated results follow from many sources, good bibliographies and many new results are given by J. Duffy, J. Rooney, and co-workers (6, 7, 8). The results marked with (?) are due to Roth, Rastegar and Scheinman (9).

For Section VIII: The notion of solvability is due to Pieper (2), and Pieper and Roth (3).

For Section IX: The figures showing the torus geometry are due to Fichter and Hunt (10), the equations and tables are from Pieper (2).

For Section IX: The idea of service coefficients (and the figure for O vs. R) comes from A.E. Kobrinski and his co-workers (11). Grashof's rule is described in (1); for some spatial versions see, for example, (12, 13, 14). The spherical indicatrix is an old concept, for a recent discussion see (8).

1. Hartenberg, R.S. and Denavit, J., Kinematic Synthesis of Linkages, McGraw-Hill Publishing Co., 1964.

2. Pieper, D.L., The Kinematics of Manipulators Under Computer Control, Ph.D. Dissertation, Stanford University, 1968, pp. 157.

3. Pieper, D.L. and Roth, B., The Kinematics of Manipulator Under Computer Control," Proceedings 2nd International Congress on The Theory of Machines and Mechanisms, 1969, Vol. 2, pp. 159-68.

4. Roth, B., "On the Screw Axes and Other Special Lines Associated With Spatial Displacements of a Rigid Body," Trans. ASME, Series B, Vol. 89, No. 1, 1967, pp. 102-10.

5. Tsai, L.W. and Roth, B., "Design of Triads using the Screw Triangle Chain," Proceedings 3rd World Congress for the Theory of Machines and Mechanisms, 1971, Vol. D., pp. 273-286.

6. Duffy, J. and Rooney, J., "Displacement Analysis of Spatial Six-Link 5R-C Mechanisms," Trans. ASME, J. of Applied Mechanics, Sept. 1974, pp. 759-66.

7. Rooney, J. and Duffy, J., "On the Closure of Spatial Mechanisms," ASME paper No. 72-MECH-77, 1972.

8. Duffy, J. and Rooney, J., "A Foundation for a Unified Theory of Analysis of Spatial Mechanisms," Trans. ASME, Vol. 97, 1975.

9. Roth, B., Rastegar, J., and Scheinman, V., "On the Design of Computer Controlled Manipulators," On the Theory and Practice of Robots and Manipulators, Springer Verlag, Vol. 1, 1974, pp. 93-113.

10. Fichter, E.F. and Hunt, K.H., "The Fecund Torus, its Bitangent-Circles and Derived Linkages," Mechanism and Machine Theory, 1975, Vol. 10, pp. 167-176.

11. Vinogradov, I.B., Kobrinski, A.E., Stepanenko, Y.A., and Tives, L.I., "Details of Kinematics of Manipulators with the Method of Volumes," (in Russian) Mexanika Mashin, no. 27-28, 1971, pp. 5-16.

12. Parmadi, P.R. and Freudenstein, F., "On the Motion of a Class of Five-Link, R-C-R-C-R, Spatial Mechanisms," Trans. ASME, Vol. 97, 1975, pp. 334-39.

13. Gupta, V.K. and Radcliffe, C.W., "Mobility Analysis of Plane and Spatial Mechanisms," Trans. ASME, 1971, pp. 125-130.

14. Freudenstein, F. and Kiss, I.S., "Type Determination of Skew Four-Bar Mechanisms," Trans. ASME, Vol. 91, 1969, pp. 220-24.

5.1.3

PERFORMANCE EVALUATION OF ROMANSY*

FROM THE VIEWPOINTS OF MECHANICS AND CONTROL

A.E. Kobrinski

Academy of Sciences
Moscow, U.S.S.R.

1. Robots and manipulators being highly functional are capable of reproducing a wide range of motions and movements. Their functional system is ensured by a large degree of freedom of the actuators, i.e. by considerable motion redundancy.

High functionality and motion redundancy are vital features of robot and/or manipulator systems (RMS) which largely determine the contents of the problem of performance evaluation under discussion.

I agree that this problem should be discussed from various standpoints and, therefore, propose to deal with questions of mechanics and control bearing on it.

We know that the existing methods enable us to analyze every particular motion of the robot and to obtain its geometrical, kinematic, accuracy, control and dynamic characteristics. But this is not sufficient to make a complete appraisal of RMS qualities. For this purpose global appraisals are required, appraisals that would cover the general properties of the whole of its configuration space and the entire plurality of its motions in this space, and not merely separate conditions of the system. In other words what we need are appraisals that would be adequate to high RMS functionality, that would help compare the different systems and reveal their advantages and weaknesses. The examples given below will give an idea of the ways that make it possible to obtain such appraisals.

2. Let us assume that we want to appraise the design of the manipulator hand, to see whether the chosen length of the elements, the combination of rotary and translation joints and limitation of motions in these joints, are expedient. To put it in a nutshell, we want to know how good the structural and geometrical properties of the hand really are and if it is possible to improve them.

Besides, we do not yet know the concrete motions the hand will be required to perform in the execution of work operations. We only know that its gripper will have to pick up, lay down, move from place to place, turn, unscrew, and insert various objects, etc., which may be located at various points of the manipulator work space and may be oriented in various ways at these points. In other words, we are eager to secure answers to our questions without looking into infinite pluralities of motion tasks and work operations for which the given robot may be used.

How are we going to get these answers?

Let us place the manipulator gripper in a point in its work space (P, see drawing below).

---

* ROMANSY - Robot and/or manipulator systems (RMS)

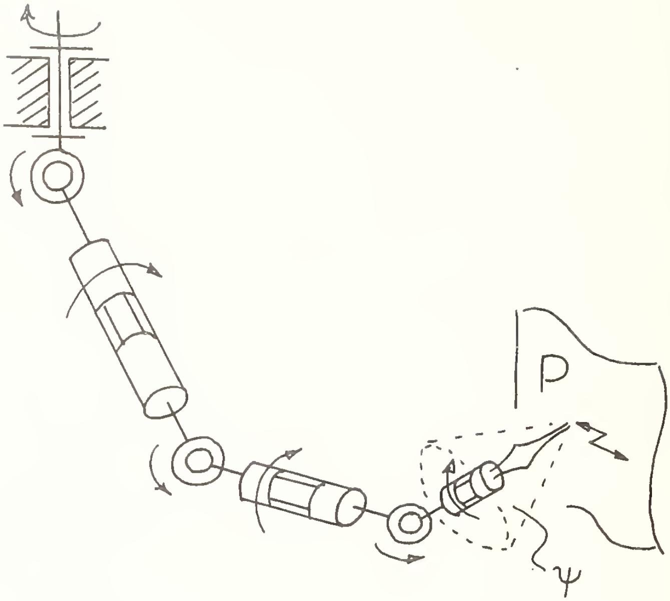


Fig. 1

Do you agree that the greater the freedom of movement enjoyed by the gripper around this point, or to be more exact, the greater the space angle Ψ which the gripper can describe around it the better will be the performance of the hand? Naturally, we are dealing with only one point at the moment.

As we see it, it is difficult to raise serious objections to such a hypothesis.

Assuming that this hypothesis refers to an arbitrary point, it would be correct to say that the size of space angle Ψ or the sizeless value $\Theta = \Psi/4\pi$ proportional to it may serve as a criterion for the appraisal of hand performance in any point of the given work space.

And now it will be easy for us to obtain the global quantitative appraisal of performance we need, for instance in the form of

$$\tilde{\Theta} = \frac{1}{V} \int_V \Theta \, dv \qquad \text{(I)}$$

as a mean value of performance $\tilde{\Theta}$ established for the entire configuration space of the manipulator hand. It appears obvious that the greater this value is, the better is the hand and its performance, and the broader are its functional potentialities. It follows herefrom that it would be advisable to use this criterion in design and in comparing various models.[1,2]

Value (I) may be given a natural statistical interpretation. It will characterize the probability with which the gripper of the manipulator may be oriented in a random direction at a random point in the work space (it is assumed that random distributions are uniform). It is again obvious that the greater the probability the higher the performance of the hand.

3. Global appraisals such as the appraisal of performance may be used as characteristics of other RMS properties.

For instance, in the case of industrial robots the accuracy of positioning of the gripper (in position control systems) is highly important. The same is true of the accuracy ensured in the reproduction of the set trajectory (in a continuous control system). It should be noted that the information on the accuracy of the available systems produced by the firms or quoted in descriptions are of a most approximate nature.

It appears obvious that the accuracy characteristics of one and the same robot are different in different points of its work space. It is only a global appraisal obtained for the entire work space that will give an adequate probability characteristic of accuracy as a means of comparative analysis of various design models.

As a rule, RMS actuators are open kinematic chains of the rod type. This considerably lowers the rigidity of the system and causes low frequency components to appear in the frequency spectrum. This circumstance is complicated by gaps in the mobile joints, extended hydraulic and pneumatic communications and finally by the elasticity of the elements themselves. It should be pointed out that the length of these elements is many times greater than the width. In the face of these circumstances it is both interesting and of practical importance to study the dynamic characteristics of RMS. It is obvious that these characteristics may be different in different positions. It appears that to compare the vibration characteristics of the different systems global appraisals are again required.

I cannot say what other appraisals are necessary to secure the client's confidence in new automation means and to get him to use it in industry. It is probable that these questions will be discussed at the present Seminar or at other seminars of this kind. At the same time I am of the opinion that the method of appraisal dealing with robot characteristics independent of concrete external actions* may be used not only in the study of hardware, but also of the software, particularly when it concerns so-called animated robots.

The progressive idea of supervisory control (W.R. Ferrel, T.B. Sheridan) has confirmed the validity of the conception of the tri-une operator-computer-robot complex. The artificial intelligence system supporting this complex should ensure effective cooperation of the operator and the computer with the robot and between themselves and contain information that would provide automatic control of the robot in intervals of self-contained performance.

---

* This method is similar to that applied in the theory of oscillations. In keeping with it the free oscillations of a system characterizing its own properties are studied above all.

In other words, the robot should be provided in advance with a whole set of "behaviours". It will be necessary to determine the criterion of these behaviors so that the robot could be guided by them in automatic performance.

It is not the object of this paper to give a detailed analysis of the existing or possible artificial intelligence systems. But you can hardly deny that one of the important tasks of the theory and practice of robots is to compare different approaches and principles in their organization. I hope that the examples quoted below will give some idea of what is meant here.

4. We have already mentioned above the considerable motion redundancy of the robot which is intended to ensure tremendous motion potentialities. Though the actuator of the robot or its gripper may be designed to perform a wide range of tasks, though the principles for the organization of the artificial intelligence system may vary widely, the function of one of its levels (let us term it the motion forming level) will remain unchanged. This level determines the laws of motion of all the links in the system (with the exception of the gripper whose motions are determined by the assignment). To accomplish this task it will be necessary to devise a general and rational method to overcome motion redundancy.

Permit me to explain how we approached the solution of this matter.[3] I shall begin with quoting a simple example to explain the idea which forms the basis of this method.

Let us assume that we have a two-dimensional two-link kinematic chain (see Fig. 2 below). We wish to shift the end point of that chain from position A_o to position A. There are many ways in which this can be achieved.

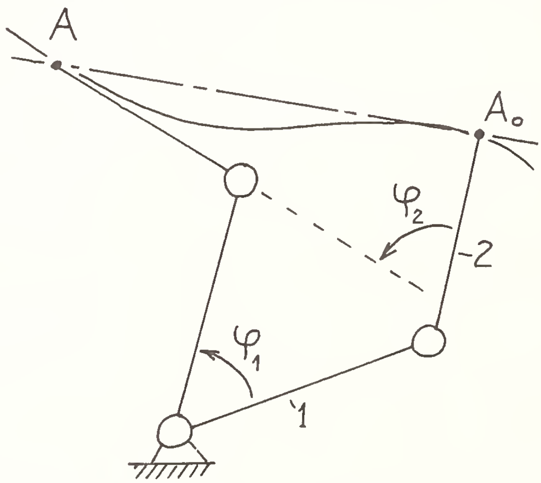


Fig. 2

For instance, the motion of the two link unit may be effected in a way to make its end point move along the straight line A_oA (bearing in mind that a straight line is the shortest distance between these points).

However, we took a different course of action. Our requirement was to ensure in the process of the shift from A_o to A a minimum sum ($\varphi_1 + \varphi_2$) of turning angles described by the links of the kinematic chain. We feel that it is precisely such movements that are most economical and, therefore, rational. The fact that, owing to the non-linear character of the system, the end point will move along a gentle curve instead of a straight line only shows that economical rational movements should be soft and smooth, and by no means rigid or angular. That is precisely how the ballet dancer, gymnast and efficient operator shape and execute their movements. The natural grace and beauty of their movements is hardly in contradiction with economy of energy.

In generalizing the idea of a mechanism of infinite complexity we formulated (in 3.) a special functional of the type of

$$\Omega = \sum_{i=1}^{n} a_i \int_{t_0}^{t_1} |\varphi_i(t)| \, dt \qquad \text{(II)}$$

which we named "volume of motion". This functional helps form criteria for the appraisal of certain "qualities" of a trajectory in the space of system configuration.

If the system redundancy is considerable, this idea can also be used in cases of free motion of the gripper and also when its motion has been planned in advance by the higher levels of the artificial intelligence system. This having been done, it may be considered that the robot has been provided with a rational (from our viewpoint) element of motion behaviour. The robot will uniformly use it in the accomplishment of various motion tasks.

Other approaches to the solution of the problem of overcoming redundancy are quite possible and they in fact exist. It would appear to me that it would be most interesting to compare them.

5. In discussing questions bearing on the construction of robot and manipulator motions it would be impossible to ignore the task of surmounting obstacles. In designing robot motions in a medium with obstacles, in addition to conditions one, arising from the set motion of the gripper, and two, determined by criteria of optimality of motions of all the other links in the system, a new group of conditions appears which is created by the external medium (environment). I do not intend to discuss the numerous ways in which tasks of overcoming obstacles are posed. I shall only set forth our approach to its accomplishment.[4]

It is based on the modelling of a quality that is inherent in simple living organisms. It is know as tropism. By this we understand purposeful movement of an organism resulting from the effect of unilateral stimuli on it.

In the case of a technical device the role of such a "stimulus" would be played by information on the mutual positions of the robot and an obstacle in its work space. By "tropism" we mean the movements of the robot away from the said obstacle. It is noteworthy that such motions are effected, thanks to the robot's motion redundancy.

The mutual positions of the robot and the obstacles are characterized in 4. by the function of the distance

$$R = \inf \rho(X, D) \qquad \text{(III)}$$

ρ being the distance between the two points in the work space: the lower edge being formed by any two pairs of points, one of which belongs to a link in the kinematic chain and the other to obstacle D. If the distance between robot link and any point of an obstacle becomes dangerously small, the latter intruding into the safety zone, the system of tropism starts to function.

Overcoming redundancy and surmounting obstacles are relatively simple elements of motion behaviour. At the same time I would like to emphasize once more that in our work on these elements we sought as always to apply the same method which has enabled us to look into the qualities of the robot (its artificial intelligence) regardless of the character of external stimuli, regardless of the concrete motion assignment and concrete form of obstacle.

As in the past reference is being made to the free qualities of the robot. The characteristics of these features are essential for the appraisal of the quality of the system which the designer may offer the client on presentation.

The motion behaviour of a "skilled" robot must include more complex elements. Thus, tropism will not always ensure success in surmounting obstacles. Then the need arises for such elements as motion adaptation and self-training.

In emphasizing the importance of appraising the qualities of an artificial intelligence system I had in view the discussion of the structure and contents of the "library" comprising the motion behaviour elements of the robot, the qualitative and quantitative criteria of such behaviour and, of course, their effectiveness in the solution of the practical problems of automation.

A philosopher of antiquity taught: "Know your own self." In the stern area of automation this wise thought could, perhaps be enlarged: "Know your own self and your creations." The better we know them, the greater will be their potentialities. This will enable us to explain them in more accurate and clear terms to the well-wishing listener and increase the chance of winning him over to our side. This is the ultimate objective of our Seminar. If our ideas do not coincide at first contact and if our hearts do not beat in unison, it really does not matter. However, even at first contact it would be preferable to have nothing to do with faultfinders.

Permit me to express my gratitude to the organizers of the Seminar for granting me the opportunity to speak on a matter of great importance to robots and manipulators.

REFERENCES

1. Vinogradov, I.B., Kobrinski, A.E., Stepanenko, Y.A., Tyves, L.I. Method of Volumes and Manipulator "Service". Mashinovedeniye, No. 3, 1975.

2. Kobrinski, A.E. Volumetric Criteria in Service Analysis of Manipulators. Advances in External Control of Human Extremities. Belgrade. 1970.

3. Kobrinski, A.A., Kobrinski, A.E. Formation of Motions in A Manipulation Systems. Papers of the U.S.S.R. Academy of Sciences. Vol. 224, No. 5. 1975.

4. Kobrinski, A.A., Kobrinski, A.E. Formation of Motions in a Manipulation System in a Medium with Obstacles. Papers of the U.S.S.R. Academy of Sciences. Vol. 224, No. 6, 1975.

PERFORMANCE MEASUREMENT AND EVALUATION OF GENERAL PURPOSE MANIPULATORS

Richard L. Paul

Stanford Research Institute

Menlo Park, CA 94025

I. Overview

This paper will evaluate the performance of general-purpose manipulators by comparing them to our only true general-purpose manipulator, the human arm. In this comparison, some fundamental differences will be demonstrated. These differences, which facilitated the initial development of mechanical manipulators, now limit their further development. By changing the design perspective to eliminate these differences, a more truly general-purpose manipulator can be created.

First, we will define the performance of a general-purpose manipulator through a functional definition of the human arm: weight, strength, actuators, control. In terms of this definition, we will consider available manipulators in order to isolate key differences and equivalences. This will lead into a discussion of the high-tolerance machine-tool approach as opposed to the sensory feedback, multimode computer servo-system. Finally, we will attempt some performance specifications for the sensory feedback system.

II. The Human Arm

In this section we describe the human arm as if it were a mechanical manipulator. This description serves as the basis for a comparison with existing mechanical manipulators. All tasks can be performed by the human arm and hand either alone or in conjunction with an appropriate tool. Our evaluation is based on the assumption that the arm performs most tasks, with the exception of holding and pushing, by using a tool.

By restricting ourselves to the "arm and hand-holding tool" model, we can greatly simplify the problem of evaluation. Many mechanical systems can be compared to such a model, whereas no system can be compared to the human hand itself. To quote Bejczy:[1]

> (1) The hand is both a powerful and delicate tool, and also a sensory organ through which information is received and transmitted. It is difficult to evaluate the relative importance of the hand as a tool and as a sensory organ; functionally it is both or either.
>
> (2) Philosophically, the hand can be regarded as one of the major determining factors of human evolution. Together with man's brain and binocular vision, the hand enabled him to be a tool user and tool maker, and to explore, manipulate and change the physical environment.

(3) The function of the arm is to position the hand (the terminal device), act as a mechanical connection, and as a power and sensation transmission link between the hand and the human. The full meaning of the arm is revealed by the hand.

While we are considering the hand only when it is holding a tool or grasping an object, we are interested in it as a "terminal device" to which forces and vibrations are transmitted through the tool it is grasping. We are not interested in digital manipulation tasks in which the fingers play a key part, such as picking a small nut out of a bin and starting it on a screw; we would use a feeder and tool to perform such tasks.

The human arm is, as a first approximation, a six-degree-of-freedom manipulator consisting of two links -- the upper arm and forearm -- with all revolute joints. It is lightweight and strong, with a strength-to-weight ratio of approximately five to one. Each link of the arm consists of bone, is strong, rigid, and resistant to damage. The joints connecting the links are almost friction free, but require the exertion of maintaining forces between the links. The actuators are muscles and work in opposing pairs, acting on the links through tendons. The difference in force of the two tendons appears as a torque acting on the joint, while the sum of the forces acts to maintain joint closure. The forces of the joint are no more than necessary for any arm configuration and task.

Such an actuator system is back-drivable, since motion at the joint can be in either direction in response to both internal and external torques exerted at the joint. We will refer to this characteristic as "compliance". This has important self-protective features in that as the external force increases, the joint moves in response. (In contrast, systems such as worm-gear drives cannot be back driven and mechanical failure may occur.)

The muscle actuator system of the human arm has great overload capabilities and rarely works at a constant power level so characteristic of mechanical systems. The muscles have low inertia and no backlash.

The joints are instrumented for force, velocity, and position, but in a non-linear manner, being very sensitive to small changes. Position control is such that the hand vibrates around plus or minus one millimeter.

An interesting arm control theory is that most tasks are learned, and are executed by controlling the timing of the switching on and off of different muscle sets. This form of control results in high-energy efficiency.

Finally, the muscles provide a shock-absorbing cushion for the links and joints in case of collision.

III. Existing Manipulators

Existing manipulator systems fall into two main classes:

- Remote-handling teleoperators
- Robots

Remote handling teleoperators are characterized by the full-time interaction of a human operator. They are frequently master-slave systems with bilateral servos allowing the operator to feel the forces that are being exerted. Vision is one of the primary control input signals that the operator uses in an intelligent manner to accomplish a given task. A powerful method of control uses an exoskeleton that surrounds the operator's arm. Such a system, coupled with a bilateral servo, implies a manipulator kinematically resembling the human arm.

These systems are, however, tools and will not be considered further.

The second class of manipulators, robots, are an attempt to replace human manipulative abilities with some form of mechanical arm and artificial neuromuscular control. Two major problems arise: first, humans normally have two arms; and second, humans have mobility. The lack of a second arm may be partially compensated for by providing jigs and clamps to perform as an elementary other hand, or by attempting only clearly defined one-handed tasks. Many tasks currently handled by robots are of the materials handling type (such as unloading a press) for which one hand is quite sufficient. When task complexity increases, the lack of a second arm becomes more apparent.

The problem of lack of mobility usually results in a basic redesign of the arm. The replacement of one or more rotary joints by prismatic joints maintains the number of degrees of freedom of the arm while adding some limited form of mobility. It is hard to seal prismatic joints compared to rotary joints and difficult to pass control and actuation signals through them to outer joints.

Mechanical manipulators usually have six degrees of freedom. They have two or more links with a combination of revolute and prismatic joints. The strength-to-weight ratio is considerably less than unity. Each link of the manipulator consists of metal, which is strong and rigid. The joints are bearings, which are strong and precise.

IV. Comparative Evaluation

The actuator systems of mechanical manipulators show the first major divergence from the human arm model. A mechanical substitute for the muscle-tendon combination has not yet been found. The actuators in mechanical manipulators are either hydraulic or electric. The hydraulic systems are strong and rugged but, unlike the human arm, are not back-drivable. Electric systems,although rugged, are heavy and require gear reductions with attendant backlash. These systems have high static friction and low back drivability.

In speed and acceleration, hydraulic manipulators perform comparably to the human arm, but because of their greater structural mass, greater forces are involved, making them dangerous. Electric-motor-powered manipulators are generally slower and weaker than the human arm.

Position sensing of the manipulator is accomplished by measuring the joint angles; such methods using resolvers and encoders have led to high accuracy, linearity, and resolution.

Joint velocity is normally measured by a tachometer generator, either on the motor shaft of electric-motor-powered manipulators, or geared to the joint in hydraulic manipulators. Joint torque is usually measured by strain gauges mounted in the links themselves.

Joint torque is closely related to motor current in electric-powered manipulators whereas in hydraulic manipulators velocity is related to servo valve opening. Thus these variables may be inferred rather than measured.

The main differences between our prototype general-purpose manipulator, the human arm, and available mechanical manipulators appear to be the following:

- The actuators of the human arm are direct, lightweight, low inertia, friction free, and strong; their rest state is free. Hydraulic actuators are stronger, but they are heavier and their rest state is rigid. Electric actuators are heavy, weak, suffer from backlash, and have high static friction.

- The human arm has sensors that are very sensitive, particularly to small changes. Mechanical manipulators' position sensors are linear, with high resolution.

- The mass and inertia of the human are low; it has the capacity for high-speed actions. In mechanical arms, the mass and inertia are high, leading to slow actions in electric powered manipulators and to excessive force in hydraulic manipulators.

With these differences in mind, we now consider the development of the mechanical manipulator and the compensation necessary to provide an apparently equivalent system to the human arm.

V. Manipulator Development

The first major area of application of manipulators was in the field of material handling. These tasks were predominantly position defined, that is, in such tasks as unloading a press, where the position of the press and the conveyor relative to the manipulator remained constant. Manipulators were able to handle such tasks by taking advantage of the high-resolution, accurate position sensing, and high-speed performance of hydraulic actuators. In material handling work, the manipulator is run as a positioning device and a program consisting of a series of positions is repeated continously. Servomechanisms or linkages force the hand to take a prescribed trajectory in space and are blind to what and where things are in the environment.

The differences between the manipulator and the human arm are not important in this case; no compliance between the manipulator and the workpiece is required. The only sensors required are position sensors. The mass of the manipulator is masked by the strength of the hydraulic drive. The weight of the drive is not significant as the system is not mobile. The fact that such a manipulator required a tremendous power input was unimportant because of the availability of cheap energy coupled with the lack of mobility, which obviates the need to carry a portable power supply.

This same technique has been extended to such tasks as spot welding, spray painting, and continuous-path arc welding, all of which are position-controlled tasks.

Not until assembly tasks were attempted did the position-controlled approach present problems. In order to insert a pin into a hole, by position control, the absolute position of the pin must be maintained coaxial with the hole axis to within the clearance between the hole and shaft. For most assemblies, this tolerance is of the order of a thousandth of an inch. This presents a problem in manipulator design. Even where the joint position control is accurate enough, structural deflection and thermal effects often far exceed the required precision. The only solution for a position-controlled device is to redesign the manipulator along the lines of a machine tool in which these high tolerances can be met.

The resulting manipulator would be costly, massive, and thus slow, and would lack the ability to reach into odd corners -- a desirable feature in manipulators. Despite these drawbacks, such a system may prove optimal for the assembly of numerically controlled machined parts in which the maintenance of tolerance must be carefully controlled. For the large mass of goods assembled not only is tolerance poorly maintained, it is unnecessary. For example, the four holes used to hold an inspection cover on a machine may have a clearance of a few thousandths of an inch but may be located only to within a tenth of an inch of nominal. Such an item cannot be assembled by any machine that relies on the maintenance of high tolerance.

VI. Sensory Feedback -- Example

How can a task such as that described above be accomplished with existing manipulators? The following excerpt from "The Use of Sensory Feedback in a Programmable Assembly System"[2] describes such an existing system performing the assembly of a pump.

> "The arm has six joints (five rotary and one sliding) and it is possible to place the hand at any position and at any orientation. Each joint is powered by an electric motor which is under computer control. The joint positions are measured by potentiometers and are read into the computer via A/D converters. Similarly, the joint velocities are read into the machine via A/D converters from tachometer generators. A real-time program (the servo loop) directly controls the joints' forces and indirectly controls joint velocities and positions. Every sixtieth of a second the servo reads the position and velocity information and determines the joint output torques from the difference between the observed and planned values. ..... [3]A more detailed description of the servo loop can be found in Reference 3.[3]

"There is a set of equations based upon the kinematic structure of the arm which relates the force, position, and velocity of the hand to the combination of forces, positions and velocities of the six joints. These equations ... are solvable on the computer even though they contain some degenerate sub-cases. The solution routine is currently part of the planning section and is used to compute the forces required to compensate for the weight of the arm and any load it may be carrying. These compensating forces are always applied when the arm is in motion. Thus, if all the brakes are turned off the arm will not fall; it will remain stationary, but will be free to be moved manually in any direction.

"If we want the hand to exert a force in some direction, the solution routine can be used to compute the required joint forces. When these forces are added to the normal compensating forces the arm will exert the specified force.

"Normally, when we have the arm exert a force, we want the hand to be free to move in the direction of the force. Sometimes it is important to provide some additional freedom so that the arm can comply with external constraints. For example, if we want the arm to slide an object across an essentially horizontal surface, we want to allow the arm to move up and down so that it can conform with the surface as it moves across it. This freedom is achieved by servoing all the joints except one joint which provides for a vertical motion. This one unservoed joint is called a 'free' joint. Free joints can also provide the freedom to spin about some axis. In the pump assembly, for example, after the pump has been located and picked up, it has to be placed in a standard position. The standard position is defined by a rectangular corner formed by a pair of aligning blocks. The first step in this alignment involves positioning a straight edge of the pump base along a surface of one of the blocks. This is accomplished freeing the joint which allows the base to spin so that it can align itself with the surface . (See Figure 1.)

"... A motion of the arm then consists of a trajectory, some compensating forces, and possibly a force to exert and some joints to free. In addition, the termination of the motion has to be specified. It can be defined as a position to be reached, a force limit to be reached, an activation of a touch sensor, etc. Thus, the arm can be told to screw in a screw until a certain torque is reached, or it can be told to insert a shaft until a certain force limit is reached (indicating that the shaft has been seated). The next section will explain in detail how the arm is programmed to perform this type of feedback.

"The positioning of the pump base relative to the arm is not accurate enough to allow the arm to insert a pin in a number 10 screw hole reliably. Therefore, to increase the reliability, a spiral search is used to try all nearby locations if the initial insertion attempt has failed.

Figure 2 shows the arm inserting a pin in a hole. The first insertion attempt fails because the pin lands on the top of the base (see Frame B in Figure 2). The second attempt succeeds.

"Three things can happen when the arm is trying to insert a pin: (1) the pin can go in the hole, (2) the pin can miss the hole and land on the top of the base beside the hole, or (3) the pin can miss the hole and also miss the top of the base. To test for these three possibilities the insertion is broken into two parts:

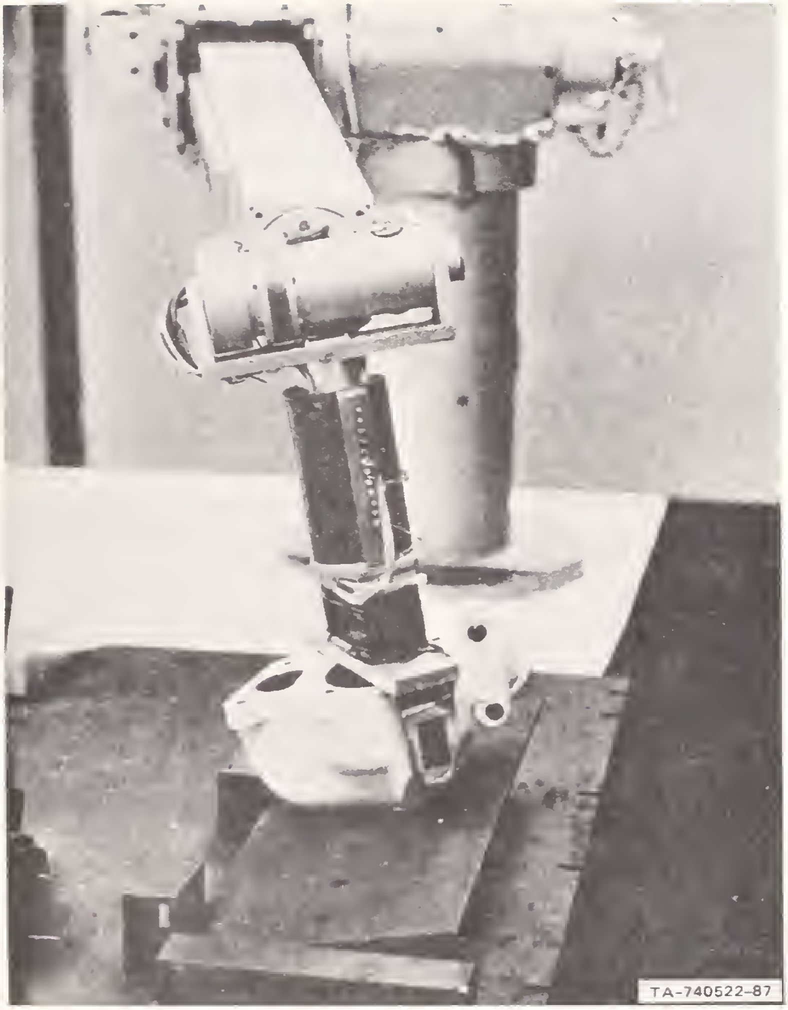
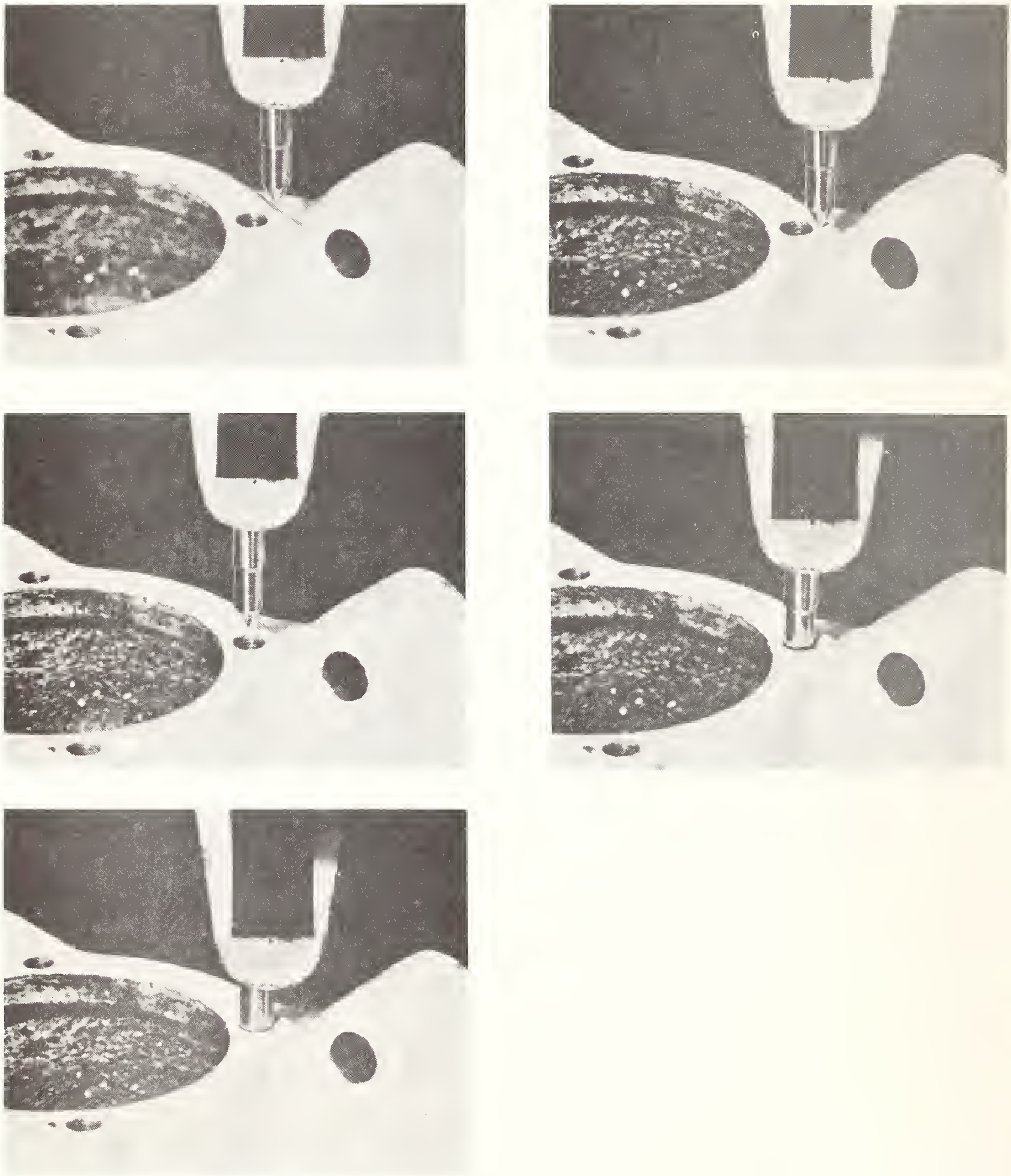


FIGURE 1   ARM PUSHING THE PUMP BASE AGAINST THE ALIGNING BLOCKS



TA-740522-88

FIGURE 2 INSERTING A PIN IN A SCREW HOLE

(a) Pin poised near hole; (b) Pin sitting on the base, beside the hole; (c) Pin poised over the hole; (d) Pin partially inserted in the hole; (e) Pin seated in the hole.

A. Try to insert the pin part way ... if it fails to go in part way, it must have landed on top of the base beside the hole, so continue around in the spiral and try another spot. If it went in part way, go to step B.

B. Try to seat the pin in the hole (i.e., move down a short distance and expect to meet some resistance as the pin seats in the hole)... if no resistance is felt, the pin must have missed the hole and the top of the base, so continue around in the spiral. If resistance is felt, the pin is properly seated.

"What follows is a hand language program to carry out this algorithm. It is included along with a detailed explanation of the various instructions in order to show the current level of programming required by the system.

"The position of the hand to pick up the pin is referred to as P. This position is defined by moving the hand to where the pin is located and typing 'HERE P.' The program reads the current position of the hand and stores it in P. Similarly the hand (holding the pin) is moved to the position for insertion and 'HERE T' is typed. Manually moving the arm to define positions and orientations is the easiest way of programming some assembly operations. It is a form of 'programming by doing' or 'learning by doing'.

```
MOVE P                          ; GO TO THE PIN
CLOSE 0.1
MOVE T                          ; GO TO THE HOLE
SEARCH .07
MOVE T                          ; GO TO THE HOLE
STOP [0 0-50]
FREE X, Y
CHANGE[0 0-1] 0.6               ; TRY TO GO DOWN WITHOUT MEETING RESISTANCE
SKIP 23
AOJ L1
STOP [0 0-50]
FREE X, Y
CHANGE [0 0-1] 0.6              ; SHOULD MEET SOME RESISTANCE
SKIPN 23
AOJ L1
SAVE H
OPEN .5
CLOSE 0.1                       ; AND CHECK THAT IT IS STILL THERE
OPEN 1
```

"The first instruction generates a trajectory from the current location of the hand to the position 'P'. The hand is then in position to grasp the pin. The next instruction, 'CLOSE 0.1', causes the fingers to close until they grasp something. Every time the hand grasps anything, the minimum thickness must be specified, and forms an implicit inspection check. If the grasp is made and the check indicates that the opening is less than the minimum specified, the arm will stop operation and indicate the error.

"With the pin now in hand the arm moves to the insertion point at 'T'. The 'SEARCH .07' instruction sets up counters to conduct a spiral search of .07 inch steps. We now enter the insertion loop at label L1, a move is made to 'T' and the hand is directed to move down 0.6 inches by the CHANGE instruction. The numbers within square bracket '[0 0-1]' indicate the direction and the scalar '0.6', the distance to move. The previous instruction 'STOP 0[0-50]' will cause the arm to stop if the force in the downwards direction exceeds 50 oz. during the 'CHANGE'. Now the relationship between the position 'T' and the hole is such that if the pin is inserted in the hole it will meet no resistance during the 0.6 inch motion. If the pin is beside the hole and lands on the top of the pump, the force will quickly reach 50 oz. and the hand will stop. If the hand fails to stop on the force limit, indicating that the pin is either in the hole or has missed the hole and the top of the base, an 'ERROR' state is generated. In this particular case, the error is error 23. The instruction following the 'CHANGE', 'SKIPE 23' will cause the next instruction to be skipped if the error occurred, indicating in this case that all is well.

"If the pin has landed on the top of the pump, missing the hole, the force limit is reached and the arm stops without generating an error state. When the SKIPE 23 instruction is executed no skip occurs and the AOJ L1 instruction is executed. AOJ is a mnemonic for 'add and jump' The adding that occurs is the addition of the search step to the current position. The jump is to the label, L1, and the spiral search continues. The arm will stay in this loop, searching around 'T' in 0.07 inch steps and trying to insert the pin in the hole until the pin moves down without meeting resistance.

"After the pin has successfully been inserted part way, the stopping force is set to 60 oz. and the hand is driven down 0.6 inches. If the pin is in the hole, the hand will stop before going 0.6 inches and no error will occur. The error test is a 'SKIPN 23' instruction which causes a skip if error 23 does not occur. If the pin has missed everything, the 'AOJ' is executed and the spiral is continued.

"The 'SAVE H' instruction saves the position that the hand was in when it inserted the pin. Thus, to return to that position, the following instructions could be executed:

```
MOVE T
RESTORE H
```

The 'RESTORE H' modifies the position T by the saved difference H.

"The last two instructions double-check the pin placement by making sure that the pin remained in the hole after the hand released it. More is said about this type of checking in the section on touch sensing."

VII. Sensory Feedback -- System

The method of manipulator control used in the pump assembly task differs in two key respects from conventional methods of manipulator control. The two control functions are compliance, which is the ability to exert arbitrary force, including zero force, at any joint, and the ability to change servomodes as a function of the algorithm.

The electric-motor-powered manipulator has back-drivability characteristics that give it some compliance. The use of a computer with sensory inputs, position, velocity, and output torque would give it the ability to change servomodes.

In the hydraulic manipulator, velocity output is characteristic, and force-sensing servo loops must be included to provide the necessary joint compliance. Such systems are, however, vulnerable to damage if the rate of application of external force exceeds the rate of response of the servo loop.

If force-sensing elements are to be used, either to provide compliance in a hydraulic manipulator, or to increase compliance in an electric manipulator, the force-sensing elements may be placed either in each link to control the appropriate joint, or between the manipulator and the hand. In each case, a matrix calculation must be performed to relate joint forces to hand forces, or vice versa. By locating the force sensors in the links, a simple analog servo loop can exist between link and joint. By locating the sensors at the hand, the effects of link inertia can be eliminated because the force measurement is made between the arm and the hand.

If we could exert forces at the hand, then, by bringing the arm to bear on some elastic material and by varying the force, we could achieve very fine motions. Such a mode of operation, coupled with the ability to detect small changes in position or velocity, would make many fine compliant tasks possible with low precision manipulators.

VIII. Computer Requirements

Computing requirements are split into two systems: training and execution.

A training system is normally highly interactive, has no real-time requirements other than good operator response,aand is used infrequently. Such systems can be written in high-level languages and run on large computers under time sharing. They range from very simple to highly complex. A simple system records manipulator positions and has some elementary editing and program branching abilities. A large, complex system relies on a symbolic data base to interpret input statements[4], such as "FIT enginehead ONTO engineblock" to generate entire manipulator programs.

Execution programs also vary from simple to complex. A simple program outputs only set points to a hardware servo; a complex program performs transformation, processes sensory input data, and makes control decisions. Execution programs have severe real-time requirements, are usually written in machine language, and use limited amounts of memory.

As the execution program must be run every time the task is performed and the training program only once, considerable effort is devoted to precomputing during the training phase in order to reduce the complexity, size, and rate of computation of the execution program. Such precomputation efforts are to some extent contradictory. For example, to precompute all alternative courses of execution in response to some test, results in a simpler, shorter execution program, but a program that has more data and is larger than one in which the alternative courses of execution are computed as required.

As task variability increases, more and more computation must be performed during execution and less during training. The training phase then consists of providing the necessary task description and relevant data to the execution program in an appropriate form.

Execution programs are in effect software servo systems, even where hardware servos exist, as they must perform an effective servo computation in order to interpret manipulator performance in terms of program execution. Bandwidth is directly related to sampling frequency of the execution program, as is cost of the execution computer whose cycle time must decrease also. Even with the advent of cheap minicomputers, this presents a major problem. One solution to this problem is to provide hardware servos, but, due to the load and manipulator-configuration-dependent dynamics, this solution is not simple.

As manipulation programs tend to be a mass of detail relating to any given task, compilation, or automatic programming techniques, would seem appropriate to the correct generation of such programs. Such techniques rely heavily on a symbolic data base, which at present must be input by hand but which will become available with the development of CAD/CAM systems. Currently, a problem exists in the lack of a high-level language in which to describe multimode, complaint, servo tasks. The major drawback of such high-level systems is the difficulty of inputting direct experience to the system in order to modify the manipulator program. Programming tends to be performed in the front office, not in the factory where the direct experience of the problem exists.

Another approach to generating manipulator programs is to develop task-oriented systems in which the program understands the task and can meaningfully interpret signals, both during training and later execution.[5] Such an approach, although lacking the apparent generality of the high-level system, will provide real systems to perform real tasks out of which the foundation for more general-purpose systems can be securely laid.

IX. Manipulator Specifications

The kinematic design of the manipulator should be evaluated in terms of its modification from the human arm. Evaluation should start with the human arm and then consider each successive modification, evaluating its effects, changes, and limitations at each stage until the proposed design is reached. In this manner, the effects on generality of additional or fewer degrees of freedom, prismatic joints, and different arm geometry can be ascertained.

Each link, starting with the link immediately before the hand and working back toward the shoulder or base, should be evaluated for structural strength and deflection, resonant frequency, and strength-to-weight ratio. The weight of the link includes all actuators, sensors, and instrumentation. As each successive link is evaluated, all links out to the hand are included as part of the link under consideration.

The ratio of maximum torque to minimum or free torque is a key parameter. The links must be compliant, either naturally or by some torque servo loop. If a torque servo loop is used, then its speed of response must also be evaluated. No backlash should exist, as any backlash or hysteresis at a detectable level markedly degrades manipulator performance. Joint motion should exhibit no cogging from gears, commutation, or other factors.

Each joint should have a high bandwidth torque servo in which output torque is linearly controlled. Each joint should also have a high bandwidth velocity servo. In either mode, torque, velocity, and position must be accessible to the computer. Position servoing can be a software servo loop in conjunction with the velocity servo. If the hand or tool has sensory signals available for local control, these signals should also be available to the computer for task algorithm execution and decision-making.

X. Conclusion

We have an excellent prototype of a general-purpose manipulator in the form of the human arm.

The basic differences between current manipulators and the arm are compliance and control. While the computer appears to be capable of solving the control problem, if provided with all sensory input signals, current manipulators do not exhibit any compliance at all.

A manipulator with torque-servoed joints would have the necessary compliance.

REFERENCES

1. Antal K. Bejczy, "Remote Manipulator Systems, Technology Review, and Planetary Operation Requirements" JPL 760-77 (July 1, 1972).

2. Robert Bolles and Richard Paul, "The Use of Sensory Feedback in a Programmable Assembly System," Stanford Artificial Intelligence Laboratory, Memo AIM-220 (October 1973).

3. Richard Paul, "Modelling, Trajectory Calculation and Servoing of a Computer Controlled Arm," Stanford Artificial Intelligence Laboratory, Memo AIM-177 (November 1972).

4. Raphael Finkel, et al., "AL, A Programming System for Automation," Stanford Artificial Intelligence Laboratory, Memo AIM-243 (November 1974).

5. C.A. Rosen and D. Nitzan, "Some Developments in Programmable Automation," SRI Technical Note 100 (January 1975).

MANIPULATOR SYSTEM PERFORMANCE EVALUATION: PROBLEMS AND APPROACHES

Nicholas L. Shields, Jr.
Thomas B. Malone
Mark Kirkpatrick

Essex Corporation
Huntsville Facility
11309-E South Memorial Parkway
Huntsville, Alabama 35803

Essex Corporation
201 North Fairfax Street
Alexandria, Virginia 22314

I. Introduction

During the past four years, Essex researchers have been actively seeking some answers to critical questions related to the National Aeronautics and Space Administration (NASA) Earth Orbital Teleoperator System (EOTS). In a graduated program of experimental investigations each major subsystem of EOTS is being evaluated. The research approaches have dealt most particularly with measures of system and subsystem performance in remote manipulator tasks where the human operator is the principal mode of system control.

While manipulator performance evaluation in teleoperators must of necessity address human performance as an evaluation item, the other system components remain very similar to those in programmable systems. Indeed, it has been pointed out that the only significant system feature which differentiates robots and teleoperators is the presence of autonomous control for the robot, versus the operator-in-the-control loop for the teleoperator. Several significant problem areas will be discussed and a review will be made of workable approaches to those problem areas taken by Essex researchers. It is felt that the on-going efforts to develop an effective and reliable evaluation program for teleoperators should complement those same efforts being carried out in programmable robotics.

II. Problem Statement

As is true for any system evaluation, a manipulator system evaluation program must address two distinct considerations: (1) what to evaluate, and (2) how to evaluate it. Thus, an evaluation program is primarily concerned with measures (the what) and methods (the how). Each of these two separate considerations has its unique problems.

The problems usually encountered in selection of evaluation measures concern questions of evaluation generalizability, standardization of measures, and applicability of measurements.

The degree of evaluation generalizability is the extent to which the measures employed are appropriate to a wide range of manipulator systems, task requirements, and operational conditions. The evaluation approach having some minimum degree of generalizability is one which is developed for a specific manipulator, a particular task, or a unique set of conditions. However, even a specific evaluation approach has some inherent generalizability due to a basic commonality which presumably exists among manipulator systems. All manipulator systems contain the same classes of subsystems: structures, actuators, sensors, control system, and end effectors. All manipulator systems perform the same basic functions, which are:

- Position and orient the end effector at the worksite
- Maintain the position and orientation of the end effector
- Move the end effector in three-dimensional space
- Apply forces and torques at the end effector
- Detect and avoid obstacles
- Perform work at the worksite using the end effector, which includes grasp, release and other manipulations of external objects.

It must be borne in mind that we are concerned here with a generally applicable manipulator evaluation approach, and not with general purpose manipulator systems as such. The generally applicable evaluation program should be equally appropriate for assessing both general purpose and special purpose manipulator systems.

The development and validation of generally applicable measures of manipulator performance is a requirement for a number of reasons. For one, different manipulator systems can only be compared with one another when they have been evaluated on tasks involving general performance measures. Secondly, the availability of validated generalizable evaluation measures relieves the system developer of the task of developing and validating measures specific to his system. Finally, a set of generally applicable measures provides the personnel responsible for an evaluation with guidance on what must be evaluated.

These requirements for generally applicable measures are closely related to the requirements for standardized measures. Standardization impacts the degree to which evaluations share identical measures and tasks, and it adds an element of control to the generalizable measures. Without standardized measures the comparison of the results of different manipulator system evaluations is virtually impossible beyond a qualitative description of differences. Standardization of measures also demands standardization of methods selected to obtain data on the specific measures. With such standardization, communication among personnel in the manipulator community will be greatly enhanced, since all will be speaking in terms of a common language.

Some of the difficulties experienced with evaluation of manipulator system performance can be traced to using an adequate performance evaluation approach for inappropriate purposes. There are evaluation programs more sensitive to certain attributes of one manipulator system than others, and if we, as users, ignore this we do a disservice to the evaluation program and to any subsequent decision concerning that manipulator system. Malone (1973) has suggested that performance evaluations generally accomplish the following items:

- Engineering feasibility of a concept - can it be made to function?
- Operational feasibility of a concept - will it function as desired?
- Environmental feasibility of a concept - will it function in the environments to which it will be subjected?
- Identification of problems of specific designs
- Providing the basis for candidate concept selection
- Providing information for future design criteria

It is not proposed that any one evaluation program accomplishes all items, or that any one item can be appropriately evaluated with all available performance evaluation programs.

The inappropriate application of specific performance evaluations or the inappropriate conclusions drawn from performance evaluations are two types of problems which could be solved with a standard approach to performance evaluation. Standardized evaluations could be classified by functional area if necessary, i.e., engineering feasibility, specific design problems, and hopefully would be useful with all types of manipulator systems by functional area. Even without such functional classifications, a single acceptable evaluation instrument would permit more appropriate and comparable conclusions to be drawn from the data while testing across all functional areas - operational, environmental, engineering, feasibility, etc.

In an investigation of the problems associated with evaluation methods it is important to establish the overall objective of the methods. The evaluation methods are implemented to maximize the degree of reliability and validity of the acquired data.

Data reliability is a derived measure of the consistency or repeatability of the acquired data. Reliability varies as a function of the degree of error in the test results. High reliability indicates that the variance in performance noted in experimenter evaluations is true variance and therefore enables predictions of the limits of system performance capability in the operational environment. There are generally two types of error which can affect data reliability: sampling error and experimental error. Sampling error refers to biases inherent in the data due to inappropriate selection of subjects, systems, or test conditions. Experimental error applies to spurious effects due to uncontrolled events or conditions.

The degree of success in predicting behavior in the operational environment is a function of the extent to which the empirical investigations reflect the type of tasks to be performed in the real world. The degree to which an evaluation program measures what it purports to measure, the degree to which it reflects the operational environment, is the validity of the measure. Validity varies as a function of fidelity of the experimental conditions to the real world situation and requires that test conditions be representative of the range of conditions expected in the real world. While validity can really only be assured by comparing test performance with performance in the real world situation, it can be approximated by correlating results of different evaluation programs.

The overall control applied within an evaluation will enhance the general acceptance of a performance measure by specifying the conditions under which the measure was taken, the levels of those conditions, the conditions under which the findings are valid and recording the conditions which must be reproduced in order to retest the hypothesis covering the initial findings. These several outcomes are derived from test control and ensure a degree of reliability with respect to the findings.

One of the major sources of sampling error in manipulator system evaluation programs involves the element of "system conviction". System conviction refers to the tendency to develop an evaluation procedure with a particular manipulator system as a model or to emphasize one class of systems over others (anthropomorphic manipulators versus non-anthropomorphic, special purpose versus general purpose, operator-in-the-loop versus automatic control). System conviction is really experimenter bias in a functional sense, but with a tone of vested interest. The elimination of system conviction from evaluation programs and statements of performance capability for manipulator systems is necessary prior to the development of an acceptable evaluation system scheme. Presently, when this bias has not been eliminated, it clearly needs to be recognized for its influence upon performance findings. This is not to suggest that all evaluation programs are biased in one way or another; it does suggest that lacking a generally acceptable evaluation program with demonstrated reliability it is prudent to examine not only the data, but the method behind the data. Quite often manipulator systems are designed to meet specific requirements for a particular task or situation. Data from an evaluation approach that examined how well that particular system performed on a specified task for which it was designed would have to be viewed somewhat differently than data taken on a general performance or "aptitude" type of examination.

Another source of sampling error in manipulator evaluations has been the inability of performance evaluations to discriminate relatively small differences within classes of manipulator systems while discriminating larger differences between classes of systems. Performance criteria would, in the best of all possible worlds, indicate the best of several candidate systems, say, anthropomorphic systems, as well as indicating the relative differences between anthropomorphic and non-anthropomorphic manipulator systems.

Making the instrument as broad or as general as possible also helps to eliminate sampling bias which may tend to favor one or another system. While both the potential for a reduction of evaluation bias and the broad applicability among different manipulator systems tend to indicate that a general type of performance evaluation measure is preferable, one serious drawback is apparent. This is the possible insensitivity of the evaluation measures to detect small differences, as a consequence of employing gross measures of manipulator performance, and the relatively gross measure might not then be meaningful in the operational, decision-making environments where finer discriminations are required as a function of economics, task requirements and similar specific constraints.

In order to reduce evaluation insensitivity one may develop evaluation criteria for each manipulator system which test that system to each of its engineering and performance limits. An especially designed, tailored evaluation is certainly the most sensitive type of testing - one designed to fully evaluate the unique system. This approach which runs counter to generalizability is appropriate where the performance of only one manipulator is in question. Difficulties may arise when attempts are made to compare findings with dissimilar systems. This comes about when comparable measures are not being taken, or when measures which can be compared are taken in different ways under differing circumstances. Individually designing test instruments for manipulator systems is also an expensive way to proceed when more than one system is to be evaluated.

While evaluation bias, insensitivity, limited utility and inappropriate application may not seem to be the most severe problems which must be dealt with in the development of acceptable performance evaluation programs, they constitute the most persistent. When the first small inquiries were made into subsystems performance of the EOTS, these were some of the first questions dealt with and continue to be the stimuli for enthusiastic debate over four years later.

A final problem area which warrants attention pertains to the degree of experimental error in the evaluation results. During test sequences it is not at all uncommon for system parameters to be slightly altered out of necessity, and the interaction of a number of these changes often significantly impacts the manipulator system performance without apparent reason. Engineering models of manipulator system are often used in concept feasibility and verification and due to the prototype nature of these manipulators, they require frequent maintenance and repair, sometimes repair or replacement with newer subsystems. When using programs and programmable systems, new instructions, new decks, even a new programmer may have subtle effects which are measurable (but not altogether explained) when they interact with other variables.

It is critical in any evaluation system to maintain the strictest of all possible controls over any variables which may have an effect on the test outcome. These variables not only need to be controlled, but the levels at which they are set need to be specified. It is assumed that not every variable which may affect the outcome of a performance evaluation is going to be recognized or necessarily identified, but a complete examination of the environment and system needs to be made to detect as many control variables as possible prior to testing.

The immediate outcome rigorous control will have on data obtained in empirical evaluations is to reduce the degree of experimental error thereby ensuring maximum reliability of the data.

III. Approaches

What procedures and programs can be used with a wide range of manipulators and still yield discriminating information? What approaches can be taken to reduce experimenter bias, or system conviction? What means are there to insure the appropriate application of evaluation instruments in investigating system performance? To what extent is it necessary to record changes and list control variables in reporting all performance measures?

It is suggested here that some approaches taken by Essex researchers in the evaluation of non-programmed or program-assisted, operator-in-the-loop manipulator systems might be of more general utility and apply to evaluation problems associated with programmed robots and manipulators.

To that end of increasing the overall utility or the degree of generalizibility of performance measures, it was determined that several appropriate figures-of-merit derived from dependent measures taken on specific tasks might yield information which would allow comparisons among similar and dissimilar manipulator systems which were capable of performing the specified task. A series of task modules was designed to measure tip positioning accuracy, minimum position change, tip orientation, and force and torque application. It is assumed that these tasks can be accomplished with virtually any manipulator system and are relatively free from bias in terms of particular manipulator systems. As an example of deriving figures-of-merit, the minimum position change requires that the manipulator tip be moved from the center of a one foot square, smooth surfaced module, to a target disc on the module surface, which is a fixed distance away from the center of the module. The target discs to which the manipulator is commanded vary in diameter, thereby varying the accuracy requirements of the task. The amount of time to accomplish the move and the accuracy of the movement can be given as one type of figure-of-merit, and utilizing information developed by Fitts and Posner (1967) for manual operations, a figure-of-merit can be derived which considers accuracy and time simultaneously. Fitts determined empirically that the mean movement time for hand movements was a logarithmic function of the ratio of movement amplitude (A) to tolerance (W) of final positioning. Utilizing information theory Fitts derived:

$$ID = \log_2 \left[\frac{2A}{W}\right]$$

Where ID is the index of difficulty measuring the relative accuracy required by a particular movement which influences the time necessary to complete the movement.

Fitts' Law is one figure-of-merit which has been found to correlate with data in manipulator performance evaluation (Kirkpatrick, et al, 1975). The tip positioning task module requires that a tip position be maintained by the system for a specified period of time. By using contact discs, the frequency and amplitudes of excursions from that commanded position can be studied. This might indicate control instability, inadequate braking, whatever, but it provides a measured basis on which to compare many systems.

The measures taken on the task modules are readily taken on any manipulator system and can be taken with a degree of accuracy to permit fine discriminations between two very similar systems. Rather than develop a test approach which exacerbates the problems of general utility and discriminating sensitivity, the Essex approach was to examine very general types of manipulator system behavior in a test situation and permit the sensitivity of the dependent measures and derived figures-of-merit to discriminate between manipulator systems.

The problems created by experimenter bias, while not always apparent, can most satisfactorily be controlled by a rigorous experimental method. This is one other important reason for control of experimental variables. It reduces the influences of experimenter bias at best, and at the least, specifies the conditions and levels under which any possibly biased data were acquired. The relation between bias and experimental control is complementary in that bias can be reduced or identified with rigorous controls, or it can be amplified with loose or no significant experimental controls.

The approach most frequently taken by Essex researchers in controlling the effects of bias is to go to the experimental or testing situation only after clearly and specifically identifying the test objectives. A written test plan and procedure is prepared prior to actual conduct of any test and this test plan is reviewed by the research team. This allows everyone to make comments and suggest changes before time and effort are expended in any inadequate data collection. It also permits a hard copy document on which to record any change if it becomes necessary to vary any level of any condition in the test program. The requirement for a prepared written document prior to data collection has been a very helpful one during the extended test program. It has been instrumental in assuring test consistency during such influential occurences as staff and personnel changes, customer changes and requirements, equipment changes, and management changes which could otherwise ruin a well thought out test and evaluation program.

Malone (1973) has prepared a listing of steps which need to be taken to maximize the effectiveness of an evaluation program and which help to control problems associated with experimenter bias or failure to control influencing variables:

- Clearly and concisely identify test objectives
- Assess system performance requirements associated with functions to be evaluated
- Establish evaluation criteria
    - parameters to be investigated
    - range of conditions to be sampled
- Specify the minimal levels of fidelity of the experimental situation to the real world situation, and identify the effects of failure to meet these levels
- Identify conditions to be systematically varied and controlled (independent variables) and those to be only controlled (control variables)
- Assess effects of failure to apply rigid control over all conditions
- Identify performance measures (dependent variables) to be evaluated
- Develop specifications for mockups, software, procedures, and experimental control
- Identify methods of acquiring data on performance measures and on experimental conditions during the test
- Identify statistical analyses to be used to assess system performance in terms of performance measures and as a function of experimental conditions
- Develop a checklist for assessing degree of control and fidelity of the experimental situation once mockups, equations of motion, procedures, etc., are completed and implemented prior to testing

IV. Summary

From an experimental standpoint, the most recurrent problems, and at times the most difficult with which to deal, include the choice of representative tasks, the way in which testing is accomplished, and the application of the findings. More often than any other problems, these have been addressed to the extent that it can be presumed they represent general concerns within the evaluation process.

It may be too much to expect that any one evaluation program is going to be able to accommodate the problems of generalizability, standardization, system conviction, appropriate control, test sensitivity, and test applicability. It is not, however, beyond reason to expect that some significant difficulties which are shared in manipulator system evaluation programs can be reduced by a stringent methodology, generally applied by evaluation teams.

REFERENCES

Fitts, P.M. The information capacity of the human motor system in controlling the amplitude of movement. J. Exp. Pschol., 1954, 48, 483-492.

Kirkpatrick, M., Shields, N.L. Jr., Frederick, P.N., and Brye, R.G. Earth Orbital Teleoperator Manipulator System Evaluation Program, Essex Corporation, Alexandria, Virginia under contract NAS8-30545, February 1975.

Kirkpatrick, M., Shields, N.L. Jr., Malone, T.B., Frederick, P.N., and Brye, R.G. Manipulator System Performance Measurement. Paper presented to the Second Conference on Remotely Manned Systems, July 1975.

Malone, T.B. Remote Manipulator System Evaluation Criteria, Essex Corporation, Alexandria, Virginia, March 1973.

Malone, T.B., Kirkpatrick, M., and Shields, N.L. Jr. Manipulator System Man-Machine Interface Evaluation Program, Essex Corporation, Alexandria, Virginia, under contract NAS8-28298, January 1974.

RESEARCH ON REMOTE MANIPULATION AT NASA/AMES RESEARCH CENTER

William L. Verplank

Stanford University

Stanford, CA

At Ames, facilities have been developed to explore human performance in computer-augmented remote manipulation. The facilities include the Ames Arm (Vykukal, 1973) with a "master-brace" which the human operator can wear to command slave-arm position through DC servos. There is no force-feedback to the master. Joint positions (both master and slave) are monitored by and positions (of the slave) can be commanded by computer (IBM 1800 with A/D and D/A converters).

Under a grant to Stanford University (NASA Grant NGR-05-020345), supervised by W. Verplank, two doctoral students have used the Ames facility.

I. Augmentation and Detailed Analysis of Peg-in-Hole

Douglas McGovern has completed a dissertation entitled: "Factors affecting control allocation for augmented remote manipulation." The abstract is appended. The special form of augmentation considered (switching control back and forth between human and computer) is proposed for space applications where time delay is significant and the human operator would be available (continually monitoring) to resume (reassume) control from the computer. One task (peg-pick-up) and one augmentation scheme ("GROPE": using two touch sensors on fingers to automatically center jaw on peg) were considered. (Hill, 1973.)

Of significance to performance evaluation are several aspects of McGovern's work:

1. Using two different manipulators, McGovern applied Fitts' index of difficulty (see Fig. 1) (Fitts, 1954, 1964) to two tasks, "pick-up-peg" and "put-peg-in-hole", varying distance (A) and tolerance (B-C). Roughly, completion times are equivalent for the two tasks; tasks of the same difficulty (I_d) take the same length of time, and average completion time (T_c) is proportional to difficulty (I_d). The same relationships were shown to hold for the two manipulators (Ames and SRI-Rancho) and for the unencumbered hand (see Fig. 2). The proportionality of time and difficulty (with different slopes for different systems) supports the notion of using the ratio of completion times (manipulator vs. hand) as a key performance measure. At least, the ratio seems to be constant over a range of task difficulties. McGovern found one ratio for two different tasks and a different ratio for each manipulator system; Pesch (same workshop) uses the same ratio of completion times to compare systems, but found different ratios for different tasks, requiring a variety of tasks for manipulator comparisons. This seems an appropriate outcome. The interesting thing from McGovern's work is finding that there are two tasks with the same ratio and that the ratio is constant over a range of task difficulties.

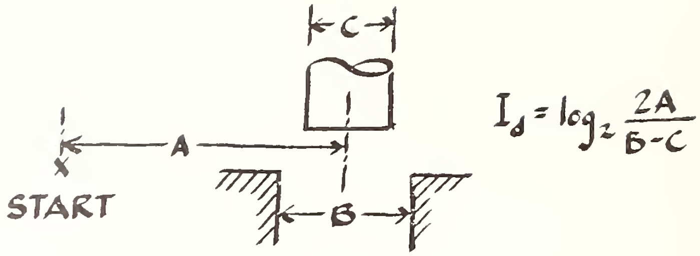


FIG. 1 FITTS' INDEX OF DIFFICULTY (I_d) FOR PEG-IN-HOLE TASK

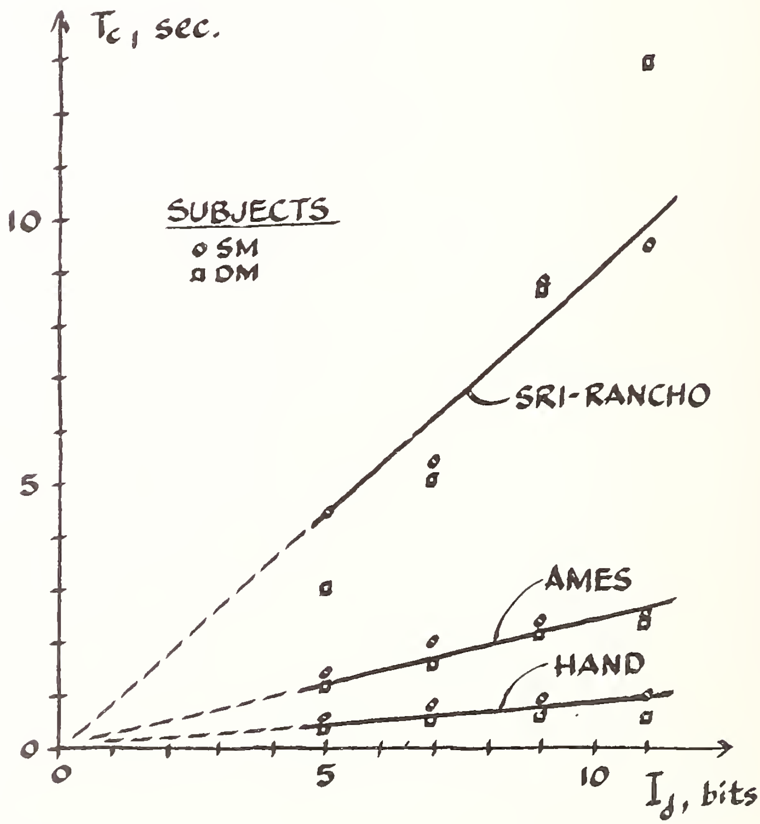


FIG. 2
AVERAGE COMPLETION TIME vs. DIFFICULTY PEG-IN-HOLE TASK (from McGOVERN, 1974)

2. Predetermined time systems (e.g. MTM) also seem an appropriate methodology for extension to manipulators. Detailed analysis of recordings of position vs. time indicate that the peg-in-hole task can be divided into two phases as in MTM: "reach" and "position". The "reach" phase is from start to within 1.5 cm of the hole. "Reach" time is linearly related (fig. 3) to distance and independent on final tolerance. "Position" time is independent of distance and best modelled as a linear function of the logarithm of the tolerance. (Fig. 4)

3. Two methods of predicting the effect of automating a portion of the task ("GROPE") were explored. One method, using Fitts' law, takes the automatic subroutine as reducing the difficulty of the task as seen by the human operator. The second uses the two phases and takes the automatic subroutine as replacing one phase ("position"). The latter is most direct and does not rely on extrapolating Fitts' Law to very low index of difficulty. No data were available to compare the prediction with actual performance using the automatic subroutine.

II. Rate Control with Time-Delay

A second doctoral dissertation using the Ames facilities is nearing completion. Greg Starr is examining rate control and position control with time delay. It is suggested that rate control may be advantageous (better than position control) with time-delay or in the situation of trading control with automatic subroutines. There are several important aspects of this work.

1. Ferrell's result for position control extends to rate control; that is, since the human operator uses a move-and-wait strategy, task completion time can be predicted from a simple model of "open-loop" positioning accuracy.

2. The MIT (Draper Lab's) 6 d.f. control stick is being used and resolved-motion-rate-control (Whitney) is being extended to the 7 d.f. Ames Arm. The tasks used by Mullen (MIT) will be used at Ames.

III. Vision Systems

Head-Mounted Stereo TV and Predictor

James L. Jones, of Ames, has implemented stereo television with a helmet-mounted display and head-aimed camera. In addition, he has developed high-speed hardware for edge detection and line-construction to compute range information directly from the video signals. Such a system connected to a computer-graphics display can provide enhanced views for the human operator (for example, rotated), or might be used in robot applications where the machine responds directly to the scene without human intervention.

Another area of on-going display development of potential value in remote manipulation with time-delay is a predictor. The current implementation uses the Evans and Sutherland LDS-1 display to compute a picture of the slave-arm from the joint angles on the master-brace. This computation is simplified considerably by the hardware matrix-multipliers of the E & S computer because the arm coordinates can be represented as successive multiplications of 4 x 4 matrices, one for each joint. The picture computed from the current position of the master-brace is superimposed on the delayed television picture of the slave-arm, providing direct display of the "future" position of the arm.

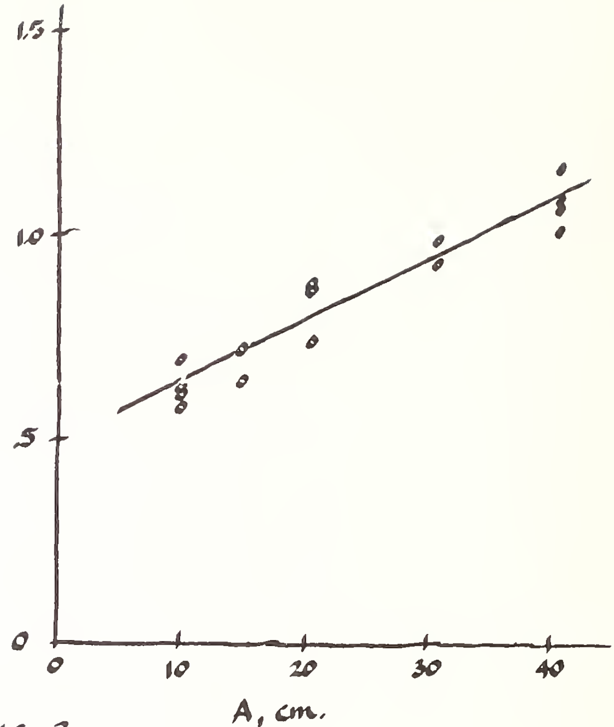


FIG. 3

TIME FOR REACH PHASE vs. DISTANCE
(from McGOVERN, 1974 Fig. 6-4)

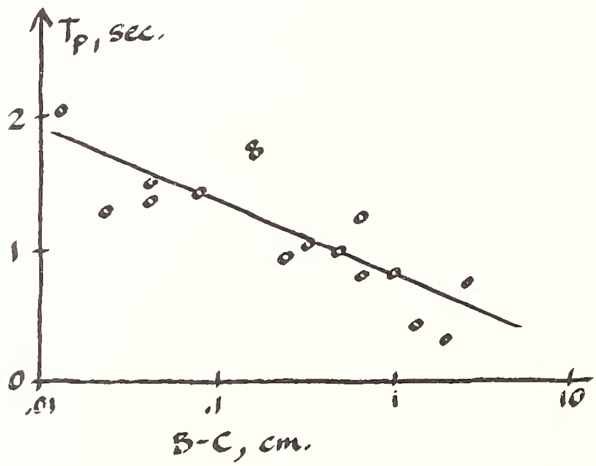


FIG. 4

TIME FOR POSITION PHASE vs. TOLERANCE
(from McGOVERN, 1974 Fig. 6-12 a)

REFERENCES

Ferrell, W.R., "Remote Manipulation with Transmission Delay," IEEE Trans. on Human Factors in Electronics, vol. HFE - 6, Sept. 1965, 24-32.

Fitts, P.M., "The Information Capacity of the Human Motor System in Controlling the Amplitude of Movement," J. Exp. Psychol., vol. 47, June 1954, 381-91.

Fitts, P.M. and Peterson, J.R., "Information Capacity of Discrete Motor Responses," J. Exp. Psychol., vol. 67, 1964, 103-12.

Hill, J.W., and Sword, A.J., "Studies to Design and Develop Improved Remote Manipulation System, Stanford Research Institute, Menlo Park, California, NASA - CR - 2238, 1973.

Vykukal, H.D., King, R.F., and Vallotton, W.C., "An Anthropomorphic Master-Slave Manipulator System," in Heer, E., ed., Remotely Manned Systems - Exploration and Operation in Space, California Institute of Technology, 1973.

APPENDIX

"Factors Effecting Control Allocation for Augmented Remote Manipulation" by Douglas E. McGovern, Ph.D. dissertation, Design Division, Department of Mechanical Engineering, Stanford University, 1974.

Abstract

This thesis develops a method for predicting the effectiveness of an augmented remote manipulator system. Such a system represents the combination of a manipulator with a human operator and a small computer. Both the human and the computer have the capability for generating commands to control the manipulator.

The performance of the integrated man-machine system can be predicted through the combination of manual control data with a model of the augmentation scheme. This involves the description of human behavior in a form which allows comparisons of the time required by the human to perform a task with and without augmentation.

A set of experiments was conducted to generate the necessary human performance data. Results are reported for a simple positioning task performed using two different manipulator systems under manual control.

Two levels of task description are used in the discussion of the experimental results. The first deals with the entire positioning task. The time required to complete the task is described by several models, including Fitts' index of difficulty, relating the distance moved to the final tolerance.

The second type of task description breaks the task into two phases, as determined by the performance of the operator. The time to complete these phases is expressed in models based on either the distance moved or on the final tolerance of the task.

Results from these experiments are used to investigate some aspects of task description and manipulator rating as well as establishing the form of human performance.

The end result of this thesis is to demonstrate how the experimentally derived manual control data can be used to predict the performance of an augmented remote manipulator system. A number of examples of augmentation are discussed and one is modeled in sufficient detail to illustrate the effect of various factors on the overall results. It is seen that such things as the type of human performance, the exact nature of the computer subroutine used in the augmentation, and the speed of the manipulator are all instrumental in determining whether augmentation decreases the time to perform a task.

EXPERIENCE AND REMARKS ON MANIPULATOR EVALUATION

J. Vertut
Commissariat de l'Energie Atomique
France

This experience was based on the force reflecting (master slave) manipulators widely used in nuclear research. My remarks then reached to unilateral arms in various applications, then our experience is now getting improved by work on bilateral servo arms and manipulator programming.

I. Basic Factors to Be Considered in Evaluation of Manipulator

1. Mechanical Characteristics

They are observed as classical mechanical measurements.

A first set is

- solid friction (force to start a motion)
- visquous friction (more important in servo)
- deflection
- backlash
- inertia as applied to the manipulator terminal
- balance

Remarks: The same characteristics can be considered for evaluation of a total system or for mechanics and control of an arm or for only the mechanics of an arm.

In the particular case of force-reflecting master-slave these factors are considered between master and slave arm, or reflected to the master (balance, inertia and friction).

In a second set we can identify

- maximum load capacity
- pay load
- duty cycle (payload could depend on duty cycle)
- maximum speed
- acceleration
- frequency response

} all three depend on load

A third set is related to combinations between the first and second set through control characteristics

. position threshold (minimal possible motions)

. minimal speed

. precision

. repeatability, etc.

Such factors are closer to the later "global" evaluation factors.

In a fourth set we can place reach and coverage which are generally only considered in addition to some of the second and third set.

Some others also never considered are:

. zoning of the coverage (ref. 1). This means the interaction of position of the terminal with available orientation capabilities of the object)

. zoning of maximum force and velocity

. zoning of payload and inertia, etc.

Remarks: To qualify a manipulator at least certain evidence can arise that the first set of characteristics might be as homogenous between different DOF as possible to not disturb their combinations.

It will seem that this leads to many conditions which are close to those found in computer control: discontinuities of speed or inertia are corresponding to matrix singularities, and not found when the articulated system is solvable and not redundant.

A certain level of evaluation will appear in the fourth set of characteristics. It is possible to keep the inertia ellipsoid at the terminal of a manipulator with an excentricity around two in any position. The same is for the maximal load capability which is represented by parallelpiped and varies with the position of the terminal device.

A very important characteristic which will be emphasized in this note is reversibility.

In case of mechanical reversibility force feedback is obtained via the position actuator used as force sensor like in mechanical master-slave.

2. Control Characteristic

Manipulator systems are extremely different in performance depending on these characteristics which are the basis of a manipulator classification; two different levels can be identified:

. a functional level related to the man in the loop, kinesthetic control or not

. a morphological level related to the system, integrated control or not

The following classifications can be submitted:

(a) Full kinesthetic control (and feedback)

. integrated bilateral force reflecting system: an example is the master-slave arm with man in the loop in real time. Another example can be a time-delay force reflecting manipulator with computer assistance to both master and slave sides. Close to this example falls an adaptive programmed robot executing a program, but teached via kinesthetic control. In this particular case global pwedoemance of the man-plus-manipulator system is showing that large distortion is very easily overcome by the operator without slowing performance (see II.1). This applies to kinematic lack of isomorphism as well as non-linear force feedback. Another fully kinesthetic control is found in vehicle control like aircraft control with force feedback corresponding to speed or acceleration. The same can be considered with a resolved motion rate control if with force feedback.

(b) Semi-kinesthetic control

It corresponds to a certain loss of easiness for the operator, with a certain loss of time efficiency. This can occur in two ways:

If the loss is morphological we find a <u>semi -integrated force feedback control</u> like with two or more sticks to control one arm or one vehicle. Systems with these controls are reversible or bilateral as far as the action on the control handle operates the slave terminal, and action to the terminal operates the handle.

If the loss is functional we can have <u>integrated position or speed</u> control with limited or no force feedback, or indirect force feedback (sound visual display, etc.). Here with the loss of force feedback we lose the bilateral property but keep a comprehensive control of the number of combined DOF. Here can be placed the resolved motion rate control as applied now. The control itself is kinesthetic but the feedback is indirect - viewing, etc., no force or dynamic feedback.

(c) Non-kinesthetic control

Here are push button and individual-stick rate controls with various forms of non-kinesthetic feedback.

(d) Systems with sensory transfer

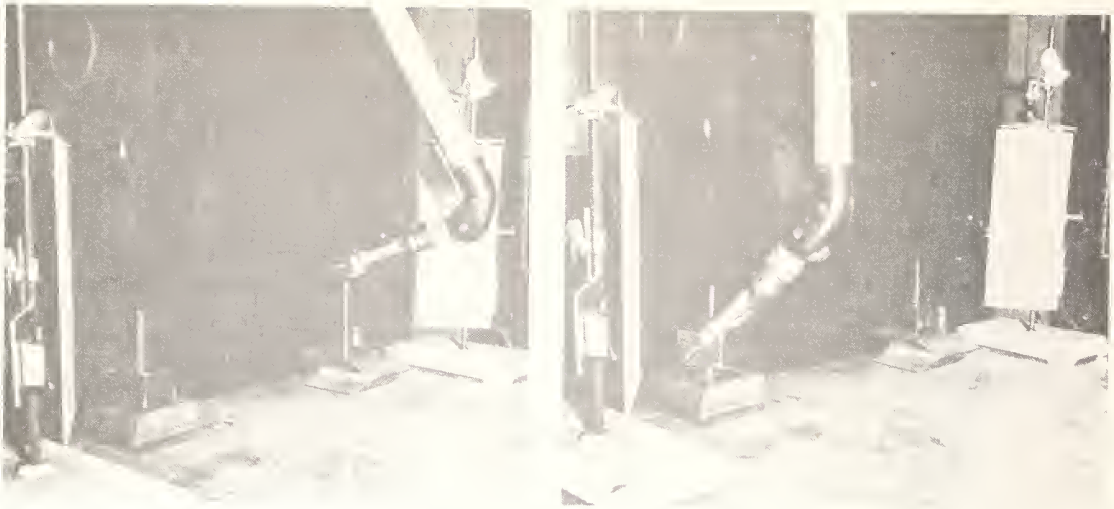
Here can be placed viewing display of touching sensors, etc.

II. Global Evaluation Criteria

1. <u>Remote Manipulators - time efficiency tests</u>

Such tests were carried out some years ago (ref. 2) with all available nuclear manipulators. The attempt was to get a time efficiency factor between the direct hand operation and the time used by the same man with a given manipulator. We suggested four standard tasks, all needing adaptive capabilities to cope with external conditions (obtained by bilateral control or compliance in open loop).

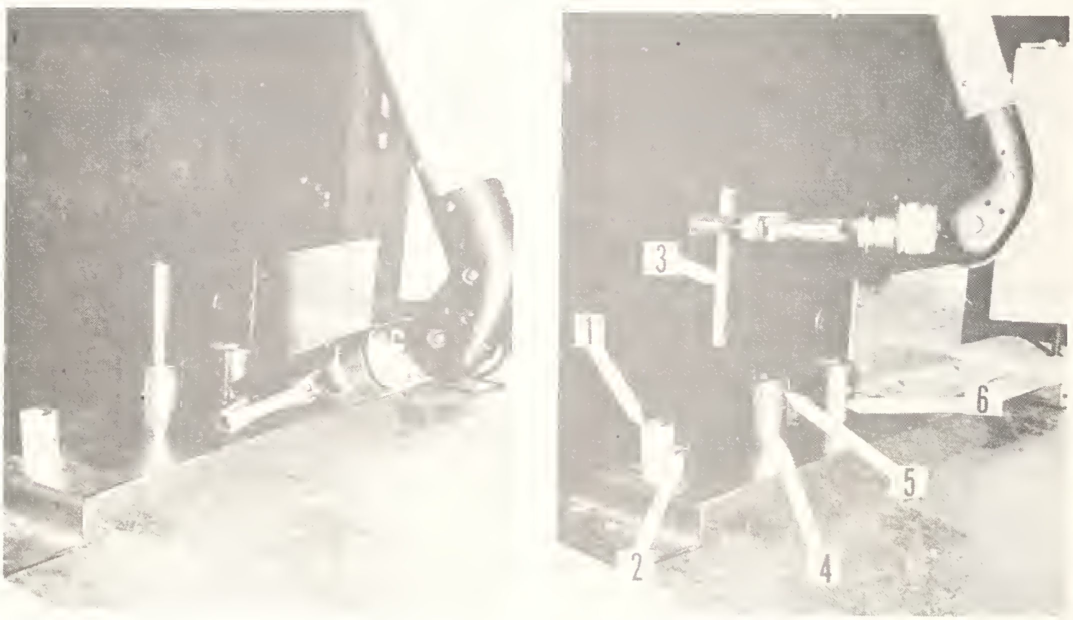
1 - block - on-peg , pick-and-place task (see picture 1)
2 - simple assembly task (see picture 2)
3 - plug test } (see picture 3)
4 - turning valve test } (see picture 3)



Fitting 0.5-kg block on pin after lifting off left pin.

Removing 1 kg block from left side to fit on right pin.

Fig. 1 Pick and Place Pins Task



Start disassembling by removing lock pin.

After fitting the pin on left block, remove peg without moving 5; then 5 is removed.

Fig. 2 Assembling Test

1. large hole block
2. locking pin
3. 1.27cm peg
4. fixed block
5. movable block
6. same as 4 and 5 but with a recess

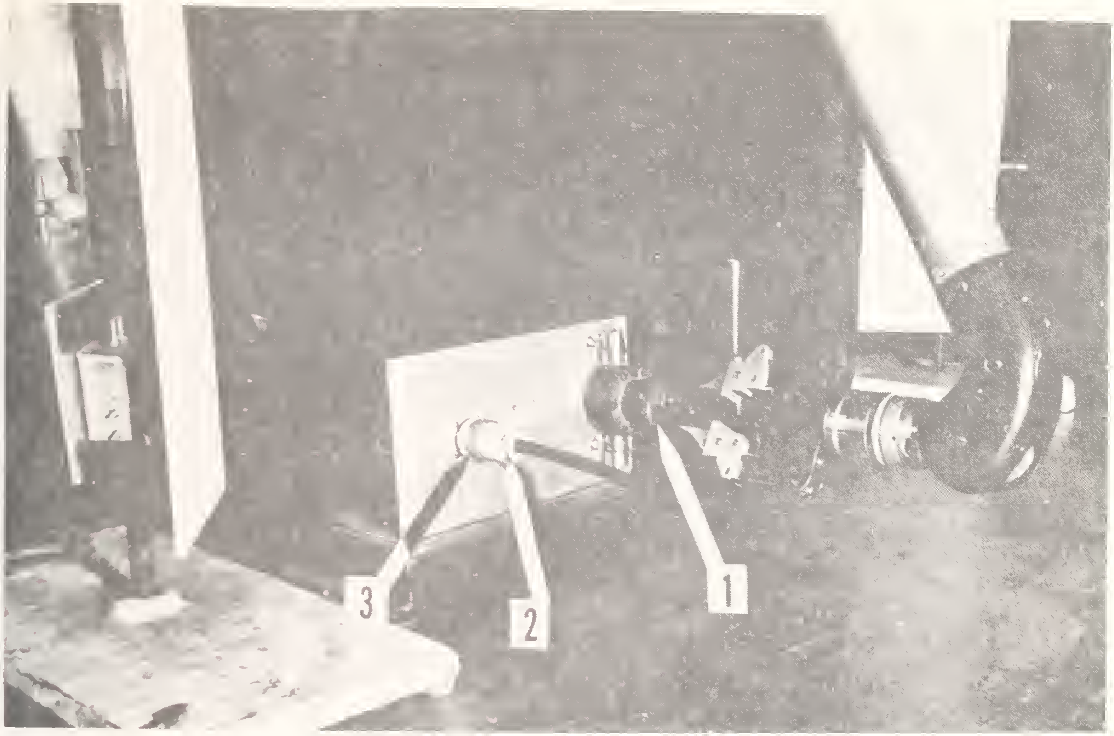


Fig. 3 Turning Valve Test and Electric Plug Test

1. valve with flat knob
2. electric plug
3. rotary lock ring

Table I is giving data from that previous work. Our recent work has been extensively devoted to sharpen our evaluation on tong effect, booting effect and handles effect. We found different figures than with previous tests for some of the tasks as shown in Table II. This method is still ineffective to reach absolute figures but it gives good relative data. We also introduced a fatigue test in addition to the previous ones. This test does not include much external constraint. We used this test ten years ago as liability test for mechanical master-slave arms. The load is fixed as the maximum load of the manipulator (usually not differentiated from the pay load). This load is made from lead bricks and the test consists in building it again on a second location 0.5 meter aside, and back. Here the data given in Table II is obtained from tests executed with the same manipulator MA 11 (see fig. 4) with the same handle we developed recently but with different tongs. On the last line are figures with the MA 22 electronic master-slave (ref. 3) - see fig. 5. Our new type of arm MA 23 (ref. 4) - see fig. 6 - will be tested the same way soon.

The first column shows higher figures because of the load which asks for the maximum squeezing force. Some tongs being slippery also give higher figures. A second reason is due to carrying the load itself. Figures with MA 22 are similar even with the 1/3 force feedback.

The turning valve test (high column) shows two data. In the first column are manipulator completion time versus hand time using the same strategy as with the two parallel fingers tong: half turn by half, turning the whole hand. In the second column, we used the normal procedure hand time, turning with three fingers in opposition. This shows a strategy factor of 1;5.

MA 22 is slower in the assembly test because of the backlash which makes it very difficult to assemble this small pin.

On the valve test MA 22 performance is limited by the maximum velocity in tong rotation.

Figure 7 shows the fatigue effect data of different handles with the same MA 11 arm in the stacking lead brick wall test. The classical CRL handle uses a natural squeezing action between two fingers (thumb and index). It gives worst time and fatigue (done with two hands), this is mostly due to two additive factors: squeezing force is poor, thus more fatigue; and lifting is difficult because two squeezing fingers are bad and the three others had to hold the handle.

All other pistol handles with a trigger squeezing are better because of their higher squeezing force and because of interactive squeezing and lifting. The best is our last model PSM 2 because of the best size (PSM 1 is too big hand).

The last curve shows the MA 22 performance, where fatigue appears around three times later, with 1/3 force feedback. Ma 11 with all pistol handles is capable of 1.5 tons, moved 0.5 meter; MA 22 is capable of 4.5 tongs in 1h 40 minutes before fatigue. An improvement period is common to all curves.

The same test will be applied now to the MA 23 new arm in programmed mode. It is expected to reach to a higher speed than by hand, from accelerated playback of a tape recording made in master-slave mode. This will also be used to test the arm liability.

Figure 8 is our previous general chart comprising force reflecting master-slave and other unilateral modes. This chart will be perfected with future tests. The large range between real-time, man-in-the-loop performance versus modes is very impressive.

TABLE I

Time efficiency of Manipulators

OPERATIONS	HAND DATA	(1) MA 11: PSM	(2) MA 11	(3) BF 680	(4) MODEL G PSM	(5) MODEL G	(6) MODEL 8: PSM	(7) MODEL 8	(8) HWM 100	(9) MODEL EHD	(10) SYNTEL: MANN*	(11) PAR 3500	(12) MR 60
	BILATERAL MASTER SLAVE										OPEN LOOP		
Task 1 - Pick and place on pins at 0,4 m 16 in. stand dev.0 %	111 s 6%	1.6	1.8	1.8 9%	1.8	1.9	1.9	2.5 7%	2	2.7 8%	10	>50	>80
Task 2 - Assembling	6.1s	2	2.2	2.4				2.9		3.7			
Disassembling	5.1s	1.5	2	2.2				2.7		3.2	20	100	100
Stand.dev. 0 %				10%				10%		10%			
Task 3 = Valve													
Turning on	2.2S	3.4	4	6				5.4		6			
Turning off	2.2S	4	6	7				6		6,5	30	>50	
Standard dev. (σ)	17%	8%	10%	13%				12%		7%			
Task 4 = Plug													
Plugging in	2.7S	3.5	5.5	5.5		5.5		5		3.5			
Plugging out	1.4S	6	6	4.5		6		7		6	30	>50	
Standard dev. (σ)	15%	27%	25%	15%				22%			30%		
Strategy slowing factor		2.6	3	3.2		3		2.3		2	3		

* Improved by high grasping with a continous twist.

(1) MA 11 French model by La Calhene also made as model H by CRL
PSM a new handle by La Calhene (see fig.4)
(2) MA 11 with CRL regular handle
(3) French articulated arm by Sorige
(4) PSM mounted on CRL model G
(5) Regular hand on CRL model G
(6) PSM mounted on CRL model H
(7) Regular mounted on CRL Model 8
(8) German model with pistol handle
(9) CRL heavy-duty extended-reach with HD pistol handle
(10) German servo open-loop arm with exoskeleton control and limited force feedback
(11) PAR rate control
(12) Model by ACB (French) constant speed and on-off control.

TABLE II

TONG EFFECT ON TIME EFFICIENCY

MA 11 PSM handle	12lbs brick wall 16 times	Pick and place on pins	Simple assembly	Plug fitting	Valve with same strategy	Valve natural hand strategy
PEM rubber fingers	3,1	2,7	2	2	2,4	3,8
PEM metal fingers	3,2	3	2,4	2	2,6	3,9
SORIGE rubber	3,4	2,4	2	2	2,7	4
CRL RCD rubber	6 [x]	2,3	1,9	1,8	3	4,5
SORIGE metal fingers	6,9 [xx]	2,4	2,1	2,2	2,5	3,8
				strategy factor	1,5	
MA 22 electronic CRL SRL HD tong	3,15	2,7	2,6	2,1	4,7	7

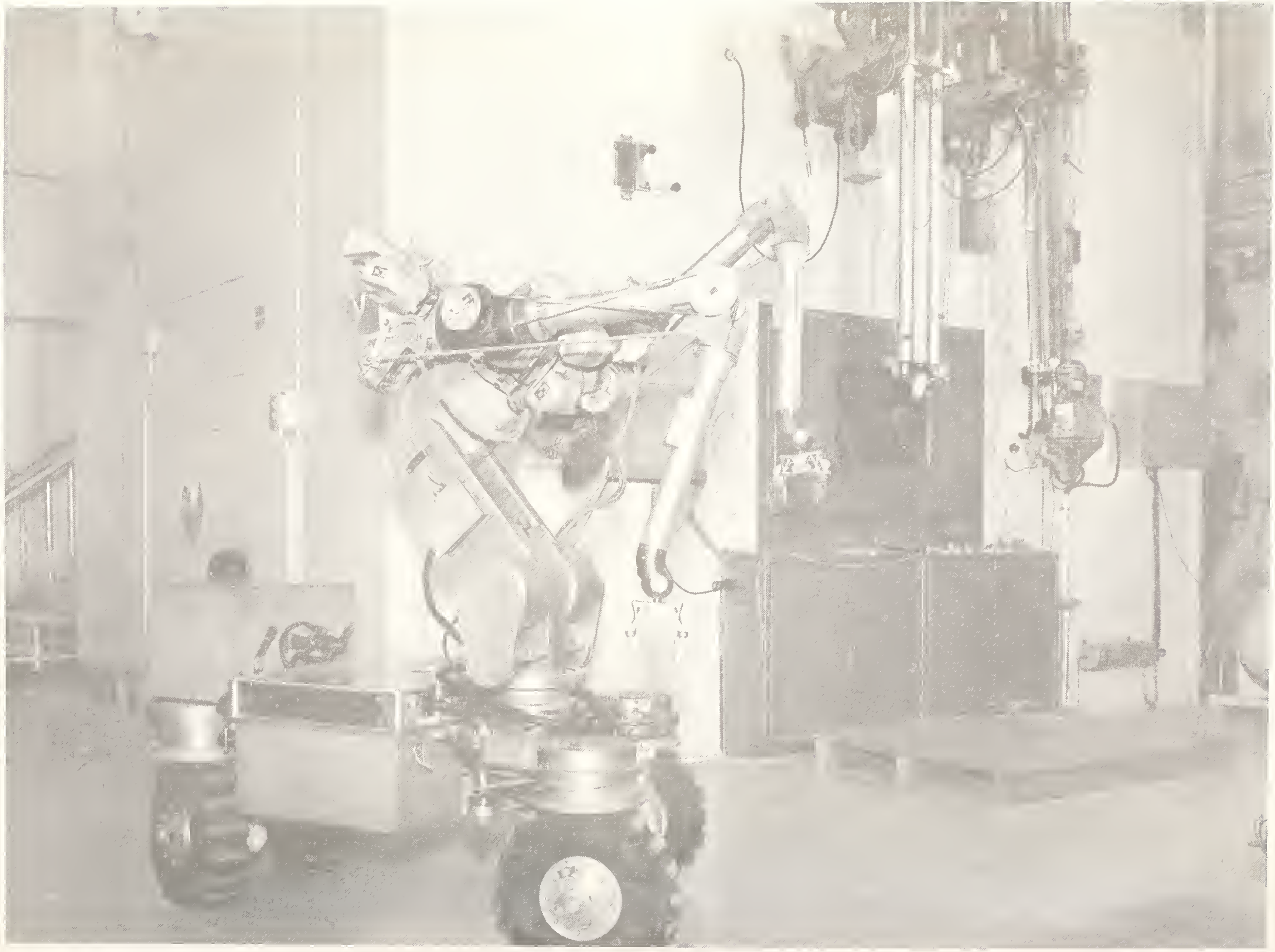
x lack of parallelism of fingers with this load makes lost time when the brick pivots. This is specific of the tested tong.

xx Fatigue by lack of squeezing force and slippery fingers.

This data is still more relative than absolute, see table I.

↑2 3↑ ↑4 ←1

FIG. 4 - Articulated manipulator MA 11
1 master arm
2 slave arm
3 shielding
4 PSM II improved handle.



3→ 2↑ 1↑

FIG. 5 - VIRGULE VEHICLE WITH MA 22 ARMS

1 four wheels advanced vehicle can steer around any center of rotation
2 batteries with power amplifiers on top
3 electronic rack (radio, multiplex)
4 articulated supporting arm (3 DOF)
5 one pair of MA 22 slave arm - Television not installed on this picture.

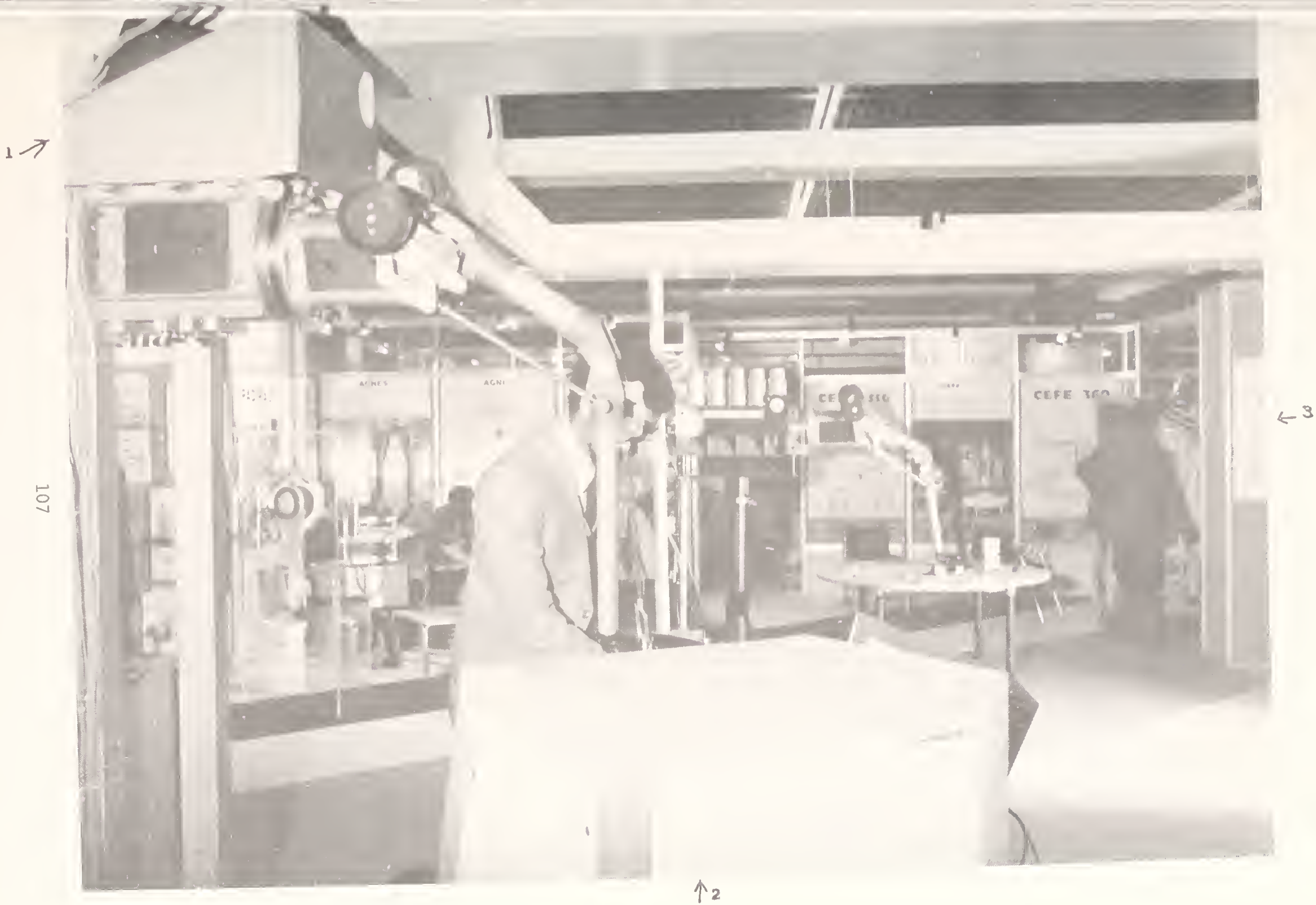


FIG. 6 - MA 23 advanced master slave svstem

1 - Master arm - including power amplifiers 60 Newton force feed-back (15 lbs)
  - similar with a 100 Newton maximal force slave arm (22 lbs)

2 - electronic rack for one pair plus tope recording - with master power supplv

3 - slave arm with 230 Newton maximal force (52 lbs)
  power supply can be close to slave arm

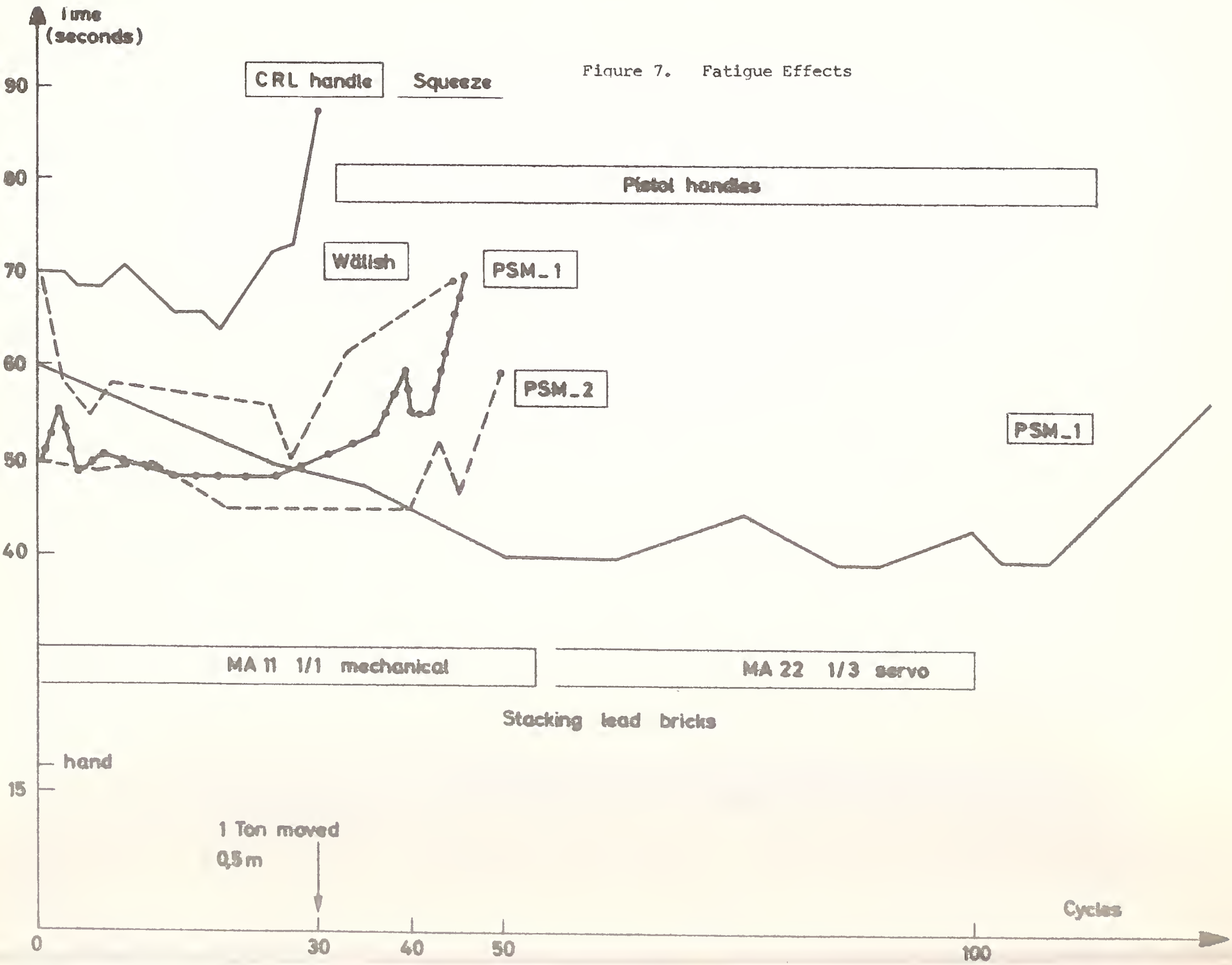
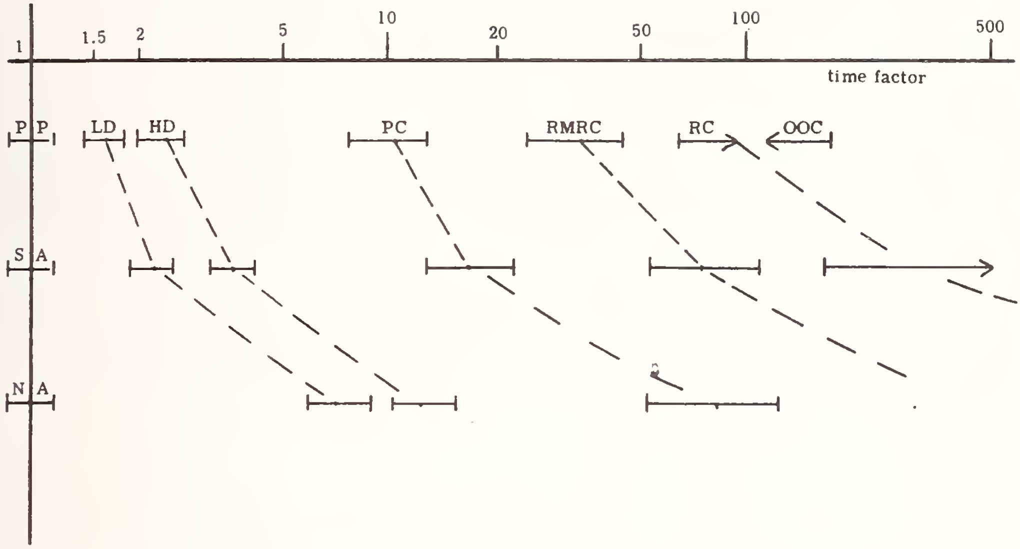


Figure 7. Fatigue Effects

Figure 8

Time-Efficiency Proposed General Chart



PP pick and place
SA simple assembly
NA normal assembly
RMRC resolved motion rate control (MIT)
RC rate control

LD light duty master slave
HD heavy duty bilateral master slave
PC position control-unilateral often called master slave
OOC on-off control

2. Programmed manipulators and manipulators with time delay

Programming (teaching) a programmable manipulator (first generation robot) is closely like remote handling. Up to now except for a few machines (Trallfa, ref. 4 and 5), teaching is always carried on by push button mode. It looks to be no problem of time to program but I expect that it will be necessary to teach faster soon. Up to now, performances of a robot are only as given in I.1. About the close future, a first level of self-adaptivity can be based on force to position - like it works via man in the loop using a force reflecting master slave. Evaluation of such ability might be based on the force errors accepted during the task completion. This error in our servo master slave (ref. 4) is a figure of 3 to 5% of the payload, and make possible to operate self-adaptive work even on small parts, using manually a reversible manipulator. The work carried in Draper Laboratory with high accuracy force transducers will certainly bring a very interesting knowledge in that field. Roughly the first level of adaptivity will provide to cope with position errors up to tong opening size. A next level of self-adaptivity now also in development is related to reaching known objects out of the tong size clearance by using proximity sensors. To evaluate such systems time performance versus distance, and maximal distance perception are to be considered. To larger distances and unknown objects the eye-hand automatic system is needed - evaluation will follow the development itself.

III. Conclusion

1. Classification - definition

So many manipulators (teleoperators and programmed manipulators) are needing first to be classified in categories. This is still early development ("robot" is still not defined) so I prefer to use the other name to develop a language to help developers, makers and users to communicate.

2. Testing

It is urgent to bring out methods to measure performance and to analyze the factors reflecting to performance to get standard evaluations by improving exchanges between specialists.

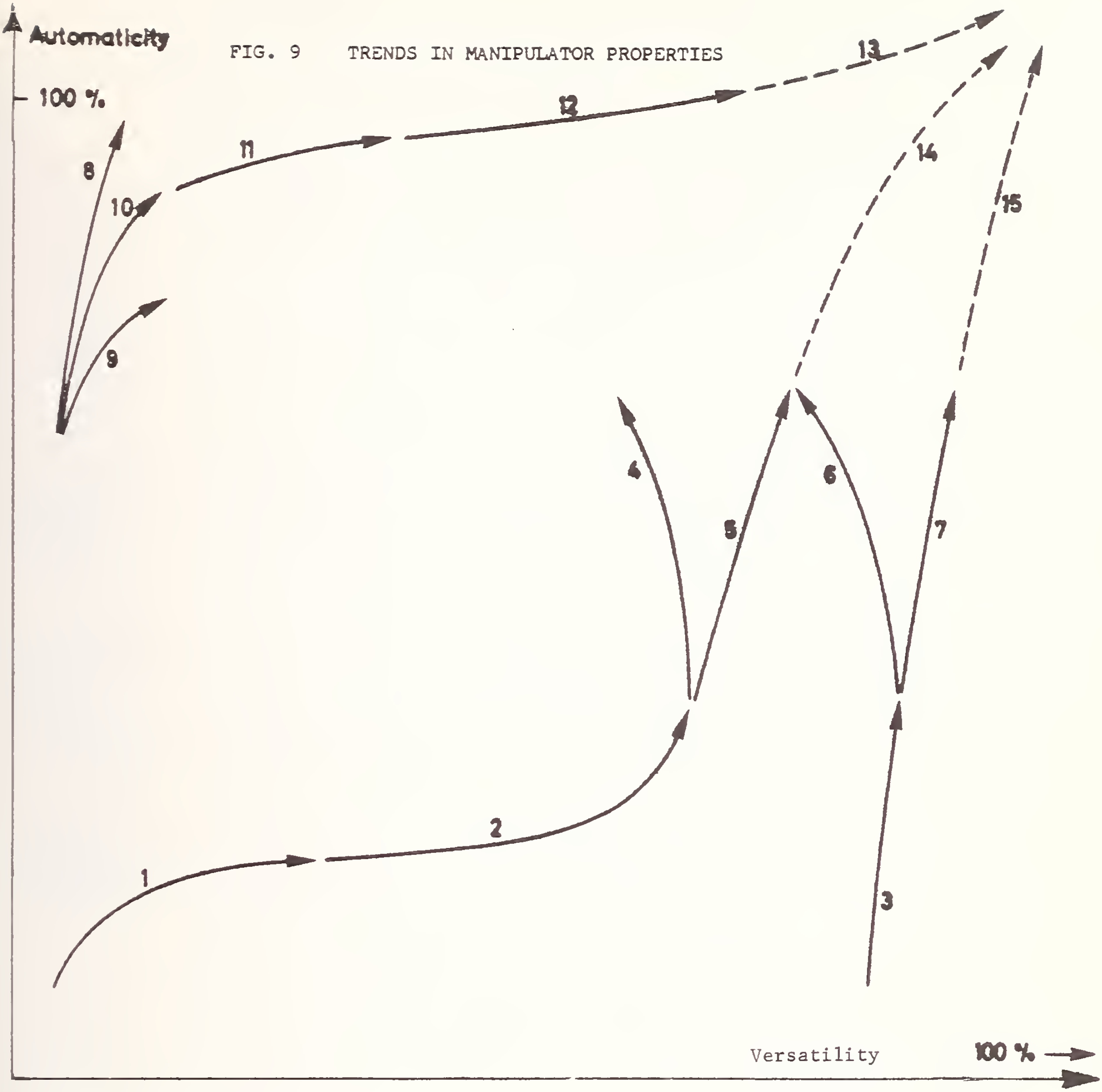
3. It is also necessary to explore new concepts to evaluate general capabilities of advancing systems. One concept I would like to propose is transparence: a transparent teleoperator system between man and any hostile environment makes possible to be in symbiosis with it, the man doesn't feel the system. This optical analogy is clear with the force-reflective bilateral manipulator. The fully transparent system does not bring performance reduction;the time efficiency factor is like the inverse of transmittance. Another notion is the ability to face unpredictable environments. It is a combination of versatility (ref. 6) and automaticity, as illustrated in Figure 9.

These notions are not clear up to now, but might lead to measurable figures in the near future.

4. Possible proposal of a standard set of characteristics for a force-reflecting manipulator system:

- friction: $\leq$ 3 to 5% of payload
- deflection: $\leq 2\text{-}5\ 10^{-2}$ m under max. load

FIG. 9 TRENDS IN MANIPULATOR PROPERTIES



1. Lifting devices from non-powered to powered
2. Lifting devices to powered open-loop manipulators to position servo manipulators with sensors but without force feed-back to operator
3. Mechanical master-slave to servo force-reflecting master-slave with sensors (2nd generation)
4. Unilateral manipulators to specialized manipulators
5. specialized manipulators to remote manned spacecraft
6. 2nd generation force-reflecting manipulator to remote manned spacecraft
7. 2nd generation force-reflecting manipulator to 3rd generation (with eye-hand coordination and pattern recognition
8. regular machine tool to automatic production lines
9. automatic production lines to NC machine tools
10. NC machines to programmed manipulators (1st generation robots)
11. 1st generation programmable manipulators to 2nd generation (position to force adaptivity)
12. 2nd to 3rd generation programmed manipulators (position, force, pattern recognition adaptivity)

13-14-15. to ideal automatic manipulator (this at last can be called "robot")

- inertia $\leq$ 50% payload
- payload $\geq$ 50% maximum load
- duty cycle 100% at payload
  50% at max. load
- no load acceleration $\geq 20 m.s.^{-2}$ (2g)
- acceleration with payload $\geq 10\ m.s.^{-2}$ (g)
- max. load $1\ m.s.^{-2}$ (0.1g)
- max. speed $1\ m.s.^{-1}$ or total range in 1 s
- angle between velocity vector and force vector $\leq 2^{o}$
- minimal speed $10^{-3}\ m.s.^{-1}$ or total range in 1000 s
- minimal displacement 10^{-4} m. or 10^{-4} total range
- backlash 10^{-4} m
- frequency response 4 to 8 Hz (no load)
  2 to 4 Hz (pay load)

All first ones are already possible with the MA 23 system, the last ones are expected. All this proposal is highly subject to revision.

REFERENCES

1. J. Vertut and al, "Analytical Zoning of Manipulator Coverage," Proc. 21st Conference on Remote Systems Technology, p. 28, 1973.

2. J. Vertut and al, "Contribution to Define a Dexterity Factor for Manipulators" Proc. 21st Conference on Remote Systems Technology, p. 38.

(1.2, See also J. Vertut and al, First ROMANSY Conference, Udine, 1973)

3. J. Vertut, C. Flatau, and al, "MA 22 Compact Bilateral Servo Master-Slave Manipulator", Proc. 20th Conference on Remote Systems Technology, 1972, p. 296.

4. J. Vertut, P. Coiffet, "Bilateral Servo Manipulator MA 23, in Direct Mode and Via Optimized Computer Control," 2nd Remote Manned Systems Conference (to be published), Los Angeles, 1975.

5. J. Vertut (C.E.A.), P. Moreau (Ateliers et Chantiers de Bretagne), "Le Robot Alpha I," on request.

6. J. Guittet, "Robotique Industrielle et Medicale," Bulletin de Liaison de la Recherche en Informatique et Automatique, IRIA n^{o} 19 - October 1975, on request.

PERFORMANCE EVALUATION OF INDUSTRIAL ROBOTS

J.F. Engelberger

Unimation, Inc.

Shelter Rock Lane

Danbury, Conn. 06810

It's just possible that attacking the question of "performance evaluation of programmable robots" is premature. Robotics is still in its technological infancy and too much structure early on could stifle healthy growth. There is obviously much innovation and invention still ahead. Roboticists' thinking should be allowed to soar for awhile longer before being circumscribed by specifications.

Some newcomers to the field plunge into product development and attempt to make contributions to the art; others less happily try to synthesize something of value out of dubious data on feeble early prototype experiments. To date this synthesis has been counterproductive. Synthesizing projects carried out by SRI and IITRI in the U.S.A., IPA in Germany and Waseda University in Japan served to mislead would-be entrants into the industrial robot field as well as to confuse potential users to the point of frozen inactivity.

There have been something over 200 attempts worldwide to develop products which their developers wishfully dubbed "robots". The Japanese Industrial Robot Association, JIRA, and Warnecke and Schraft in "Industrie Roboter" have made the most exhaustive compilations of projected performance specifications. The data base permitted extraction of trend information such as:

Drives: 39% pneumatic, 51% hydraulic, 10% electric
Controls: 57% against stops, 25% analog, 18% digital

Also kinematic descriptions showed what articulations different developers espoused.

So what? Where does this leave the manufacturers who are potential users?

In a more fruitful line of enquiry, IPA examined robot specifications from the point of view of the working place. However, it is this author's considered opinion that the analysis failed to be useful largely because of inexperience on the part of the investigators with the subtleties of the working place. This is the kind of data better accumulated by roboticists who have struggled with the problem of replacing a human operator with a robot operator.

By way of example:

At the Third International Symposium on Industrial Robots, Dr. G. Herrmann, defending the IPA survey, reported that he had found 150 jobs in Daimler Benz that could be done by relatively simple robots with but 4 articulations and 10 steps of memory. He was confronted with the observation that there were 11 such "simple" robots on exhibit and asked why these quite inexpensive machines were not being used by Daimler. He replied, "There seems always to be some facet of the work which needs human attention."

So, the developer who dutifully produces a machine to match the requirements outlined by IPA is probably heading for disappointment. And, a majority of the 200 or so developers around the world have already tasted that disappointment and abandoned the field.

A workshop on performance evaluation of programmable robots would probably do well to ignore most products touted as being robots. These "limited sequence" devices are really automation components. They may be fine ones indeed and they may be destined to broad, profitable acceptance; but, they are part of the modular, adjustable automation field. Robotics is another branch of Automation.

(This is the proper place for introducing a succinct definition of "robot" but I will demure; I can't define robot, but I know one when I see one.)

With the warning flag raised, it is time to return to the assigned task. Just how do we evaluate performance of programmable robots, be they exciting or conjectured? The jumping off point for the president of Unimation, Inc. has to be the Unimate Industrial Robot.

The Unimate is unabashedly sophisticated and its manufacturer is dedicated to increasing that sophistication wherever technically and economically feasible. This is <u>the</u> direction for Robotics.

At this writing there are approximately 1000 Unimates in the field and they have accumulated over 5,000,000 hours of field experience. With cavalier discounting of "limited sequence", or "pick and place" devices, I can opine that Unimation Inc. is the world's only viable robot manufacturer. There is no other builder that profitably produces a general purpose, programmable industrial robot. (There are, of course, some interesting and competent designs making tentative entrance into the marketplace.)

The Unimate had its origins in 1956. It started with the raw idea that a robot should be useful to industry and that a performance spec should be created against which design concepts could be evaluated. With much of the naiveté that has been laid at the doorstep of IPA et al, a group of young engineers studied jobs in all of the major automotive companies and in a variety of other industries. Figure 1 is a typical data sheet of the time.

A product appeared in 1959 and it finally went to work in 1961. That was the beginning of a long agonizing refinement of the data base. Every application tried was shot through with surprises. Both product (robot) and application instructions underwent continual change on the way to a satisfactory fit. Fortunately, the product specification changes pointed toward a universal product design (hence, vindication of the company name, Unimation, a contraction of UNIversal AutoMATION). Unimation Inc. is completely sanguine in defending the concept of a universally applicable robot over the more widely promoted "limited sequence" devices.

It happens that Unimates are built and bought to a specification; but, it must be admitted that it takes some imaginative extrapolation to go from that spec to assurance that the robot will be effective in any specific job. Moreover, the spec is hardly adequate to prove that the machine is sufficiently robotic to be obsolescence

CONSOLIDATED CONTROLS CORPORATION
UNIMATION SURVEY DATA SHEET

DATE: 5-16-56

OBSERVER MJD

LOCATION ____________

TYPE OF WORK PERFORMED:

Press forming of centrifugal rotors

SEQUENCE OF PRESENT OPERATION:

Transfer of stock through a series of presses which form, punch & trim

APPROXIMATE CYCLES PER MINUTE:

10

MAXIMUM NO. OF SEQUENCES:

Horizontal	Vertical	Rotary
5	4	3

ACCURACY AND MAXIMUM SPEED:

Horizontal Traverse: 3 ft. ± 1/8 in.; 24 in/sec.

Vertical Traverse: 2 ft ± 1/8 in; 24 in/sec

Rotary Traverse: 180°; ± 12 min, 90°/sec

HAND ACTION REQUIRED:

Clamp, 90° & 100° rotation

APPROXIMATE WEIGHT OF PART:

3 lbs.

NO. OF OPERATORS:

12 per shift - 2 shifts

PROCESS MODIFICATION REQUIRED:

None

AVAILABLE AREA:

4 ft. x 5 ft.

/1b
5/2/56

FIGURE 1 - TYPICAL DATA SHEET

proof - that is, versatile enough to succeed in a variety of job assignments.

The gap is filled by application data sheets, films, etc., that demonstrate the broad capability. Physical characteristics are enumerated in the specification. "Show and tell" is the method for communicating information on the robot's talents.

Could a more elegant method be devised for evaluating any industrial robot's performance? Well, it might be useful to think of the robot as an artificial human being and rate the robot accordingly. One might then generate a resumé comparable to that submitted by human job applicants. Figure 2 is a prototype job application form, including appropriate responses of a Unimate.

The more sophisticated robots become, the more likely it is that the resumé will become a practical means for evaluating performance against potential applications.

Still, there are many who would continue to feel more comfortable thinking of the industrial robot as a machine. Clear specifications on machine characteristics then become the evaluation base. For a sophisticated robot, specs would have to be quite exhaustive to tell the story. The data sheets in "Industrie Roboter" which show little more than spatial command, number of articulations, kinematics, accuracy, load rating, and control mode, are so limited as to be almost useless.

Perhaps the most glaring omission in most robot specification sheets is dynamic data. Usually slew rates and maximum strokes are given for all articulations. This is of marginal value in estimating how long a particular robot would take to carry out a specific task. One would like to interrogate the specification as follows:

"For each discrete motion required in this task, considering the loads involved, and presuming critically damped action, what is the elapsed time?"

It's not easy to create a specification that would be simpler than a complex multiple input nomograph to provide a reasonably accurate answer. Even though we in Unimation Inc. recognize the importance of dynamic criteria, we avoid a generic specification in our product literature. Rather we use trained application engineers to examine a work station and estimate total cycle time. We also give customers a very crude rule of thumb to make a preliminary appraisal. "For any load less than rated assume that all steps will average out to 0.8 seconds per step." From experience we have learned that the mix of short and long steps in a typical program will defend this average.

At this juncture it is proper to report that IPA has recognized the gap in previous reportage and is suggesting that "point-to-point" time should be made up of three Δ Ts' - acceleration ΔT, deceleration ΔT, and slew rate ΔT.

For one robot task, spot welding, Unimation Inc. does provide a more precise tool for estimating time to carry out a complex task. This is an 18 page document! It is worth using because it permits very accurate estimating of the number of spot welds that a Unimate can place while a car body is in station before it. Robots are expensive. Knowing beforehand how many are needed to complete a body in the allotted time is a key factor in payout analysis.

Figure 2

APPLICATION FOR EMPLOYMENT

NAME Unimate 2000B SOCIAL SECURITY NO. None

ADDRESS Shelter Rock Lane, Danbury, Connecticut 06810

AGE 300 hours (by software extension - 5,000,000 hours)

SEX None HEIGHT 5 ft. WEIGHT 2800 lbs.

LIFE EXPECTANCY 40,000 working hours (20 man-shift years)

DEPENDENTS Human employees of Unimation Inc.

NOTIFY IN EMERGENCY Service Manager, Unimation Inc. (203/744-1800)

PHYSICAL LIMITATIONS Deaf, dumb, blind, no tactile sense, one armed, immobile.

SPECIAL QUALIFICATION Strong(100 lb. load), untiring 24 hours per day, learn fast, never forget except on command, no wage increase demands, accurate to 0.05" throughout sphere of influence, equable despite abuse.

HISTORY OF ACCIDENTS OR SERIOUS ILLNESS Suffered from Parkinson's Disease (since corrected), lost hand (since replaced), lost memory (restored by cassette) hemorrhaged (sutured and fluid replaced)

POSITION DESIRED Die cast machine operator

OTHER POSITIONS FOR WHICH QUALIFIED Forging press, plastic molding, spot welding, arc welding, palletizing, machine loading, conveyor transfer, paint spraying, investment casting, heat treatment, etc.

SALARY REQUIRED $4.00/hour

RELATIVES IN THIS PLANT Five 2000A Unimates in forging department

LANGUAGES Record-playback, assembly, Fortran

EDUCATION On the job training to journeyman skill level for all jobs listed above.

REFERENCES General Motors, Ford, Caterpillar, Babcock Wilcox, Xerox and 65 other major manufacturers

Using the estimating document, the application engineer is able to consider "squeeze, weld, and cool" time, robot motion time for adjacent welds, time to make large motions to new operating zones, time to approach work piece, time to retract arm from work piece, and the impact of weldgun size and type on these times.

It will not be easy to create a crisp, dynamic performance standard that would be generically applicable to all industrial robots.

An important philosophical aside comes from one of Unimation's customers. This customer settled for a rough average of number of spots that could be placed per minute and then assigned robots at an 80% efficiency factor. When the production line went on stream, the equivalent of an MTM study was done and the excess robots were pulled off the line to be assigned elsewhere.

The circumstances above pertain to a production line wherein the single largest capital investment is in robots. A 20% variation in number used did not significantly change the economic attractiveness of the system. And, being robots rather than special purpose automation, the Unimates could readily be used on other jobs. In the case where a robot is assigned to an expensive piece of capital equipment, timing can be very critical. A 10% loss in production when robotized could completely scrub the application.

The performance specification problem is easily compounded by cataloging other robot attributes for which one would like to have a quantitative evaluation.

1. Manipulative power - This is approached qualitatively by describing the number and range of articulations in the robot arm and wrist. But there is application significance to the coordinate system used, to interaction between articulations, if any, and to space intrusion of the forearm, wrist and end effectors.

2. Programming ease - Complex jobs can consume much high skill programming time. How much is heavily dependent upon programming methods available. Discounting every method less sophisticated than infinitely adjustable record-playback programming, there are "joy-stick" operations, computer generated sub-routines, and feedback assistance to think about. Adding sensory perception further complicates the issue.

3. Interface compatibility - Robots are not "stand alone" machines. They interface with equipment, parts, people, and systems much as do humans. Ideally specificatio would predict performance in the modern factory environment which would include DNC equipment, automatic warehousing, group technology and computer-aided manufacturing, etc

4. Reliability - Possibly this factor could be sufficiently covered by historical evidence of MTBF, meantime between failure, and MTTR, meantime to repair, for different factory roles. (One gets different figures for forging applications than for plastic molding applications.)

5. Sensory perception - Do rudimentary eyesight and/or tactile sensing provide orientation data, recognition data or physical interaction data? What quantitative measures can be applied?

6. End effectors - Does a robot have a general purpose end effector (i.e., hand)? How flexible is it? What dexterity and what range of strength?

7. Mobility - If the robot is not stationary, how is mobility performance evaluated? Speeds, random walking, umbilical cords, spatial awareness, terrain capability, etc.

8. Self-diagnosis - "Robot heal thyself." The ability to offer nostrums for its own performance lapses will be a valued robot attribute. Diagnostic skill will be hard to quantify.

9. Cost effectiveness - Robot hourly cost versus human hourly cost should be added to classical standards such as payback, return on investment, and discounted cash flow.

10. Inherent safety - What confidence factor can be applied to a robot with respect to each of Asimov's three laws of Robotics?

In the foregoing catalog only some of the stickier issues are enumerated. There are no problems with power consumption, weight, floor space required, load capacity, slew rates, reach, memory size, accuracy, interlocks, time delays, random program selection and such, which already appear in commercial product spec sheets.

One final complication can be added to industrial robot performance evaluation and that is the matter of the work place. An argument can be made for evaluating (and changing) the work place as well as the robot.

If the work place is rationalized, the robot performance requirements could be alleviated. Where parts are oriented in pallets, the robot might forego eyesight, for example. Thus, Unimation engineers instinctively evaluate work places against the limited performance available in their current product. Sometimes there's a fit, sometimes process changes can be recommended, and sometimes we simply throw up our hands in utter dismay.

The industrial robot concept is gaining a grudging acceptance. As this acceptance mounts, there is every reason to expect the work place to be bent to the robot qualities available. Meanwhile, roboticists can strain to more closely match robot attributes to those offered by humans.

A cocked ear at the foregoing finds support for the opening conjecture. It may be too early to solidify robot performance specifications. So much performance and projected performance is tenuous. There are many wide open performance objectives to which engineering contributions may be made - even without concise problem statements. One may literally depend upon "gut" feelings in selecting development projects.

Tom Sheridan in setting forth the problem statement thinks one of the options is an "I.Q. Test" for robots. Somehow this has appeal over a machine specification. Ultimately, the resumé, summarizing available skills, should be the more useful document to employers who contemplate hiring artificial human workers. The employers of robots need only higher order performance standards. Roboticists, for their part, can look introspectively for worthy design goals. Robotics is still that far from its destiny of providing mechanical workers to take over for homo sapiens in the factory.

ROBOTS FOR AUTOMATED PRODUCTION OF CONVENTIONAL AMMUNITION

Douglas A. Morlock

United States Army Materiel Command
Office of the Project Manager for Munitions Production Base
Modernization and Expansion (AMCPM-PBM)
Dover, New Jersey 07801

The Army Materiel Command is currently modernizing and expanding its conventional munitions production base. Modernization and expansion makes use of modern process automation and process control technology to complement existing munition production capabilities for future forecasted potential needs. The scope of the products range from small fuze parts to large steel forming machines. New technology in chemical processes for the manufacture of propellants and explosives, load, assemble and pack items, automated testing, warehousing, inventory control, and also field test-production traceability is actively sought. Some of the demanding design goals for these new facilities directly impact on the purpose and objectives of this Workshop. Some time spent on discussion of these goals will serve as background for further discussion on more specific areas.

The maximizing of production line availability is of critical importance for obvious reasons, since the product demand for these facilities is of strategic importance. Most of the succeeding criteria directly or indirectly relate back to this point. All process and process control hardware must therefore exhibit strong reliability in order to provide suitable operation. Closely related to this point is that system operation and component interaction must be such to assure safe system operation under normal and abnormal operating conditions. The system safety and process security area contains two major divisions due to the hazardous atmospheres associated with the munitions production processes. The propellants and explosives manufacturing buildings and areas for assembly of these products to their associated metal parts are rated as hazardous and must be protected as are petrochemical and other similar industries. The protection measures which must be employed to assure that electrical energy above certain specified levels cannot exist within these hazardous areas is therefore of prime concern in munitions production plant design. The use of intrinsic safety hardware and procedures, fluidics, optics, pneumatics, and hydraulics is therefore being emphasized. The operational safety aspects implementable within the process and process control design are also being emphasized.

The minimization of operating staff exposure to the processes, especially in hazardous areas, is also being emphasized. This goal not only strives to save human life, but can be traced back to the concern for line availability by minimizing human decision requirements during abnormal crisis periods. The minimization of human dependence for tasks which can best be pre-programmed and performed by machine while not de-humanizing the operator because of a feeling of non-importance and involvement are considered heavily in systems design. Process and process control systems must exhibit a certain degree of flexibility in order to incorporate any process improvements affecting product uniformity or production cost. As with all industry today, we are also committed to the conservation of natural resources and the minimization of pollution to our atmosphere and waterways. And of course, all of this must be accomplished with the minimum capital investment possible.

So far the munitions production business appears similar to many other industries using process and process control equipment. We have, however, one quite unique problem not faced by many others. Most industries produce a product having a fairly defined, uniform demand or demand cycle. Conventional munitions are only required in volume during a time of conflict or war. However, we cannot build the required production capability at that time for obvious reasons. Therefore, the strategy is to maintain our production facilities in a state of readiness (layaway), being able to recommission them upon demand which is usually considered to be within ninety days from notice. During this period the stockpile reserves are used in place of the production. This layaway period is considered to be from five to fifteen years for design purposes.

Leaving the general area to deal with items manufactured and past and future applications of robotics requires that the functional areas of munitions production be segregated. These major areas are: metal parts manufacture; load, assemble, and packing; and warehousing and inventory control. Each of these areas contains several different categories of application and I will touch on as many of these areas as possible and therefore by necessity will not go into great depth on any of them.

Metal parts manufacture covers the large area from small caliber ammunition to artillery shells to small fuze parts. Robotics could efficiently be applied to the packing of small caliber ammunition by transferring the finished product from the material handling equipment to the shipping boxes. A manipulator could be used to transfer a sheared, heated billet from a conveyor to a forming machine and another used to position the drawn shell for machining, while yet another performs gaging functions on the finished product. The artillery shells in question range from the 105mm to the 8 inch rounds. The physical data on these items can be found in munitions handbooks. The gaging and assembly of fuze parts eliminates the human dependence within the operation, assuring a uniform product.

Plans are currently under consideration for using robots for remote sample extraction of propellants and explosives within the manufacturing process. In certain areas, on-stream analyzers are being employed for in-process analyses; however, where analyzers are not available, samples must be extracted, in liquid or solid state, and be transported to laboratories for analysis. Applications in the packing areas where finished products are placed in cans and boxes are also possible.

The loading of explosive into artillery shells involves the melting, pouring, and controlled cooling of the explosives. Due to the expansion characteristics of explosives when heated, funnels are placed in the top of the shells to be poured which are subsequently removed after cooling. These operations are likely candidates for manipulators. After being poured, shells are X-rayed to detect possible voids present in the pour. Shells exhibiting these defects must be extracted from the line and transferred to alternate rework lines. This transfer is a function which could be performed by a manipulator. The shells then progress to the assembly area where fuzes or fuze plugs are inserted and the shell is mated to the cartridge case and placed in boxes to be palletized and warehoused. Certain materials handling functions in this area could use manipulators.

Efficient automated warehousing would make use of non-stationary robots for product placement and subsequent shipment by identified lot numbers upon demand.

From this overview, it can be seen that the potential application of robotics to munitions production is quite broad with some unique design requirements. We are embarking within the MOD/EXP program on a large scale documentation standardization program to aid in more efficiently identifying systems requirements, more efficiently specifying those requirements, to better identify costs, and to aid in the recommissioning from layaway problem. In summary, we are dedicated to using evolving technology in the accomplishment of our task and desire to include all pertinent specification guidelines generated as a result of this Workshop into our overall documentation package. We require continued feedback from industry in order to make this interface more efficient and thereby enable us to make use of the available technology.

SERVICING OF INDUSTRIAL ROBOTS - THE MODULAR CONCEPT

Michael S. Konstantinov

Central Laboratory for Manipulators and Robots

Sofia, Bulgaria

I. Abstract

The problem of on-site servicing of industrial robots lies in the field of interest of modern automation. Whilst successful use of robots depends on their positioning accuracy, reliability, ease of servicing and security, measuring of their performance in terms of reliability versus ease of servicing indicates that there are very good reasons for the development of "modular robots". This paper shows that the modular design approach is successful and profitable. The new modular robot system "Matador" is described in detail.

II. Introduction

Whilst the control system design of a programmable robot or manipulator generally determines its positioning characteristics, it is the mechanical design that principally dictates its rigidity, load carrying performance and ease of servicing. If the robot does not operate or its positioning accuracy fails, production is down. Successful robot users have set up their own servicing departments for robots. They stock their own set of spare parts. But what of the smaller, short run manufacturer that doesn't have his own trained servicing personnel? He is then dependent on having to send across the country, or around the world for spares. In view of this, it is pertinent to look at the modular concept in relation to the design of present day robots.

The concept of modular standardized control systems is not new. The technique is well established in the solid state electronics field, where it is accepted that ease of servicing and trouble shooting result in favourable economics. In the fluid control systems such techniques are less well established. Concerning the mechanical design of a programmable robot or manipulator, there is over the last few years a conflict of opinion between the "modular robot" concept and the "universal robot" philosophy. Unimation Inc. (and now Unimation Limited) has borne the universal industrial robot for considerably more than a decade. Today, the battle lines are drawn and both camps have set down their ideas and thoughts, but the long awaited "boom" is far behind the clouds.

This position paper outlines the author's experience on the subject of measuring performance of relatively sophisticated robots in terms of reliability and servicing. The lessons learned indicate the advantages of the modular concept and determine the rational tradeoffs of a new modular design and assembly system for industrial robots and all kinds of manipulators.

III. Characteristics and Attributes of Robots

Industrial Robots (IRs) are divided into three categories of increasing complexity on the basis of capital cost and capabilities[1]. Load, speed, positioning accuracy, range of motion, dexterity, control quality, program memory capacity and robot-to-process line control logic are salient operating characteristics that must be defined as guidelines for the selection of the proper robot system. Consideration should be given to the intrinsic and to the logged reliability, the ease of its servicing, and the security of such a machine. The best selection of a robot depends on the combined effort of both designer and user.

1. Positioning Accuracy

This characteristic is closely related with motion speed and handling weight. Positioning accuracy limits the usage of robots, and this is especially true for machine assembly work. As motion speed and handling weight are also important robot characteristics, these must be examined simultaneously with the positioning accuracy item.

2. Reliability

There are two concepts to be considered in an examination of this attribute, one is "Mean Time Between Failure" (MTBF), and other is "Mean Down Time" (MDT). No less an authority than Joe Engelberger, President of Unimation, Inc., envisages a relationship between the time interval between failures and the total amount of down time [2]. But he states that the correlation is not proportional because there is the additional variable of time of repair. Thus, an otherwise satisfactory MTBF could result in unacceptable downtime if the time to repair is excessive. According to this roboticist, industrial experience indicates that for most applications, uptime must exceed 97% to satisfy most users of IRs. And, he continues, "this rule of thumb is somewhat dependent upon the specific application; in a glass manufacturing plant, for instance, there may be need for uptime of 99.5%."

In this connection, the German roboticist, O. Gengenbach, suggests the correlation for uptime (in %)[3]:

$$B \text{ (mittlere Verfugbarkeit)} = \frac{MTBF}{MTBF + MDT}$$

Two typical examples are given:

Example 1. To predict the failure rates for all the components in a Unimate, a USA organization relied upon notebooks which were prepared under U.S. government contract to aid prediction of reliability of space vehicle systems. For electronics components, the Rome Air Development Center Notebook, TR-67-108, was used and for mechanical hydraulic components the organization used U.S. Navy's Failure Rate Data (FARADA) Notebook. Both of these references were cross-correlated with other similar data banks. Since field experience is crucial to determine true reliability, the robot was placed in the field and the experience results fed back into a reliability control system. In the case of one 2000 Series Unimate, the opening experience produced an MTBF of 145 hours and was slowly brought over the ensuing three years of production up to 415 hours.

Example 2. It considers downtime. If we assume that servicing is done by local service personnel, and that the IRs are working on a two shift basis, and that the service can always offer next-day help, then the most likely MDT per incident would be eight hours. Of course, the situation could be more complex.

It is clear from the above considerations and examples that robot reliability is a very complex issue.

3. Ease of Servicing

To evaluate servicing, in general, it is useful to look at past failures and defects that occured on the robot already built and on other robots of the same model. Recently an effort has been made at COMSAT Laboratories to classify failures in terms of reliability. Accordingly, a "design" failure occurs early in life. Its identification shows that the reliability was not as high as planned. This can result from actual design or from quality control. A "random" failure may occur at any time. Its occurance does not change the estimate of the attribute reliability. A "wearout" failure occurs late in the design life of the robot; it may be actual wearing out. Four types of failure or defects could be distinguished: reparable, difficult reparable, probably reparable and no reparable. Thus "reparable" is an estimate of whether a failure is serviceable. This depends on how much of the robot is built to be serviceable.

Furthermore, failures in electronically programmable robots and manipulators with hydraulic actuators could be classified in two main groups, (a) part failures only: electronic/electrical and mechanical/hydraulic. The non-part failures are system failures due to tolerance build-up, critical interface tolerances, customer abuse, environmental problems, etc. This type of failure occurs in robot systems at a rate proportional to the complexity of the system.

Generally servicing is defined as preventive maintenance and repair of equipment. Given the working conditions, one must consider that on site servicing is cost effective for long term robot operations when compared either with robot replacement or with robot removal and assignment of a human operator. Robot servicing on site could be accomplished either by local service personnel or by the user's trained personnel. So too, even where training of a user's personnel is minimal, a robot could be "repaired" through telephone consultation, "remote control" of the personnel.

In fact, the servicing personnel has to perform the following tasks:

- permanently
  (a) preventive maintenance
  (b) early preventive diagnostics
  (c) running repair

- incidentally (when a failure occurs)
  (a) arrangements for a clear of purpose servicing
  (b) diagnosis of the failure (part or non-part)
  (c) part disassembly or elimination of the non-part failure cause, i.e. environmental hazard (ambient temperature rise, radiant heating, shock, electrical noise, etc.)
  (d) part repair or spare part exchange
  (e) part(s) assembly
  (f) short service test
  (g) disassembling of servicing facilities

Ease of servicing means facilitating the above tasks in order to gain time and cost. Ease of robot's servicing is closely related with robot design. IR can be designed so that failed or worn-out parts can be replaced in a few minutes while the robot remains on site. In addition to cost, such a mode of servicing offers the possibility of improved service and can improve robot's reliability in both concepts, MTBF and MDT.

4. Security

The necessity of sharing the robot environment with people, as well as other equipment, forces designers to give more than the usual amount of attention to identifying potential failures which could be destructive to people and equipment. Evaluation of this physical attribute of an already built IR necessitates a step by step structural analysis of each robot linkage and a kinematical and dynamical analysis of the robot hardware in terms of some "worst anticipated case". These should be followed by engineering speculations to identify all possible failures or malfunctions in the robot that could be destructive to people and to equipment. For instance, the multiple degrees of freedom are a great advantage for the robot versatility and dexterity but they carry with them an equally great responsibility to reduce the potential for destruction.

IV. Measuring Performance - Reliability Versus Ease of Servicing

In 1969-70, IRs were introduced on the European market and three years thereafter a manufacturing company in this country bought such a programmable manipulator. The type of robot selected, still in the forefront today, was just emerging and gaining acceptance. It is equipped with 5 degrees of freedom and is of the relatively sophisticated universal type, offered as a completely self contained device, well designed and made. The manufacturer claimed that it was thoroughly tested, with industrial machine life expectancy, a minimum of maintenance and down time.

In fact, the manufacturing people of this company were not familiar with IRs. Furthermore, local service and local stock of spare parts were not available. Therefore, it was decided to begin with the education of the company people on what an IR is and how it is to be used and programmed. The lack of spare parts and of a local service was also considered and it was not envisaged to put the robot in their production, at least for a performance test period.

As a first step in bringing the users in direct contact with the robot a so-called "flexible automatic manufacturing cell" was installed. Such a system constitutes the linking of one numerical controlled machine tool with an industrial robot and a magazine for workpieces. Thus, a service test was made under simulated conditions of use.

1. Performance Evaluation

The robot worked on a two shift basis. Generally speaking, MTBF was satisfactory but resulted in unacceptable downtime. Two "design" mechanical/hydraulic part failures occured and another electrical/electronics non-part failure, due to ambient temperature rise, worsened the positioning accuracy during the test period. Whilst the non-part failure was easily identified and removed by an electronics serviceman of the same plant, the part failures caused considerable troubles to the manufacturing people. No spares were available on site and the robot repair turned out to be a complicated issue, despite the fact that the first incident was due to a relatively simple failure in a hydraulic throttle valve. The operations of diagnosis and identification, part disassembly, spare part provision, exchange and assembly were painful and a great deal of time was taken up to this end. The completely self-contained-device design worsened the situation. The second part failure showed almost the same picture; the time to repair was also too excessive and both failures resulted in a higher rate of downtime.

In conclusion, the manufacturing engineers and the plant managers stated that the most serious disadvantages of this robot are: (a) its low reliability; (b) completely self contained design; and (c) its non-standardized component parts. Finally, it was decided not to install the robot into full production, since it is not easily serviceable even by skilled personnel.

The lessons learned with this relatively sophisticated robot indicate that there are very good reasons for the development of modular robots, especially for short run manufacturers who can really benefit from the use of only a few robots.

V. The Modular Robot Concept

Recent efforts in the design and development of modular IR systems have resulted in some interesting, new and unique designs.

The basic configuration approach adopted groups the standardized sub-systems into four main modules: the manipulator, the controller, the power pack and the application gripper. In many cases any, if not all, of these main modules are also modularized, so that all modules including those of the application gripper and the sensor modules (if any) are replaceable in the event of malfunction, wearout, or the availability of an improved version. Studies of the potential economic benefits of the modular approach have consistently shown lower emergency repair costs and time and, therefore, a minimization of the MDT. The exchange operations are made on site, while in a normal repair activity on a sophisticated industrial robot, the whole unit would be disconnected and moved to a safe distance. It must be emphasized also that the more sophisticated a robot is, the more important is maintenance and the more skilled must be the type of mechanic or electrician engaged upon it. Robot repair must be kept simple! This is particularly true when the robot is installed in a plant where no high-grade maintenance and servicing personnel is available. A practical approach is to design the modules so that their removal and exchange can be effected very simply. The modules can be repaired and re-used, so that additional savings accrue.

The number of modules used in a system is a design variable. Two contradictory factors operate. Weight minimization is favored by using a few modules. On the other hand, preventive maintenance on a group of modular robots is favored by using many modules since each is then replaceable. Mechanical modules can contain parts of kinematic chains; elemental chains of the manipulator can have the actuator elements in the module or can have them spread over several modules.

A survey of modular industrial robots identified different system concepts that exhibited a range of versatility, complexity, and capability to accept a wide range of workpiece and tool operations characteristics. VERSATRAN (U.K.), MANTA (GFR), ELECTROLUX - MHU (Sweden/GFR) are a few european examples. The number of robots offered in modular form in Japan is noticeable. Of the six on show at the International Industrial and Materials Handling Exhibition in Tokyo (18-23 November, 1974), two, the Kayaba Industries KMR-2, and the Tokyo Keiki IAX, were hydraulically powered, the remainder being driven pneumatically.

VI. The Matador Concept

Several mechanical IR modular systems are in present use and development as an important part of IRs. The extent of modularization ranges from complete sub-system autonomy (ROBITUS - Japan) to simple movement modules: rotary and translatory modules (MANTA - GFR). Studies led to the conclusion that all known IR modular systems are serviceable, with some weight and volume penalties but with relatively low cost penalties, affected by the extent of modularization. Positioning accuracy and security are limited when the extent of modularization is increased. MDT is improved in all cases.

There are two fundamental concepts in robot R & D. In the one, the structure and all functions and characteristics are compared with real man. On the other hand,[4] it is not necessary to think of human beings as the ideal target. The "Matador" concept was borne by the marriage of both concepts.

Analysis of IR structures and their kinematics (the arms) established in a very simplified approach two types of joints: R (revolute) and P (prismatic) ones. One of the stipulations for IR modules states specifically that they shall form an open multi-link chain, which kinematically connects a moving body to a "fixed" frame. The mechanical modules require a mechanism which incorporates high operational and volumetric efficiency plus high reliability. With this requirement as a guide, the objective is therefore the synthesis of an open modular linkage, used to move a further member (the gripper or end effector) through many arbitrary positions in the space (workzone). The basic "Matador" concept is the synthesis of required modules in the form of linkage elements. Synthesis of binary links for both finitely and infinitesimally separated position problems has previously been extensively studied by Professor B. Roth of Stanford University. In addition to presenting a new and unified approach to the modular design and assembly problems in the field of robotics, the "Matador" system presents an entirely new type of binary link ("dyads"). The new binary links are with revolute (R), prismatic (P) and R-P "half"-joints. Thus, we may regard a R or P joint as the combination of two "half" joints interconnecting their respective dyads. Thus, following modules (dyads with "half" joints) are defined: 1/2 RR module, 1/2 RP module, and 1/2 PP module. The frame link and the output link are 1/2 R or 1/2 P modules.

Now, to the mother nature. Analysis of the human arm structure establishes a two-link chain comprising an upper link (upper arm) and a lower link (lower arm), which are used to move a member (hand) through a hemispherical workzone. Kinematical analysis shows that in order to reach the envelope of the hemisphere with the outstretched two-link chain (arm) the upper link requires two degrees of freedom with regard to the frame (shoulder). To accomplish contact with the frame by the member (hand), the links of the chain are of equal length, which requires one degree of freedom. In such a manner the member could be placed at any point within the hemisphere (workzone) by a RRR linkage.

In IRs design the arm (regional) linkage just described can be provided with the following joints' combinations:

RRR	RRP	RPR	PRR
RPP	PRP	PPR	PPP

Most present-day equipment utilize RRR (spherical coordinates), RPP (cylindrical coordinates), and PPP (Cartesian coordinates) joints.

As an example, the arm sub-system (regional structure) of an IR working in cylindrical coordinates comprises a series of 1/2 R - 1/2 RP - 1/2 PP - 1/2 P "Matador" modules.

VII. Conclusions

The development of modular low cost serviceable robotic devices needs a significant amount of engineering effort to better satisfy the needs of the smaller, short run manufacturer. Performance measurements of specific modular systems should be made, especially in terms of their physical attributes, such as reliability and ease of servicing. International "standardization" efforts will, among others, reduce production costs and improve the servicing of industrial robots.

REFERENCES

1. Bryant, S., Carne, E.B. "Some Observations on the Economics of Complex Industrial Robots", paper No. F2, pp. F2.9-F2.20, Proc. 2nd Conference on Industrial Robot Technology, Univ. Birmingham, (March 27-29, 1974).

2. Engelberger, J.F. "Three million hours of robot field experience", The Industrial Robot, Vol. 1, No. 4, June 1974, pp. 164-168.

3. Gengenbach, O. "Zuverlassigkeit, Instandhaltung, Arbeitssicherheit". 5 Arbeitstagung des IPA - Erfahrungsaustausch Industrieroboter '75, Vortrag Nr. 35.

4. Konstantinov, M.S. "Inertia forces of robots and manipulators", paper presented at the Second Conference on Remotely Manned Systems (June 9-11, 1975), University of Southern California, Los Angeles, USA.

A COMPUTER-AIDED ROBOT OPERATION SYSTEMS DESIGN (Part 1)*

Yukio Hasegawa (Waseda University)
Ichiro Masaki (Kasawaki Heavy Industries Ltd.)
Masahiro Iwasawa (Oki Electric Industry Co., Ltd.)

PALS Committee of Japan Industrial Robot Association
and Japan Metal Stamping Association, JAPAN

System Science Institute, Waseda University
Shinjuku-ku, Tokyo 160, JAPAN

ABSTRACT

In industrial robot operation systems design, there are many conditions to be considered such as work pieces, fabricating machines, dies, peripheral equipments, layout, cycle time, and so forth. For developing more systematic and logical procedure to design the robot operation systems, we applied a conversational type computer technique and refined the procedure. It was started from system elements construction of metal stamping operations as static state and proceeded of dynamic characteristics determination of the system. The paper introduces the outline and the early stage of the research.

I. INTRODUCTION

In the robot application field, most of the robot operation systems are designed by robot application engineers. In order to obtain good results, we need to have good engineers and methodology. The application technology of the industrial robot is composed of need analysis for the new robotized production system, the selection and synthetic combination of hard wares such as fabricating machines, robots, conveyors, peripheral devices and so forth. Up until today, the robot application technique has depended on the implicit accumulation of an engineer's practical experience, and we had no systematically organized technique.

So we need many man-hours of proficient engineers for the robot systems design work. We are anxious that the shortage of engineering man-power and the high cost of the robot application soft ware will be a serious bottle neck when we introduce large numbers of robots into production lines in the future. For solving the above problems we started a research project to develop the computer-aided robot operation design systems, so-called CAROD (Computer-Aided Robots and Robot Operation Systems Design). As a practical foundation to develop the system, we applied metal stamping operations. Fig. 1 shows the general view of our CAROD system development.

* reprinted from Proc. 5th Intl. Symposium on Industrial Robots, Chicago, Illinois, Sept. 22-24, 1975, pp. 203-213 (with permission)

II. OUTLINE OF CAROD

CAROD is composed of two phases. One is the static phase and the other is the dynamic phase (DP-CAROD) of the system. The static phase (SP-CAROD) handles the layout of the robot operation systems, the motion pattern of the robots and so forth. The CAROD robot operation systems design is done by following the procedure shown in Fig. 2.

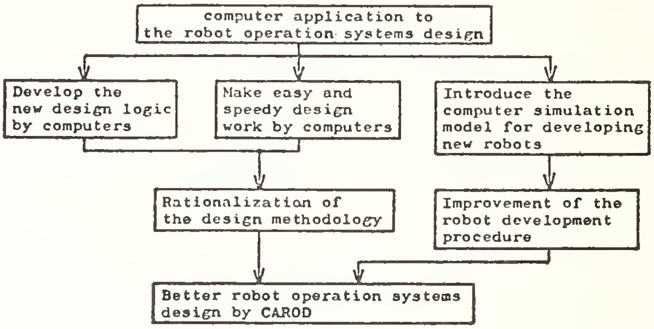


Fig. 1 General view of CAROD development

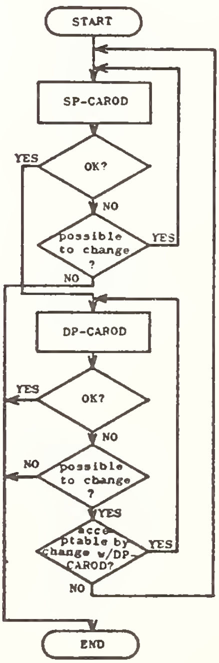


Fig. 2 General flow of CAROD

In the SP-CAROD, the design result is drawn by a plotter that is connected with CPU. The design procedure is executed by conversation form. If a designer thinks that the design alternative that comes out from the plotter is undesirable, he can re-design the model by utilizing the local feed-back loop. After a designer gets a desirable result of SP-CAROD, he proceeds to DP-CAROD. In DP-CAROD the designer inputs the results of SP-CAROD and the dynamic characteristics of the system elements into the CPU and generates dynamic characteristics of the integrated robot operation systems.

If the designer thinks the result (dynamic characteristics of the robot operation systems) is not appropriate, he modifies dynamic characteristic of the system elements and re-designs the DP-CAROD. In this case the designer cannot accept the result by using the local feed-back loop, and also it is anticipated that there is some problem in the static phase design, then he must return to SP-CAROD through the general feed-back loop. By following the above procedure he can get an elevation and plain figure (projected on the cathod ray tube) of the system.

The CAROD is also useful for robot selection and development. For instance, in SP-CAROD, if we can make statistic data of robot operation systems design restrictions, those are to be used for input into the CPU; then the designer finds statistically the appropriate type of robots for particular conditions.

III. STATIC PHASE CAROD

In SP-CAROD, the designer exchanges conversation with CPU through the tele-typewriter. Then he chooses an appropriate robot that has suitable motion patterns. The CPU outputs the layout drawing through the plotter. We need to classify the main components and restrictions for forming the robot operation system patterns. For instance, we classified the robots into eight categories, the two classes by press machine frame type, diesets into two types by having front guide posts or not, the peripheral devices into two parts by feeding methods, and the layouts into two patterns by longitudinal and side long restrictions.

By combining those patterns we can classify the robot operation systems into 128 types as shown in Fig. 3. As you see in the figure, for instance, the robot operation system pattern No.1 is composed of a multi-armed robot, a C type frame press machine, a no-front-guide-posts dieset, a continuously fed type peripheral device, and longitudinal type layout. In this research, we constringed from 128 to 36 patterns.

IV. DYNAMIC PHASE CAROD

In DP-CAROD, we analize and inspect the behavior of a robot operation system by feeding in information about the system into the CPU as shown in Fig. 4. We feed in such information as SP-CAROD design specifications, dynamic characteristics of the robot and the press machine which are used for the operation system, and display operating conditions on a cathod ray tube in the computer system.

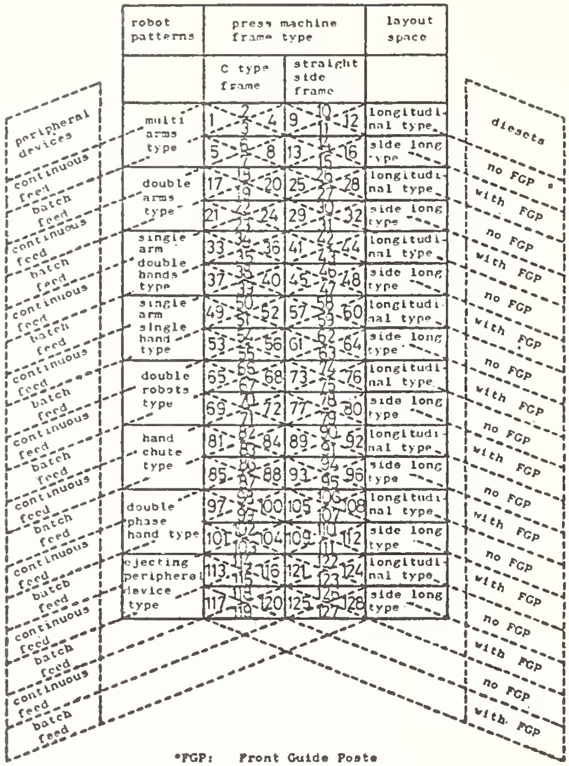
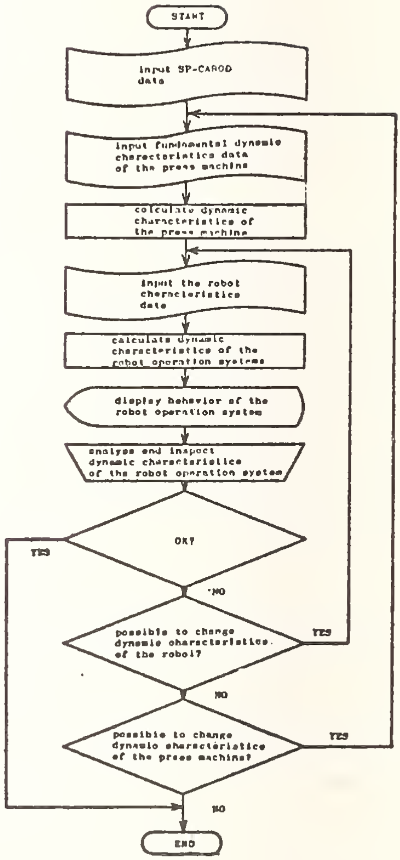


Fig.3 Classification of robotized press operations

Fig.4 General flow of DP-CAROD



The designer inspects moving pictures in the cathod ray tube display by referring to the related materials, and determines appropriate conditions. If the designer considers that dynamic characteristics of the operating system are inadequate and there is some possibility to change the dynamic characteristics of the robot or the press machine, he again displays the behavior of the robot operation system.

At the start the designer inputs the dimensional data which are based on SP-CAROD design result and calculates the co-dominant area. A "co-dominant area" is an over-wrapping area of robot and press machine slide movements, and if matching movements are inadequate, a crushing accident will be probable in this area. From dynamic characteristics of the robot and "co-dominant area" dimensions, the designer can calculate the time that the robot does not intrude into the "co-dominant area". This time is the one when the press machine slide can intrude into the area without crushing against the robot. Therefore, the time is called "possible intrude time of press machine slide".

Then from the fundamental dynamic characteristics data of press machine slide and the dimension of "co-dominant area", the designer calculates the time when the press machine slide has to intrude into the area ("necessary time of press machine to intrude into the co-dominant area"). As shown in Figs. 5 & 6 the designer adjusts the "necessary press machine slide intrude time" coming at the middle of "possible press machine slide intrude time" by matching both movements, and determines the stopping (waiting) time at upper dead-end point of the press machine.

From the above data processing work the designer can display the behavior of the robot operation system. In the case of the robot development and allied aspects, the analysis of the dynamic characteristics is the most important problem. In the above case we can utilize CAROD as a simulator. For instance, dynamic characteristics of the robot is limited by characteristics of actuaters and control mechanisms and it also has particular speed curves as synthesis of the characteristics. By giving these data to DP-CAROD with other dynamic characteristics of the robot, the designer can get useful data for designing and selecting robots in each case.

V. CAROD APPLICATION CASES

Fig. 7 shows an example of conversations between the designer and the computer system in SP-CAROD. In these Q & A type conversations, the computer system asks questionnaires through the typewriter output and lets the designer input simple answers through the typewriter, too.

In these questions and answers the designer has received the following instructions.

1) As to drawing scale, there are two choices of 1:25 and 1:50.

2) As to the width of the work piece, it must be shown with the maximum width of raw material and the finished stage.

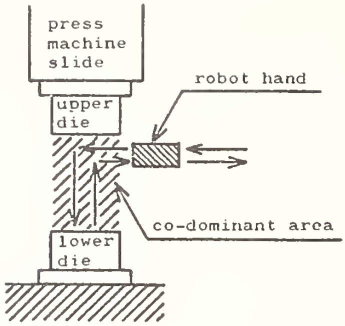


Fig. 5 Co-dominant area of the robot
and press machine

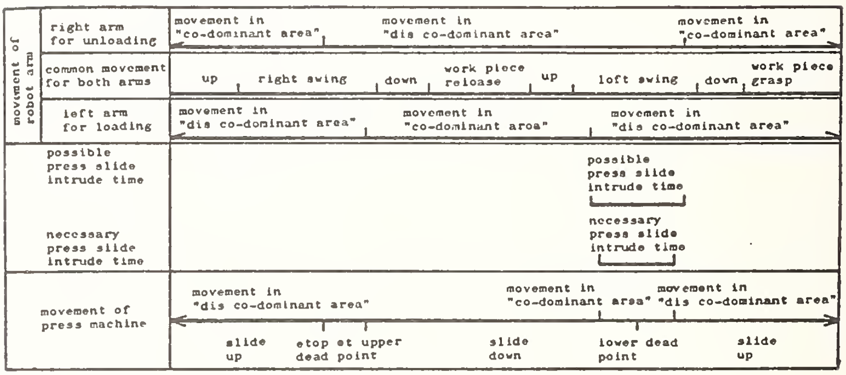


Fig. 6 An example of time chart

```
WHAT IS THE SCALE OF ONE TO "***" IN DRAWING ?
PLEASE WRITE "***".
50
WHAT IS THE MAX. WIDTH OF THE WORK? "****"MM.
500
WHAT IS THE CAPACITY OF THE PRESS MACHINE? "***"TON.
300
THE FRAME OF THE PRESS MACHINE IS THE " STRAIGHT TYPE ".IS NOT IT?
YE
THE FRAME OF THE PRESS MACHINE IS THE "STRAIGHT TYPE ".
IS THE DRAWING OPERATION MORE IMPORTANT THAN THE OTHER OPERATIONS?
NO
THE WORK ATTACHS TO THE LOWER DIE.DOES NOT IT?
YE
THE WORK ATTACHS TO THE LOWER DIE.
IS IT ADMITTED TO DESTROY THE ORIENTATION OF THE WORK?
NO
IS THE TYPE OF THE ROBOT DETERMINED?
NO
IS THE CYCLE TIME MORE IMPORTANT THAN THE COST?
YE
"CAN THE ROBOT TRANSFER THE WORK TO THE NEXT STAGE DIRECTLY?
YE
"MULTI ARMS ROTARY TYPE ROBOT"IS USED.IS NOT IT?
YE
"MULTI ARMS ROTARY TYPE ROBOT"IS USED.
THE MATERIAL IS FEEDED CONTINUOUSLY TO THE SYSTEM.IS NOT IT?
YE
"CONVEYOR-POSITIONER SYSTEM"IS USED.IS NOT IT?
YE
"CONVEYOR-POSITIONER SYSTEM"IS USED.
 S31
```

Fig. 7 An example of SP-CAROD conversation

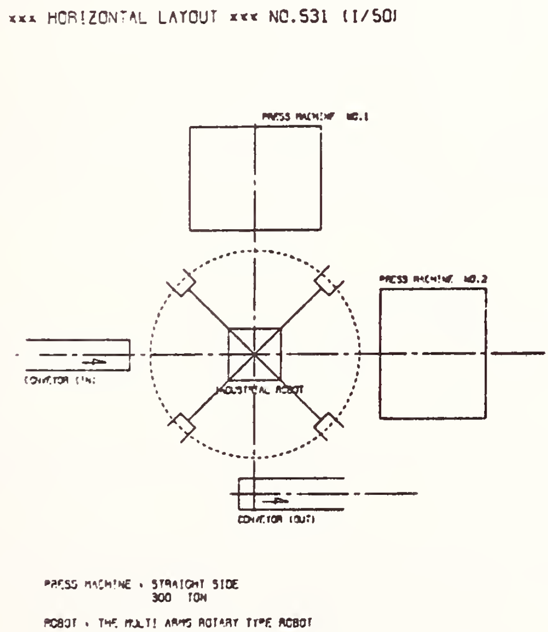


Fig. 8 An example of SP-CAROD layout drawing made by the plotter

3) As to the capacity of the press machine, the designer has to calculate the tonnage of the machine in advance.

4) As to the frame type of the machine, there are two choices: "C" type and "straight side" type.

5) In the case of the "C" type frame machine, the existence of hazards such as front guide posts and tie rods and so forth influence motion patterns of the robots.

6) When there is no guide post in front of the dies, the computer asks the above type of fabrication by asking the importance to think of the drawing operation. Because in the case of the no drawing process, the possibility of the finished work pieces sticking on lower die is very great.

7) As to the possibility of destroying the orientation of the work, if we do not need to keep the orientation, we can simplify the unloading operation by using low-cost devices.

8) As to the type of the robot, the designer is asked only to answer whether he has already decided on the selection of the robot or not.

9) As to the relationship of the investment cost and the operation speeds the author is only asked to answer by the word "yes" or "no".

10) As to transferring work pieces from the robot to the next stage, the condition is expressed by using the word "yes" or "no". If the designer answers "no", he needs two robots to one operation for loading and unloading.

11) As to the robot type some alternatives are proposed to the designer based on the former conversation. Then the designer makes the decision about the robot type selection.

12) As to the raw materials feed type, there are two possibilities: continuous or batch.

13) As to the use of the feeder, there are two types of answers: "yes" or "no".

14) As to the layout restriction, the answer is limited to one or two: longitudinal or side long to the production line.

15) Finally, the computer system automatically selects the most suitable system pattern by pattern number and output layout drawing through the plotter.

Fig. 8 is a system pattern example selected through the above mentioned conversation of the designer and the computer system. In DP-CAROD based on the design result of SP-CAROD, the computer system displayed the output of dynamic conditions the designer determines the dynamic characteristics of the robot and the press machines.

VI. CONCLUSION

In this research, the authors could accomplish the following targets:

1) To develop a logical procedure of designing a robot operation system by using the computer systems, and optimization of the design result.

2) To develop a simulation model by using the computer system and making dynamic analysis of the robot operation systems. Also, to generate the data for future robot development.

3) To introduce the computer systems into robot operation systems design, and to save engineering man-power and also the application engineering cost of industrial robots.

For the above targets the authors developed SP- and DP-CARODs. But it is just on the starting line based on metal stamping. operations. The field to be applied is yet narrow and we shall have to refine the technology and spread the application field of the technique.

ACKNOWLEDGEMENT

This research has been done based on a research project called "Pressing and Allied Operations Labour Saving & Safety Promotion Project." The project was sponsored by Japan Industrial Robot Association and Japan Metal Stamping Association, and received financial aids from MITI. The actual research work was done at the System Science Institute of Waseda University under the management of PALS committee, while the several working members from both associations stayed at the institute.

Also we would like to express our hearty thanks to the Industrial Safety Research Laboratory of Bureau of Labor and Mechanical Engineering Laboratory of MITI, who gave advice and facilities' conveniences, and to the members of the above committee and associations who encouraged and gave advice.

REFERENCES

1. Y. Hasegawa (PALS Committee), Industrial Robot Application Models Design for Labour Saving and Safety Promotion in Press Operation, Proceedings of 4th International Symposium on Industrial Robots, 1974

2. Y. Hasegawa, An Approach to Industrial Robot Application Research, Proceedings of 2nd International Symposium on Industrial Robots, 1972

3. Japan Industrial Robot Association, The Report on Research Project of Industrial Robot Application Models Design for Labour Saving and Safety Promotion in Press Operation, 1974

CHARACTERISTICS AND EVALUATION OF "MASTER-SLAVE MANIPULATORS"

Demetrius G. Jelatis
Central Research Laboratories, Inc.
Red Wing, Minnesota 55066

I. Introduction

The author and his organization have been involved for about 25 years in the design and fabrication of a class of remote handling devices known as "Master-Slave Manipulators". Based on the seminal developments in the late forties and early fifties of Ray Goertz and the Remote Control Engineering Division, directed by Harvard L. Hull, of the Argonne National Laboratory, some six to seven thousand of these devices are currently in use throughout the world. Most of them are used in shielded "hot cells" for handling radioactive materials. Details and surveys of their design, characteristics, and applications (both achieved and proposed) have been presented at technical conferences and in numerous reports and publications. The basic attributes of these "Master-Slave" devices which have made them indispensable in the nuclear field, serving as effective extensions of a human operator's hands and arms into a hostile environment have been variously described: by Goertz (1) as "Force-reflection"; by Johnsen and Corliss (2) as "Spatial correspondence" and "Sensory correspondence"; and by Jelatis (3) as "Naturalness, Feel, and Compliance".* Yet, in spite of widespread successful use and extensive literature, these basic master-slave attributes are not only unknown to many equipment designers and potential users, but are often unappreciated by users and even denigrated by designers who may feel that the all-too-obvious increases in cost and complexity will outweigh the less readily quantifiable benefits of improved performance.

It therefore seems desirable to look at what it is that sets "master-slave" manipulators apart from other manipulators and programmable robots, as a prelude to a discussion of the evaluation of their performance.

II. What is a "Master-Slave" Manipulator?

Master-slave manipulators are:

general purpose mechanical devices, used by a
human operator in a normal environment, to extend his
hand and arm manipulative capacity into a more-or-less remote
hostile environment with the aid of direct (or indirect)
visual observation, with movements characterized by
naturalness, to obviate the need for extensive training,
feel, to reflect the elastic characteristics of task objects and forces exerted on them,
and compliance to follow task-constrained paths or orientations at substantial misalignments with operator-applied forces.

To the extent that a master-slave manipulator approaches the nirvana of perfection, it sheds the mundane mechanical burdens of inertial mass, friction, elastic deflection, and finite strength; it becomes invisible and impalpable to the operator whose hand is thus magically transported into the remote hostile environment.

It is in this spirit that the poet-pilot, Antoine de Saint Exupery, described the airplane as "The Tool" with which a pilot works in his "Wind, Sand and Stars", written about 35 years ago:

> ".... Startling as it is that all visible evidence of invention should have been refined out of this instrument and that there should be delivered to us an object as natural as a pebble polished by the waves, it is equally wonderful that he who uses this instrument should be able to forget that it is a machine.
>
> There was a time when a flyer sat at the centre of a complicated work. Flight set us factory problems. The indicators that oscillated on the instrument panel warned us of a thousand dangers. But in the machine of today we forget that motors are whirring: the motor, finally, has come to fulfill its function, which is to whirr as a heart beats--and we give no thought to the beating of our heart. Thus, precisely because it is perfect the machine dissembles its own existence instead of forcing itself upon our notice."

Ideally, then, the master-slave manipulator, as an extension of the human hand, should be used not as the tool itself, but as the hand which holds and guides the tool: not to weigh an object directly, but to place it on a balance pan and manipulate the controls; not to turn a nut, but to hold a wrench or impact driver and apply it to the nut; not as a pry-bar, but to apply and operate a pry-bar; not to drive a nail, but to hold and swing the hammer; not as a crane, but to apply the hook and guide the work; not as a stored-program machine to do a repetitive job (except in very unusual cases), but as a maintenance and intervention device to repair or assist a malfunctioning automatic machine. This ideal, of course, is seldom attainable. A master-slave manipulator is often the only accessible general-purpose tool in a critical facility and in an emergency may be abused in undreamed-of-ways.

A wide variety of mechanically-coupled master-slave manipulators have been designed as real-life approximations to the ideal based on various trade-offs and compromises with economic and performance constraints. A number of these are described in Ref. (2) and in a 1970 survey by Jelatis (4). To overcome the constraint of direct mechanical coupling, electric servo-motors and position transducers at widely-separable master and slave arms connected only by multi-conductor cables were first introduced by Goertz and his group at Argonne National Laboratory (5). This work and other comparable developments are also described in considerable detail in Ref. (2) and in the published proceedings of two 1964 seminars on Remotely Operated Special Equipment (6) and (7). The last Argonne Development, the "ANL Mark E4A Electric Master-Slave Manipulator" is described in Ref.(8). A commercial version of this device has been manufacturer by Central Research Laboratories, Inc., designated as their Model M Electric Servo Master-Slave Manipulator. A computer-controlled Model M with independent Master and Slave power supplies, coupled only by a two-way 10 KHz digital data link, has been built and demonstrated at the American Nuclear Society exhibit in Washington, D.C., in November, 1974.

As to potential applications and problems, the author is happy to stand pat with his 1970 speculations (Ref. 4).

III. Performance Evaluation

Armed with this brief historical and definitional diversion, we return to the main program. It is of course a truism to state that everything we need to know about performance evaluation is implicit in the initial defining paragraph of the preceding section: since a perfect master-slave manipulator is invisible and impalpable, the measure of perfection is simply unobtrusiveness. Anything that obtrudes on the operator's consciousness and veils the sense of "presence" of the master hand in the slave environment can be ranked or graded and scored against the device being evaluated. The "best" manipulator is obviously the one with the fewest black marks against it. Alas! This obvious and simple evaluation method has at least three flaws; we can ask: what is the task that the manipulator is expected to perform? how do we grade the degree of obtrusiveness? what is the role of the human operator? To some extent we can idealize the situation, abstract what we can identify as relevant characteristics, and construct a "model" conforming more-or-less to the real world, then derive numbers describing our abstraction. But we must be on guard lest we deceive ourselves into believing that our abstract model can tell us "the whole truth, and nothing but the truth" without verification by experience which, except for adequate statistical data on a sufficiently large population exposed to carefully controlled conditions, may be exceedingly hard to come by.

This problem of performance evaluation is of course not unique to the manipulators under consideration, but is instead characteristic of a "small" population of any complex mechanical device used for a variety of non-standardized tasks, in highly variable conditions, by a variety of operators. Here is a closely analogous situation in the field of aviation: (excerpt from The Aviation Consumer, Nov., 1972, article "Who Says Your Airplane is Airworthy?").

> "The Quantity of Quality
>
> Much of the testing that goes on with a new airplane is qualitative. This means that it depends on such things as feel, experience, sixth sense, or what have you, of the person making the test. The test pilot, particularly, has to make an abundance of qualitative decisions. Only part of the tests he makes can be measured in quantitative parameters -- i.e., numbers. Assessing the handling qualities of an airplane is axiomatically a qualitative judgement. Likewise, some of the limitations of the airplane require qualitative assessments.
>
> Test pilots also have to judge the airworthiness of certain qualities of an airplane in terms of the capabilities of the pilots who will be flying it. Understandably, such a judgement is wide open to all sorts of varieties of opinions."

The subjects of performance criteria and performance evaluation have been discussed at considerable length by the author in a 1962 paper (9) (included with the NBS Workshop Paper) and need not be repeated. We should, however, look into the specific questions illustrating the flaws in our initial method of assessing "obtrusiveness". First, what is the task the manipulator is expected to perform? This calls attention to one aspect of performance evaluation that may not be immediately obvious: the suitability of the manipulator for its intended task. This is discussed in detail in Ref. (9), p. 158, under Load Ratings; the uncertainties associated with an absolute numerical load rating are discussed and some arguments advanced for the alternative concept of adaptability or suitability to function based on a comparison with the evolutionary process of development of common hand tools. However, the value of numerical data of adequate statistical significance in guiding the design and improvement of individual mechanical elements is emphasized.

The second question, how do we grade the degree of obtrusiveness?, is also dealt with in great detail in Ref. (9), in the section headed "Responsiveness", starting at the bottom of p. 159. The mechanical transfer function of an idealized three-parameter model, characterized by a lumped inertia, deflection, and friction, is considered adequate for describing the usual deliberate actions carried out by master-slave manipulators. Practical methods of measuring these parameters are described, and the diagnostic value of a mechanical hysteresis-curve, obtained by plotting displacement vs. an applied cyclic load is pointed out. These are, in fact, objective parameters that are useful not only for quality-control acceptance tests, but also (in simplified forms) for routine performance evaluation to determine need for maintenance and to evaluate the results of maintenance operations after repairs, etc.

The third question, regarding the role of the human operator, brings us back to the difficult subjective realm and is also briefly discussed in Ref. (9). Considerable work has been done on various factors affecting task performance, and comparing the times required by direct manual contact, under various lighting conditions, use of aural cues to determine contact, etc. Although statistically significant data may be obtained under carefully controlled conditions, the choice of test procedure can greatly bias the results for or against a particular manipulator configuration. Indeed, it is possible to select a task that can be easily accomplished by a manipulator (A) and nearly impossible with manipulator (B), and another task that can completely reverse this ranking.

The advent of high quality servo-coupled master-slave manipulators presents the interesting capability of carrying out a standardized task with a single manipulator and various operators while varying the parameters of the mechanical transfer function. Thus the effects of controlled amounts of friction, backlash, inertia, springiness, etc. on standardized tasks could be useful in establishing acceptable limits for various "obtrusive" parameters. One dramatic demonstration of the value of force feedback is easily achieved by cutting off the power which provides the reaction forces of the "master" handle to the operator of an electric servo manipulator. This experience too is fearfully portrayed by Exupery in the chapter of "Wind, Sand and Stars" entitled "The Elements" in which he describes a flight along the Atlantic seaboard of the Patagonian Argentine. He has been spat out to sea sixty feet above the waves and five miles from shore by a cyclonic gust and is fighting his way back to shore into the gale with a plane that has a top speed of 150 miles per hour:

> "One has a pair of hands and they obey. How are one's orders transmitted to one's hands?
>
> I had made a discovery that horrified me: my hands were numb. My hands were dead. They sent me no message. Probably they had been numb a long time and I had not noticed it. The pity was that I had noticed it, had raised the question. That was serious.
>
> Lashed by the wind, the wings of the plane had been dragging and jerking at the cables by which they were controlled from the wheel, and the wheel in my hands had not ceased jerking a single second. I had been gripping the wheel with all my might for forty minutes, fearful lest the strain snap the cables. So desperate had been my grip that now I could not feel my hands.
>
> What a discovery! My hands were not my own. I looked at them and decided to lift a finger: it obeyed me. I looked away and issued

the same order: now I could not feel whether the finger had obeyed or not. No message had reached me. I thought: "Suppose my hands were to open: how would I know it?" I swung my head round and looked again: my hands were still locked round the wheel. Nevertheless, I was afraid ....."

After an hour and twenty minutes, still five miles out, he had managed to climb to 900 feet, and in another hour made the five miles to shore and finally reached his destination, where, he concludes:

"I came away with little booty indeed, with no more than this meager discovery, this contribution: How can one tell an act of the will from a simple image when there is no transmission of sensation?"

To those who doubt the value of force reflection in manipulation, one can do little better than to echo Exupery: "How, indeed?"

IV. Conclusion

A functional definition of a "Master-Slave Manipulator" is presented and evidence adduced for the value of its special attributes of NATURALNESS resulting from a design configuration providing substantial positional and motional correspondence between the master handle and the slave tong, FEEL resulting from the use of low-friction low-inertia and high performance bilateral coupling elements, and COMPLIANCE to follow paths of operation or orientational constraints imposed by the slave environment, even though forces applied by the operator to the master handle may be grossly misaligned with the slave constraints. The importance of sensory feedback has been emphasized. Numerical ratings of LOAD CAPACITY were shown to be rather tenuously based and subjective; the equally subjective suitability or adaptability to intended function are deemed to be generally more valid indicators of capacity. The easily-quantifiable mechanical transfer function of a simplified three-parameter model utilizing lumped inertia, friction, and deflection (preferably as a hysteresis loop responding to cyclic applied forces) is presented as an excellent objective evaluation and diagnostic tool. Comparisons of times to accomplish "standard" tasks are described as too subjective (especially in task selection) to be of much value except under strictly controlled and standardized conditions with careful planning to validate statistical reliability. Suggestions are made for procedures to seek correlations between "performance" of properly-planned standard tasks by electric-servo master-slave manipulators and intentional measured alterations of the mechanical transfer function parameters; resulting "sensitivity" functions for different types of degradation would be useful in cost-benefit analyses.

Finally, an important evaluation tool not heretofore mentioned is the "application feedback" from users who invariably find flaws undreamed of by the designers and who may also quite often make suggestions for improvements. Both of these are helpful in guiding the evolutionary development of retro-fittable modifications or even new models.

REFERENCES

1. R.C. Goertz, "Fundamentals of General-Purpose Remote Manipulators", Nucleonics, Vol. 10, No. 11, pp. 36-42 (November, 1952).

2. Edwin G. Johnsen and William R. Corliss, "Teleoperators and Human Augmentation", NASA SP-5047, Washington, D.C., December, 1967. U.S. Govt. Printing Office (LC Cat. Card No. 67-62098).

3. D.G. Jelatis, "Design Criteria for Heavy-Duty Master-Slave Manipulator", Proceedings of Seventh Hot Laboratory and Equipment Conference, Cleveland, Ohio, April 7-9, 1959, (American Nuclear Society).

4. D.G. Jelatis, "Where Do We Go From Here with Master-Slave Manipulators?", Proceedings of 18th Conference on Remote Systems Technology, 1970, (American Nuclear Society).

5. R.C. Goertz and W.M. Thompson, "Electronically Controlled Manipulator", Nucleonics, Vol. 12, No. 11, pp. 46-47 (November, 1954).

6. Edwin G. Johnsen, Seminar Chairman, "Proceedings of the 1964 Seminars on Remotely Operated Special Equipment", Vol. I, CONF - 640508, AEC Hqtrs., Germantown, MD, May 26-27, 1964.

7. Ibid, Vol. II, CONF - 641120, Jackass Flats, Nev., Nov. 4-5, 1964.

8. R. Goertz, J. Grimson, C. Potts, D. Mingesz, and G. Forster, "ANL Mark E4A Electric Master-Slave Manipulator", Proceedings 14th Conf. on Remote Systems Technology, 1966, (American Nuclear Society).

9. D.G. Jelatis, L.W. Haaker, and R. A. Olsen, "A Rugged-Duty Man-Capacity Master-Slave Manipulator", 10th Hot Lab Proceedings, Nov. 1962, (American Nuclear Society).

DESIGN AND PERFORMANCE REQUIREMENTS FOR FUEL RECYCLE MANIPULATION SYSTEMS*

J.G. Grundmann

Oak Ridge National Laboratory

Oak Ridge, Tennessee 37830

I. Introduction

Remote material-handling and maintenance techniques have been investigated and remote systems successfully developed over the past 25 years. These systems rely on mechanical master-slave manipulators for replacement of human arms and hands to carry out tasks in radioactive environments. The human hand equivalent is the slave hand (called "tong"). This tong is remotely controlled by steel tape drives through shielded walls (Fig. 1). Although the main feedback to the operator of the manipulator is visual, force feedback through the cable drives gives a sense of "feel" to the master arm and aids in determining the location of the tong for grasping objects. The operations in a hot cell can be seen through a radiation attenuating window (several feet thick) that is in the wall of the hot cell. Systems such as the one shown in Fig. 1 have worked well for remote execution of research tasks, but speed of execution is limited by the rate at which an operator can complete a task. Typically, such units can be operated at about 0.1 the speed of a person performing the same task without such mechanical aid. Although this low rate of operation may be satisfactory in research cells, it is unacceptably slow for tasks related to remote work in production cells which support the reactor-fuel recycle processes. For the latter work, new remote handling systems are needed that have greater mobility, faster speed, and better operator visual feedback. Such systems are not commercially available and must be developed.

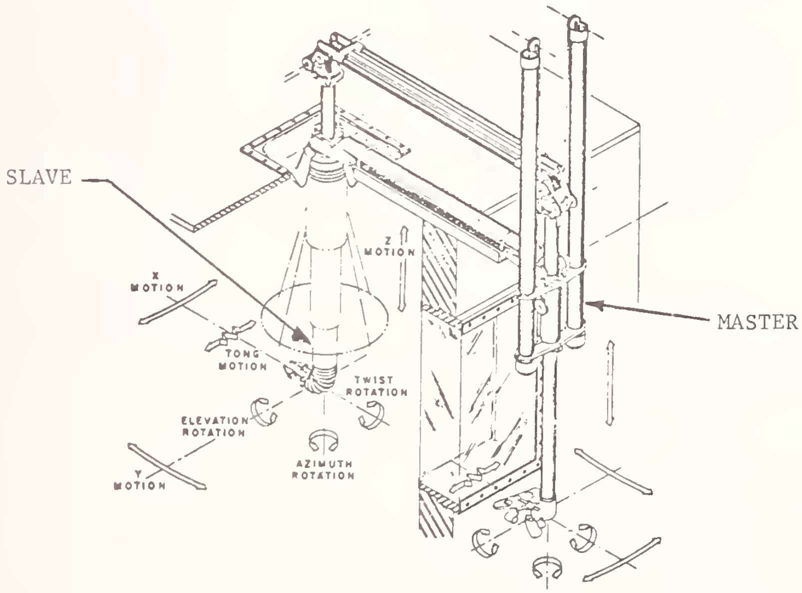


Fig. 1. A research facility mechanical master-slave manipulator (courtesy of ANL[1]).

* Research sponsored by the Energy Research and Development Administration under contract with the Union Carbide Corporation.

In this paper we will first discuss some basic areas where development is necessary to improve remote handling systems, then describe an example of an improved production manipulator system, and finally consider some remote handling system performance and construction standards. All of the standards are tentative, and we expect their modification as new development experience is evaluated.

II. Basic Development Necessary to Upgrade Remote Handling Systems

1. Mobile Manipulators

Compared with research equipment, production equipment requires more space to handle the high throughput rates of a reactor fuel-recycle process. Thus, the floor area in production cells must be larger than in research cells. To operate a manipulator over large floor areas, it is necessary to provide manipulator movement to any location in a production cell area.

Mobility is available in many commercial forms. Typical mobile manipulator arms are shown in Figs. 2-4. The nuclear industry has used all these types, but the bridge-mounted, overhead system is preferred because it allows utilization of the entire floor space in a cell for production equipment. Furthermore, even on equipment-crowded hot-cell floors, the overhead manipulator usually can be lowered into position

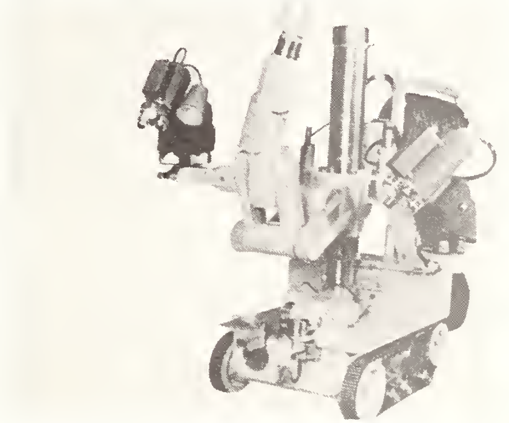


Fig. 2. Manipulator mounted on a vehicle which rides on rails or treads.[2]

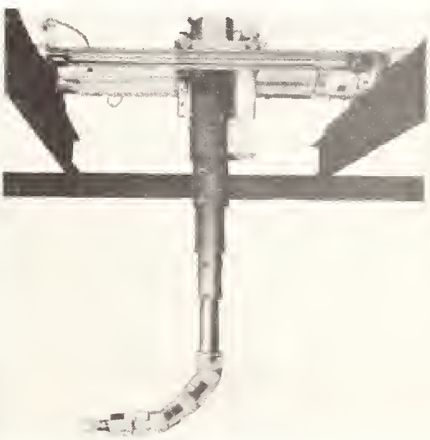


Fig. 3. Manipulator mounted overhead on a bridge carriage-hoist.[2]

Fig. 4. Wall-boom mounted manipulator.[2]

to do the work. Wall-boom manipulators also do not require cell floor space, but they carry less weight per dollar invested and lack the ability of the overhead manipulator to reach all equipment on a crowded floor.

2. Master-slave control

The mechanical master-slave manipulator (Fig. 1), with force feedback (is bilateral), has demonstrated its excellent dexterity and is a model of performance for future manipulators. Several mobile, electric, bilateral master-slave manipulators have been constructed[3,4] (Fig. 5), but none are designed for use in production cells without being modified (Sect. 3.2).

Mobile electric prototype manipulators are needed for development of production fuel-recycle facilities. These new units need (as minimum performance requirements) a sense of feel and dexterous master-slave control.

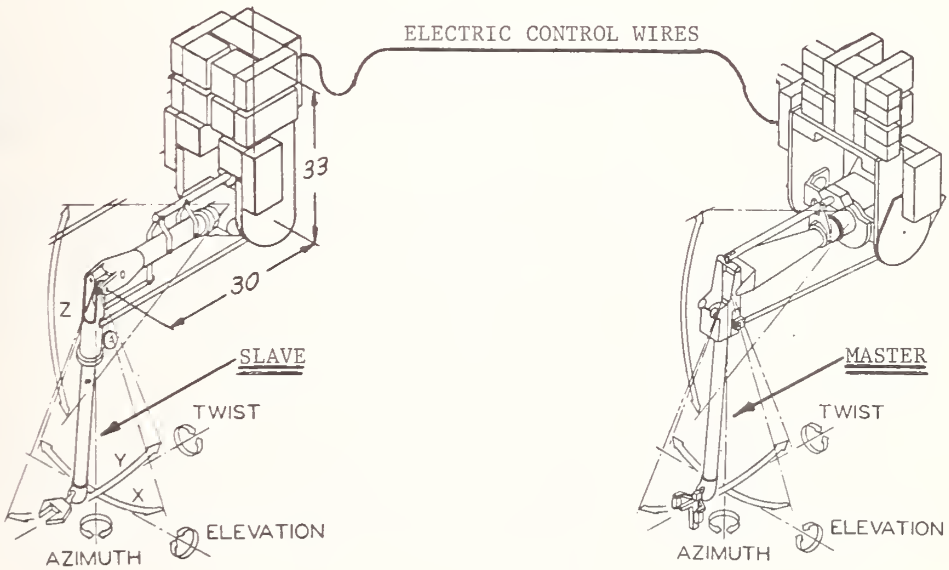


Fig. 5. Typical mobile, electric, bilateral master-slave manipulator (A modified ANL illustration[3]).

3. TV Viewing

To manually operate a manipulator, the operator must have a clear view of the tong and its movements. Tests indicate that master-slave manipulators can perform very delicate tasks when the operator can see close-up what he is doing. (Even threading a needle has been done.[5]) In most research hot cells, the operations are viewed through shielded windows (several feet of window thickness plus clearance for the swing of master and slave arms). For this arrangement, the minimum viewing distance is about 183 cm (6ft). At this distance, tasks with tolerance less than 0.32 cm (1/8 in.) are difficult because of inadequate visibility.[5]

A television camera with a zoom lens inside a cell can enable an operator outside the cell to observe the work from an apparent distance of only a few inches. Although depth perception has been insufficient in the past, new stereo television systems, with two cameras that view at different angles and three-dimensional (3D) TV systems are available. The 3D-TV systems have been improved rapidly, and one system now gives close-up images that are so accurate that it is used to perform eye surgery.[6]

Use of TV viewing for hot-cell work is increasing, and its advantages are being realized in production hot cells with equipment-crowded floors. Without TV systems in such cells, some equipment cannot be seen by the operator through the fixed, shielded windows, and other equipment may be visible, but only at a distance. To enable remote maintenance by manipulators to crowded and distant hot cell equipment, mobile close-up vision must be available. TV systems are most practicable for this purpose.

4. Minicomputer control for increased speed of operations

Minicomputer control of manipulator systems[7] will be necessary for production processing. Minicomputers can be used in at least five ways, all of which will effectively increase the speed at which manipulator tasks (which support production and maintenance operations) can be completed.

(a) <u>production</u>: to increase the speed of routine material transfers during production processing, automation should be utilized, such as the "industrial robot teach and playback" technique. By this technique, each repetitive production task is learned as a point-to-point or as a continuous path trajectory, and then the "learned" trajectory is played back when needed during plant operation. Since such automation is faster than an operator's slow movements (slowness is the result of vision and dexterity limitations), tasks are completed in less time.

(b) <u>manual maintenance</u>: many maintenance tasks in hot cells will be non-routine and nonrepetitive, and these will be accomplished most efficiently when done manually. Even though manual operation of the manipulators will be utilized for most maintenance, a minicomputer could decrease the time in which the manual tasks are completed, as explained in the following discussion of four features.

- automatic robot traverse execution: mobile manipulators, cranes, and TV cameras could be equipped with automatic traverse control. Hence, for manual maintenance, all necessary equipment could be brought to the maintenance location automatically and in less time than manual traverse of the equipment would require. Automatic traverse would be accomplished by defining work stations at all anticipated in-cell maintenance locations, and then programming the trajectories between the stations by the robot teach and playback technique. The traverses could be played back when needed during production operations.

- automatic TV camera sighting and focusing: considerable time is lost during manual maintenance operations because the operator must sight and focus the TV cameras on the work area. A minicomputer could do this much faster by calculating a camera sighting and focusing vector from information provided by position transducers on in-cell equipment. Servo loops, mounted on the camera, would "lock" onto the calculated sighting and focusing vector and control the camera angle and focus.

- automatic robot tool changes: tool changing takes too much time during manual maintenance operations. With tools mounted in tables at known locations, all tool changes could be made automatically by the industrial robot teach and playback technique.

- monitoring in-cell devices for collision avoidance: since production hot cells will be crowded with process equipment and mobile handling devices (manipulators, TV cameras, and cranes), the operator will have to work slowly to avoid errors and collisions. If a minicomputer were available to check for collisions, the operator could concentrate on his work and accomplish it more rapidly. To avoid collisions, a minicomputer would have to be on line to monitor the positions of all in-cell devices, periodically utilize the position data to update device position vectors, and then compute algorithms to compare the position vectors with stationary in-cell topography (in storage). If the computer determined that a collision were impending, it would stop the operations that would result in a collision and would sound an alarm.

III. Production Fuel-Recycle Manipulator System and Specifications

1. A Prototype Production System

An improved system for refabrication of fuel for the High-Temperature Gas-Cooled Reactor (HTGR) has been proposed by ORNL[7] (Fig. 6).

This system has equipment within the hot cell as described in Sect. 2. Briefly, this equipment includes:

- a mobile electric master-slave manipulator with automatic robot, automatic rapid traverse, and automatic collision avoidance capabilities.

- a mobile crane that can be operated manually, with automatic robot, automatic rapid traverse, and automatic collision avoidance capabilities.

- two mobile TV cameras with automatic sighting and focusing, automatic rapid traverse, and automatic collision avoidance capabilities.

2. Design standards for manipulators, cranes and TV cameras

The major design standards for HTGR fuel refabrication environments are summarized as follows:

- All movements should be actuated by electric or pneumatic motors. Hydraulic fluids are usually not allowed in the hot cell radiation environment.

- All devices in hot cells should be constructed simply and be disassembled easily. All components should be modular if possible, with easily released connections to other assemblies.

- Reliability of in-cell equipment is of great importance because remote maintenance is much slower and much more expensive than direct maintenance.

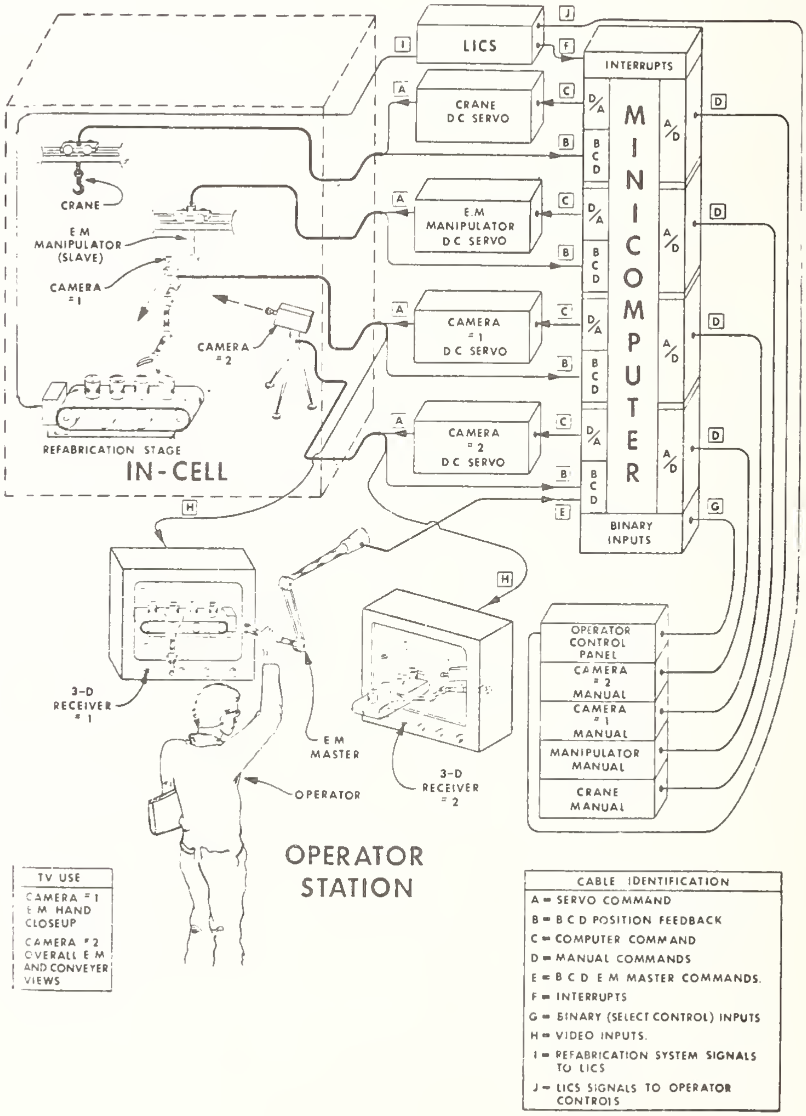


Fig. 6. An improved, reactor fuel-recycle, remote manipulator system proposed for HTGR fuel refabrication.

The HTGR fuel recycle process is divided into two stages. The first stage is called fuel processing and the second stage is called fuel refabrication. Since the author is involved in the design of manipulator systems for the second stage, comments made below regarding effects of nuclear particles and radiation upon the proposed manipulator system (Fig. 6) apply only to the refabrication environment. However, the manipulator system could also be used in the first HTGR recycle stage (or any other fuel recycle process) if proper materials were selected which could withstand the particular nuclear environment involved.

Radiation levels cannot be accurately determined for hot cells within an HTGR fuel refabrication plant because the levels will depend on the floor layout, and floor layout at this time has not been determined. However, preliminary guesses of "worst case" radiation levels are available and they are suitable for manipulator design. We estimate that there will be two primary radioactive difficulties within HTGR fuel refabrication hot cells:

(a) First, there will be alpha particle contamination. Since these particles have little penetration capability, sealed equipment will not be damaged. However, if the equipment is not sealed, materials such as rubber and lubricants will deteriorate. Since alpha particles are also harmful to humans if inhaled or swallowed (some are lethal in extremely small amounts), the alpha particles must be removed by decontamination reagents prior to direct maintenance. Decontamination is faster and more effective when equipment is sealed (water tight) in smooth containers.

(b) Second, there will be gamma radiation. Since gamma radiation is very penetrating, it often requires lead shielding to reduce the radiation to tolerable levels. Additional radiation resistance results from the use of special "hardened" materials which withstand larger radiation dosage than "standard" materials before deterioration (radiation deteriorates common insulations, plastics, greases, solid state electronic devices, optical glass, etc.)[8]. Fortunately, gamma radiation intensity rapidly decreases as the distance from the source is increased. If in-cell HTGR manipulator equipment is no closer than 6 in. from a gamma source, the radiation level will be less than 300 R/hr. Although such a radiation level would deteriorate most standard devices, it could be tolerated with properly shielded and "hardened" equipment.

3. Performance standards for electric, bilateral master-slave manipulators

We recommend the following performance standards for this class of manipulators:

(a) Six degrees of freedom:[5] three translations at the wrist--reach, lift, and sweep; and three rotations of the hand at the wrist--twist (roll), tilt (pitch), and turn (yaw).

(b) The entire manipulator should be mobile on overhead rails for movement to any location.

(c) The manipulator speeds required[3] for natural action of master-slave control are: wrist translations of 75 cm/sec and hand rotations of 10 radians/sec.

(d) Most fuel recycle process equipment designers specify a load capacity of 75-100 kg per manipulator arm. (Unfortunately, current commercial electric master-slave manipulators lift only 25 kg.)

(e) The accuracy of manipulator jaw positioning under automatic control should be 0.25 cm.[5]

(f) The feedback elements should be high reliability synchros or resolvers.

4. Performance standards for TV viewing systems

Few current performance standards for TV systems are available. Recently the picture quality of TV monitors has greatly increased, and remote controls for in-cell cameras have become more convenient. Since these TV equipment improvements have been rapid, current performance information is sparse.

It would be beneficial to the industry and users if such information were collected and published as it becomes available. Object recognition is one of the most significant measures of the merit of a TV viewing system, and object recognition can best be determined by human factors studies. The Marshall Space Flight Center (MSFC) has sponsored several human factors studies to evaluate various stereo and 3D-TV systems.[9, 10] They have several additional studies now in progress.

REFERENCES

1. R.C. Goertz, "Manipulator Systems Development at ANL," Proc. 12th Conf. Remote Sys. Technol., Amer. Nucl. Soc., Nov. 1964, p. 123.

2. "Advanced Handling and Inspection Systems," Programmed and Remote System Corporation, St. Paul, Minnesota.

3. R.C. Goertz, J. Grimson, C. Potts, D. Mingesz, and G. Forester, "ANL Mark E4A Electric Master-Slave Manipulator," Proc. 14th Conf. Remote Sys. Technol., Amer. Nucl. Soc., Nov. 1966, p. 117.

4. C.R. Flatau, "Compact Servo Master-Slave Manipulator with Optimized Communication Links," Proc. 17th Conf. Remote Sys. Technol., Amer. Nucl. Soc., Nov. 1969.

5. D.P. Mullen, "An Evaluation of Resolved Motion Rate Control for Remote Manipulators," M.S. thesis, MIT (Jan. 1973).

6. J.F. Butterfield, "Development of a Surgical Stereo-Video Microscope," SPIE Seminar No. 7, Aug. 21, 1974, San Diego, California.

7. J.G. Grundmann, "A Proposed Master-Slave and Automated Remote Handling System for High-Temperature Gas-Cooled Reactor Fuel Refabrication," Proc. 5th Int. Symp. Industrial Robots, Chicago, Sept. 1975, p. 533.

8. Radiation Effects Symp., vols 1 to 6, sponsored by Air Research and Development Command, USAF, Lockheed Nuclear Products, Lockheed Aircraft Corporation, Georgia Div.

9. M. Kirpatrick, T. Malone, and N. Shields, Jr., Earth Orbital Teleoperator Visual System Evaluation Program, Report 1, Essex Corp., Huntsville, Ala., for Marshall Space Flight Center (March 1973).

10. M. Kirkpatrick, T. Malone, and N. Shields, Jr., Earth Orbital Teleoperator Visual System Evaluation Program, Report H-4-2, Essex Corp., Huntsville, Ala., for Marshall Space Flight Center (Jan. 1974).

MASTER SLAVE MANIPULATORS AND REMOTE MAINTENANCE AT THE OAK RIDGE NATIONAL LABORATORY*

R.G. Jenness & C.D. Wicker

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Abstract

The volume of master-slave manipulator maintenance at Oak Ridge National Laboratory has necessitated the establishment of a repair facility and the organization of a specially trained group of craftsmen. Emphasis on cell containment requires the use of manipulator boots and the development of precise procedures for accomplishing the maintenance of 283 installed units. To provide the most economical type of preventive maintenance, a very satisfactory computer-programmed maintenance system has been established at the Laboratory.

I. Introduction

Master-slave manipulators were developed because a need arose for a tool that could operate in hostile environments behind barricades or through shielding walls. This tool must be capable of making all the manipulations that could be performed by a human hand. The resulting master-slave manipulators have proven to be a very useful device for research activities, particularly in the nuclear energy field. Early handling techniques included tongs, over-the-wall mechanical devices, and other simple techniques to minimize personnel radiation exposure.

Remotely operated manipulator-type work started at Oak Ridge National Laboratory in 1953 with the installation of a CRL Model 4 unit in the Solid State Division hot cells. Since that time, the number of manipulators has increased to 283 (see Table 1). To provide the necessary maintenance for this number of manipulators, the Laboratory has developed a specially trained crew of one foreman, eleven millwrights, and one electrician.

The contents of this paper will be limited to the maintenance history and the available information used at the Laboratory for procuring present-generation manipulators and manipulators' booting.

With the advent of reactor fuel recycle systems and the environmental impact of waste handling, it is conceivable that we are at the threshold of an entirely new generation of remote handling devices.

* Research sponsored by the Energy Research and Development Administration under contract with the Union Carbide Corporation.

II. Facilities and Equipment

The manipulator repair facility at ORNL has approximately 6000 square feet of floor space, which is divided into four areas of operation. Two of these areas are used for contaminated repairs, and the other two are used for clean repairs and boot fabrication.

The units weigh from 140 to 450 kilograms and are awkward to handle; so it was necessary to design and fabricate all the handling equipment for the dual purposes of cell installation or removal and transportation to and from the repair facility. The Laboratory has fabricated six portable dollies of a modified "A" frame design that incorporates a hydraulic cylinder. The dollies are designed so that they become part of the unit for transportation purposes. When taken to the repair shop, the manipulator is placed in a glove box for cleaning or decontamination, and the dolly is then available for other service.

III. Manipulator Boots

The special emphasis on cell containment at ORNL requires that all manipulators be equipped with boots to seal the cell opening for the manipulator. This requirement has enlarged the maintenance problem in that, with booted units, 50 to 60 percent of the maintenance lies in replacing worn or damaged boots. Therefore, in 1961 the Research Services Department instituted a development program to provide a material and means of producing boots that would meet the needs of the Laboratory. This investigation resulted in a spray method of boot fabrication in which liquid urethane rubber is used.[1]

From a maintenance standpoint, the protection afforded a manipulator by the use of boots has prolonged slave-end bearing life and has considerably decreased mechanical failures.

Since the number of manipulator removals for boot changes needed to be reduced and since nearly all boot failures occurred in the gauntlet area, a two-piece boot is now in use in many hot cells at the Laboratory. This two-piece boot is fabricated so that the lower section, including gauntlet, can be remotely removed and replaced by a manipulator[2]. Also, because the activities at ORNL involve transuranium elements and because of rigid safety requirements for handling these materials, a double-layered boot is fabricated for 12 Model F manipulators in the Transuranium Processing Plant (TRU).

IV. Programmed Maintenance

Until 1961, all manipulator maintenance work was performed on an "as-needed" basis. Machines remained in operation until a failure occurred and the unit was inoperable. Experience had shown that if minor adjustments could be made from time to time, the more serious difficulties could be alleviated. To minimize cell downtime and to achieve more efficient manipulator performance, a computer programmed maintenance system was introduced. This program includes a two-week to one-month check on each installed manipulator. Tape and cable tensions are measured and adjusted, all motions are checked for possible malfunctions, and linkages are inspected for wear or out-of-tolerance conditions. A preventive maintenance program of this type has proven very satisfactory at the Laboratory, and an approximate 30% savings in maintenance costs has been realized. Prior to programmed maintenance, the average unit was taken to the manipulator repair facility twice per year for complete overhaul; after the programmed system was established, the units now average one trip per year to the maintenance facility for these extensive repairs.

In general, statistics available from the programmed maintenance activities show that annual costs of manipulator repairs will vary from $800 to $1200 per unit, excluding booting. The cell downtime due to manipulator removal and installation will vary from five to ten days per year. It should be noted, however, that the maximum time required to remove or install a unit is three hours. The five-to-ten days figure is acquired by using an accumulation of the total time required for each service call. Another interesting statistic shown by programmed maintenance is that the right-hand manipulator requires twice as many repairs as the left-hand unit. This may indicate that when designing an in-cell system, consideration should be given to a right handed operation.

V. Future Needs

Discussions with ORNL hot-cell operators reveal that the presently available manipulators are generally satisfactory for their research-type activities. Improvements could possibly be made in feedback information such as feel, temperature, etc.; but for their research, which is nonrepetitive in nature, present units provide the needed dexterity. These units are detailed in ORNL specifications 10017-N-111-X, XSP-239, and MP-200. However, for scientific personnel designing fuel recycling systems or waste handling systems, presently available manipulators are not satisfactory. It appears that programmable modules to work in conjunction with automated equipment are rapidly becoming a requirement in this remote handling area.

Unfortunately, units available on the open market are in no way adequate to be considered for these needs. Also, the criteria for such programmable units are incomplete.

VI. Conclusion

As a result of the techniques and facilities described in this paper, it is felt from both the maintenance and research viewpoint that a very satisfactory manipulator maintenance program has been established at ORNL. This program will be continuing since the number of manipulators is increasing and since the demands on the functions are broadening.

Table 1

Master-Slave Manipulators

Type	Model	Units
MSM	4	5
MSM	7	12
MSM	8	114
MSM	A	49
MSM	D	7
MSM	E	42
MSM	F	14
MSM	G	23
MSM	H	4
MSM	L	2
Electro Mechanical		11

5.4.1

PERFORMANCE EVALUATION STUDIES AT JPL
FOR SPACE MANIPULATOR SYSTEMS*

Dr. Antal K. Bejczy
Member of the Technical Staff
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103

I. Manipulators in Space

Space missions in the shuttle era will involve a large number of manipulative handling tasks never before performed by man-machine systems in space. E.g., cargo handling in the shuttle, assembly of structures and satellite servicing in earth orbit, exploration of lunar and planetary terrains, or sample analysis in sealed space laboratories will require the extension and augmentation of man's manipulative capabilities by employing remotely operated manipulator systems. Remote manipulation implies operating conditions which exclude or greatly impair the direct visual or other human sensory (e.g. force) contact between the operator and the manipulator, and impose various information and control communication limits.

As indicated above, the spectrum of projected applications of manipulators in space ranges from various operational tasks to primarily exploratory or research tasks. Operational tasks involve the handling of artifacts under prepared or known conditions, while exploratory or research tasks will also involve the handling of natural objects under partially unknown or unpredictable conditions.

The various space applications logically dictate various requirements for the manipulator's size, work space, load lifting capability, and effector dexterity, feedback sensors, control system, and system interfaces. Further, the variety of space environment characteristics (local g-level, radiation hazard, dust, communication distance, etc.) impose different constraints on the design and use of manipulators in the projected space missions. An overview and some technical details for the performance requirements of several space manipulators can be found in Refs. 1 and 2. Manipulator performance requirements for unmanned exploratory or research missions (e.g., to explore the martian terrain using a roving vehicle equipped with a manipulator) have been outlined in detail in Refs. 3 through 10.

Despite the variety of the mechanical, control, system interface, or environmental characteristics of manipulators required for various future space missions, improved efficiency in remote control and improved man-machine interface are common requirements for all space manipulator systems. Therefore, the problems of remote control and man-machine interface have been selected as central issues for performance evaluation studies at JPL.

---

* This work represents one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract No. NAS7-100, sponsored by the National Aeronautics and Space Administration.

II. JPL Breadboard Systems

The JPL performance evaluation studies are of experimental nature and utilize two types of breadboard systems: a teleoperator (or man-machine) breadboard and a robot breadboard.

1. The man-machine breadboard for remote manipulator control is organized into two separate areas: the work room and the remote control station. Table 1 lists the present elements and the operational status of the man-machine breadboard system.

Table 1. Elements of JPL Teleoperator Breadboard

WORK ROOM	REMOTE CONTROL STATION
. Humanoid Slave Arm (O)	. Exoskeleton Master Arm (O)
. "CURV" Linkage Arm (O-D)	. Universal Control Panel (D)
. Parallel Jaw Hands (O)	. Convertible Hand Controller (O)
. Swinging Hand (O)	. TV, Pan Tilt, Zoom Control (O)
. Humanoid Hand (O)	. Stereo } TV Displays (O)
. Stereo TV Cameras (O)	
. Mono TV Camera (O)	. Mono } TV Displays (O)
. Proximity Sensors (O)	. Audio and Digital Displays for Four Proximity Sensors (O)
. Touch Sensors (B-D)	
. Force/Torque Sensor (D)	. Visual Display for Multipoint Proportional Touch Sensor (O)
. Minicomputer, Interdata M70 (O)	
. Control Programs (O)	. Force/Torque Sensor Display (D)
. Six-Wheel Flexible Vehicle (O)	. Teletype for Computer Command (O)
. Four-Wheel Rigid Vehicle (O)	. Voice Command System (D)

Notes:

(O): Operational; (B): Bench Model; (D): Development

Fig. 1 shows the JPL/Ames anthropomorphic manipulator with the master arm worn by the operator, manual control console, Interdata M70 minicomputer dedicated to manipulator control, and TV cameras for stereo and mono viewing of the work scene. The arm (see also Ref. 11) has eight degrees of freedom: seven revolute joints for arm motion, each joint driven by d.c. torque motors through harmonic drive gears, plus one motor for driving the end effector. The slave arm can be position controlled in three ways: from the master arm, from the manual control console (one control per joint), or from the dedicated minicomputer. Fig. 2 shows part of the interior of the remote control station with stereo and mono TV displays, the operator in the master arm, and various control input and information display devices.

Fig. 3 shows the JPL/CURV linkage arm. As seen in this figure, the arm is mounted to a turret on a vehicle. The turret can be rotated and elevated. The arm (see also Ref. 12) has seven degrees of freedom (six for arm motion and one for end effector opening

Figure 1. JPL/Ames Arm with Minicomputer, Master Arm, Manual Control Panel, and TV Cameras.

Figure 2. Remote Control Station Interior

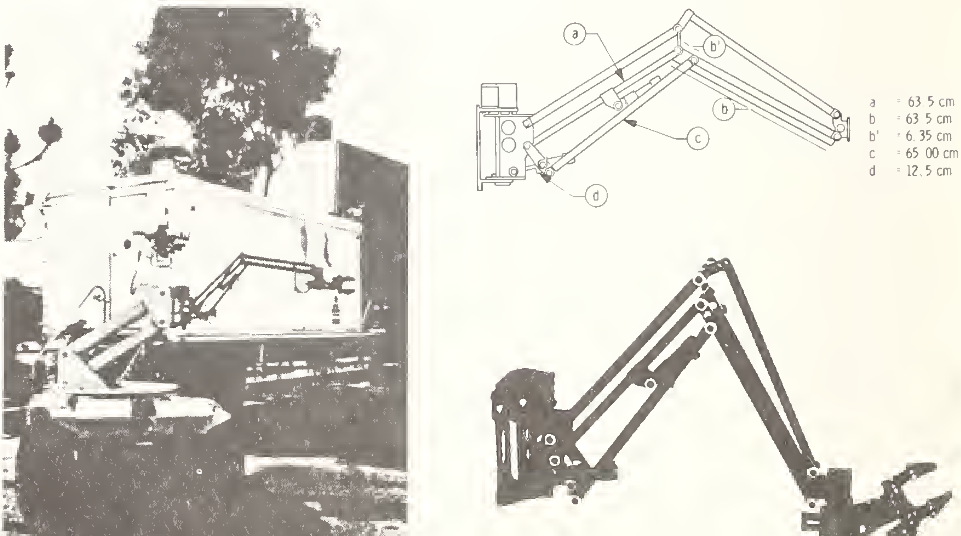


Figure 3. JPL/CURV Arm

or closing) and is driven by hydraulic actuators. The arm has two interesting features: it provides true linear extension by the use of an idler gear, and wrist disorientation is eliminated during changes in elevation and extension of the arm by the use of a double parallelogram added to the linkage. The arm is also equipped with a full force/torque sensor (built by Vicarm Inc., Mountain View, CA) mounted between the end effector and last wrist joint.

The new control system of the JPL/CURV arm, developed at JPL, includes proportional servo valves, position feedback at each joint, interfaces to the Interdata M70 minicomputer, and a universal control panel shown in Fig. 4 together with the stereo and mono TV displays. The panel is a combined control and switch board and has been designed with the specific purpose in mind to develop, study, and evaluate various schemes and capabilities of distributing control functions between man and machine. The control can be fully computer control, partly computer and partly manual control, or fully manual control. But even manual commands can be addressed to the computer. Of course, manual commands can also be addressed directly to the servo system. Manual inputs can be position or rate commands for each joint individually, or rate commands combined for several joints using two three-dimensional joysticks.

Fig. 5 shows the breadboard of a multipoint proportional tactile sensor with visual display. The sensor is built from two diagonally arranged nets of electrodes separated by conductive rubber. In the breadboard, the electrodes form a 4 by 8 matrix pattern, and the intersections of electrodes (the "sensitive cells") possess diode characteristics so that the pattern of pressure distribution can be found by electronically scanning the state of the sensitive surface. The tactile sensor is flexible, and can be wrapped around a curved body.

2. The JPL robot breadboard is organized around the concept of an "information gathering mobile laboratory system." The manipulator, mounted on a surface roving vehicle, is part of the system and is fully computer controlled. The elements of the robot breadboard are listed in Table 2.

Table 2. Elements of JPL Robot Breadboard

- Stanford Electric Arm
- TV "Eye" with Pan-Tilt Control
- Laser Range Finder
- Four-wheel Vehicle, Independent Drive, Dual Steering
- Expanded Minicomputer (SPC-16)
- Link to PDP-10 Computer
- IMLAC, TV Displays
- Key-boards for Computer Commands
- Large Amount of Computer Programs for
  - Arm Control
  - Scene Analysis

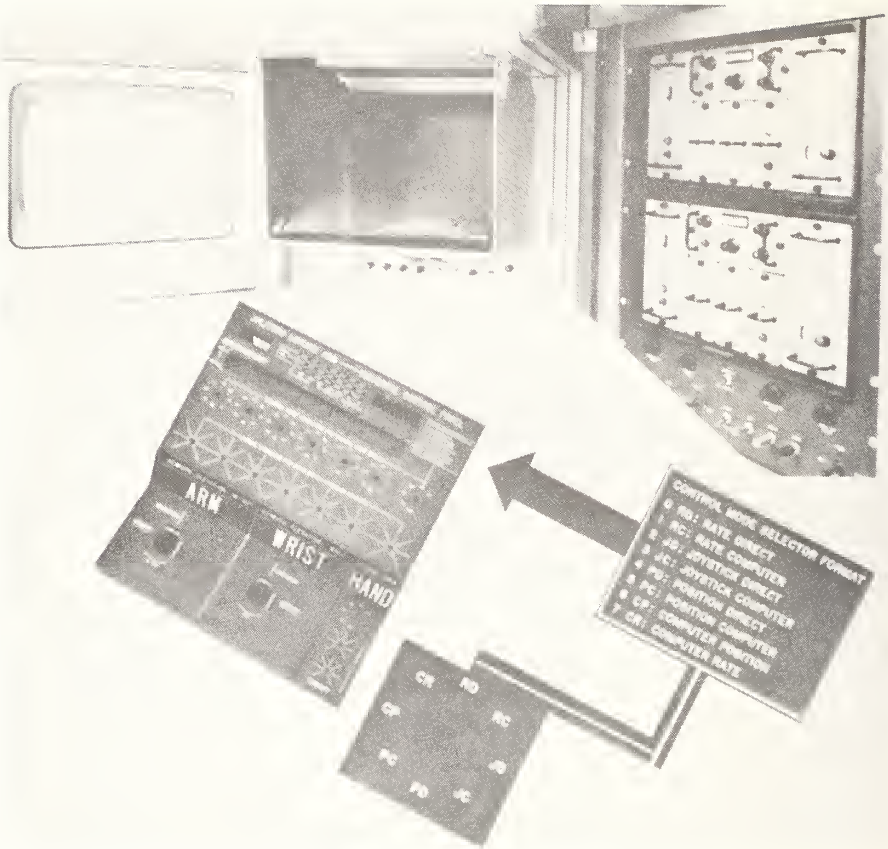


Figure 4. JPL/CURV Arm Universal Control Panel

Figure 5. Proportional Tactile Sensor with Visual Display

Fig. 6 shows the vehicle-arm-TV-laser system of the robot breadboard in two views. The two racks on the vehicle contain part of the system electronics. The package at the center rack contains the gyro compass for vehicle guidance and navigation. More on the robot breadboard and the manipulator can be found in Refs. 13 through 15.

Further literature on the JPL teleoperator and robot work, respectively, are listed from Refs. 16 through 36 and from 37 through 53.

III. JPL Performance Study Objectives

The teleoperator (or man-machine system) performance studies at JPL are organized around the following specific objectives:

Study the effect of local sensory feedback, end effector design, and man-machine information/control interface on remote manipulator control performance, and complement the study by the development of mathematical models for predictive performance evaluation of remotely controlled systems to the extent it is feasible.

1. Local sensory feedback includes proximity, tactile, and force/torque sensors which supplement the visual information for manipulator control. In this area, two items are of particular interest: (a) the type and quality of sensor information required for an efficient control, and (b) the properties of schemes for integrating information from different sensors for various tasks.

2. The end effector design study is aimed at the development of efficient multi-functional terminal devices for remote operation and investigates the following specific areas: (a) the number, articulation, and control of "fingers", and (b) the integration of the end effector with proprioceptive and exteroceptive sensors.

3. The man-machine information/control interface design study is aimed at the evaluation of the human operator's interaction with the remote manipulator control with or without a computer in the control system. The study is being conducted within the framework of a "supervisory control system" (see Ferrell, W.R., Sheridan, T.B., "Supervisory Control of Remote Manipulation", IEEE Spectrum, October 1967, pp. 81-88) and is centered around two main items: (a) Formulation of a computer control language for remote manipulation, that is, formulation of the human input end of the control algorithms which should be able to combine positional or directional coordinates with information generated by proximity, tactile, and force/torque sensors mounted to the end effector, and (b) convenient display of relevant sensor information to the human operator, using also computer algorithms for display purposes.

4. The development of mathematical models for predictive performance evaluation of remotely controlled manipulators serves two purposes: (a) to rationalize the empirical data in a quantitative framework, and (b) to reduce the dimensionality (or number) of performance experiments required to evaluate alternative systems.

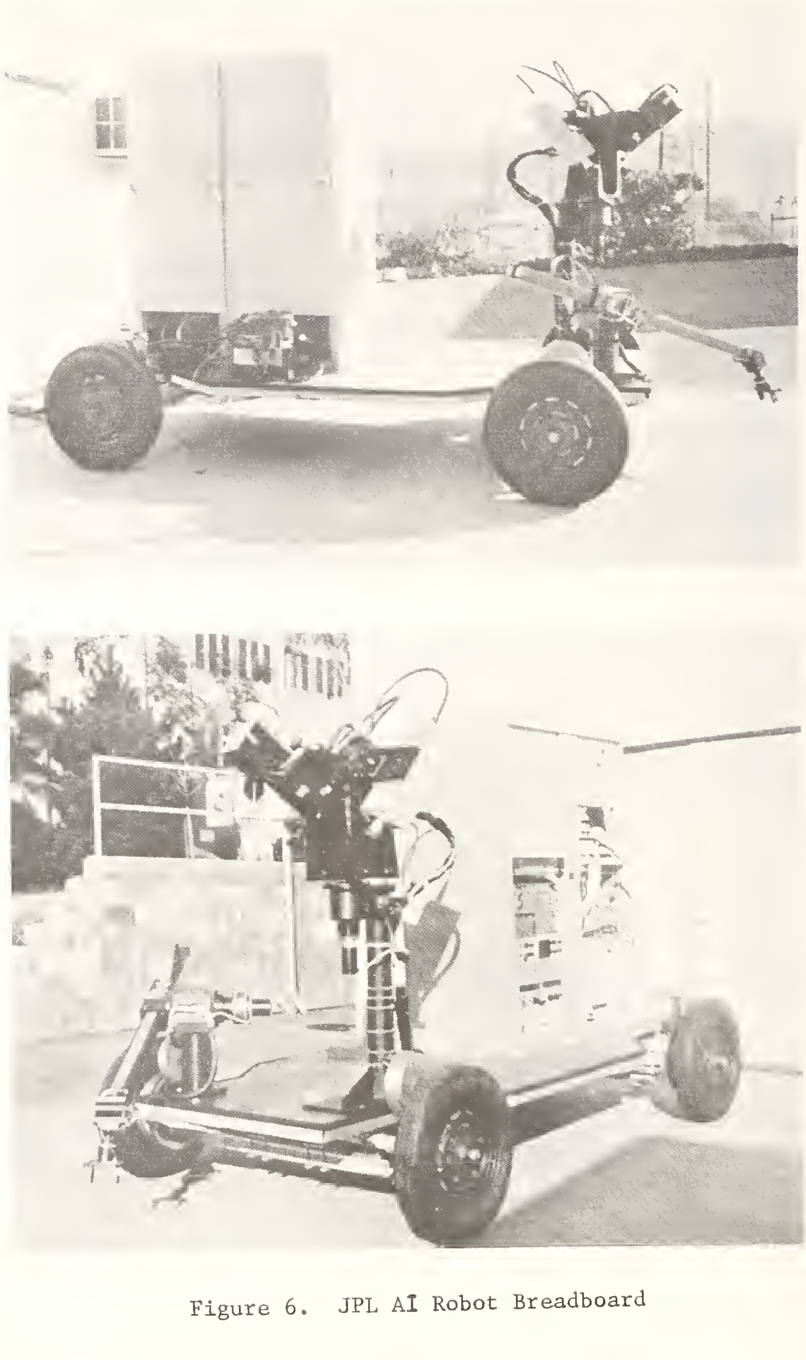


Figure 6. JPL AI Robot Breadboard

IV. Control Performance Experiments and Results

The teleoperator control experiments so far have been concentrated on the problem of terminal phase control of manipulator motion: approaching, finding, contacting, and grasping various regular or irregular objects using different terminal devices and proximity sensors attached to the terminal device. The proximity sensors have been developed at JPL and are described in Ref. 32. The proximity sensor produces a voltage signal when the sensor's sensitive volume -- which is permanently focused at a distance of about 10 cm in front of the sensor head --"touches" a solid surface as the end effector approaches the surface.

The end effector-proximity sensor configurations employed in the control performance experiments are shown in Figs. 7 and 8. Fig. 7 shows a parallel jaw end effector mounted to the JPL/Ames arm and equipped with four proximity sensors, two sensors on each finger. Fig. 8 shows a humanoid hand (the Belgrade prosthetic hand) mounted to the JPL/Ames arm and equipped with three miniaturized proximity sensors.

Control performance experiments have been conducted both in manual and computer control modes. In the computer control experiments, the operator can specify four voltage levels (or five "distance regions") to be "recognized" by the computer programs which automatically guide the manipulator's motion. The programs can presently use signals from four proximity sensors. The operator specifies the control meaning of the sensor signals for each task. Typical computer control experiments were: locate an object for grasping; stop the manipulator's motion at a given distance from an object; avoid obstacles by a specified maneuver; etc.

In the manual control experiments, the information from four proximity sensors was directly presented to the operator through four different audio tones. Each sensor was connected to a different loudspeaker. The four loudspeakers are arranged at the corners of a two by two meters vertical quadrangle around the operator. The pitch of the tone generated by the voltage output of the sensor indicates increasing or decreasing distance between sensor head and objects. The manual control experiments were designed to test the operator's ability to integrate the information content of the proximity sensor signals with incomplete visual feedback and perform remote manipulator control tasks which are very difficult or nearly impossible under a given visual feedback arrangement. Typical tasks were: find a block hidden in a box; locate critical parts of the work scene (e.g., edges, balls, blocks); etc.

Both the computer control and manual control experiments with proximity sensors are described and evaluated in detail in Refs. 20 and 21, and are shown in a movie.* As an illustration, Fig. 9 shows two task arrangements. The two tasks were:

<u>Task 1</u>: Move from standby position to the rectangular block at "A", pick it up, and place it on top of another rectangular block located at "B", and align the two blocks. The two blocks are of equal size. See the left part of Fig. 9 for the physical dimensions of this task.

---

* "Crossing Visual Barriers in Remote Manipulator Control," Jet Propulsion Laboratory Sound Movie, No. 1015, 16 mm, May 1975.

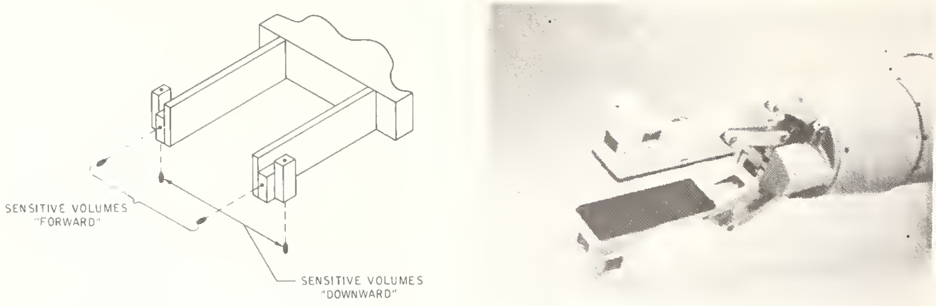


Figure 7. Parallel Jaw End Effector with Four Proximity Sensors

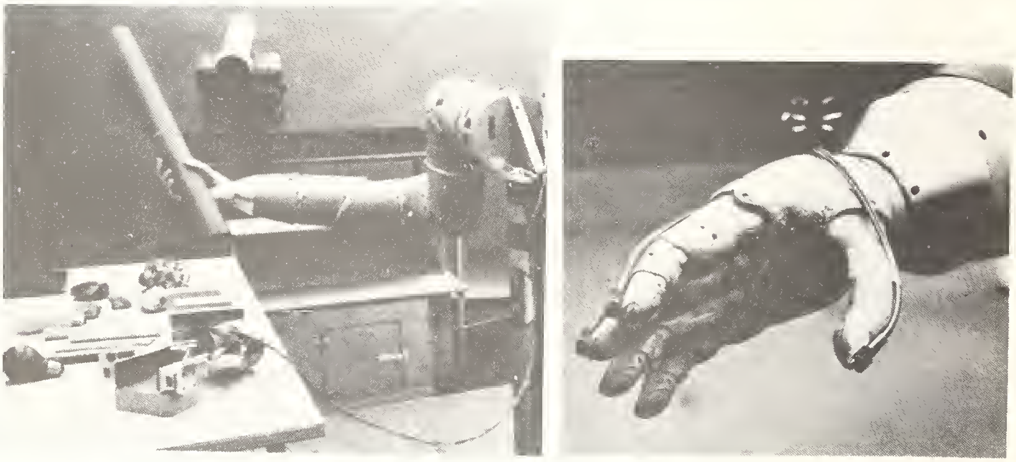


Figure 8. JPL/Ames Arm with Humanoid Hand Equipped with Three Miniaturized Proximity Sensors

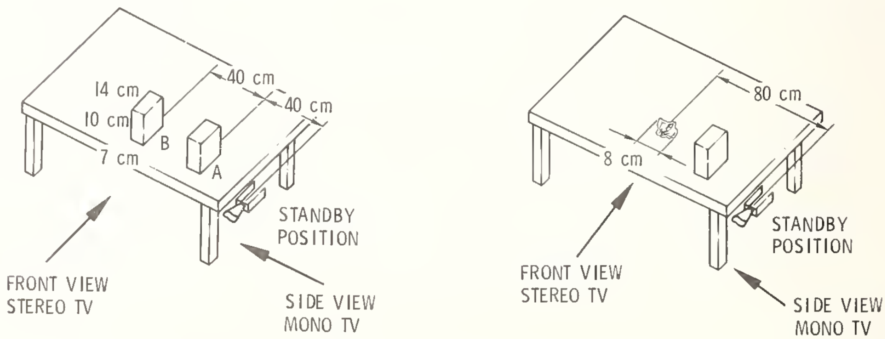


Figure 9. Arrangements for Performance Tests Using Proximity Sensors

Task 2: Move from standby position and pick up a partially obscured irregular object (a rock). See the right part of Fig. 9 for the physical dimensions of this task.

Table 3 summarizes the information feedback conditions and performance data for tasks 1 and 2.

Table 3. Performance Data for Tasks 1 and 2

Visual and Sensing Conditions	Mean time of ten experiments (sec)		Standard deviation (sec)	
	Task 1	Task 2	Task 1	Task 2
1. Only visual information; stereo plus mono TV	24	25	2.3	3.2
2. Stereo TV plus two front sensors	25	24	3.1	3.1
3. Stereo TV plus two down sensors	27	25	2.9	2.9
4. Stereo TV plus all four sensors	31	32	4.2	4.6
5. Mono TV plus two front sensors	22	24	1.9	3.0
6. Mono TV plus two down sensors	23	21	2.0	2.8
7. Mono TV plus all four sensors	30	29	3.8	3.8
8. Only mono TV information	36*	39+	6.1	5.9
9. Only stereo TV information	38**	38++	7.4	6.1

* Two mistakes or bad alignments
** Four mistakes or bad alignments
\+ Three mistakes
++ Five mistakes

As seen in Table 3, tasks 1 and 2 could be successfully performed using visual information alone provided that the operator had access to two different views simultaneously as shown in Fig. 9. When the operator had access only to one view, stereo front view or mono side view, systematic success could not be achieved. Several attempts ended with mistakes or bad alignments, and whenever the operation was successful, it took about 50% longer time to achieve success as compared to the performance time with two different simultaneous views. But control performance was always successful using one view (mono or stereo) combined with proximity sensor information, and the performance time was nearly identical to the performance time with two different simultaneous views. It is also noted that dealing with one view combined with audio information from proximity sensors resulted in less mental stress for the operator than handling two different views simultaneously.

Fig. 10 shows a few real task scenes compared to the TV views presented to the operator.

The main conclusions of the control performance experiments can be summarized as follows: (1) Automated proximity sensor control can result in faster, safer, easier, and more economical operation. But the operator must have a clear a priori notion on the expected outcome of an automated proximity control loop as applied to a given task before he can confidently initiate the use of that automatic loop. (2) Proximity sensor

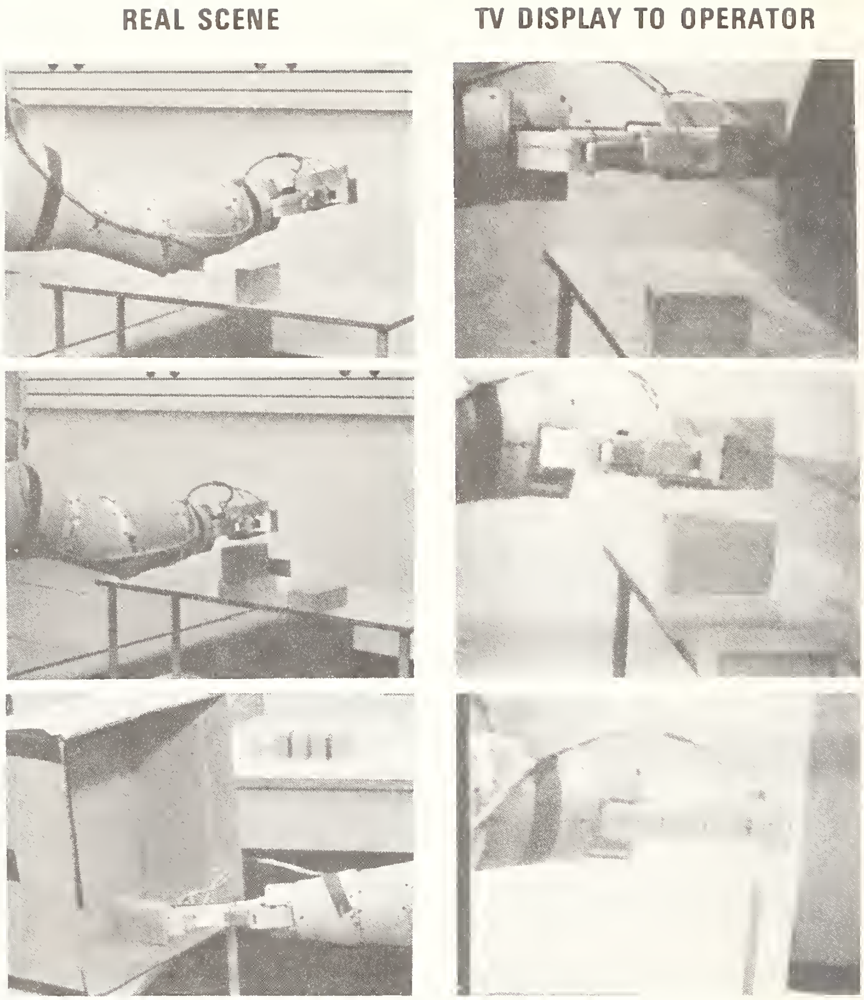


Figure 10. Examples of Control Experiments with Proximity Sensors Supplementing Visual Information

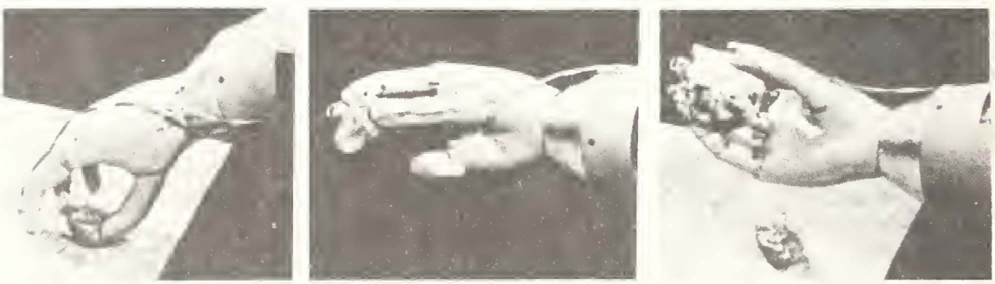


Figure 11. Handling Irregular Objects with Articulated Adaptive Hand Interfaced with Proximity Sensors

information can replace or supplement part of the visual information required for control. (3) Control tasks which cannot be performed using visual information alone can be performed by a combined use of proximity sensor and visual information. (4) The number of independent proximity sensor signal displays affects the operator's control performance. (5) Control performance is strongly influenced by the location of the proximity sensors on the end effector. (6) In general, handling irregular objects requires considerably more information and control effort than handling regular objects. But the effort on the conscious level can greatly be reduced by employing an articulated and adaptively controlled end effector ("hand") as illustrated in Fig. 11.

The remote manipulator control experiments have shown so far that a realistic performance evaluation requires the simultaneous consideration of at least three somewhat overlapping performance measures: (a) The binary categories of "success or failure" for evaluating the effectiveness of control. (b) The combination of "accuracy and time" for evaluating the quality of control. (c) The integrated "consumption of resources" for evaluating the cost of control.

The control experiments have also shown that the performance evaluation studies will have an important effect on the definition and development of computer-aided remote manipulator control technology. In fact, this technology is still in the early state of development (or, better, in the early state of "inventiveness"). Therefore, at the present time, the real significance of the performance evaluation studies lies mostly in assisting the development of computer-aided manipulator control.

The performance evaluation studies allow three concluding remarks. (1) It became evident that more systematic work is needed on task analysis and "mechanical" task description. (2) The quality of breadboard hardware has a significant impact on practical performance evaluation studies. (3) It is established that proximity sensors mounted to the end effector have a significant effect on the control performance of remote manipulators.

Ongoing and future performance evaluation studies at JPL include: (1) The use of both tactile and force/torque information in both manual and computer control modes. (2) Integration of TV and other external sensory information within a variable video frame. (3) Display-oriented control. (4) Development of a new type dexterous end effector integrated with proprioceptive and exteroceptive sensors. (5) Development of a convenient and versatile "supervisory control language."

REFERENCES

1. Heer, E., Ed., "Remotely Manned Systems, Exploration and Operation in Space," Proceedings of the First National Conference, California Institute of Technology Publ. 1973.

2. Proceedings of the Second Conference on Remotely Manned Systems, Technology and Applications, University of Southern California, Los Angeles, California, June 9-11, 1975.

3. Heer, E., "Remotely Manned Systems for Exploration and Operation in Space -- An Overview," JPL Internal Report 760-81, 1 July 1972.

4. Heer, E., et al. "Summary Report -- Advanced Teleoperator/Robot Studies for Planetary Surface Roving Vehicles," JPL Internal Report 760-75, 1 July 1972.

5. Choate, R., and Jaffe, L.D., "Science Aspects of a Remotely Controlled Mars Surface Roving Vehicle," JPL Internal Report 760-77, 1 July 1972.

6. Bejczy, A.K., "Remote Manipulator Systems, Technology Review and Planetary Operation Requirements," JPL Internal Report 760-77, 1 July 1972.

7. Anthony, V.F., "Motion Control Requirements for Planetary Surface Roving Vehicles," JPL Internal Report 760-78, 1 July 1972.

8. Jaffe, L.D., "Problems of Previous Scientist/Machine Operation Interfaces," JPL Internal Report 760-79, 1 July 1972.

9. Seifert, H.S., "Analytical/Experimental Definition of Man-Machine Interface Characteristics in Remotely Manned Systems," JPL Internal Report 760-80, 1 July 1972.

10. Bejczy, A. K., "Advanced Automation Systems for Manipulator Control," JPL Internal Report 760-93, December 1972.

11. Vykukal, H.C., et al, "An Anthropomorphic Master-Slave Manipulator System," in Remotely Manned Systems -- Exploration and Operations in Space, E. Heer, ed., California Institute of Technology Publ., Pasadena, California, 1973.

12. Uhrich, R.W., "NUC Manipulators", Ocean Technology Department Contributions to IEEE 1971 Ocean Environment Conference, NUC, San Diego, California, September 1971.

13. Dobrotin, B.M., Scheinman, V., "Design for Computer-Controlled Manipulator for Robot Research," Third IJCAI, Stanford, California, August 1973.

14. Lewis, R.A., Bejczy, A.K., "Planning Considerations for a Roving Robot With Arm," Third IJCAI, Stanford, August 1973.

15. Whitney, W.M., "Human vs. Autonomous Control of Planetary Roving Vehicles," IEEE Symposium on Systems, Man, and Cybernetics, Dallas, Texas, October 1974.

Further References on JPL Teleoperator and Robot Work

A. Teleoperator Project

16. Alsberg, H., "An Augmented Active Image Transmission System for Visual Man-Machine Interaction," 1973 IEEE Conference on Systems, Man, and Cybernetics, Boston, November 5-7, 1973.

17. Alsberg, H., and Nathan, R., "Man-Machine Interactive Imaging and Data Processing Using High Speed Digital Mass Storage," Proceedings of the Human Factors Society, 18th Annual Meeting, October 1974.

18. Ancker, Jr., C.J., "Stochastic Modelling of Remotely Manned Systems," JPL Internal Report 760-116, December 1, 1974.

19. Bejczy, A.K., "Machine Intelligence for Autonomous Manipulation" in Remotely Manned Systems, Exploration and Operation in Space, E. Heer, ed., California Institute of Technology Pub., Pasadena, California, 1973.

20. Bejczy, A.K., "Environment-Sensitive Manipulator Control, " Proceedings, IEEE Conference on Decision and Control, Phoenix, Arizona, November 1974.

21. Bejczy, A.K., "Effect of Hand-Based Sensors on Manipulator Control Performance," Proceedings of Second Conference on Remotely Manned Systems, Technology and Applications, University of Southern California, Los Angeles, California. June 9-11, 1975. (To appear in a special issue of "Mechanism and Machine Theory.")

22. Bejczy, A.K., "Algorithmic Formulation of Control Problems in Manipulation," Proceedings of the 1975 IEEE International Conference on Cybernetics and Society, San Francisco, California, September 23-25, 1975.

23. Bejczy, A.K., "Distribution of Control Decisions in Remote Manipulation," Proceedings of the 1975 IEEE Conference on Decision and Control, Houston, Texas, December 10-12, 1975.

24. Bejczy, A.K., Johnston, A.R., "New Techniques for Terminal Phase Control of Manipulator Motion," JPL Internal Report,760-98, February 1974.

25. Deutsch, S., and Heer, E., "Manipulative Systems Extend Man's Capabilities in Space," Astronautics and Aeronautics, June 1972.

26. Freedy, A., "Remote Manipulation by Means of the Autonomous Control Sub-System," Final Report, Jet Propulsion Contract No. 953402, Perceptronics, Inc., August 24, 1972.

27. Heer, E., "Teleoperators: Status and Technology Requirements," Presented to SAE Aerospace Control and Guidance Systems Committee, September 23, 1971.

28. Heer, E., "NASA Developments and Their Spin-Off to Undersea Applications," Presented to Navy Workshop on Undersea Manipulator Operator Performance, Williamsburg, October 26, 1971.

29. Heer, E., "Remote Control of Planetary Space Vehicles, " IEEE '73 INTERCON, New York, March 26-30, 1973.

30. Heer, E., "Remotely Manned Systems for Exploration and Operation in Space," Proceedings of the First International Symposium on Theory and Practice of Robots and Manipulators, Udine, Italy, September 5-8, 1973.

31. Heer, E., Bejczy, A.K., "Teleoperator/Robot Technology Can Help Solve Biomedical Problems," JPL TM 33-271, January 1, 1975.

32. Johnston, A.R., "Optical Proximity Sensors for Manipulators," JPL TM 33-612, May 1, 1973.

33. Johnston, A.R., "Proximity Sensing for Manipulators and A Laser Rangefinder for a Robot," Third International Joint Conference on Artificial Intelligence, Stanford, August 1973.

34. Johnston, A.R., "An Experiment in Manipulator Control with Proximity Sensors," JPL TM 33-678, April 1, 1974.

35. Johnston, A.R., "Proximity Sensor Technology for Manipulator End Effectors," Proceedings of Second Conference on Remotely Manned Systems, Technology and Applications, University of California, Los Angeles, California, June 9-11, 1975.

36. Tippins, H.H., Johnston, A.R., "Application of Multiple Detector Arrays to Optical Proximity Sensors," JPL Internal Report 760-128, August 8, 1975.

B. Robot Project

37. Bejczy, A.K., "Robot Arm Dynamics and Control," JPL TM 33-669, February 15, 1974.

38. Dobrotin, B.M., "JPL's Robotics Program as an Extended Control System," SAE Control Meeting, April 1973.

39. Dobrotin, B.M., "Robots for Space Exploration," IEEE Symposium on Systems, Man and Cybernetics, Dallas, Texas, October 1974.

40. Feldman, J., Yakimovsky, Y., "Design Theory and Artificial Intelligence: A Semantic-Based Region Analysis," Artificial Intelligence Journal 5 (1974).

41. Hong, J.P., "Registration of Points," Princeton Conference on Information Sciences and Systems.

42. Hong, J.P., Liporace, L., "A Terrain and Object Model Derived from Range Data and Useful to a Robot," Sixth International Conference on Systems Sciences.

43. Hooke, A.A., et al, "The Impact of Robots on Planetary Mission Operations" International Telemetry Conference, Los Angeles, California, October 1974.

44. Levine, M.D., "Digital Processing of Stereoscopic Image Pairs," Proceedings of the 1973 IEEE International Symposium, Toronto, Canada.

45. Levine, M.D., "Scene Analysis for a Breadboard Mars Robot Functioning in an Indoor Environment," JPL TM 33-645, September 1, 1973.

46. Lewis, R.A., "Autonomous Manipulation on a Robot," JPL TM 33-679, March 15, 1974.

47. Markiewicz, B.R., "Analysis of the Computer Torque Drive Method and Comparison with a Conventional Position Servo for a Computer-Controlled Manipulator," JPL TM 33-601, December 1972.

48. Mathur, F.P., "Phase I Report on A Cognitive Operating System for JPL's Robot," JPL TM 33-568, September 15, 1972.

49. O'Handley, D.A., "Scene Analysis in Support of a Mars Robot Rover," Computer Graphics and Image Processing.

50. Yakimovsky, Y., "A Semantics-Based Decision Theoretic Region Analyzer," Third IJCAI, August 1973.

51. Yakimovsky, Y., "Boundary and Object Detection in Real-World Images," IEEE Conference on Decision and Control, November 20-22, 1974, Phoenix, Arizona; JPL Technical Memo 33-709, November 15, 1974.

52. Yakimovsky, Y., "Extracting 3-D Information for 2-D Images Using Multi-camera System," presented at Milwaukee Symposium on Automatic Control.

53. Yakimovsky, Y., "Computer Software Using Artificial Intelligence Applied to Pattern Recognition," Proc. 2nd Intl. Joint Conference on Pattern Recognition, August 1974.

PERFORMANCE MEASUREMENT FOR UNDERSEA SYSTEMS*

Alan J. Pesch

William R. Bertsche

Eclectech Associates, Inc.

North Stonington, Conn. 06359

I. Introduction

Remote manipulators have found increasing application in the undersea environment for the past two decades. The earliest systems were basic in design and were utilized primarily for object recovery and limited scientific tests. More recent systems, however, have been designed to perform complex work. Undersea remote manipulators are now deployed which can drill holes, operate impact hammers, wire cutters, and a host of special interchangeable tools and scientific equipment. The interest in the efficient utilization of the increased capability of the latest generation of manipulators has led to the study and documentation of manipulator design factors which potentially affect an operator's ability to utilize the manipulator to perform undersea work assignments. The testing and measurement procedures adopted to evaluate these systems are of a pragmatic design such that results may be directly applied to undersea remote manipulators by the various individuals and agencies involved in manipulator design.

This paper presents an overview of a measurement and testing methodology which has been effectively used to evaluate the performance of numerous types of undersea remote manipulators. It is the opinion of the authors that for the types of undersea remote manipulators described, this methodology allows a comprehensive comparison of system type and performance and provides guidance in design of new systems. The methodology has been utilized to experimentally evaluate four rate controllers and two position controllers on the same manipulator. The methodology has recently been expanded for the evaluation of force feedback manipulator systems.

II. Remote Underwater Manipulator Systems

The majority of the manipulator systems utilized underwater are of a similar design with respect to operator interface characteristics. Below is a general description of the systems to which this paper is addressed. Figure 1 illustrates the relation of the basic components.

---

* This paper is based on research supported by the Office of Naval Research, Engineering Psychology Programs.

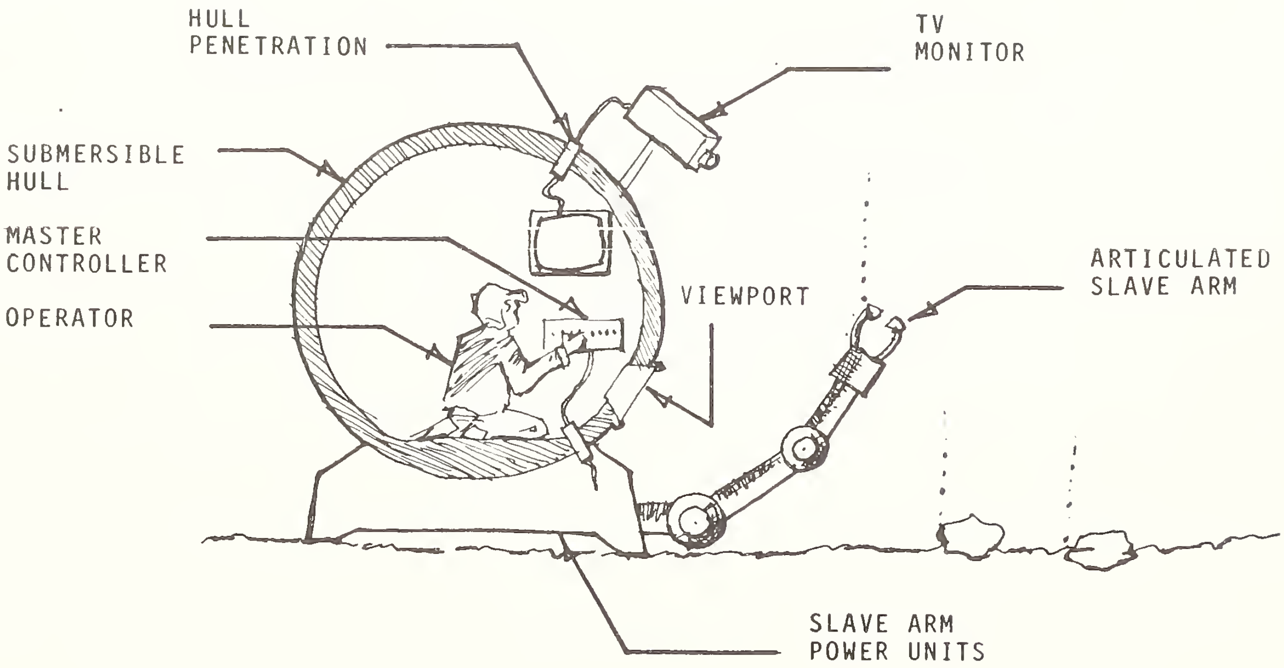


Figure 1. Typical Elements In
Underwater Remote Manipulator Systems

- Slave Arm: work is achieved in the water environment by an articulated slave arm. This arm is hydraulically and electrically powered. The arm payload is medium (50 pounds) to high (200 - 300 pounds). Control signals to the slave arm components are generally electrical. The slave arm is usually mounted on a maneuverable submersible vehicle.

- Controller: the operator utilizes a controller to generate analog or discrete command signals for the slave arm. The controller may consist of push buttons, switches, joystick, anthropomorphic harness, or an end effector grip. The master controller is located in a submersible or on a surface ship.

- Operator Interface Problems: the operator controls motion, position, and in some instances, force of the slave arm. This is accomplished by operating the controller while observing the results of his control actions remotely through a viewport, on closed circuit TV, or on various electronic displays. Lack of visual depth cues is a prevalent problem in all viewing methods. Visual distortion is greatest when using only the viewport due to the air-glass-water interface for any uncorrected optical or TV system.

- Work Requirements: underwater work varies from light to heavy tasks. Light work includes sample gathering , rigging cables and hooks, and operating scientific equipment. Heavy work includes wire cable cutting, drilling steel plates, retrieval of heavy objects. The water environment can vary from clear to turbid. Underwater auxiliary lighting is usually required.

The critical design requirements which set underwater remote manipulators apart from hot lab remote manipulators are massiveness, water seal of the slave arm, and the remote position and conditions under which the operator exercises control of the slave arm. Design of these systems must necessarily be directed to account for these effects.

III. Measurement/Testing Methodology

Rate and Position Controller Manipulators

There are two portions of the measurement/testing methodology. The first is simply a method of determining the definition and nature of the variables which comprise the system under test. The second is the method of testing, documenting, and evaluating the work potential of the system with an operator in control. Each is discussed below.

1. Definition of System Variable

Preliminary comparison of underwater remote manipulator systems may be made by comparing plans and specifications of the various systems. Required is a comprehensive and standard set of variables to allow comparison. Table 1 indicates a set of proposed variables which may adequately specify a rate or position control remote manipulator. The upper set of variables in Table 1 indicates measures of the manipulator's static and dynamic response to standard input signals. These data are measures of the tip response of the articulated arm, not individual actuators.

Table 1. System Variable Definition for Rate and Postion Control Remote Manipulators

RESPONSE VARIABLES

It is recommended that these variables be specified for each of the 6 degrees of freedom in polar coordinates. The response variables are those of the "tip" of the articulated arm.

Rise Time	Time required for the output response to a step input to rise from 10 to 90% of its final value
Setting Time	Time required for the output to reach and maintain the final value ± 10%, for a step input
Overshoot	The percentage of signal change the output exceeds its final value in response to a step input
Slew rate	The maximum constant velocity a joint will attain
Time delay	Time the output response is displaced from the corresponding input response
Bandwidth	The range of frequencies over which the system will respond satisfactorily
Dead Band	The positional difference the master controller may move before the slave begins to track
Droop: Compliance	Droop is a measure of how much the tip of the manipulator is deflected from no load to full load conditions (inches). Compliance is droop divided by the full load (pounds)
Minimum Motion	The minimum distance a joint may be reliably moved
Drift	The displacement of a joint over an arbitrary time increment divided by the time of the increment

Table 1. (Continued)

DESIGN ALTERNATIVES	
Operational Envelope	A definition of the working volume of the slave arm
Degrees of freedom	The number and arrangement of rotatable or extendable joints
Anthropomorphic or terminus design	Terminus design is an arbitrary arrangement of joints to spatially position wrist and hand joints in the X, Y, Z space. Wrist joints provide pivoting and rotations of the hand. Anthropomorphic design is a one for one match of joints to the corresponding joints of the human arm
Motion range	The number of degrees (inches) a joint is free to move
Linear extension	Implies that the articulated arm can extend or contract in a straightline fashion
Continuous rotation	Implies that a joint may be rotated continuously in one or the other direction
Tool design	Includes design provisions for handling and utilizing special tools
MASTER CONTROLLER POSITION CONTROL	
Exoskeletal strap-on	Refers to postion controllers that strap onto operator's arm. Joints are matched one to one to the arm
Exoskeletal harness	Refers to position controllers into which the operator inserts his arm. It is loose fitting and joints are approximately matched to the operator's arm
Terminus grip	Refers to a terminus configured position controller. The operator touches only the hand grip and inputs all motions to the grip
Individual controls	A particular arrangement of controls for ordering the position of individual joints
MASTER CONTROLLER RATE CONTROL	
Pushbutton/switch controls	Bi-directional or unidirectional switches to control joint motions individually or in combined motions
Variable rate	Displacement controls which control the rate and direction of individual joint motions
Programmed motions	Controls which provide automatically coordinated motion of several joints

The lower set of variables indicate selected examples of several typical design alternatives which the system may incorporate. A manipulator system under consideration might incorporate any practical combination of these design alternatives.

The variables shown in Table 1 were defined during the research program in order to define the nature and characteristics of the various manipulator systems which were examined. The interest in system variable definition and measurements resulted from the requirement to define a set of independent variables which may be related to dependent measures of operator performance in applied undersea work tasks. The variables listed in Table 1 are meant to serve as primers to an encompassing set of definitions required for widespread application.

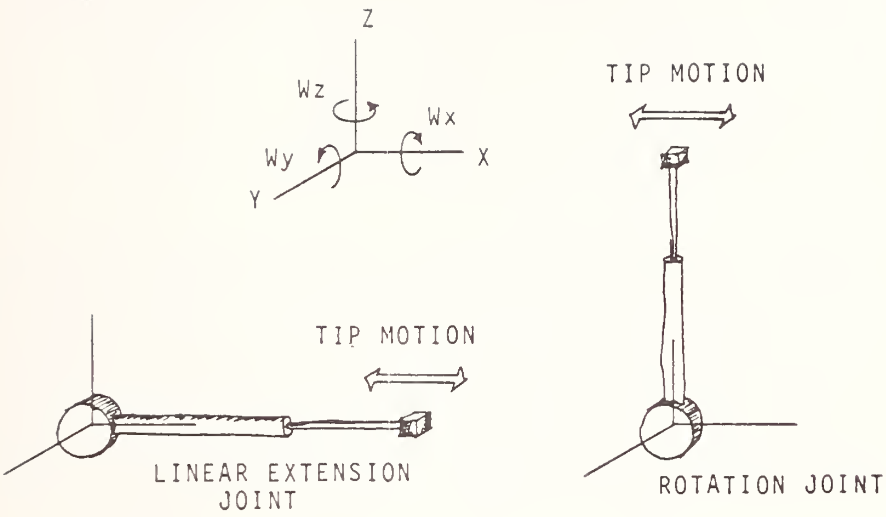
Measurement of the response variables in terms of arm tip motion is recommended to provide a common set of data for comparison. Previously, only the response of individual actuators was commonly specified. Systems were difficult to compare when the articulated arms were vastly different, e.g., terminus configuration vs. anthropomorphic configuration. Documentation in polar coordinates is recommended because study of existing articulated arm manipulators indicates many of the polar coordinate motions are controlled by single actuators, thus simplifying the experimental procedure required to measure responses. Additionally, location of the tip in its motion range does not usually change the actuators controlling polar coordinate motion. Figure 2 illustrates the polar coordinate motions.

Measurement of the response variables in an orthogonal set of axes, X, Y, Z, Wx, Wy, Wz, is not recommended because of several inherent problems. Motion of the tip of the manipulator in any of the axes directions almost always requires the coordinated movement of several actuators. Additionally, the position of the manipulator tip in its motion range may change the actuators which contribute to the motion of interest. Figure 2A illustrates that motion in the X direction may be controlled wholly by two different actuators, depending on the tip location.

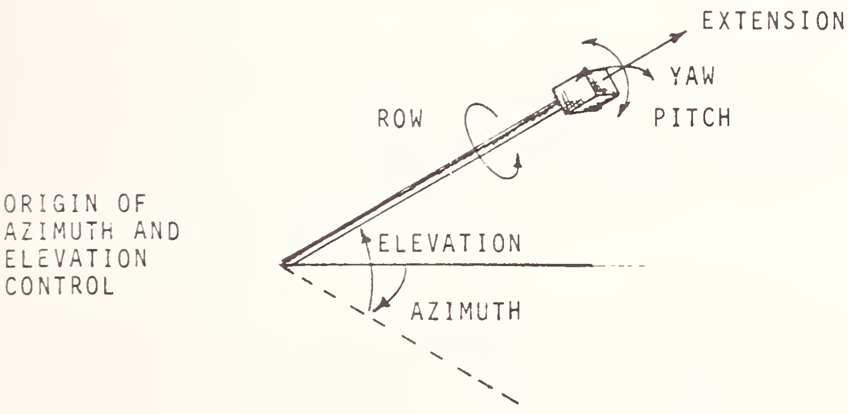
2. System Performance Evaluation

The above set of variables can be utilized to identify differences between candidate systems. This knowledge, however, is not sufficient to judge how well each system can be utilized to perform underwater work. Performance evaluation is achieved by performing a set of prognostic tests, evaluating the test results, and documenting the relative and potential performance of each system.

The prognostic tests selected to evaluate underwater remote manipulators are unique in several ways. First, the tests are conducted in a simulated underwater environment to closely replicate the distorted visual feedback path presented to the operator. Then, a series of selected tasks representative of both light and heavy work, typical of underwater tasks, are performed. The tasks range in difficulty from simple to a high degree of difficulty. All of the tasks are of an "applied" nature, that is, they are identical to realistic tasks that may be performed at-sea. Each test is designed to require certain basic control and behavior response on the part of the operator. These responses were selected as basic elements of underwater work from time-motion studies.



A. ORTHOGONAL AXES SYSTEM



B. POLAR COORDINATES

Figure 2. Coordinate Systems For Response Variables, Six Degrees of Freedom

The prognostic tests are performed repeatedly under controlled conditions by groups of operators to determine average performance times and eliminate learning trends. Data are collected during the various elements of the prognostic tests. Data are generally a time measurement. Accuracy of work, operator comments, and the subjective opinions are also recorded. The data are compiled and analysed and presented in three forms.

(a) Completion time of each test.

(b) Average time for basic behavior elements.

(c) Accuracies of test performance.

Completion times of applied tasks are shown in Figure 3 as ratios for the comparison of manipulator performance to direct work by a diver. These data appear in D/R matrices (diver times/remote manipulator times). Data collected in this format are shown for four rate controlled manipulators and two position controlled manipulators. The larger numbers in the denominators of the ratios indicate in multiples how much longer the manipulator took to perform the work than the diver. Careful study of the data indicates that certain manipulator systems were better for specific types of tasks, but not necessarily all tasks. An important property of this matrix is that these data are indicative of the ability to sequentially perform basic control responses in the execution of a complex task in the environment.

Average completion times for the behavior elements of all the work are plotted in a second matrix. The data points are D/R ratios (diver/remote) of completion times. Figure 4 illustrates these data compiled for the four rate controllers and two position controllers. The behavior elements selected from time-motion studies represent common control responses performed time after time in various combinations to perform the prognostic tests. These data are particularly important in the design of a system for specific work. A system or combination of systems may be selected which best perform selected work elements if the work can be broken down into behavior elements. This procedure may then be termed "projective" and may be useful for designing systems in the future with some prior knowledge of performance.

The third set of data recorded during the prognostic tests are various measures of accuracy. These measures record the success of performing certain of the prognostic tests. For example, drill hole angle in the drilling task indicates the success with which operators held and moved the drill bit perpendicular to the drilled surface. Figure 5 illustrates data collected for drill angle for the two position control manipulators. This type of data may be considered by the designer where behavior sequences and particular related tasks are contemplated.

3. Application of Methodology

The measurement and testing methodology described in this section has been utilized to evaluate four rate control and two position control underwater remote manipulators (data in Figures 3, 4, and 5). The testing methodology documents changes in system performance as system specifications are changed. These data should be useful in extrapolating from performance measures to system design.

D/R Matrix for Applied Tasks

	RATE CONTROL				POSITION CONTROL	
	Discrete Actuator Switches, buttons		Combined Actuator Joystick		Discrete Position	Combined Position
	PBFR Fixed Rate	PBVR Variable Rate	JSFR Fixed rate	JSVR Variable rate	Knobs dials	Anthropomorphic harness
Sample Collection	1/14	1/12	1/14	1/11	1/15	1/5
Valve Manipulation	1/10	1/9	1/9	1/9	1/10	1/3
Rigging chain, hooks	1/16	1/16	1/20	1/19	1/19	1/8
Bolt removal with power tool	1/9	1/9	1/12	1/10	1/15	1/6
Tapping	1/1.5	1/1.3	1/1.4	1/1.4	1/1.8	1/1.1
Threading	1/10	1/9	1/8	1/10	1/13	1/9
Drilling	1/1.6	1/1.6	1/2.8	1/2.5	1/2.3	1/1.6
Connect/ disconnect	1/27	1/29	1/24	1/31	1/24	1/11

PBFR Pushbutton fixed rate
PBVR Pushbutton variable rate
JSFR Joystick fixed rate
JSVR Joystick variable rate

Figure 3. D/R Matrix For Applied Tasks

D/R Matrix for Behavioral Elements

	RATE CONTROL				POSITION CONTROL	
	Discrete Actuator Switches, buttons		Combined Actuator Joystick		Discrete Position	Combined Position
	PBFR Fixed Rate	PBVR Variable Rate	JSFR Fixed Rate	JSVR Variable Rate	Knobs dials	Anthropomorphic harness
Simple Travel	1/12	1/10	1/11	1/9	1/9.8	1/3
Complex Travel	1/12	1/9	1/13	1/12	1/10	1/4
Simple grasp	1/36	1/31	1/36	1/34	1/48	1/15
Alignment	1/18	1/20	1/26	1/22	1/43	1/17
Tool Use	1/1.2	1/1.1	1/2.1	1/1.8	1/1.8	1/1.6

Figure 4. D/R Matrix for Behavior Elements

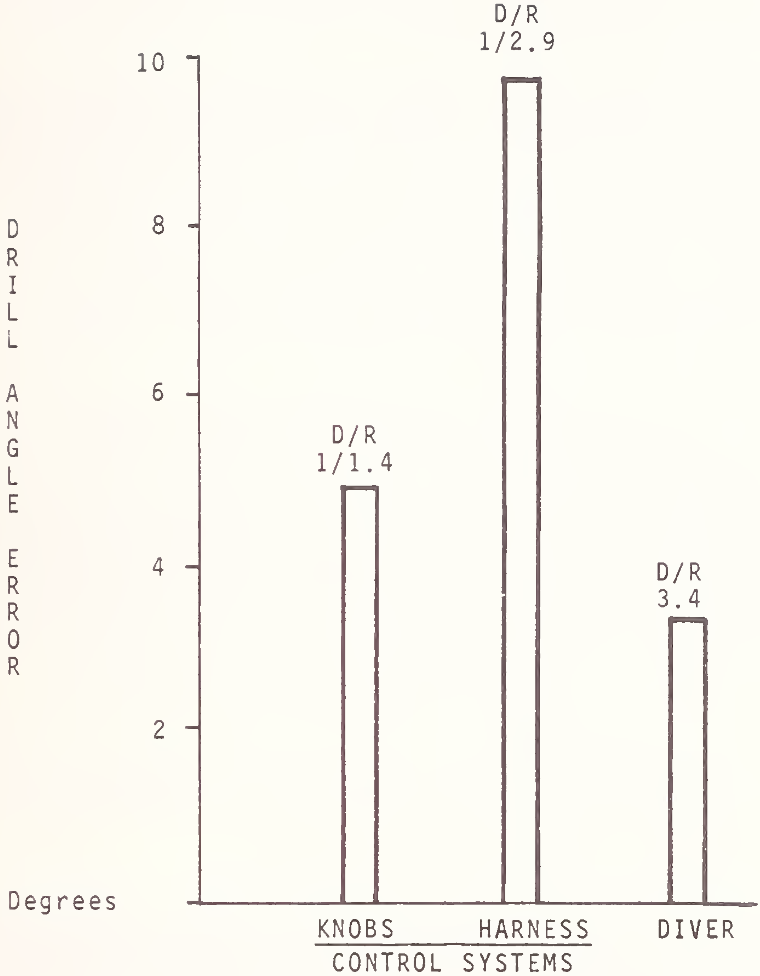


Figure 5. Drill Angle Performance

The question remaining is how to utilize the methodology in the future to add to the existing data base. One direct solution is to replicate the tests in this paper and simply continue compilation of data. This is a viable solution where identical facilities exist. A second approach is to utilize the methodology but change the specifics of the tests. Resulting data, although not directly comparable, should be of equal value, if interpreted properly. The methodology is summarized below to serve as a guide for developing similar tests.

Measurement and Testing Methodology, Rate and Position Controlled Manipulators:

1. Determine system specifications according to the standard format.

2. Perform prognostic tests which have the following features:

   (a) tests represent the entire range of typical tasks

   (b) tests are performed under simulated conditions

   (c) tests range from simple to difficult

   (d) tests are selected to repeatedly require basic control responses to be exercises in various combinations

   (e) a reference set of data is compiled for continued comparison. Reference data might best be recorded for man performing the tasks directly to maintain a continuity of the human sequencing of tasks, and to provide a common element for interpreting various sets of data.

3. Evaluate and document data collected during prognostic tests:

   (a) Times to complete tests.

   (b) Times to perform typical behavior elements within those tasks.

   (c) Accuracy and quality of test performance.

Utilization of this methodology to evaluate other types of rate and position control manipulators (e.g., hot labs, space) is straightforward. The simulated conditions change, the types of tasks change, and the reference data base changes. These changes, however, do not affect the basic methodology.

IV. Considerations for Measurement of Force Feedback Systems

Evaluation of undersea remote manipulator systems with force feedback capability is more complex than the evaluation of rate and position control systems. The basic testing methodology, however, is essentially the same: system variables are determined and a series of prognostic tests are conducted.

The task of determining system variables here is technically more difficult than that for ordinary rate and position controlled manipulators. System response must be measured in terms of both force response and position response. Additionally, force and position responses must be measured from the master to the slave and from the slave to the master in bilateral systems. Design alternatives of force feedback systems are expanded due to the various system configurations and hardware concepts developed. Table 2 presents typical variables and alternatives which are available. Where definitions are similar or identical with those in Table 1, they are so noted. It is important to note that the variables listed in Table 2 are intended as an indication of the scope of variables and alternatives. The acceptance of standard definitions and testing methods is required to permit meaningful comparisons to be made between systems.

Prognostic testing of remote force feedback manipulator systems requires increased data collection. Tests are chosen from time-motion studies of typical underwater work with particular emphasis on force control behavior required by the test. Data collection during these tests reflects not only completion times and accuracy, but also force control responses. Research presently being conducted by the authors is investigating the effectiveness of performance measures such as integrated, maximum and average forces exerted by the slave arm during selected force control behavior elements. The objective of this research is to establish a data base and an effective set of performance measures which will be meaningful in comparing system designs in terms of operator performance and in projecting performance of similar systems in the future.

An example of one type of test is given in the Appendix. The test in this case is concerned with the production of electrical signals proportional to the torque exerted by the slave (which in turn determines the torque applied to the master).

V. Summary

An overview of the testing and measurement methodology has been presented to provide an understanding of its application to undersea remote manipulators. The intent of this paper is to present the methodology for an open discussion of the merits of the approach as it relates to a standard set of measures for remote manipulators and programmable robots. The implications of the methodology are as follows:

1. System variable definition

Comparison of similar or diverse manipulator systems requires a standard method of variable definition over the various systems. One set of definitions and terminologies for all specifications should be applied across all the manipulator design fields. A standard set of coordinate axes or conversion techniques between dissimilar axes should be accepted across all manipulator design fields. Standard testing methods for system response should be established across the various manipulator design fields.

Table 2. Definition of System Variables, Force Feedback Manipulator Systems

RESPONSE VARIABLES*

Rise Time (position) Settling Time (position) Overshoot Time (position) Slew Rate (position) Time Delay (position) Bandwidth (position) Dead Band (position) Droop: Compliance Minimum Motion (position) Drift (position) Rise Time (force) Settling Time (force) Overshoot (force) Time Delay (force) Band Width (force) Minimum Force (force) Drift (force)	SAME AS IN TABLE 1
Feedback Ratio:	The ratio between slave and master forces. It is denoted as slave:master.
Backlash:	The measure of the force at the master (slave) which must be reversed before the slave (master) force will begin to reverse.
Force to Move or Viscous Friction:	The force required to move at a constant velocity. A Figure of Merit is the force divided by the velocity.
Effective System Inertia:	The mass of the system sensed when operating the system.

* It is recommended that these variables be documented for each of the 6 degrees of freedom in polar coordinates. For bilateral systems these variables must be documented for master-to-slave response and slave-to-master response.

Table 2. (Continued)

DESIGN ALTERNATIVES

Operational Envelope:
Degrees of Freedom
Anthropomorphic or
Terminus Design
Motion Range
Linear Extension
Continuous Rotation
Tool Design
Master Controller
Position Control
Exoskeletal Strap On
Exoskeletal Harness
Terminus Grip
Master Controller Rate Control
Joystick Controls
Variable Rate
Programmed Motions
Signal Conditioning and Enhancement

SAME AS IN TABLE 1

	Examples
Velocity Damping:	Position rate signals are utilized to provide damping.
Friction reduction:	Positive feedback reduces force to move.
Electronic counterbalancing:	Generation of signals to automatically support the dead weight of the arm.
Computer with supervisory control:	Intelligent computer control of forces exerted by the system.

Feedback Type	Examples
Visual/Auditory:	Force Feedback information provided on visual and/or audio displays.
Tactile indications:	Touch information presented to the operator via vibration or air jet pulsations.
Proportional force reflections:	Proportion forces are produced at the master and the slave. Passively at brakes, reactively via actuators or motors. Proportional force sensation created via subcutaneous neural stimulation.

Force Detection Method	Examples
Position Servo error:	Forces are generated in the master and slave proportional to the position error.
Force transducers:	Forces generated are measured directly by transducers. Strain gages or leds and photo cells.
Mechanical transmission:	Direct transmission of force via mechanical linkage or incompressible fluid.
Transducer location:	Transduces one-to-one in joints or all loaded into one compact multi-axis unit.

2. System Performance Evaluation

The basic approach of the prognostic testing described in this paper is that of time and motion studies (i.e., how long does each simple element of a complex task take?). The number of behavior elements in the example research, although limited, imply that a complete breakdown of manipulator behavior elements will provide a standard for comparison of the performance potential of various manipulator types. This method of comparison was chosen over other methods for the following reasons:

(a) The data provide a direct measure of work performance.

(b) The data are collected in an undersea environment to directly account for the complex man-machine-environment interface.

(c) The data are indicative of the ability to variously string simple tasks together in the performance of a multifaceted task.

(d) The data are easily and readily comprehended by individuals asked to design or select undersea remote manipulator systems.

(e) The data base documents man-machine performance differences as a function of changing basic design aspects of the manipulator. Generally, the data are indicative of how well specific "types" of remote manipulators can be utilized to perform work. As such, data need not be collected on every system if data exist for an equivalent "type" of system.

(f) The data base serves as a reference from which the designer may project the potential of a new system (provided data are documented for that type of system).

3. Application of Methodology

The methodology described in this paper has been utilized to examine a selected number of variables listed in Tables 1 and 2. Resultant data have closely interrelated system performance in applied undersea contexts to various design alternatives and response variable values. It is this methodology of interrelating independent engineering variables with operator performance data which is offered towards the development of performance evaluation standards for remote manipulator systems.

APPENDIX

Signals Generated

Purpose: The tests determine the ability of the system in producing signals proportional to an external torque applied to an effector. The system is not under motion. Maximum input torque, backlash, linearity, rise and settling times, and tracking are determined.

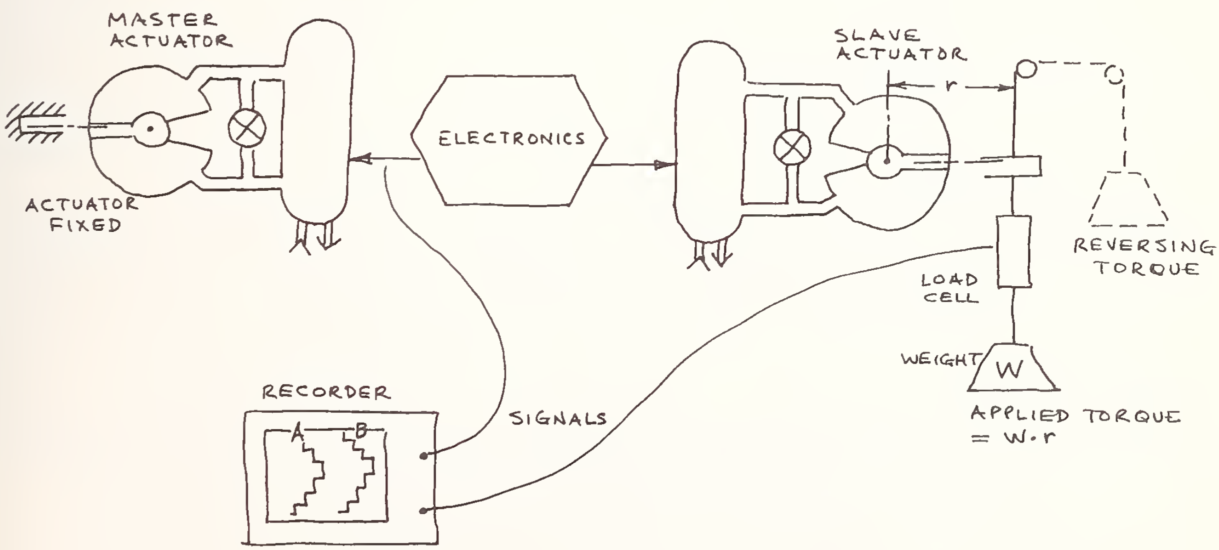
Procedure:

1. In this test, torque is applied to an effector and the input signal to its bilateral pair effector is measured. The torque is added in 20% increments of the design payload until payload is reached. Torque is then reduced in increments to zero. Torque in the opposite direction is now applied in 20% increments until zero torque is being applied. At each increment, the proportional signal generated is measured. Between increments, sufficient time must be allowed for the signals to settle to a fixed value. The proportional signal is recorded on a strip chart recorder to determine rise and settling time. The loading procedure is repeated to determine repeatability.

2. Tracking of force variations is now measured using an identical set-up to Procedure 1. 75% of the payload torque is applied to the effector. An incremental torque of 20% payload is removed, the proportional signal measured. The 20% increment is then re-added, signal measured. Continue removing and replacing increments of 40% and 60% of payload measuring the proportional signal at each iteration.

Data Format: Backlash is the amount the control must be moved in the opposite direction before the commanded variable begins to respond. It may be a measure of force or position.

Example: The following curves were determined for a sample joint of the experimental manipulator. The test configuration for Procedures 1 and 2 was as follows:



Note:

1. For bilateral force systems, data is also collected for the situation where the master actuator is loaded and the signal to the slave actuator is recorded.

2. The slave actuator is oriented so as to remove any torque produced by the effect of gravity on the actuator mass.

The following data was derived from the example curves:

	Hand Joint: Master Generated Signal	Data Source
Payload	4.5 lb-ft	Figure A1
Signal backlash	.3 lb-ft	Figure A1
Full scale error	10%	Figure A1
Repeatability	4%	Figure A2
Signal Rise Time	.4 sec	Figure A1
Signal Settling Time	.7 sec	Figure A1
Tracking Error		
20% Torque Increment	10	Figure A3
40% Torque Increment	0	Figure A3
60% Torque Increment	5	Figure A3

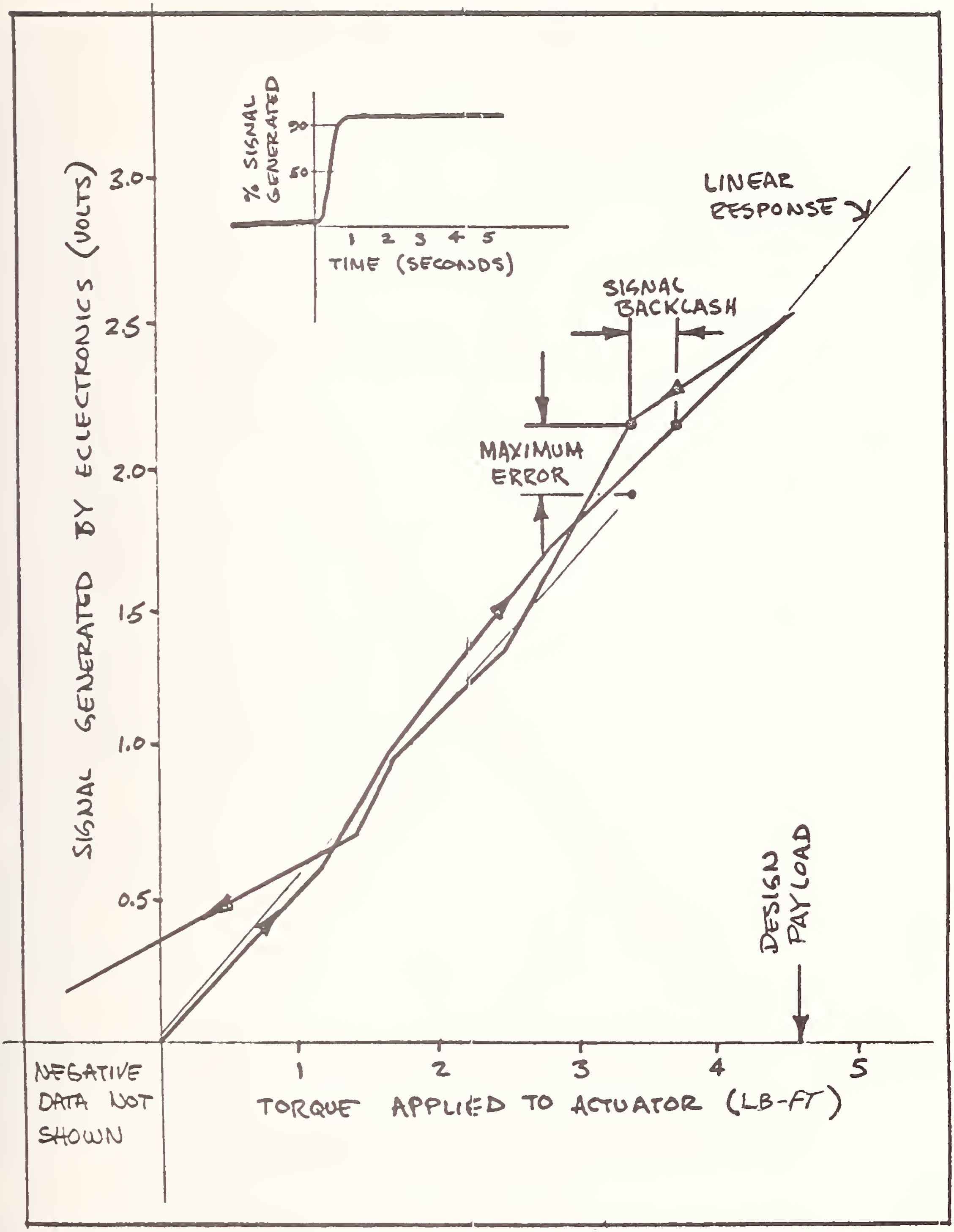


FIGURE A.1 SIGNAL GENERATION: BACKLASH, FULL SCALE ERROR, PAYLOAD, RISE & SETTLING TIME

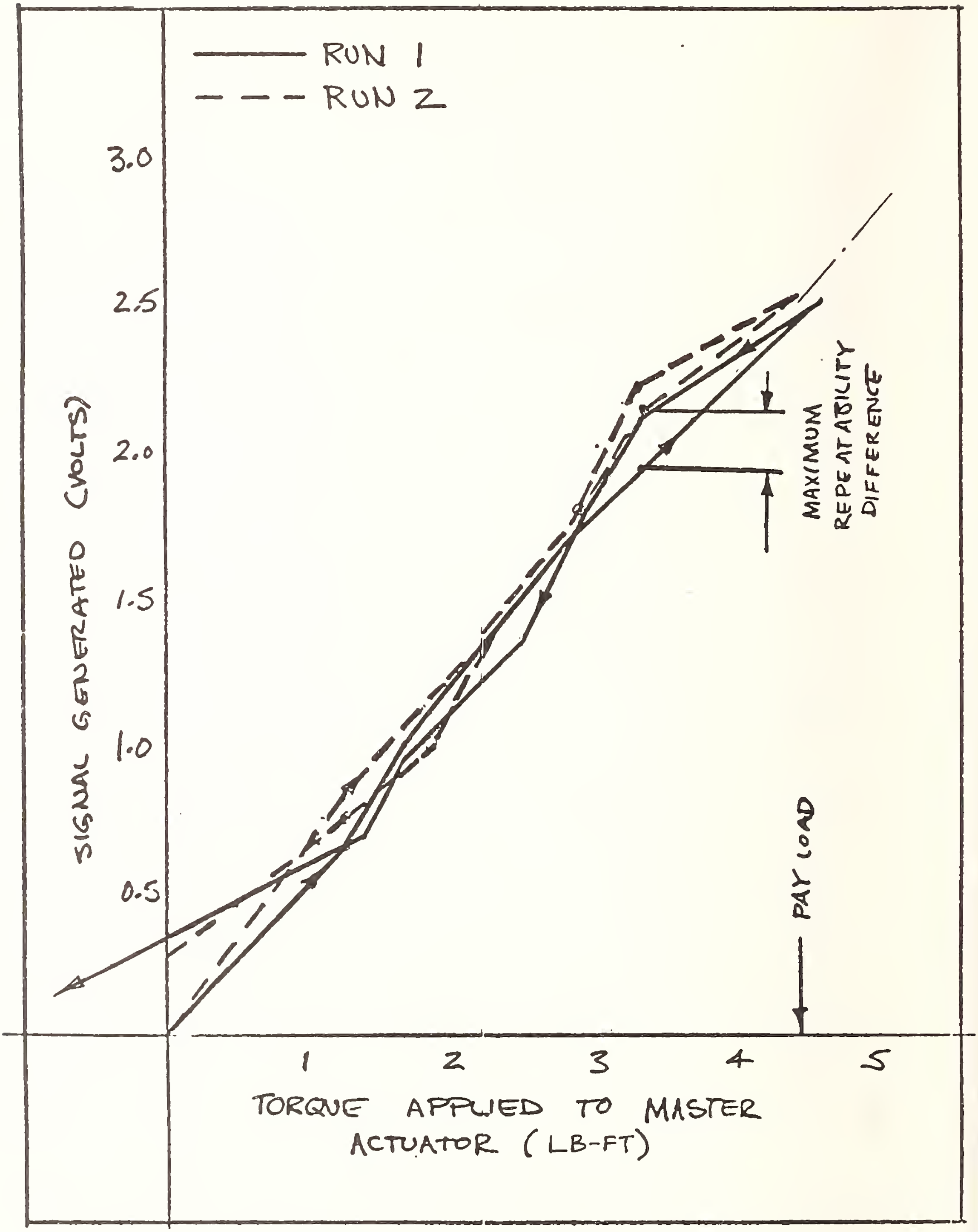


FIGURE A.2 SIGNAL GENERATION: REPEATABILITY

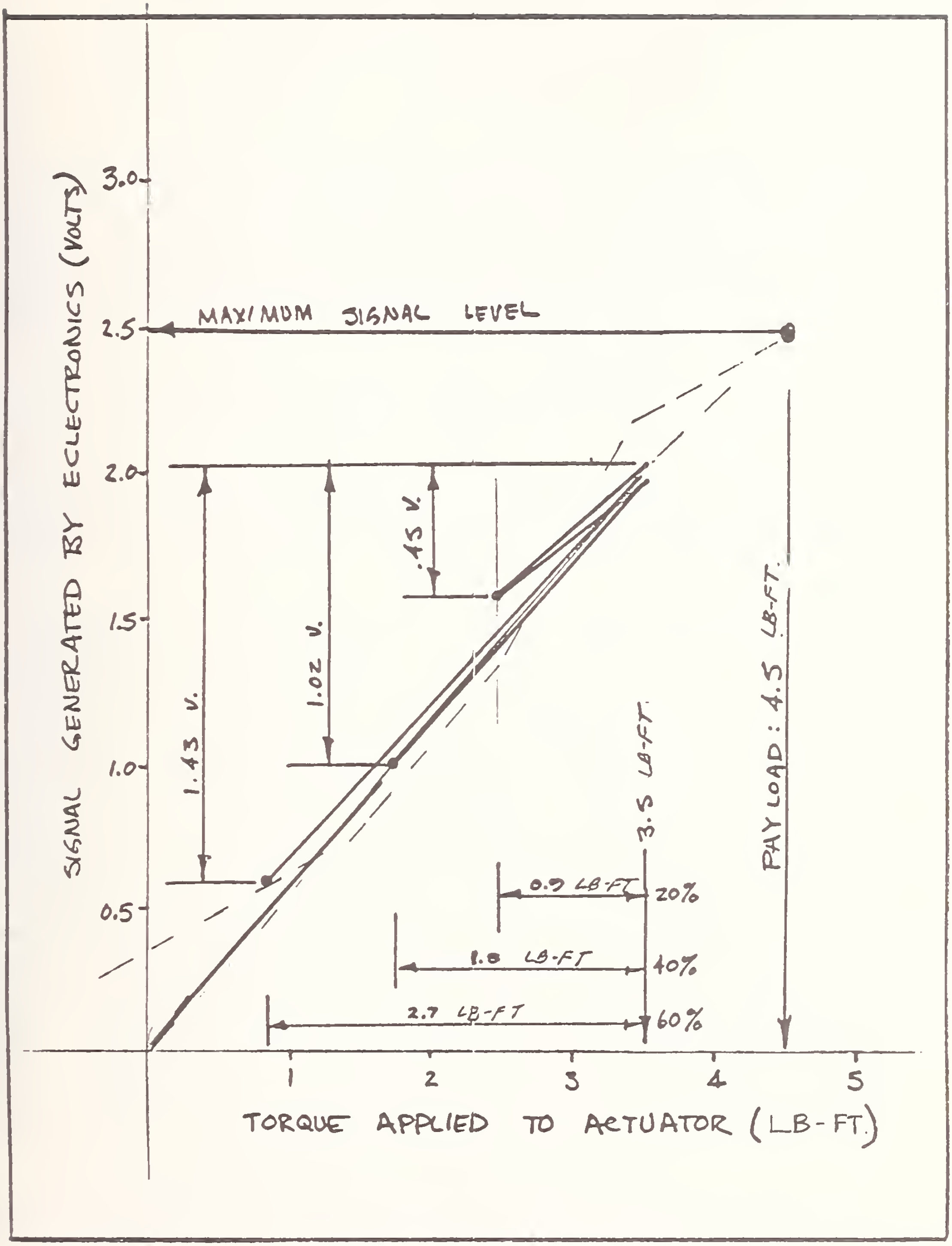


FIGURE A.3 SIGNAL GENERATED: TRACKING ERRORS

CONTRIBUTIONS TO FORMING CRITERIA FOR THE EVALUATION OF ROBOTS AND MANIPULATORS

M. Vukobratovic

It is in any case clear that forming criteria for the evaluation of robots and manipulators depends on many factors. First of all, the fact should be admitted that every criterion is of conditional character and hence has a limited value. Then it becomes more evident that here cannot be spoken about some general criterion, according to which the performances of various types of robots and manipulators would be estimated. To begin with, one must mention robots and manipulators, which are used industrially, in underwater explorations, on other planets and in outer space. Robots are also present in rehabilitation activity of handicapped persons, and similar.

Each of these robot types requires careful analysis from the viewpoint of its validity. It follows that the structure of the criterion itself must have various marks in function of the mentioned classes of robots.

Something should be said already at the beginning, and this is that all robots do not have, at the present state of development, full economic justification, understood in the conventional way. Consequently, it is my opinion that the economic index should not have some decisive influence on the evaluation criteria of robots and manipulators, except in some cases of mass production applying industrial programmed robots.

Because of this statement, let the structure of the evaluation criterion be considered, or at least our standpoint be presented, what the same should look like when the rehabilitation robots class is in question.

First of all, rehabilitation robots are in the initial phase of large-scale application. It follows that there must be determined some parameters which would participate in the evaluation formula of such robots. What are these parameters? Even more, a unique criterion cannot be synthesized even for one class of robots. Consider hand prostheses (under-elbow amputation). There are some fifteen makes existing on the world market today from the most perfected concerning imitation of a human hand (fig. 1) to the simplest ones, performing the similar functions (Fig. 2). To what extent a criterion for assessing the validity of devices of that type can lead to surprising results is amply illustrated by the fact that the prostheses of the second mentioned version have found application with handicapped persons, while the first ones practically stayed without regular users, in spite of the fact that they were produced seven years ago. One is without doubt here: in the case of forming some criterion of validity post factum the sole parameter valuable is the acceptance of the prosthesis by the patients-users. If the said criterion had been formed earlier, it is probable that it would include such indeces as <u>cosmesis, multifunctionality of movements, reliability, etc</u>. It is propable that the weight would be neglected, or at least its role underestimated. Experience has shown, however, that this factor is very important, and that the weight of such a prosthesis should not be much greater than the weight of the missing part of the human arm.

Let now let a more complex case of rehabilitation robots be considered, that of a rehabilitation manipulator which is intended to enable a tetraplegic or very high bilateral amputee certain manipulation activities. Here, too, we can judge the quality of the assistive device only by the number of accepted ones. It must be said here that none of some fifteen developed prototypes in many countries, have profited of broad application. Why is this so? In any case not because it is not possible to produce a dependable and precise manipulator, but for the reason that the behaviour of man, coupled with an assistive device is practically unpredictable. Let here one statement be stressed illustrating the impossibility to form some criterion via technical parameters. Namely, it is unlikely that a handicapped person will really use the manipulator if he has one healthy arm left. There is a limited number of operations a person must perform with both arms simultaneously, when the class of heavily handicapped persons is in question. That means, into the criterion for evaluation of the rehabilitation manipulators must enter such a non-technical category as indispensability and purposefulness. Only after that can enter some technical data, as weight, reliability, precision, simplicity or the control system, energetic autonomy, autonomy of using, total system cost, etc. Surely these technical data have a great influence on acceptability of the device.

It follows that only when the human factor has been eliminated, i.e. his attitude towards the active assistive device from the standpoint of its indispensability, which for itself can frequently present a purely subjective category, one can proceed to the judgement of the system from the standpoint of the above-mentioned technical parameters.

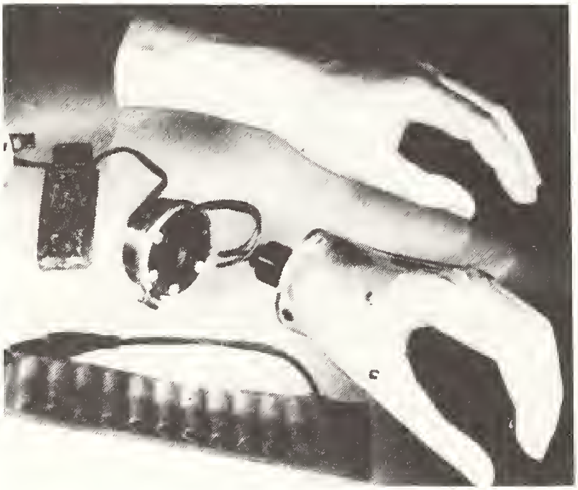


Fig.1 Multi-functional prosthetic hand

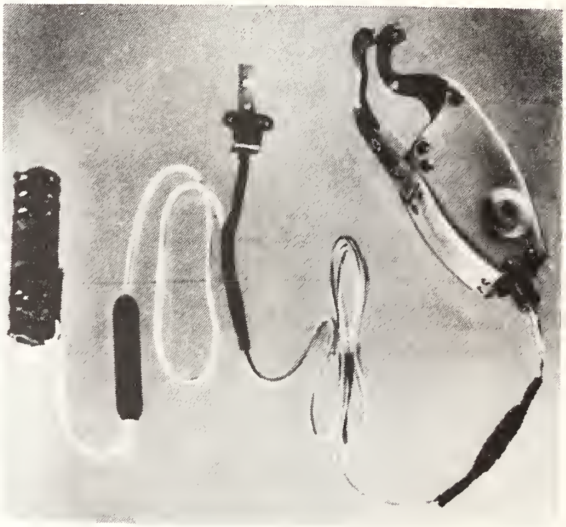


Fig.2 Simple prosthetic hook

The situation is similar in the case of the most complicated rehabilitation robot - the active exoskeleton (Fig. 3). How to form some criterion, which weighs out the performances of such a complex assistive device? When the youngest member of the family of rehabilitation robots is concerned one must start again from the fact that this sort of robot has still not been applied and accepted broadly. For the moment handicapped persons of the paraplegic type are still using the wheelchairs and from time to time leg braces, which are blocking their flaccid joints to enable motion by means of crutches. Here, as in the preceding examples, the patient has two alternatives for the same activity. There exists big difference between the two ways of locomotion, but the common feature is that they serve only to enable changing place in the environment. Both can perform this task in an non-anthropomorphic way , consuming great physical power, especially in the case of the brace-crutches combination. Both are very limited from the aspect of surmounting obstacles in the form of various terrain configurations. On the other hand, active exoskeletons enable anthropomorphic (humanoid) motion with minimal participation of physical efforts from the patient's side and give possibility to surmount various configurations of the living and working space (e.g. gait on staircases).

Consequently, it follows that as the first technical factor of qualitative character must be adopted the <u>factor or degree of anthropomorphicity</u>. Directly to that can be connected the factors of <u>fatigue, reliability, dimensions (bulkiness), weight, energetic and control autonomy</u>, i.e. the degree of the same, then autonomy of using the device (degree of autonomous "dressing" or "undressing" the exoskeleton), <u>complexity of the control mechanism, degree of dynamic system stability</u>, degree of unification of exoskeleton construction (by means of assembling standard modules), and, finally, <u>price of system in function of the production series</u>.

As can be concluded, with rehabilitation robots one cannot speak about some more fixed exclusively technical criteria. The human factor is included here to such a degree that the technical parameters alone have little influence on the final judgement of the system.

The case is somewhat different when criteria of other type robots and manipulators are concerned. All devices of these types present practically without exception purely technical categories, and as such can be treated by technical criteria when evaluated.

Each class of robots, notably industrial type manipulators, have their specificities. Let now some types of robots be enumerated and the specific demands discussed, imposed by the same.

Rough division of these robots could be as follows:

- robots for underwater explorations;
- robots for unexplored environments, e.g. other planets;
- robots for activity under irregular terrestrial conditions;
- industrial robots of non-anthropomorphic type;
- industrial robots of anthropomorphic type.

Without entering closer into the differences, i.e. their specificities, let some common properties of the same be displayed, present to a more or less expressed degree in concordance with the demanded performances. These same properties influence implicitely or explicitely on forming the criteria for the evaluation of a rather broad class of robots and manipulators.

Consecution of the discussed properties will not mean their rating in the criterion for evaluation of the performances of robots and manipulators.

As one of the interesting properties could be underlied the degree or factor of intelligence. Here it is intended to define the artificial intellect as a set of algorithms, oriented towards performing some definite control task. It is evident that the intelligence factor is directly dependent on the size of this set, which means there exists no mystification in that notion. The robot is made capable to immitate certain situations, memorized in the simulator, or being calculated in real time by means of a processor in the scope of the control system. The algorithmic level is connected to a set of various type sensors, from tactile and distancemeters, to force and pressure transducers. The algorithmic complex incorporates the supplied information about the environment by means of the sensors and the processor into the outputs (control signals), defining the new state vector of the system (robot). According to our opinion, this would be a sufficiently broad definition of intelligent robots from the technical aspect.

Examples of intelligent robots in the broader sense are rather few. As one of such examples can be mentioned the six-legged walking machine (Fig. 4). It possesses multi-level control, starting from the level of optimal trajectory choice, as the highest one, to the level controlling placing of the feet to form a stable configuration of the supporting polygon, as the lowest one. The robot inspects the environment, chooses favourable passes, adapts itself to local obstacles on the chosen path and realizes a stable configuration of the supporting polygon. The machine is equipped with video-sensors, tactile sensors and distancemeters. The processor gets the necessary information and takes decisions about the further motion strategy.

The next property is directly connected to the first one, and is the adaptability of the robot. Adaptability of the system can be defined in the broadest sense as capability of choosing algorithms for surmounting new situations, conditions and working regimes. Consequently it is evident that adaptability is a necessary condition for the existence of artificial intelligence and that the A.I., with respect to its possibilities, is directly proportional to the broadness of the adaptability. Beside the examples as represented by the six-legged machine, possessing a separate adaptation level for solving the task of passing over obstacles of various forms in the scope of its geometric dimensions and kinematic constraints, the property of adaptation can be connected to some other robotic activities, too, as for instance the process of pattern recognition.

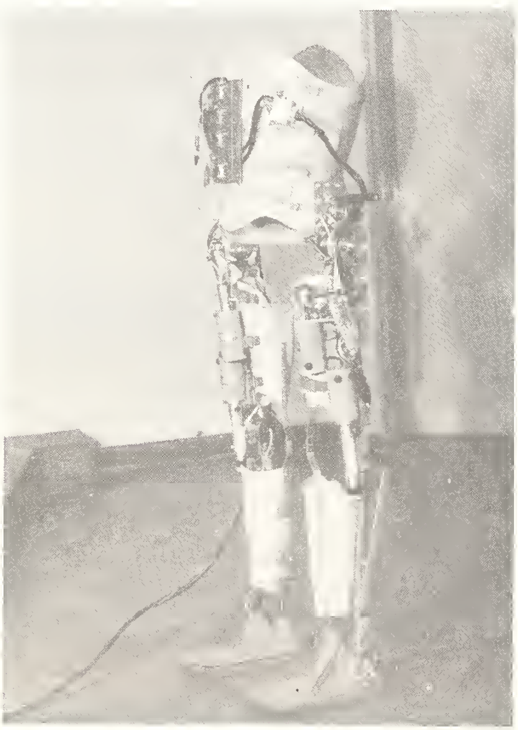


Fig.3 Active exoskeleton

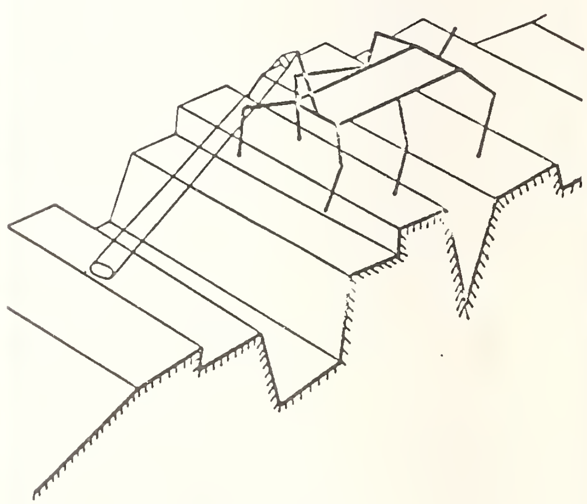


Fig.4 Six-legged machine

Pattern recognition is today a largely developed scientific category, connected to the theory and robot application in the broader sense. In this occasion we would like to stress one dilemma concerning pattern recognition. This activity, evidently initially developed with the goal of military objects (predominantly flying) recognition, was transferred to some other cases. Thus in essence industrial manipulation was started with the development of pattern recognition algorithms. There appeared even some works connected with rehabilitation manipulation, where it could be easily proven that such investigations have practically no sense. Not too great a technical sense have also investigations of pattern recognition for industrial manipulators. What would be profitable is if information about the pattern, or form, by means of algorithms for pattern recognition, when every such machine is equipped with a TV camera, were used for other purposes in the process of industrial manipulation. There exists something else, which should be developed as well in rehabilitation robotics, and in industrial use, and that is the adaptive algorithms in the range of one class of objects or holes. That means for some noted object one must dispose, on the basis of distance-meters and tactile sensors, along with the information about the forces between the gripper (hand) and the object, also with algorithms capable to perform in the scope of one characteristic class of objects (balls, cones, prisms, pyramids, openings of various depths and forms) the necessary scalings with respect to geometry, distribution of tactile sensors, values of forces in the contact points, the needed adaptation to changed parameters of some object in consideration, which cannot be distinguished precisely by the more rough video sensors. That means one handles here some "micro-recognition" of objects or forms, in the general case for a certain class of the same, leading to full adaptation in the scope of a certain tolerance in geometry and the control forces. Such property of adaptation can find its full justification in in strial manipulation, as well as manipulation in the rehabilitation field.

The next property which could be included into the criterion could be denominated the minimum of the control system. It is a very delicate question to discuss this robot property as control process. Namely, it is known that certain robot properties in the broader sense depend on mobility, dimensions, capability, even the price of the control mechanism, the central part of which is represented by a processor in conventional cases. First steps in this direction have been made during the last years. They reflected in passing over from general type computers to specialized processors, made capable to perform some particular type of control task. However, this is not enough to carry out on-line calculation of new dynamic states, even at the present high level of technology development. As proof of this statement can be cited the example of exoskeleton type anthropomorphic robot, dedicated to restoring basic locomotor acts of handicapped persons. The fact is known that a robot of this type is an inherently unstable configuration and that during gait the problem of dynamic equilibrium must be solved continuously. Let for a moment be imagined that in real time the solution of a system should be found, the same system consisting of differential nonlinear equation with variable coefficients. Regardless of the adopted computer language, the time for solving such a system is few seconds. It follows that every pertubation (let it be large) would demand the mentioned time interval. This interval can be shortened by means of special organizations of calculations on the hierarchical principle, which on its side leads to a technical absurdity if it is known what is the final use foreseen for that robot. In the same time the question can be posed, if the biped robot can "wait" so long in some unstable pose for the processor to give the new solution? Comment is not necessary here.

To surpass such or some similar situation it was arrived at the idea to prepare a solution, or nominal working regimes, for a set of initial conditions or characteristic control parameters. Thus it has been arrived to the possibility, by memorizing off-line calculated trajectories, to synthesize a simulator of the robot operation in a certain range of characteristic control parameters. Such a control concept has been realized for the first time in the case of biped gait control via the exoskeleton (Fig. 3). Unacceptable duration of the calculation time intervals via some processor is in this case reduced to time intervals smaller by a whole magnitude of order. In the concrete case the time for choosing some new control parameters lies in the limits of 0.1 - 0.2 sec., which is essential, if it is known that the half-period of an artificial gait step is approx. 1 sec. In order to clear this up thoroughly, the time interval of 0.1 - 0.2 sec. in fact represents the time needed for the choice of some corresponding set of memorized trajectories, at the basis of the measured state vector due to perturbations, together with the reaction time of the system actuators. In some other types of robots, where the time of information processing is not so critical, as in the preceding case, some half-way version of control can be adopted. Namely, the simulator, or programmer of the nominal (stationary) working regimes, could be broadened by some supplementary operative memory, capable to perform in some limited scope calculations of the model, by which a certain flexibility of the control system would be obtained.

The next important property of the robot influencing the evaluation of its capability could be nominated structural kinematic adaptivity. This property is directly expressed via the possibility, for instance when multi-legged walking machines are concerned, to modify the length of the "legs" according to the terrain configuration. Such adaptivity would also reflect in the variation of some other parameters, as for instance, step length (stride), vehicle track and velocity, introducing supplementary (emergency) supports in critical situations of the terrain, and sim. (Fig. 4). As direct consequence of this property, there appears a feature which could be called multifunctionality of robot. It designates here capability of the robot to perform several types of activity. So for instance a vehicle-robot with special wheels or legs, if equipped with manipulators, has evidently greater possibilities. Such a vehicle is not only used for reconnaissance, but can perform also some other actions, as for instance detecting artificially impaired advancing (in military applications), or taking samples of the soil (if unexplored environments are in question). A robot of that type can have special manipulators - cutters, enabling to clear up trespassing of very dense vegetation. Manipulators on flanks could load some cargo on the robot - transporter. Imagination of such a complex multi-functional robot is given in Fig. 5. Such multi-functionality could be achieved with industrial robots, too, in the case of manipulators, where they would be equipped with various types of terminal devices in order to be capable to perform more complex manipulation tasks in some sequence and without delay. Multifunctionality can be noted with underwater robots, too, where exploration of the sea bed is performed in combined actions of a vehicle and manipulator (Fig. 6).

Goal of this discussion has been to prove, at least as opinion of this author, to what extent the question of performance evaluation of robots and manipulators presents a delicate matter. I am convinced that only some functionally simpler robot types can be treated more precisely, with which their performance can be clearly identified and some correlation established between the same and the factors on the basis of which this performance is being evaluated. Only in these cases there can be attained some quantification of the evaluation criterion. In the other, more complex cases, when still new unique realizations are in question, both of industrial and rehabilitation robots, as already seen only some functional relations can be established between the performances in the broader sense and some properties having larger meaning. Hence such criteria, if they can be called that way at all, have only a qualitative character.

However, it is clear that discussion regarding this matter display much sense, and they should be observed as actions, intended to create some order in some questions of robotics, which evidently is in full growth.

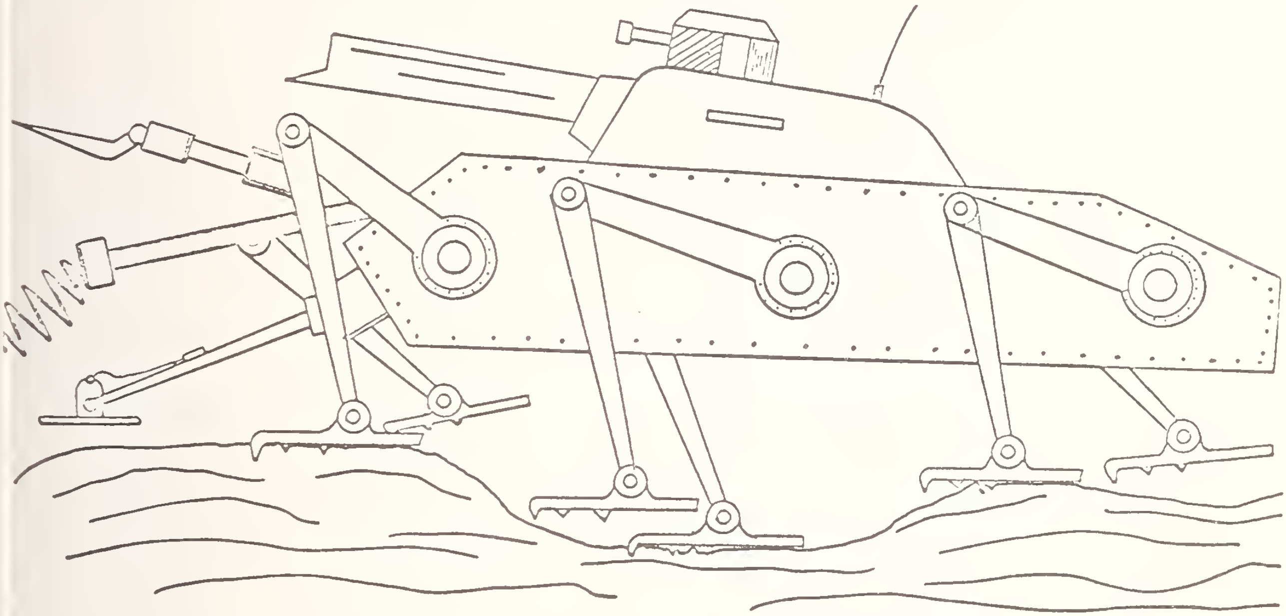


Fig.5 Legged vehicle with multiple manipulators

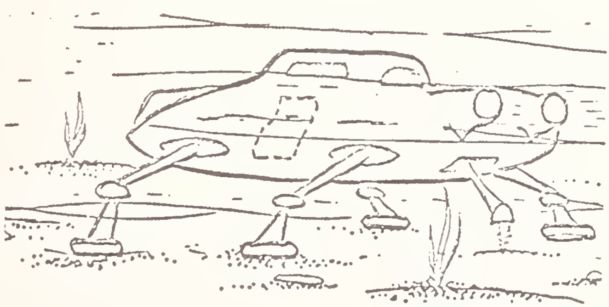


Fig.6 Legged vehicle for underwater explorations

APPENDIX 1

ADDRESS LIST OF WORKSHOP PARTICIPANTS

Dr. James Albus
Inst. for Computer Sciences
National Bureau of Standards
Washington, DC 20234

Dr. Anthony Barberra
Inst. for Computer Sciences
National Bureau of Standards
Washington, DC 20234

Dr. Antal Bejczy
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91103

Mr. Alan Case
Bldg. 37
General Electric Co.
Schenectady, NY 12345

Mr. Joseph F. Engelberger, President
Unimation, Inc.
Shelter Rock Lane
Danbury, CT 06810

Dr. John Evans, Jr.
Inst. for Computer Sciences
National Bureau of Standards
Washington, DC 20234

Dr. Jack G. Grundmann
Experimental Equipment Engr.
Oak Ridge Nat. Laboratory
Oak Ridge, Tenn. 37830

Mr. William Hamel
Oak Ridge Nat. Laboratory
Oak Ridge, Tenn. 37830

Mr. Dennis W. Hanify, Manager
ITT Research Institute,
Mechanical Systems Dept.
10 West 35th St.,
Chicago, Illinois 60616

Mr.Richard E. Hohn
Manager Industrial Automation R & D
Cincinnati Millacron Co.
Cincinnati, Ohio 45209

Dr. Demetrius G. Jelatis
Vice President and Director of Research
Central Research Laboratories
Red Wing, Minnesota 55066

Mr. Paul M. Lynch
C.S. Draper Laboratory
77 Cambridge Pkwy.
Cambridge, MA 02139

Mr. Gerald Malecki
Office of Naval Research
1800 North Quincy St.,
Arlington, VA 22217

Mr. Douglas A. Morlock
Control Systems Support Branch
Technical Support Directorate
US Army Picatinny Arsenal
Dover, NJ 07801

Dr. Richard L. Paul
Artificial Intelligence Center
Stanford Research Institute
Menlo Park, CA 94025

Mr. Alan J. Pesch, President
Eclectech Associates
PO Box 178
N. Stonington, Conn. 06359

Professor Bernard Roth
Mechanical Engineering Department
Stanford University
Stanford, CA 94305

Dr. Andreas V. Rechnitzer
Office of the Oceanographer of the Navy
Hoffman Bldg.
200 Stovall St.,
Alexandria, VA 22332

Mr. Bernard M. Sallot
Executive Director
Robot Institute of America
20501 Ford Road
Dearborn, Michigan 48128

Dr. Thomas B. Sheridan
32 Sewall St.,
West Newton, MA 02165

Mr. Nicholas L. Shields, Jr.
Essex Corporation
201 N. Fairfax St.,
Alexandria, VA 22314

Mr. William Verplank
Room:3-351, MIT
Cambridge, MA 02139

Dr. Jean Vertut
Commissariat de l'Energie Atomique
Department de Protection
Boite Postale 2
91190 Gif-sur-Yvette, FRANCE

Mr. Charles D. Wicker
Oak Ridge Operations Service
Holi Field
Oak Ridge, Tenn. 37830

ADDITIONAL CONTRIBUTORS

Prof. Y. Hasegawa
Waseda University
Tokyo 160 JAPAN
with I. Masaki
Kawasabi Heavy Industries, Ltd.
and M. Iwasawa
Oki Electric Industry Co., Ltd.

Prof. A.E. Kobrinski
Academy of Sciences of the USSR
ul Griboedova 4
Moscow Center 10100 USSR

Prof. M.S. Konstantinov
Head of the Central Laboratory for Manipulators and Robots
19 February St.,
Sophia C BULGARIA

Dr. M. Vukobratovic
Institut Mihailo Pupin
PO Box 906
Beograd YUGOSLAVIA

APPENDIX 2

WORKSHOP PROGRAM

Thursday, October 23

4:30 Registration
5:00 Reception
6:00 Dinner
8:00 Goals of the workshop, overview (Sheridan, Evans)
Summary Remarks: manipulator design and evaluation
- Jelatis
- Roth
- Vertut

Discussion

Friday, October 24

8:30 Summary remarks: industrial automation (first session)
- Engelberger
- Paul
- Case
- Lynch

10:00 Coffee
10:30 Summary Remarks: space and undersea applications
- Bejczy
- Shields
- Malecki
- Rechnitzer
- Pesch

Discussion
12:15 Luncheon
1:30 Summary Remarks: nuclear applications
- Grundmann
- Hamel
- Verplank
- Wicker

Discussion
3:30 Small group sessions

Saturday, October 25

8:30 Summary Remarks: industrial automation (second session)
- Sallot
- Hohn
- Morelock
- Albus
- Barbera

10:00 Coffee
10:30 Reports of small groups and plenary discussion
12:00 Luncheon
1:00 Concluding discussion
3:00 Adjourn

APPENDIX 3.

PROCUREMENT SPECIFICATION No. XSP-239

Oak Ridge National Laboratory
Operated by
Union Carbide Corporation, Nuclear Division

Date 5-20-66

MASTER-SLAVE MANIPULATOR -- STANDARD DUTY

1. SCOPE

1.1 This specification covers normal and extended reach Model-8 standard-duty master-slave manipulators for remote handling of materials in radioactive hot cells and caves.

1.2 Type, principal dimensions, and special requirements shall be as specified in the attached Manipulator Data Sheet.

2. PERFORMANCE REQUIREMENTS

2.1 Tong Capacity - 20 pounds minimum in all positions and motions (except 18 pounds minimum in twist) at all points within the operating volume and at extreme Y position. Tong squeeze, 20 pounds minimum.

2.2 Operating Volume - As specified in Data Sheet.

2.3 Electrically Driven Indexing Speeds - Carrying the rated load specified in paragraph 2.1, indexing speed shall be infinitely variable or step variable in at least four steps. from zero to:

X motion:	3 1/2 degrees per second
Y motion:	10 degrees per second
Z motion:	2 inches per second

2.4 Balance and Friction

a. X Motion: With manipulator mounted on rollers and boom fully extended, the force required to move the manipulator at a constant slow speed shall not exceed 2 ounces, measured at the differential wrist joint with the manipulator near its rest position.

b. Y Motion: With boom fully extended, the force required to move the manipulator at a constant slow speed shall not exceed 2 ounces, measured at the differential wrist joint with the manipulator near its rest position.

c. Z Motion: The force required to raise or lower the boom at a constant slow speed shall not exceed 12 ounces. The difference in force to raise and lower the boom shall not exceed 3 ounces.

d. Elevation Rotation: The torque required to raise or lower the hand and tong shall not exceed 18 inch-ounces, measured about the differential gear axis, excluding the torque created by the weight of the handle and tong.

e. Twist Rotation: The torque required to twist the handle and tong shall not exceed 18 inch-ounces.

f. Azimuth Rotation: The torque required to rotate the manipulator in azimuth shall not exceed 21 inch-ounces.

g. Balance: With master and slave arms parallel, the counterweights shall be adjusted so that, for all positions of the Z motion, the manipulator will either retain any angular position (in both the X and Y planes) up to 30 degrees, or return to vertical (within $\pm$ 10 degrees) in no less than 5 seconds.

2.5 Rigidity and Lost Motion - With booms fully extended, extension of extended reach fully retracted, and tong anchored to prevent motion in any direction:

a. Maximum deflection with 20 inch-pounds torque applied to hand about the longitudinal axis of the boom for azimuth and about the differential gear center for elevation and twist:

Azimuth:	2 degrees
Elevation:	3 1/2 degrees
Twist:	3 3/4 degrees

b. Maximum deflection with 20 pounds force applied perpendicularly to the boom axis at a point 90 inches from the shoulder pivot:

X motion:	2 1/2 inches
Y motion:	3 1/2 inches
Z motion:	1/8 inch

2.6 System Slack and Operating Smoothness - With the tong carrying a 400 ml beaker filled with water within one mm of the top, a competent operator shall control the tong to describe an approximately square pattern, 2 feet on a side, in an approximately horizontal plane, starting from rest and accelerating to approximately the full speed specified in paragraph 2.3 on each side of the pattern, without spilling more than 10 ml, as determined by weighing the flask before and after the test. If electrically driven indexing is specified in the Data Sheet, the test shall be repeated with electrically driven indexing.

2.7 Hand Rigidity - With a block installed in the track to limit ratchet motion so that the finger tubes are restrained in an approximately parallel position, and with one finger tube rigidly anchored, a 10-pound load applied perpendicularly to the other finger tube shall produce a maximum deflection of 7/32 inch; a 24-pound load shall produce a maximum deflection of 5/16 inch; as measured by the distance between the finger tubes.

3. EQUIPMENT REQUIREMENTS

3.1 Power Supply - A multistep or infinitely variable speed-control rheostat and extension cord for operation from a 110-V, 30-amp A.C. receptacle shall be provided. Cap shall be NEMA Type 5-15P in accordance with NEMA Standard WD1-1965.

3.2 Hand

a. Ambidextrous, ratchet locking with ratchet release and lock-out, with totally enclosed wrist joint, pistol grip handle, and closed finger tubes. When electrically driven indexing is specified a finger controlled trigger switch, operable without removing the operator's hand from the handle, shall be provided for indexing speed control. Grip sensation shall be proportional to tong squeeze.

b. Indexing selector switch shall be mounted on the rear of the boom no more than 8 inches above the wrist. Selector switch shall have off position and one position for each electrically driven motion, with indicator light(s) to show which motion is in operation.

c. Hand shall be wired to connections within the boom by means of a male and female electrical connector with locking nut, one member of which shall be rigidly attached to the boom at a point no more than 4 inches above the wrist.

3.3 Tong - Remotely removable Argonne Laboratories RDC type with non-replaceable fingers. Coiled tension springs are preferred for finger opening; maximum expansion of coil spring shall be 1/20 of the relaxed spring length. If torsion springs are used, maximum rotation shall be 20 degrees. Tong castings shall be Almag 35 or ASTM B108, Grade GM-70b. Springs, pivots, and side links shall be stainless steel.

3.4 Cable Tension - Azimuth cables shall have spring-loaded dash-pot tension devices mounted between the cables and the adjusting turnbuckles. Azimuth cables shall be adjusted to 8 pounds tension, ± 1/4 pound, before making performance tests. Cables shall be stainless steel aircraft type cable. All cable adjustments shall be on the master boom.

3.5 Tapes shall have no visible slack when prestressed to operating tension. Twist and elevation tape tension shall be 12 pounds ± 1/4 pound for performance tests. Tapes shall be 3/16 inch × 5 mil Elgiloy or CRL Flexendur. All tape adjustments shall be on the master boom. Tape pulleys shall be crowned to minimize tape and pulley wear.

3.6 Booting - Construction shall permit booting of the slave end; boots will be furnished and installed by the Company at the installation site.

3.7 Locks - When motion locks are specified in the Data Sheet, a minimum number of locking clamps to provide the locking actions specified shall be furnished. All locking clamps shall be located on or adjacent to the master boom within 8 inches from the bottom of the non-telescoping portion of the boom. Clamps shall lock the specified motions with tongs unloaded and with tongs carrying the full load specified in paragraph 2.1.

3.8 Gears and Pulleys - Master and slave wrist drums and gears shall be stainless steel. Other gears and pulleys shall be chromium plated carbon steel or stainless steel. Master arm boom tube rollers shall be nylon.

4. TEST AND ACCEPTANCE

4.1 With his bid, Seller shall furnish three copies of:

a. A certified test report showing performance characteristics of a manipulator of the same type, showing values for all performance requirements specified in paragraphs 2.1, 2.3, 2.4, 2.5, 2.6, and 2.7.

b. A schedule and procedures for testing to confirm compliance of the completed manipulator with the requirements of Section 2, including a description of measuring devices, including sensitivity, to be used for acceptance tests.

4.2 Seller shall assemble, adjust, and test the manipulator prior to shipment and shall notify the Company at least 10 working days before the start of test to permit witnessing should the Company elect to witness the tests. The Company may elect to accept a certified test report in lieu of witness tests. In any event, the Seller shall submit a certified test report for Company approval; test report must be approved by the Company prior to shipment.

4.3 Final acceptance shall be at the installation site at Oak Ridge, Tennessee, following inspection, installation, and operational testing in accordance with the procedures furnished by the Seller.

5. MANUFACTURER'S DATA

5.1 Seller shall furnish manufacturer's data, test procedures, and test reports as specified in attached Company form UCN-3296.

MANUFACTURER'S DATA REQUIREMENTS OAK RIDGE NATIONAL LABORATORY OPERATED BY UNION CARBIDE CORPORATION NUCLEAR DIVISION POST OFFICE BOX X OAK RIDGE, TENNESSEE 37831	
	WORK REQUEST
	SPEC. NUMBER XSP-239
	REQ. NUMBER
	P. O. NUMBER

ITEM:

MASTER SLAVE MANIPULATOR

	Three Copies, With Bid	Three Copies for Company Approval Before Fabrication	Copies With Order, As Noted; One Copy to be Packed With Equipment	REMARKS
Assembly drawings	3		2	
Electrical and control schematics			2	
Electrical wiring diagrams			2	
Parts list, including recommendations for spare parts to be stocked.			2	Each part shall be described and identified to permit procurement from the original manufacturer.
Operating and service manual			2	
Outline dimension sketches	3			
Operating characteristics and test report	3			
Schedule of materials	3			
Test procedures and schedule of tests	3			Approved by Company prior to shipment.
Acceptance test report		3		
Dimensional sketch showing coverage of slave arm	3			

MANIPULATOR DATA SHEET

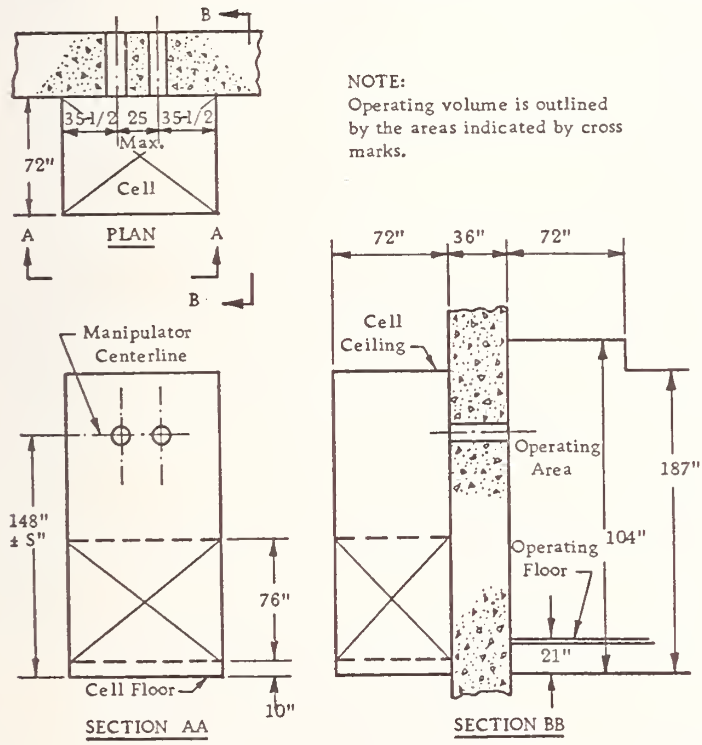
Requisition No.________

Requisition Date________

Requisitioner ________

MODEL 8 MASTER-SLAVE MANIPULATOR - STANDARD DUTY XSP-239

Installation Dimensions	Mounting wall Thickness 36 in.	Mounting Sleeve diameter, 10 in. ± 1/16 in.	Barrel Pivot to Pivot Length 78 in.
	Height of through-tube axis above operating floor 127 ± 5 in.	Height of through-tube axis above cell floor 148 ± 5 in.	
	Overhang Operating Side 24 in.	Overhang Cell Side 18 in.	Shielding: Lead Equivalent 6 in. Max. Open Area 8 %
	Maximum vertical projection of counterweight above master pivot 21 in.		



Operating Volume

One or the other equal reach tongs shall be operable in any position or motion at all points within the operating volume (see sketch)

MSL - Minimum Slave arm length	See Sketch
X	See Sketch
Y	See Sketch
Z	See Sketch

Other dimensional requirements

Separation See Sketch

Special Features	Extended Reach ☑ Mounting:* Roller Tube ☐; Universal Roller Mount ☐ Electrically Driven Indexing: X ☑; Y ☑; Z ☑; Lateral Rotation ☐ Motion Locks: X ☑; Y ☑; Z ☑; Twist ☑; Azimuth ☑; Elev ☑ Squeeze ☑ Tong replacement jig required ☑; Hood adapter and fixture required ☐
Other Requirements	* Roller Track Mounts

APPENDIX 4.

Japanese Industrial Robot Association Standardization Plan for Industrial Robots

reprinted from Industrial Robot, Intl. Fluidics Services Ltd., Carlton, Bedford, MK 43 7JS England, March , 1975 (with permission)

A Standardisation Plan for IRs

Editorial Note:

It was thought that the Japanese draft proposals for standardisation would be of interest to readers. The more that common terminology and standards are discussed and adopted the more likely will it be that Industrial Robots will spread their influences. Some dialogue is therefore necessary and it is hoped that the following proposals will provike comment from readers. Any comments should be sent to:

Mr. Kanji Yonemoto
Executive Director J.I.R.A.
Kikaishinko Building
3-5-8 Shibakoen
Minato-ku
TOKYO
Japan

1. Reason for and Purpose of the Study

The shortage of labor, a sharp increase in wages, the need for improvement in work place environments and human welfare in Today's industrial world have drastically enhanced the need for labor saving by safe automated systems. Therefore the rapid development of industrial robots where research and development and the development of the technologies necessary to utilize them can lead to rapid progress in application.

The rapid growth and increasing importance of industrial robots as mentioned above deserves special attention being paid to their standardization thus forming a basis on which the need for such studies can be explained:-

1) As it will be almost impossible to standardize them after they will have been widely applied, and if such standardization will be forcibly imposed then, the growth of the industrial robot manufacturing industry as well as Japan's industrial structures could be seriously affected.
2) The standardization of industrial robots will lead to a more applicable operation of such robots and contribute to the safety of workers.
3) Such standardization will reduce maintenance costs of industrial robots and improve their maintenance.
4) Such standardization will improve and stabilize the quality and performance of industrial robots and reduce production costs.
5) Such standardization will enable the industrial robot manufacturing industry to establish a firm basis for specialized production of parts and complete systems.
6) Such standardization will enable industry to allocate its targets for technological development, leading to further technological progress.
7) The standardization of industrial robots will enable Japan's industries to orient themselves toward labor saving. Therefore, such standardization should be examined on a national basis.

In view of such a need for standardization, this study will aim to improve and stabilizing the quality and performance of industrial robots, reducing production costs, establishing systems for specialized production, improving their maintenance, as well as achieving labor safety and advanced technological development. By doing so, the study is intended to contribute widely to labor saving, by automation and promote safety in the industrial world.

2. Period for the Study

From April 1974 to March 1977 (to be conducted for three consecutive years from fiscal 1974).

3. Contents of the Study

During Fiscal 1974:

(a) Study on standardization of fundamental terminology and figure signs or symbols.
   (a)-1 Extraction of fundamental terminology concerning hardware, functions, and systems, their systematization and definition.
   (a)-2 Extraction of figure signs and their systematization.

(b) Study on various actual functions and analysis of fields and ranges of actual utilization.
   (b)-1 Study on actual working functions such as moving functions, holding functions, locomotive functions, etc. as well as control functions such as moving control functions, learning functions, information exchanging functions, sensing functions, etc.
   (b)-2 Analysis of fields and ranges of actual utilization.

(c) Study on applied technologies
The study will be conducted so as to understand the optimum relationships for the function of robots and to be carried out (to find optimal conditions for cost performance) by selecting four working processes such as cutting, punching, etc.

During Fiscal 1975:

(a) Complementary study on fundamental terminology and symbols for industrial robots and a study on related terminology
- (a)-1 Complementing fundamental terminology and extraction, definition and systematization of related terminology.
- (a)-2 Working out a draft for unifying figure signs or symbols.
- (a)-3 Study on and extraction of letter signs.

(b) Study on standardization of functions
- (b)-1 Complementary study on various actual functions and complementary analysis of fields and ranges of actual utilization.
- (b)-2 Study on standardization of testing methods
- (b)-3 Classification of functions and study on indicating methods.
- (b)-4 Study on methods for indication functions, and study for standardization of functional and electrical couplings, interchangeable adaptors for interchargable wrists, and elements consisting of robots.
- (b)-5 Studies on electrical signal systems and standardization thereof between robots and control devices, robots and machines, and robots and work.

(c) Study on applied technologies
- (c)-1 Study will be conducted for grasping optimum relations between the functions of robots and matters to be handled (to find optimum conditions for cost performance) by selecting five to six working processes which were not selected in the study during fiscal 1974.
- (c)-2 Study on standardization of safety measures
- (c)-3 Study for standardization of minimum necessary functions of robots in accordance with their working environments (for heat resistance, dust prevention, etc).

During Fiscal 1976:

(a) Study on robot modules

(b) Overall coordination of study results conducted in the first and second years

4. Organization to Conduct the Study
Japan Industrial Robot Association

5. Structures of Study Committees

In order to conduct this study, the following general committee and four specialized committees will be established:

(1) General Committee for Study on Standardization (Main Committee) (30 members)
2) Specialized Committee on Study (20 members)
3) Committee for Study on Standardization of Terminology and Signs (20 members)
4) Committee for Study on Functions (20 members)
5) Committee for Study on Applied Technologies (20 members)

6. Budget for Study

Fiscal 1974:	¥15, 000, 000.	£ 21, 000	
" 1975:	20, 000, 000.	£ 28, 000	
" 1976:	15, 000, 000.	£ 21, 000	£70, 000
Total:	¥50, 000, 000		

Terminology and definitions for Industrial Robots.

1. Terminology for classification of industrial robots.

(Classified by sequential information)

(1)	manual manipulator:	See later.
(2)	single purpose :	Manipulator the constitution of which fixes its function. It cannot be modified into another robot by a supplementary control unit.
(3)	repeatable robot :	Manipulator which repeats its function in compliance with the pre-memorized program.
(3)-1	single programmed : repeatable robot	fixed program is defined as a program of working cycles that cannot easily be modified (example: the robot programmed with a cam or relay circuit) variable program 1 = program of the working cycle can be changed easily, and the working sequence depends on its program. (example: the robot programmed with pin-board, tape or cards). variable program 2 = program of the working cycle can be changed easily, and it has facility for branch functions in its cycle. (example: the robot programmed with programmable logic controller)
(3)-2	multi-programmed : repeatable robot	one that has more than two working cycles and the command program can select an optional cycle. (example: the robot programmed with 9 mini-computer or programmable logic controller)
(4)	intelligent robot :	Robot which can decide its behavior by itself through its sensing and recognizing capabilities.

manipulator : "Manipulator" has a function similar to that of human upper limbs and has itself more than two of the motion capabilities such as revolution, out-in, up-down, right-left travelling, swinging or bending, so that it can spatially transport an object by holding, adhering to, and so on.

<u>(Classified by input information and teaching)</u>

(1) manual manipulator: Manipulator which is directly operated by man.

(2) sequence robot : Manipulator the working step of which operates sequencially in compliance with the preset procedure, conditions and positions.

(2)-1 fixed sequence robot : Sequence robot as defined above, the preset information of which cannot be easily changed.

(2)-2 variable sequence robot : Sequence robot as defined above, the preset information of which can be easily changed.

(3) playback robot : At first, man teaches the manipulator the working procedure through operating it, so that the robot itself memorizes the procedure, then it can continuously repeat its operation.

(4) N.C. robot : Manipulator which can execute the commanded operation in compliance with numerically loaded working information about position.

(5) intelligent robot : see previous page.

<u>(Classified by motion form)</u>

(1) Cylindrical coordinates robot : Manipulator whose arm's operate in a universe defined by cylindrical coordinates.

(2) polar coordinates robot : Manipulator whose arm's operate in a universe defined by polar coordinate system.

(3) Cartesian coordinates robot : Manipulator whose arm's operate in a working universe defined by orthogonal coordinates.

(4) prosthetic robot : Manipulator which has an articulated arm.

(5) robots with other coordinates types : Manipulator whose arm's operate in a universe defined by other sets of coordinates.

<u>(Classified by degrees of freedom)</u>

(1) robot with one degree of freedom : Manipulator which has the functional degree of freedom of 1. (note: open-shut of the hand and on-off of the vacuum cap are defined as one degree of freedom)

(2) robot with two degrees of freedom : Manipulator which has the functional degree of freedom of 2.

(3) robot with n degrees of freedom : Manipulator which has the functional degree of freedom of n.

<u>(Classified by operating space and holding weight)</u>

(1) giant robot : Robot which can transport more than 1000 kg.

(2) large scale robot : Robot which can transport 100 to 1000 kg, or the volume of whose working space is more than 10 m.

(3) medium scale robot : Robot which can transport 10 to 100 kg, or the volume of whose working space is 1 to 10 m.

(4) small scale robot : Robot which can transport 0.1 to 1 kg, or the volume of whose working space is 0.1 to 1 m.

(5) micro(mini) robot : Robot which can handle less than 0.1 kg, or the volume of whose working space is less than 0.1 m.

II. Fundamental terminology for the function of an industrial robot

working function : Functions in the working operation of robot.

moving function : Functions in spatial motion such as of arm or wrist.

holding function : Functions in grasping and holding actions of fingers

locomotive function : Functions of pedestals or wheels which enable the robot to travel.

arm : Its purpose is to move the hand which holds the object.

unprosthetic arm : Arm which has no articulation. (example: arm which has only linear motion eg. a hydraulic in/out actuator.

prosthetic arm : Arm which has articulations.

wrist : It locates at the tip of arm and its function is to hold the hand.

hand : Both fingers and thenar.

finger : It is a part of the hand,

and its function is to grasp and hold the work. (As some work needs to be held by other means than grasping, the form of the finger should be clearly described).

control function	: Functions in the control of robot.
moving control function	: Functions which control the working operation of robot to be effective.
playback	: To read the recorded information according to the demand, so as to transmit certain commands to the actuator.
motion control	: Control functions mainly in the mechanical field.
sequencial mode control	: Functions in the control of the operation sequence.
teaching	Recording of the information by man which is required to operate the robot.
teaching function	: Functions in teaching the working program.
teaching methods	: Methods of information handling at the time of teaching.
direct teaching	: To teach the working information to the machine by directly operating the robot.
indirect teaching method	: To teach by inputting the working information in the form of numerals or language.
operation method for teaching	: Methods in teaching operation.
lumped teaching method	: To teach the whole information at each working step in one lot.
separated teaching method	: To teach each information such as positions, sequence or speeds separately.
memory	: To retain the taught information for a required period.
memory storing method	: Methods in the storage of taught text.
lumped memory storing method	: To store the whole information in one memory device.
separated memory storing method	: To store the information separately in more than two memory devices.
position memory	: To memorize the positions to stop or change actions of each axis. (example: potentiometer method)
sequencial mode memory	: To memorize the operational step sequence of each axis. (example: pin-board method)
measuring and recognizing capability	: Functions* in the measurement and the recognition of the robot.
measuring capability	: Measuring functions of robot.
internal measuring	: Functions in measuring the state of the robot itself.
external measuring	: Functions in measuring the conditions of the object.
recognizing capability	: Functions* in the recognition system of the robot.
shape recognition	: Functions* in the recognition of the shape of the object.
speech recognition	: Functions* in the recognition of speech.

*Functions (Capabilities)

III. Fundamental terminology on characteristics or capability of an industrial robot.

up-down turning of the arm	: Up-down turning of the arm in the vertical plane of robot.
up-down of the arm	: Up-down parallel movement of the arm in the vertical plane of robot.
in-out of the arm	: Movement along the longitudinal axis of the arm.
right-left turning of the arm (rotating of the arm)	Turning of the arm around the vertical axis.
right-left traverse of the arm	: Right-left parallel movement of the arm in the horizontal plane of robot actuation.
revolution of the	: Revolution of the arm around its longitudinal axis.
bending of the hand (swing of the hand)	: Swinging of the hand alone around the wrist.
revolution of the hand	: Revolutionary movement of the hand relative to the arm.
grip, clamp	: Open-and-shut function to hold the work.
operating space	: Volume space where the robot can operate.
operating distance	: Motion range of the movement in each degree of freedom.
operating angle	: Angle range of the movement in each degree of freedom.
travelling performance	: Travelling functions of the robot with its pedestals or wheels.
maximum speed	: The maximum velocity of the given part of robot under the given conditions. (example: no load maximum speed, rated load maximum speed-part and condition should be clearly described-).

positioning accuracy : Degree of agreement between the commanded position and the actual position. (example: -axis ±E/L -L is stroke-).

repeatability : Accuracy in reproducibility.

playback accuracy : Difference between teaching and play back positions.

degree of freedom : Measurement of the flexibility in the control or the operation. (note: the flexibility in the control is, for example, storage capacity of position, time and sequence)

freedom of motion : Number of linear movements, & revolutions

memory capacity.) storage capacity) : Amount of the loadable information.

number of setting points : Number of the settable points in each axis.

external synchronizing : Signal which is transferred between the robot and other machines so that the robot is to be synchronized with them.

interlock signai : To synchronize more than two signals so that while one operates the other is not to operate whenever any input is accessed.

holding weight, (pay load) : The maximum weight of the work which the robot can handle in its normal performance.

sub-program : Program which is to be repeatedly executed by the main program.

branch function : Function which yields more than two programs to be selected.

continuous path control : To control the robot by recording the operation path in a continuous format. (C.P. control)

point to point : To control the robot by recording the operation path in the form of the coordinates of finite positions. (P.T.P. control)

Figure signs, Symbols

First proposal for questionnaire on figure signs and symbols.

(I) One can roughly classify the figure signs and symbols relating to industrial robots as follows.

(1) The figure signs and symbols relating to industrial robots that are used in the flow-charts for manufacturing process.

(2) The figure signs and symbols relating to industrial robots that are used in the layout of manufacturing process.

(3) The figure signs and symbols showing the structure and the function of an industrial robot itself.

(4) The figure signs and symbols relating to peripheral equipments.

(II) The present questionnaire is connected to (I)-(1) and (I)-(2) among what were mentioned above, and the following is the proposal made by the committee on symbols. Please let us know your remarks on this proposal and if there are some figure signs or symbols relating to (I)-(1) or (I)-(2) which have been already used in your company, show us them also.

(III) Proposal made by the committee on symbols

(1) Figure signs for flow-chart.

(i) Figure signs of industrial robots entered in a flow-chart of manufacturing process.

1: Symbols of coordinate system of arm are entered. (In the case of prosthetic type its symbols (unfixed) are entered).

2: Mechanisms and functions required with this robot are entered. (Or only the symbol of the robot is entered).

3: Figure sign of driving source of arm (Fig.1-c) is entered.

4: Figure sign of driving source of wrist (Fig.1-c) is entered.

5: Figure sign of driving source of finger (Fig.1-c) is entered. (However, in the case where the driving source is common to all, only 3 is entered. If the driving source of the wrist is in common with that of the arm, 3 is entered as the representative of those two. Similarly, 4 is entered if the driving source of wrist is in common with that of the finger, and 3 is entered if the driving source of arm is in common with that of the finger).

6: In the case that there are several arms, arm signs as many as their number are entered.

7: This indicates a control system, where required functions are entered. (Or only the symbol of the control system is entered).

If the articles mentioned above are too many, or if entering of the articles is too complicated due to the size of the system, only the symbols of the robot and the control system are entered and the details are collected in an additional table. (See Ex.1-b)

(ii) Allied symbols

(a) Industrial robot IR

In the case that there are n robots in the flow-chart,

IR-1, IR-2, --- IR-n,

(b) Control system for robot

CONT. CONT-1, CONT-2, ---CONT-n

(c) Symbols relating to coordinate system

The coordinate systems of industrial robots' arm are fixed as in the following figures. The swing axis of a robot's arm is regarded to be the Z-axis. The origin 0 is fixed on the Z-axis.

The original line coincides with the neutral line of the arm.

Positive values for θ are measured clockwise toward the direction of positive Z. (Right-hand system)
Zo is the height of the origin from the datum surface of the robot.

Polar coordinate system whose origin is the swing axis of the arm and whose original line is the neutral line of the arm.
Zo is the height of the origin from set surface of the robot.

Polar coordinate system

In the case of an orthogonal coordinate system, a right-hand system whose origin is fixed on the robot is used and its X-axis is coincidal with the shaft line of the arm. Zo is the height of the origin from the datum surface of the robot.

	Symbol	Coordinates
Cylindrical coordinate system	C	r, θ, Z,
Polar coordinate system	P	r, θ, Q,
Orthogonal coordinate system	R	x, y, z,
(Prosthetic type)	unfixed	

Note. In the case of combinational type, the additional coordinate is suffixed by a small letter to the symbol of the main coordinate system.
Example: In the case where the Z-axis is added to the Polar coordinate system, Pz

(d) Symbols relating to degrees of freedom

Freedoms of arm motion	Freedoms of wrist motion	Freedoms of hand (finger) motion

F: + / + / +

Optional degrees of freedom are entered ( ).
Each number of freedoms is entered in
Example: F: 3 + (1) / 2 / 1

(e) Symbols relating to paths
CP: Continuous Path
PTP: Point-to-Point

Example for indication of (1)

Industrial robot — Cylindrical coordinate system — The range needed for the r axis is 700 2000.
The range needed for the θ axis is +120°~ -100°.
The range needed for the z axis is 0 100.
Zo is 700.
There is only one arm hydraulically driven.
The freedoms of the wrist are :- rotation and up-down (option).
It is hydraulically driven.
The fingers are driven pneumatically. On-off grip.
The path is Point-to-Point.

Example 1

Please write down in the following space the figure signs and symbols on
(1) already used in your company

(2) Figure signs for layout
These are the figure signs of robots used in a layout of manufacturing process, and the chief purpose is to show the whole range of motion of the robot finger.

(i) Cylindrical coordinates type

r_{max} : Length between the origin and the finger tip when the arm is fully extended.
r_{min} : Length between the origin and the finger tip when the arm is fully retracted.
+θ : The maximum swing angle of the arm in the positive direction.
-θ : The maximum swing angle of the arm in the negative direction.
+z : The highest position of the arm.
-z : The lowest position of the arm.
zo : Height of the origin from the set surface.
r_{bmax} : The most protruding position of the back end of the arm when the arm is fully retracted.

The range of motion is described with a full line.
The dangerous region is described with a broken line.

(ii) Polar coordinates type
r_{max}, r_{min}, +θ, -θ, r_{bmax} are defined in the same way as (i).
+ Q : The maximum value of Q in the positive direction.
- Q : The maximum value of Q in the negative direction.

(iii) Orthogonal coordinates type

Example for indication of (2)

r
0: ±120°
z: 0~500
Zo: 300
rb max: 600

Space for remarks

Please write down in the following space the figure signs on (2) already used in your company.

Name of company
Department for correspondence — Address; Name of Dep. tel.( )
Writer of this questionnaire — Name

MEASUREMENTS OF CHARACTERISTICS OF INDUSTRIAL ROBOTS

OBJECTS

(1) Robots with electric drives, 1 freedom(arm) 3 types

(2) Robots with pneumatic drives, 3 freedoms(arm), cylindrical coordinate, 2 types

(3) Robots with hydraulic drives, 3 freedoms(arm), cylindrical coordinate, 2 types

(4) Robots with hydraulic drives, 3 freedoms(arm), polar coordinate, 2 types

All the Industrial Robots described here are on the markets, and their type is point-to-point.

ITEMS OF MEASUREMENT

(1) Checking of dimension; Data of catalogues or technical reports are checked.

(2) Operating space;

(3) Operating time; Operating time of linear movements are measured. The results are shown in the Figure. In this measurement, the "stop action" is not clearly defined.

(4) Acceleration;

(5) Accuracy of positioning; In each case, measurements should be repeated until the randomness of data are confirmed. Parameters used here are as follows:
stroke: full, half quarter, etc.
load: full, half, zero, etc.

(6) Resolution; Factors described below are examined,
the minimum of setting distance in operating,
the minimum of inching distance available

(7) Drift; deviation distance in "stopped state".

(8) Overrun; The time intervals between "command" and "stop" in emergency stop-motion are measured.

(9) Holding ability in "rest state"; The travelling distance of arm when all parts of the Industrial Robot are in "rest state".

ITEMS OF PENDING (because measurements are too difficult or way of measurements are not decided yet)

(1) Operating time in non-linear movement cases;

(2) Warming up time;

(3) Exchangeability; exchangeable to another or not.

(4) Reliability against atmosphere;

(5) Convenience; Whether the Industrial Robots are well adopted for use.

(6) Noise;

(7) Durable year;

(8) The actions caused by electric power failure;

NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET**	1. PUBLICATION OR REPORT NO. NBS SP-459	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

Performance Evaluation of Programmable Robots and Manipulators - Report of a Workshop held at Annapolis, Maryland October 23-25, 1975

5. Publication Date: October 1976

6. Performing Organization Code

7. AUTHOR(S)

Edited by Thomas B. Sheridan

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

10. Project/Task/Work Unit No.: 6006111

11. Contract/Grant No.: 5-35922

12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*

Under Contract 5-35922 with
Office of Development Automation & Control Technology
Institute of Computer Science and Technology
National Bureau of Standards, Washington D. C. 20234

13. Type of Report & Period Covered: Final

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

Library of Congress Catalog Card No. 76-600057

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The Workshop brought together representatives of industry, academic institutions and government agencies, including the potential designers, suppliers and users of a new generation of manipulators and robots which include varying degrees of control by both people and computers. The Conference was motivated by the lack of common bases for comparing one such device with another in terms of performance, or one task with another in terms of how well a given device will perform it.

The Workshop concluded that there is a need for (1) common definitions of many terms which now are the source of pervasive confusion, (2) common test codes, (3) checklists, guidelines, and specifications to help users and suppliers better communicate with one another, and (4) common tests for demonstration and exhibition of new research and development in this field. Conference participants emphasized that once these needs were met to allow communication in the field, actual performance testing should be left to the user and supplier in the free marketplace.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Guidelines; industrial robots; manipulator; performance evaluation; programmable robots; and specifications.

18. AVAILABILITY [x] Unlimited

[ ] For Official Distribution. Do Not Release to NTIS

[x] Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13.10:459

[ ] Order From National Technical Information Service (NTIS) Springfield, Virginia 22151

19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
UNCLASSIFIED	213
20. SECURITY CLASS (THIS PAGE)	**22. Price**
UNCLASSIFIED	$3.40

USCOMM-DC 29042-P74

NBS TECHNICAL PUBLICATIONS

PERIODICALS

JOURNAL OF RESEARCH reports National Bureau of Standards research and development in physics, mathematics, and chemistry. It is published in two sections, available separately:

- Physics and Chemistry (Section A)

Papers of interest primarily to scientists working in these fields. This section covers a broad range of physical and chemical research, with major emphasis on standards of physical measurement, fundamental constants, and properties of matter. Issued six times a year. Annual subscription: Domestic, $17.00; Foreign, $21.25.

- Mathematical Sciences (Section B)

Studies and compilations designed mainly for the mathematician and theoretical physicist. Topics in mathematical statistics, theory of experiment design, numerical analysis, theoretical physics and chemistry, logical design and programming of computers and computer systems. Short numerical tables. Issued quarterly. Annual subscription: Domestic, $9.00; Foreign, $11.25.

DIMENSIONS/NBS (formerly Technical News Bulletin)—This monthly magazine is published to inform scientists, engineers, businessmen, industry, teachers, students, and consumers of the latest advances in science and technology, with primary emphasis on the work at NBS. The magazine highlights and reviews such issues as energy research, fire protection, building technology, metric conversion, pollution abatement, health and safety, and consumer product performance. In addition, it reports the results of Bureau programs in measurement standards and techniques, properties of matter and materials, engineering standards and services, instrumentation, and automatic data processing.

Annual subscription: Domestic, $9.45; Foreign, $11.85.

NONPERIODICALS

Monographs—Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

Handbooks—Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications—Include proceedings of conferences sponsored by NBS, NBS annual reports, and other special publications appropriate to this grouping such as wall charts, pocket cards, and bibliographies.

Applied Mathematics Series—Mathematical tables, manuals, and studies of special interest to physicists, engineers, chemists, biologists, mathematicians, computer programmers, and others engaged in scientific and technical work.

National Standard Reference Data Series—Provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated. Developed under a world-wide program coordinated by NBS. Program under authority of National Standard Data Act (Public Law 90-396).

NOTE: At present the principal publication outlet for these data is the Journal of Physical and Chemical Reference Data (JPCRD) published quarterly for NBS by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements available from ACS, 1155 Sixteenth St. N.W., Wash. D. C. 20056.

Building Science Series—Disseminates technical information developed at the Bureau on building materials, components, systems, and whole structures. The series presents research results, test methods, and performance criteria related to the structural and environmental functions and the durability and safety characteristics of building elements and systems.

Technical Notes—Studies or reports which are complete in themselves but restrictive in their treatment of a subject. Analogous to monographs but not so comprehensive in scope or definitive in treatment of the subject area. Often serve as a vehicle for final reports of work performed at NBS under the sponsorship of other government agencies.

Voluntary Product Standards—Developed under procedures published by the Department of Commerce in Part 10, Title 15, of the Code of Federal Regulations. The purpose of the standards is to establish nationally recognized requirements for products, and to provide all concerned interests with a basis for common understanding of the characteristics of the products. NBS administers this program as a supplement to the activities of the private sector standardizing organizations.

Consumer Information Series—Practical information, based on NBS research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.

Order above *NBS publications from: Superintendent of Documents, Government Printing Office, Washington, D.C. 20402.*

Order following *NBS publications—NBSIR's and FIPS from the National Technical Information Services, Springfield, Va. 22161.*

Federal Information Processing Standards Publications (FIPS PUBS)—Publications in this series collectively constitute the Federal Information Processing Standards Register. Register serves as the official source of information in the Federal Government regarding standards issued by NBS pursuant to the Federal Property and Administrative Services Act of 1949 as amended, Public Law 89-306 (79 Stat. 1127), and as implemented by Executive Order 11717 (38 FR 12315, dated May 11, 1973) and Part 6 of Title 15 CFR (Code of Federal Regulations).

NBS Interagency Reports (NBSIR)—A special series of interim or final reports on work performed by NBS for outside sponsors (both government and non-government). In general, initial distribution is handled by the sponsor; public distribution is by the National Technical Information Services (Springfield, Va. 22161) in paper copy or microfiche form.

BIBLIOGRAPHIC SUBSCRIPTION SERVICES

The following current-awareness and literature-survey bibliographies are issued periodically by the Bureau:

Cryogenic Data Center Current Awareness Service. A literature survey issued biweekly. Annual subscription: Domestic, $20.00; Foreign, $25.00.

Liquified Natural Gas. A literature survey issued quarterly. Annual subscription: $20.00.

Superconducting Devices and Materials. A literature survey issued quarterly. Annual subscription: $20.00. Send subscription orders and remittances for the preceding bibliographic services to National Bureau of Standards, Cryogenic Data Center (275.02) Boulder, Colorado 80302.