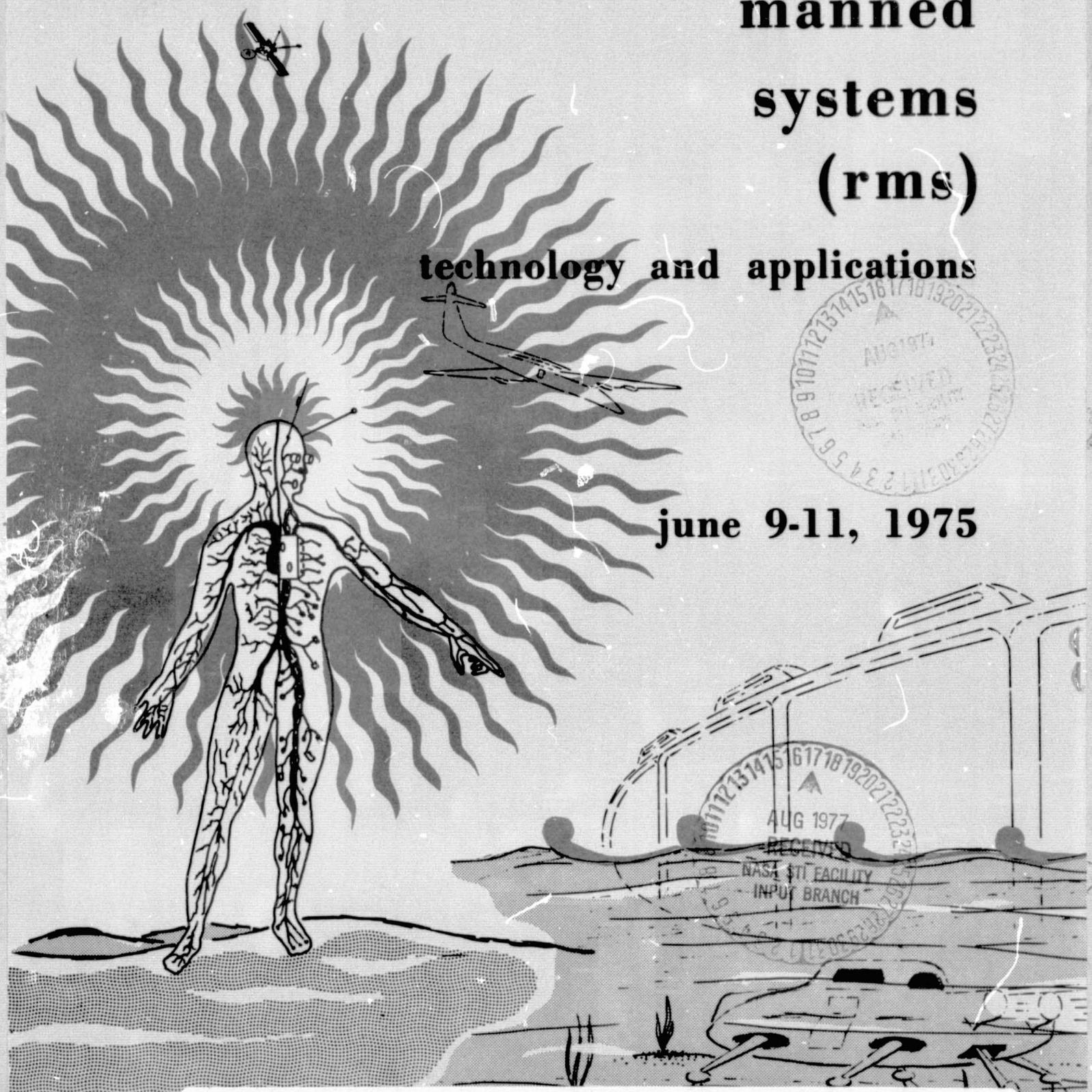


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second conference on  
remotely  
manned  
systems  
(rms)

technology and applications

june 9-11, 1975



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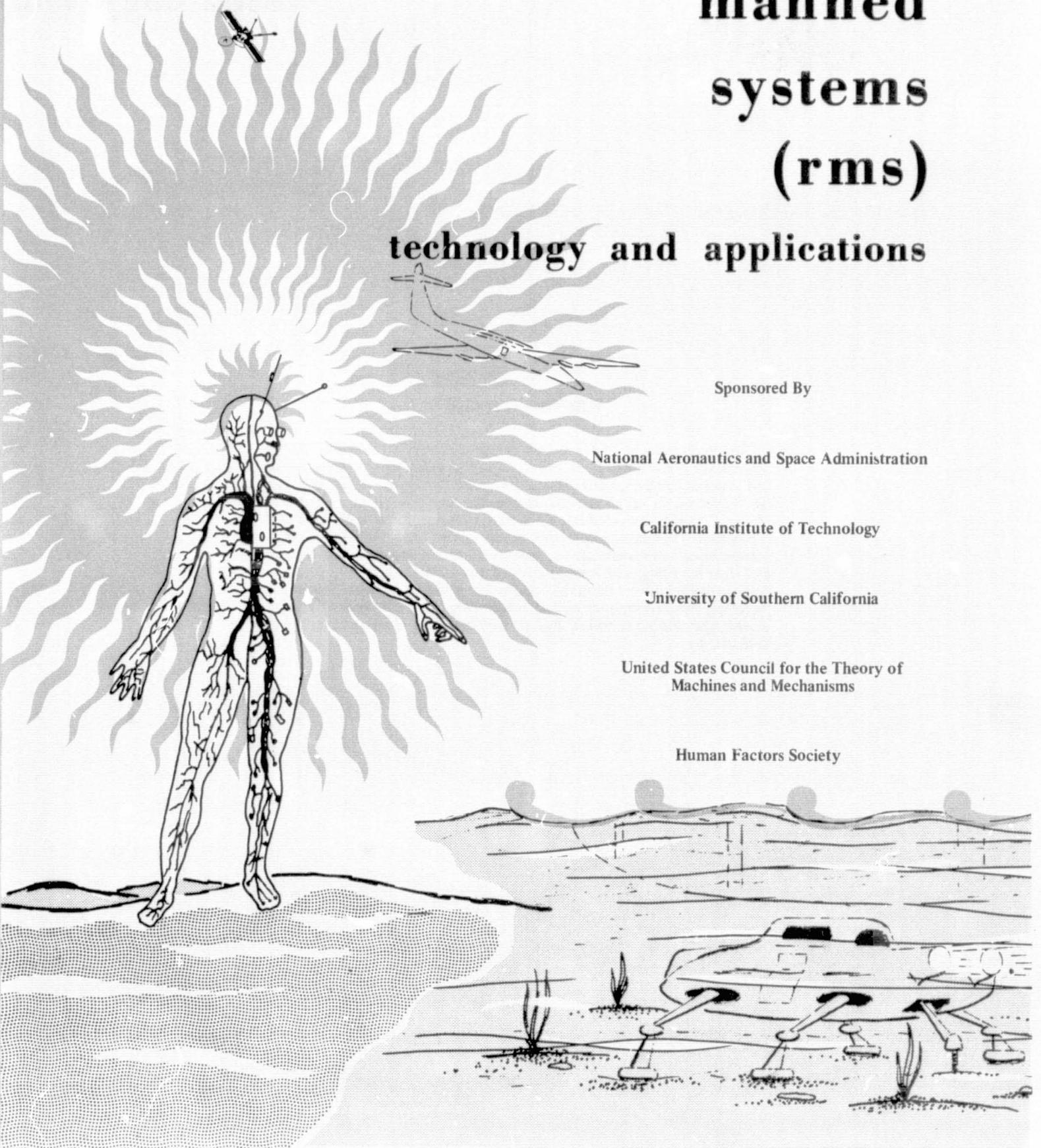
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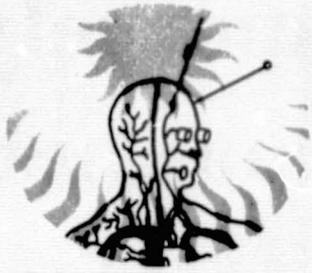
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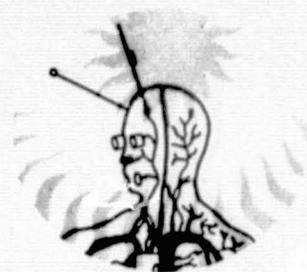
# remotely manned technology and

## PURPOSE AND SCOPE

*The main purpose of the SECOND CONFERENCE ON REMOTELY MANNED SYSTEMS -- Technology and Applications is to continue and expand technical interchange and communication in a field that has experienced rapid growth during the last few years. Remotely Manned Systems extend man's sensory, manipulative and cognitive capabilities to remote places and are concerned with the man-machine interfaces and communications, manipulators and end effectors, sensors and data handling, and remote control and automation. The scope of this conference covers recent developments closely related to these areas including new techniques and developments, new concepts of system design and implementation, and developments in design analysis and evaluation.*

# systems (rms)

## applications



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## PREFACE

During the FIRST CONFERENCE ON REMOTELY MANNED SYSTEMS (RMS) - Exploration and Operation in Space, many valid questions arose concerning technology availability and broad potential applications in areas other than space. For example:

- What kinds of RMS should be developed, and what are their optimum characteristics to satisfy the requirements?
- What is the trend of manipulator systems technology?
- What is the sensor and display technology?
- What are the man-machine interface implications and requirements?
- How can modern control developments be utilized in Remotely Manned Systems?
- What are the commonalities of RMS for space systems and for earth-based systems?
- What areas other than space are in need of RMS applications and what are the benefits?

These questions are as valid today as they have been in 1972.

The SECOND CONFERENCE ON REMOTELY MANNED SYSTEMS has therefore the subtitle "Technology and Applications" with the intent to cover as much as possible recent technological developments and associated applications in major areas of need. The first two Sessions are devoted to generally applicable techniques and developments, while the following four sessions treat applications and associated developments (frequently also generally applicable) related to space, undersea, industry and productivity, and rehabilitation.

Ewald Heer  
June 9, 1975

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KEYNOTE ADDRESS

A MAN'S REACH SHOULD EXCEED HIS GRASP

Dr. Stanley Deutsch

NASA Office of Life Sciences, Washington, D. C.

Welcome to the Second Conference on Remotely Manned Systems. The first conference in this series was held in September 1972 at the California Institute of Technology in Pasadena. At that time, the theme was the exploration and operation in space. One session was devoted to non-space applications. The participants were primarily Americans.

At this second conference, we can see a broadening of coverage to other arenas of activity, and we have participation from many parts of the world. The Program Committee under the able Chairmanship of Dr. Ewald Heer has developed a fascinating array of talent and extensive areas of interest. This second conference is much more international in scope.

Some of you may have seen the popular TV program, "The Six Million Dollar Man." The premise of the series is that a NASA astronaut, after surviving a near fatal crash of a test aircraft, is fitted with new limbs and organs. Each weekly segment of the program revolves around the exceptional capability possessed by the astronaut by virtue of his new legs and one arm and his enhanced vision and hearing. Colonel Austin's artificial arm and legs impart the capability for untold human speed and strength that were unrivalled by his natural limbs.

We are concerned with the augmentation of human capability, including the extension of capability beyond the person's physical presence or strength or the enhancement provided to restore lost functions. The capabilities include manipulation, mobility, sensation and dexterity.

Systems and technologies which apply here include those which are remotely controlled by man to perform some designated function at a place where man, for good reason, is not present. A typical example is a Mars unmanned roving vehicle that includes a system of sensors, surface locomotion, and manipulation devices which enable it to physically interact with the Martian surface under some degree of adaptive control by a man on earth.

Systems and technologies of concern also include the devices provided to a handicapped individual to provide him with restored manipulative, mobility, or sensory capability. The science devoted to the investigation of such augmentation/extension systems has been designated teleoperations, and the systems themselves have been termed teleoperators.

A teleoperator system is typified by two distinguishing characteristics: it is controlled by man, and it exists to extend or enhance specific capabilities of man. It is in a very real sense a man-machine system. As such its development must depend on concerns for human capabilities which are being extended or restored.

These two different but related aspects of concern, the hardware and the man, serve to distinguish the technologies. These technologies include: the man-machine interface at the control end of the system and the manipulators, end effectors, mobility devices, with the appropriate sensors at the working end. The technologies also involve techniques and systems which support those specified above, including control systems and communication systems.

The Technology and the Applications

Although we have had master/slave manipulators for many years, teleoperations is a relatively young discipline. At our first conference, we explored the state-of-knowledge and the state-of-the-technology in the teleoperator world with a focus on formalizing the subject matter, the research techniques, and the applications.

The objectives of this Second Conference on Remotely Manned Systems are to review recent developments in hardware, subsystems, and system design and implementation, to further explore the technology and applications with an eye to establishing a general orientation for future work, and to discuss some of the limitations in the field.

A review of the Proceedings of our first Conference and the Proceedings of this second Conference will confirm the strides and advancements made in the last three years.

Space Science Exploration

The adaptive behavior of a teleoperator requires that it sense and process data concerning its environment, understand relationships of objects within the environment, and make decisions that are compatible with both the mission objectives and the real world. The more unstructured the environment, the greater the hierarchy of decision making level required. Except in the realm of science fiction, we have not yet achieved the ultimate, i. e., a robot that has achieved complete independence of thought and action.

The Mars surface roving teleoperator that I mentioned earlier is an example of a remotely manned system dependent on adaptive control. Because of the inordinately long communication delays attributed to transmission and data processing, a direct control link from Earth to Mars would be uneconomical from a time, power, and perhaps vehicle safety standpoint. At least 40 minutes are required to receive sensor inputs from Mars, process the information, make the necessary decisions and relay the commands to a waiting teleoperator on Mars. Operations that could normally be accomplished in hours would take days, even weeks under such crude direct manual control.

How much autonomy must be given to a Mars teleoperator? As much as it can use efficiently and still accomplish its mission.

### Underseas Applications

The Navy has pioneered extensively in the development and operations of underwater manipulators. Because of the critical visibility problems encountered in the salt water environment, the Navy is looking at advanced sensor technology including bilateral force feedback systems. We will hear more about the Navy accomplishments and problems tomorrow.

### Hire the Handicapped -- It's Good Business

How often have you heard that slogan? According to the President's Committee on Employment of the Handicapped, about 11-1/4 million Americans, aged 16 to 64 are classified as physically or mentally handicapped. This includes almost two million paralyzed or physically deformed, another million with advanced arthritis, and 350,000 amputees. Studies are underway to develop advanced lightweight, structurally strong prosthetic and orthotic arms and hands that may be used to replace those lost due to accident, disease or warfare.

A session on Rehabilitation Systems provides us with information on efforts in the United States, Europe, and Japan aimed at helping the technically handicapped to become self-sufficient members of society. These devices assist the handicapped to become self-sufficient members of society. These devices assist the handicapped in various ways, probably the most important of which is to give them a sense of independence.

### Applications of Technology in Industry

Remotely manned systems are being applied to increasing areas. The technology developed for the space program is currently being used to solve the safety problems inherent in long wall coal mining. In a study for the Bureau of Mines, the NASA Marshall Space Flight Center is developing a manually controlled mining machine that operates in hazardous areas where men cannot penetrate either due to the danger of cave-in or because ceilings are too low to permit efficient manual tasks.

According to an article in the Washington Post, robots outnumber human beings at a new Volvo plant in Sweden by 400 to 60. The robots do the heavy work leaving the humans free to make management decisions. The advances in industrial automation and machine augmentation have been extensive, as you will see in the session on Industrial Applications Systems.

I'm looking forward to our next conference three years hence. Unlike the ancient gentleman who resigned as Director of the Patent Bureau around the turn of the century because he believed that anything worthwhile had already been invented, I visualize remotely manned systems technology development and applications, in late 1970's and 1980's, that we can't even imagine today. The countries all around the world will be the beneficiaries of advancements in this multi-disciplinary field.

# **SESSION I**

## **Theories and Techniques**

## CURRENT THEORIES OF MAN-MACHINE SYSTEMS

Thomas B. Sheridan

Massachusetts Institute of Technology

## ABSTRACT

This paper provides a very brief overview of theories and models conventionally employed to analyze man-machine systems such as remotely manned vehicles and processes. It presents the basic ideas of supervisory or hierarchical manning, and assesses needs for modelling here. Finally it poses some very general questions about remotely manned systems.

## MODELS OF PEOPLE AND MODELS OF MACHINES

Modeling man-machine systems is perilous business. Common sense tells us that what machines are good at (speed, power, reliability) people are not, and what people are good at (associative memory, complex pattern recognition, planning) machines are not. So why force them into the same Procrustean bed?

The reason is that to predict behavior of a man-machine system one must have simultaneous equations (or experimental simulations) for the people elements and machine elements in the same set of variables. The best analysis of an aircraft control system is useless without the display-to-control equations for the pilot in a given flight mode.

And only through such commonality of measures can one face up to the fundamental allocation or design problem: given the task to be performed, what should people do, what should machines do?

## WHAT IS A REMOTELY MANNED SYSTEM?

We are inclined to think that a remotely manned system is where the human operator performs an operation spatially remote from himself. In most cases of interest, however, spatial remoteness is not a variable of functional interest. More important are: 1) remoteness in certainty (lack of precise knowledge about key state variables); 2) remoteness in time (there is a delay in time from issuing commands until receipt of confirmation of action or lack of it); and 3) remoteness in connection.

Remoteness in certainty is explicitly characterized by the standard metrics of information theory and statistical signal theory. Remoteness in time, including both delay and distortion of signals in time, is what dynamical system and control theory treat explicitly through use of differential equation models. Remoteness in connection is more closely characterized by graph and decision theory. These are not clean and distinct separations, but they are worth considering in the context of remotely manned vehicles and processes.

## INFORMATION MODELS

The best known approach is Shannon's, which requires for each element to be modeled an event matrix of input, output and joint-event probabilities. From these one may calculate measures of input information, output information, transmitted information, noise generated from within the element, and equivocation - information which goes in and doesn't come out - (please see reference 1 Ch.5 for derivations). The advantages of these measures are that the event matrix

is easily obtained by experiment. The main disadvantage is that the measures are only time-averaged indices of consistency or relative channel quality; they tell little of rightness and wrongness and have little predictive value for engineering purposes. One exception is in the analysis of channel "matching" where the assignment of more reliable channels to more frequent or more important messages is shown to make a significant difference.

Empirically we know the human information ("bit") processing rate is relatively constant for well-defined tasks of low stimulus dimensionality, where differences between 4 and 20 bits per second depend upon subtleties of instructions to subject, stimulus mode and number of dimensions, compatibility between display and control, etc. We also know that short term memory is a relatively constant number of bits (three for one stimulus dimension, more for more complex stimuli).

## CONTROL MODELS

Much experimentation and model development has shown the human operator controlling (error-nulling) a one-dimensional continuous linear process to closely approximate a low order linear differential equation plus a noise generator. The simplest model of all, valid across a variety of controlled processes, really models the human and controlled process combined, where

$$\frac{\text{output of process}}{\text{error input to human}} = \frac{K_1}{j\omega} \exp. (-j\omega K_2),$$

a simple integrator plus time delay, where coefficients  $K_1$  and  $K_2$  vary systematically with error (input) bandwidth and the order or difficulty of the controlled process.<sup>1</sup> The noise power goes from practically nothing to a large fraction of the response power as input bandwidth exceeds 1 hz and the process becomes undamped or of high order. Best linear fits are made with such models using standard describing function techniques.

More sophisticated models have employed samplers, several dimensions of control, and often Kalman filters and optimal control relative to assumed objective functions. These are undergoing rapid development at the present time, but have been applied primarily to continuous stationary tasks.

Many remotely manned operations are discontinuous and nonstationary, such as manipulation tasks or vehicle rendezvous (or takeoff and landing). The simple error-correcting or even optimal predicting continuous control model just doesn't fit.

There is a kind of discrete-category control model which has been widely employed in industry for many years for a narrow class of predictions. I refer to the predetermined motion-time techniques wherein manipulation tasks are categorized into "transport loaded", "transport empty", "grasp", "release", "preposition" or "reposition", "use", "assemble", "disassemble" and "mental process" (or similar variants). Standardized base times for these task elements, which vary according to load and other task variables, can be added to predict total task times. Unfortunately, however, many manipulation tasks are not simply

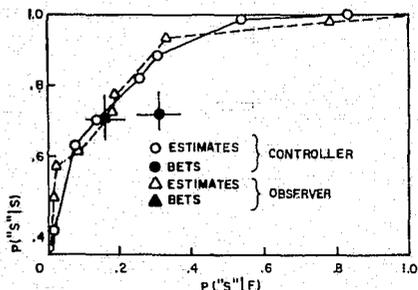
adaptable to this categorization, and the technique depends upon the human observer's ability to make subjective judgments of when one element stops and another begins. It is not particularly useful as an analytic tool.

#### DECISION MODELS

In recent years, the analytic techniques of decision theory have been found more and more useful for analyzing man-machine systems. Mostly, decision theory provides normative models. The problem is, given an objective function, what are the best decisions, how closely do the human (or man-machine) decisions match?

In situations where the need is to make an optimal binary choice given conflicting sensory data, so-called signal detection theory (e.g. discriminating noisy patterns from pure noise) has proven useful. Cohen and Ferrell extended the signals vs. noise discrimination theory to the problem of deciding whether you will succeed or fail in a given task, relative to whether in the end you do indeed succeed or fail.<sup>2</sup> Their models, in the form of ROC (relative operating characteristics, Figure 1), fit human data well, and indicate by independent parameters both how well the person predicts his own success but also how risk-prone or risk-averse he is. The author has extended this idea to decisions about how far to move (in time or space) to strike an optimal compromise between reward gained and the cost of failure.

ROC Curve  
for manned  
vehicle  
maneuver  
S=success  
F=failure  
quotes=  
prediction



An important problem in remote control concerns the cost of getting information, and under what conditions it is worthwhile to test before committing to an action, when not. Given prior probability  $P_i$  of environmental state  $i$ , the value  $V_{ij}$  of employing action  $j$  when the environment is  $i$ , and given the tendency  $p(k|j)$  of the test to say the environment is  $k$  when in reality it is  $j$ , one can determine the expected value of

$$V_j EV_T = \sum_k P_k \max_j \left[ \sum_i P(i|k) V_{ij} \right]$$

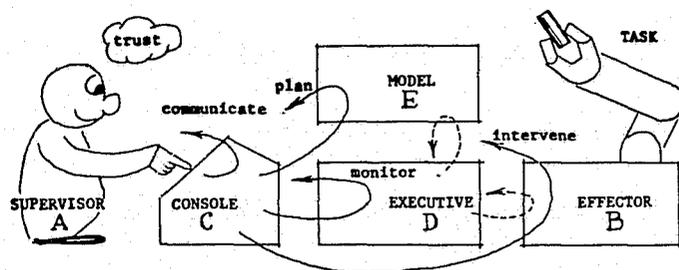
where  $P(i|k) = P(k|i) P_i / P_k$ ;  $P_k = \sum_i P(k|i) P_i$  and compare this to the expected value without the test

$$EV_{NT} = \max_j \sum_i P_i V_{ij}$$

to determine whether the test is worth its cost.

#### SUPERVISORY MANNING

Most man-machine systems models have considered the human operator to be an element in series with the electromechanical processes which remotely perform the desired task. Robot technology, however, has increasingly relegated man to a supervisory role (Figure 2) where he interacts with a computer on "human terms" (many bits per message, but few messages per second) while the computer does the task on "machine terms" (closing the loop with the environment at a high sampling rate).



The functions of the supervisor have been reviewed by the author elsewhere as: 1) planning (done off-line); 2) communication (initializing the on-line operation); 3) monitoring (of the on line automatic phase); 4) intervention (inserting himself directly in the control loop in emergencies); 5) developing "trust" or understanding of the system at an intuitive or instinctive level.

To theorize about the human supervisor poses considerably more difficulty than theorizing about a human operator directly in a control or communication loop or making a decision in a well-defined context. Presumably the reason he is still necessary to the system at all is because of his adaptability, as compared to the computer's, in dealing with variability and ambiguity. Otherwise the computer could be counted on for all of it. A quantitative model, however, requires experimentation in a controlled simulation (which may render the supervisor role unreal and therefore of questionable validity) and precise definition of the task (which, if we could do it, would only necessitate computer intelligence for task solution).

Probably theories about the supervisor should not concentrate on describing the wondrous things the human supervisor can do - because that is a very large set and perhaps best reserved for anecdote and poetic form. Perhaps theories of the supervisor should best attend to his constraints - and how those constraints limit the large set of things he can do. What kinds of constraints, then?

One of these is the generally accepted notion that the human supervisor can attend consciously to but one thing at a time, though the time constants of moving physically from one thing to another, changing gaze, or changing thought are different and have different conditional dependencies. Thus one of the fundamental problems is the differential allocation of the precious resource called human attention.

Differential attention is one thing. The absolute (averaged) level of attention is another, and depends upon task interest, physical fatigue, personal recognition and the person's own sense of being productive. This may be quite different from the production engineer's sense of productivity.

Beyond allocating the supervisor's attention are many problems of how to help him - through aids to memory, aids to pattern recognition, aids to control, fast time simulations, etc. We are still alchemists here.

1. Sheridan, T.B. and Ferrell, W.R., Man Machine Systems, MIT Press, 1974.
2. Cohen, H.S. and Ferrell, W.R., "Human Operator Decision Making in Manual Control", IEEE Trans. MMS, (10,2), June 1969, p. 41.

## STOCHASTIC MODELLING OF REMOTELY MANNED SYSTEMS

Clinton J. Ancker, Jr., Chairman, Department of Industrial and Systems Engineering  
University of Southern California, Los Angeles

Introduction

The systems of concern here have been dubbed "Remotely Manned Systems" and are described in more detail elsewhere (Refs. 1-3). For our purposes, we may first consider a simplified system as depicted in Figure 1.

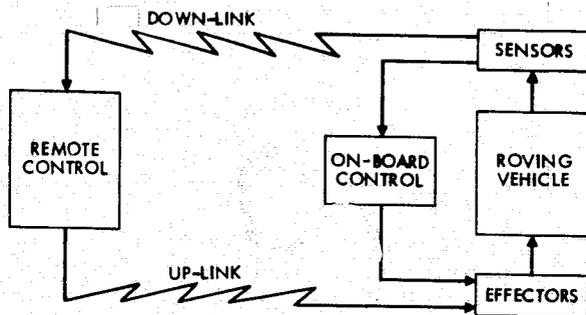


Figure 1. Simplified Remotely Manned System

The roving vehicle will move and perform scientific experiments on command. It will be remotely controlled and the state of the rover and its experiments will be reported by various sensors. The remote control will involve one or more humans as decision maker(s) and various display and computation devices.

The vehicle and remote control are linked electronically and are expected to experience significant time delays in the link. The possibility of autonomous on-board control to perform automatically at least some of the rudimentary control functions will be considered.

It is possible to model such a system in different ways. The choice of method will depend primarily on what questions one wishes to answer (and how much one can afford to spend in seeking answers). For example, the human decision-making element in the system is critical and therefore one might wish to examine just that aspect. Various microscopic models for this purpose are available or can be adapted or can be built from scratch. These models usually depend on some theory of human behavior or theory of how the human mind works as an information processing device and require mathematical techniques such as statistical decision theory, information theory, control theory, dynamic programming, etc. The purpose is to predict how well the human can receive, process, and respond to stimuli (i. e., process information) under various conditions of environmental stress, etc.

Another technique might be to macroscopically model the entire system as a servo mechanism, identifying each component with

its corresponding electrical analogue. The primary emphasis here would be on questions such as criteria for stability, compatibility of components, etc.

In contrast to the methods mentioned above, it is proposed in this paper to model macroscopically the system as a group of stochastic system elements. The major objective here is to predict times, e. g., time to cycle sensor signals and response commands, or time to complete a task. The emphasis is on the system as a whole, rather than its parts, and on time. Various candidate models are proposed with the ultimate objective of selecting one or more and its (their) refinement for greatest utility. After modelling is completed, it is contemplated that a series of experiments will be designed to determine unknown parameters and distributions wherever this is possible. If the model(s) can be handled analytically, then it may be desirable to program a digital simulation of the model(s) and exercise it (them) on a suitable computer. This then would involve not only programming, but validation, verification, and design of computer runs to answer specific questions.

Analytical Models

Four analytical models were developed ranging in increasing complexity from the simplest (see Model I below) to the most complicated (see Model IIA below).

Model I.

First consider a situation in which there is no autonomous on-board control capability (Fig. 2). Let us assume

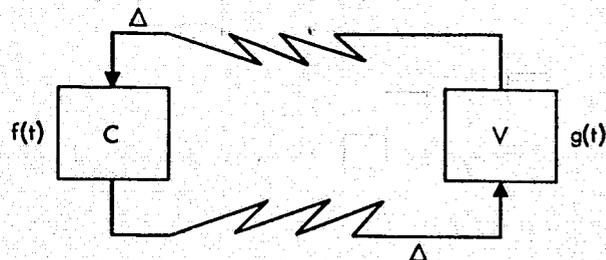


Figure 2. System for Model I.

that sensors on the roving vehicle (V) send a signal to the remote control center (C) giving some information on the state of the vehicle. There is a time delay  $\Delta$  before the signal is received. C then spends some time,  $T_C$  (a positive random variable (RV) with probability density function (pdf)  $f(t)$ ), generating a response (command) which is then transmitted with time delay  $\Delta$  back to V. V then executes

the command which takes some time,  $T_V$  (a positive random variable with pdf  $g(t)$ ), and either completes the task with probability  $p$  or fails to complete the task with probability  $q=1-p$ . If the task is completed we stop. If the task is not completed, a new signal is generated indicating the task is incomplete and we continue the process until success has been attained. Each trial is assumed to be independent of all preceding trials. This model may be thought of as representing situations such as one in which the vehicle is being moved or repositioned.

### Model IIA.

Now, Model IIA includes on-board control. Thus, we add a diversified on-board capability which is only used with probability  $1-\gamma$ , whereas on each cycle the remote control center may be required with probability  $\gamma$  (see Fig. 3).

We have added 0, the on-board capability. We now assume that the total number of signals which may be generated is equal to  $m+r$  and that  $m$  will require a response from 0. Further, the set of  $m$  signals intended for C will occur with probability  $\gamma$ , and the set of  $r$  signals intended for 0 occur with probability  $1-\gamma$ . Furthermore, if a signal belongs to C, the conditional probability that it is a signal for the  $j$ th responder in C is  $\alpha_j$ , and if it belongs to 0, the conditional probability that it belongs

to the  $l$ th responder is  $\rho_l$ ,  $\sum_{l=1}^r \rho_l = 1$  whose response time is a random variable  $T_{0l}$  with pdf  $e_l(t)$ . For C there is still the constant time lag  $\Delta$  (both ways) but no such lags apply to 0. We also assume that both C and 0 can generate the same set of commands  $C_k$ ,  $k=1, 2, \dots, n$ , but that the associated probabilities are different. That is, C generates

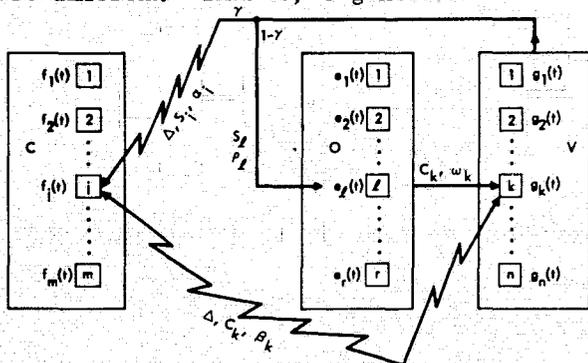


Figure 3 System for Model IIA

command  $C_k$  with probability  $\beta_k$ ,  $k=1, 2, \dots, n$ , whereas 0 generates command  $C_k$  with probability  $\omega_k$ ,  $\sum_{k=1}^n \omega_k = 1$ . The reason we differen-

tiate between signal types for 0 and C is that it is assumed that all tasks suitable for 0 will go to 0 and that only those tasks 0 is incapable of doing will be routed to C. On the other hand, we are assuming that either 0 or C can

issue a full set of commands to V although not necessarily with the same frequencies.

For each of these models the characteristic function (cf) of the time to complete the task is derived. For example, for Model IA we have

$$\hat{\phi}(u) = \frac{p\psi(u) e^{i\Delta u} [(1-\gamma)\eta(u) + \gamma\varphi(u) e^{i2\Delta u}]}{1 - q\psi(u) [(1-\gamma)\eta(u) + \gamma\varphi(u) e^{i2\Delta u}]} \quad (1)$$

where  $\phi(u)$ ,  $\psi(u)$ ,  $\eta(u)$  and  $\varphi(u)$  are the cf's for time to complete the task,  $g(t)$ ,  $e(t)$  and  $f(t)$  respectively.

We then analyze each model by deriving the mean and variance of time-to-completion from the cf's. For example, for Model I we have

$$E[T] = \{E[T_C] + E[T_V] + 2\Delta\} / p$$

$$V[T] = \{V[T_C] + V[T_V]\} / p + q\{E[T_C] + E[T_V] + 2\Delta\}^2 / p^2$$

Next, the difficulty of inverting the cf's of the completion time are illustrated for Model I by assuming all times are negative-exponentially distributed.

We also show that these models can easily accommodate an assumption of changing probability of success on each trial and a specific case is derived.

### Simulation Models

Finally, digital simulation models are discussed in a general fashion and recommendation for statistical validation of all the models are considered.

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## THE HUMAN CONTROLLER IN CAR FOLLOWING

G. O. Burnham

Jet Propulsion Laboratory, Pasadena

and

G. A. Bekey

Department of Electrical Engineering, University of Southern California, Los Angeles

## ABSTRACT

This paper is concerned with the man machine interface between the human driver and his automobile during car following tasks. A direct connection between models of the human operator obtained by other experimenters and those obtained from the theory of optimal control was established for car following situations involving both linear and nonlinear car dynamics. An essential part of this development is the assumption that the well trained human operator behaves as an optimal controller, subject to his own limitations.

Results obtained from several types of mathematical models have been obtained. Conventional parameter identification techniques were used to obtain the parameters of these models by comparing their performance to data obtained by aerial photogrammetry. The results indicate that there are two general classes of model structures: models assumed to have preview information and models without preview.

## 1. INTRODUCTION

It is well known that the remote control of dynamic systems by human operators is strongly affected by the dynamic performance limitations of the operators themselves. The major limitations affecting total system performance arise from the human operator's reaction time and his limited bandwidth. In a qualitative way it has been known for some time that the human driver's limitations are responsible for the propagation of disturbances and multiple collisions which sometimes arise in single lane car following. This paper is concerned with the development of mathematical models of the human driver-vehicle system. It is hoped that the results of continuing investigations of this type will be useful in the development of improved man-machine interfaces for automobiles as well as automated remote control vehicles or automated highways.

The models presented are based on the application of optimal control theory to car following and result in a relatively simple structure, which performs fairly well as compared with actual vehicle tracking data during acceleration and deceleration phases of a trajectory.

## 2. ANALYTICAL MODELS

Simple car following models of driver behavior

were proposed by Pipes [1] and others in the early 1950's and extensively developed by Chandler and others [2]. Such models assume that in a single lane with no passing and fairly dense traffic conditions a driver follows a lead car largely according to the following stimulus response relationship:

$$\text{Response} = \text{Sensitivity} \times \text{Stimulus} \quad (1)$$

Numerous mathematical formulations have been given to the above idea, the simplest of which is

$$a = \lambda [v_{n-1}(t-T) - v_n(t-T)] \quad (2)$$

where  $\lambda$  is a constant,  $T$  is a reaction time lag,  $v_n$  and  $v_{n-1}$  are the velocities of the leader and follower vehicles respectively, and  $a$  represents acceleration. Since in general both position and velocity information need to be considered, a block diagram of a general two vehicle following situation is shown in Figure 1. Many investigators have analyzed and verified simple models of this type. They are generally successful for small disturbances near a steady state, when vehicle dynamics are assumed linear.

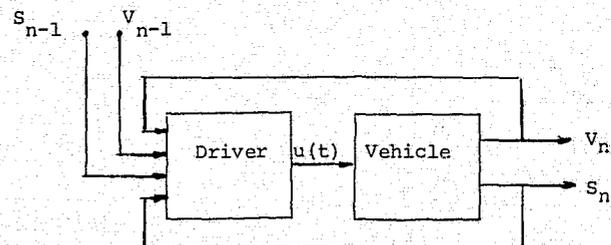


Figure 1

Recently a number of attempts have been made to apply optimal control theory to the development of human driver models. An optimal controller for a string of moving vehicles has been proposed by Athans and Levine [3] and others, who show that the problem can be formulated as a standard state regulator problem and thereby solved using well known techniques. The optimal controller derived is a function of the positions and velocities of all vehicles in the string. To implement

such a control system in an automatic highway remote control system would impose serious economic and communication problems, not to mention adding weight to the vehicles. Clearly, such a model is not a reasonable representation of the human driver strategy, since the driver does not have all the state information necessary for its implementation at all times.

The approach taken in this research is to reformulate the problem into a model tracking problem, where each vehicle is required to track only the vehicle directly ahead of him. This effectively decouples each vehicle in the string from all other vehicles except the one directly ahead.

The optimal control laws can be obtained by minimizing a quadratic cost function

$$J = \int_0^{\infty} (x'Qx + u'Ru) dt \quad (3)$$

where  $u(t)$  is the control vector,  $x(t)$  is the system state vector made up of the relative velocity between the vehicles and velocity dependent spacing term, and  $Q$  and  $R$  are constant weighting matrices. Burnham [4] obtained the following time invariant specific optimal control law for this case:

$$u(t) = C_s(s_l(t) - s_f(t)) - C_v v_l(t) - C_v(v_l(t) - v_f(t)) \quad (4)$$

where  $u(t)$  represents the human driver's control strategy,  $C_s$  is a spacing error gain constant,  $C_v$  is a velocity error gain constant, and  $C_v$  is a velocity dependent spacing term which relates the desired distance between vehicles to their speed. The subscripts  $l$  and  $f$  denote the leader and follower respectively. The model structure obtained from this representation is shown in Figure 2. It is interesting to note that the structure is very similar to that proposed by Helly [5] who studied simulation of bottlenecks in single lane traffic flow using stimulus response arguments. The parameters of both a simpler Chandler model such as equation (2) and of the optimal control model of equation (4) were obtained by standard parameter optimization techniques. The reference data was obtained from a study by Clear and Treiterer [6] in which aerial photographic techniques were used to obtain position and velocity information on a string of moving vehicles on highway 71 in Columbus, Ohio.

When data on various vehicles were used to

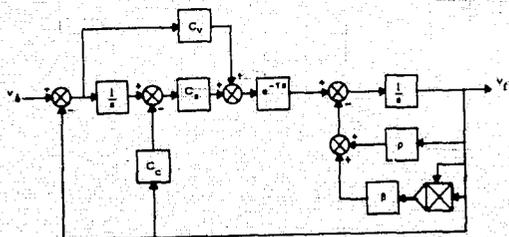


Fig. 2. Optimal controller model with nonlinear car dynamics.

estimate the parameters of the basic Chandler model, it was found that the parameters fell into two groups. For one group the model time delay was equal to zero, while for others the model time delay was of the order of 0.25 seconds. A possible explanation of the zero time delay of certain drivers is that these drivers receive preview information, e.g. if the size of the leading vehicle or the contour of the roadway allowed the driver to see more than one car ahead.

The optimal control model was also identified. It was discovered that significant weights had to be attached to the position error term in the criterion function, as well as the velocity error term in order to obtain meaningful results. Typical curves showing the performance of both the Chandler model and the optimal control model are shown in Figure 3. Further results are given by Seo [7].

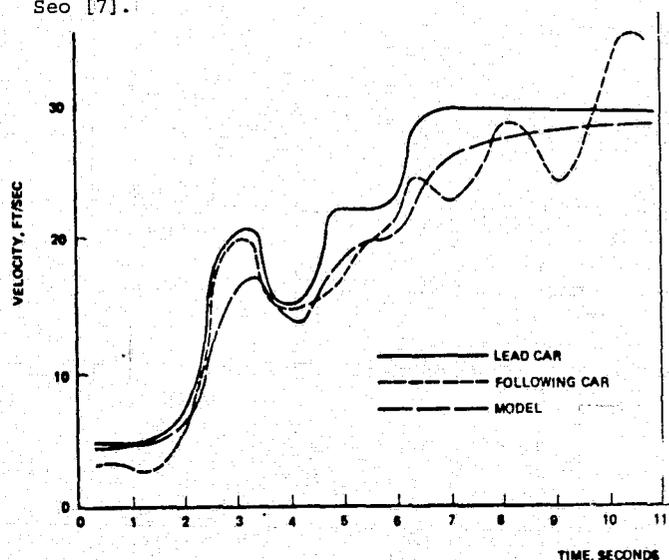


Figure 3

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## AN INVESTIGATION OF SUPERVISORY CONTROL OF REMOTE MANIPULATION

Douglas E. McGovern

Sandia Laboratories, Albuquerque, New Mexico

## ABSTRACT

Various types of augmented control for remote manipulation are discussed. A simple supervisory control program is described and an estimate of system performance is given.

## 1. INTRODUCTION

In any manipulation task, the operator must observe the actions of the remote manipulator, make judgements on the commands necessary to enact the task at hand, and carry out those judgements in terms of manipulator control. One approach to reducing the requirements on the operator is to provide a computer capable of some limited decision making and command generation as part of the manipulator system. Thus, a limited form of computer intelligence augments the operator.

## 2. TYPES OF CONTROL

The extent of augmentation can range from almost none (manual control) to complete system autonomy (artificial intelligence) as illustrated in Figure 1. Two types of augmented control are illustrated. Supervisory control represents a trading of control between operator and machine. For instance, in a task involving retrieving blocks, the computer can take command when a block is grasped to deposit it in a prespecified receptacle.

In automated control, a dual responsibility is present in that both the operator and the machine have distinct, separate functions. For example, touch sensing local to the manipulator jaws can be used to adjust the grasp tension. The operator exercises no control over this function and does not need to acknowledge its existence.

## CONTROL LOCATION

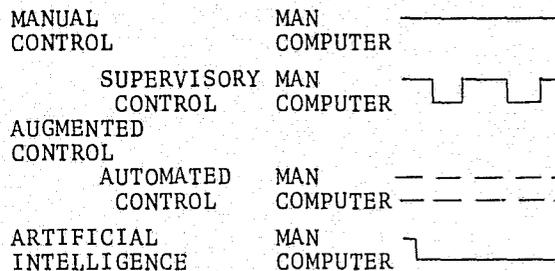


Figure 1. Types of Control

## 3. SYSTEM MODELING

Supervisory control lends itself to modeling since, if performance can be characterized by various subtasks, the system response time can be estimated by adding the times required for a series of manual control subtasks alternated with computer control subtasks. The results of such a performance model are discussed below. Data used in this model are drawn from the author's work (1) using a particular manipulator and supervisory control algorithm in a grasping task.

## 4. MACHINE PERFORMANCE

The supervisory control algorithm used in this example is the GROPE program of Hill and Sword (2). The operator is in control until one of the manipulator fingers is touched, at which time the computer assumes control. The jaws are raised slightly, moved by an increment  $\Delta I$ , and lowered. This is repeated until the block is between the fingers. The jaws are then lowered, the block is grasped, and control returns to the operator. The time required by GROPE can be

modeled from the speed of the manipulator and the details of the program.

The effect of this program is to increase the size target the operator needs to aim at. That is, merely touching the block is a sufficient condition for grasping.

#### 5. OPERATOR PERFORMANCE

Previous work (3,4) showed that various human performance models could be applied to describe the time required to perform precision positioning tasks under manual control. Thus, the time for operator subtasks can be determined.

#### 6. PERFORMANCE OF SYSTEM

The results can be presented by estimating the time required to complete the total task using GROPE (the manual control time plus the time required by GROPE) and comparing it to the time required to perform the task completely under manual control. Figure 2 illustrates the results of this comparison. The circles indicate conditions of task placement, tolerance, and GROPE movement increment for which task times were compared.

GROPE cannot be reliably used in the upper left portion of the graph since  $\Delta I$  is larger than task tolerance. For this set of task conditions each adjustment of  $\Delta I$  will overshoot the target tolerance and GROPE will oscillate. In the lower right is a region where GROPE could be used but its use results in longer task times than under manual control. Only for conditions in the upper right region can GROPE be used efficiently.

#### 7. CONCLUSIONS

The most striking conclusion of this performance evaluation is that this particular supervisory control program is effective in reducing task time only at larger tolerances. Different forms of GROPE will, of course, yield different results.

Combining performance estimates as above with the appropriate factors for the return of control from the machine to the operator provides a means for evaluating numerous supervisory control systems without the

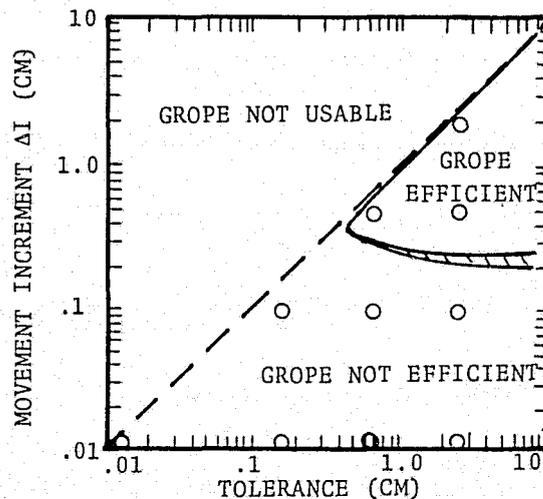


Fig. 2 Performance Evaluation

expense of full scale implementation and experimentation.

#### ACKNOWLEDGEMENTS

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EFFECT OF HAND-BASED SENSORS ON MANIPULATOR CONTROL PERFORMANCE\*

Antal K. Bejczy, Member of the Technical Staff  
 Jet Propulsion Laboratory, Pasadena

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SUMMARY

This paper discusses the effect of hand-based sensors (e.g. tactile, force, and proximity sensors) on the performance of manipulator control. A brief overview is presented on various experimental hand-based information systems which provide the manipulator controller some non-visual "awareness" of the task environment. It is established that differences in manipulator task categories and motion phases require different hand-based information systems to cope with control performance requirements.

The bulk of the paper is devoted to the description and evaluation of control experiments

four different audio tones. The control is performed from a remote control station fully isolated from the task scene. The operator in the remote control station can utilize both mono and stereo TV displays, and listen to the audio tones of the four loudspeakers displaying the proximity sensor signals. The four loudspeakers are arranged in a two by two meters vertical quadrangle around the operator. The vantage point of the stereo TV cameras is from the shoulder of the slave arm and about 0.5 m above it. The vantage point of the mono camera is from the side, varying between 50 to 90 degrees relative to the field of view of the stereo cameras. Neither the

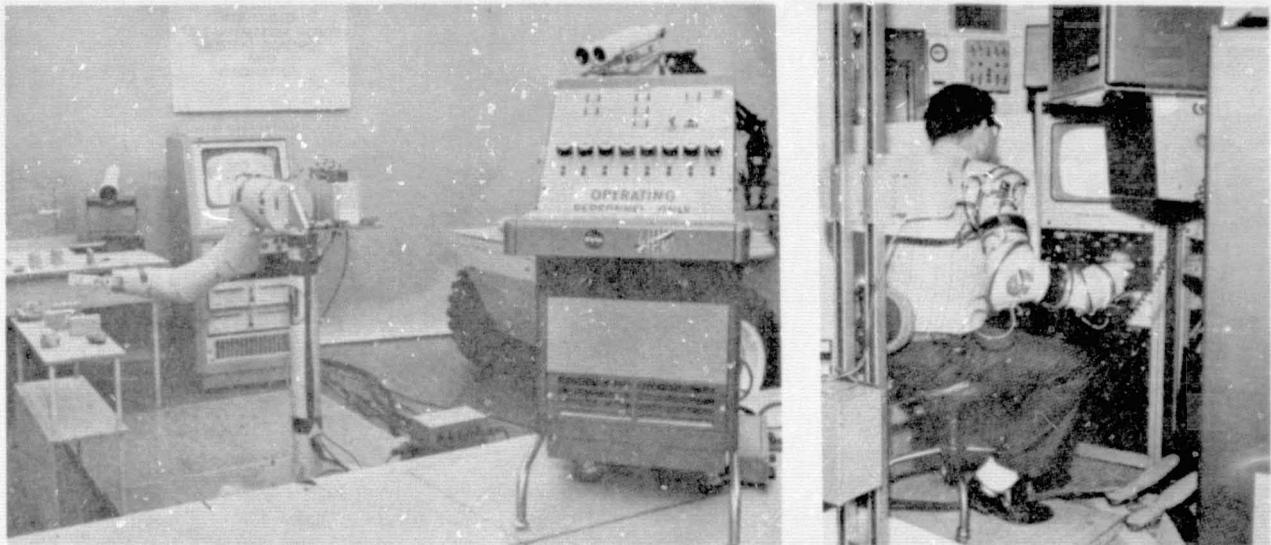


Figure 1. System Set-up for Remote Manipulator Control Experiments

performed at JPL using hand-mounted proximity sensors to guide and control hand motion near solid objects.

The experimental system set-up is shown in Fig. 1. The manipulator employed in the control experiments is the JPL/Ames exoskeleton arm in the master/slave position control mode (Refs. 1 and 2). The slave arm is equipped with a parallel finger hand. Four proximity sensors are mounted on the hand, with two sensors on each finger in a configuration as shown in Fig. 2. The proximity sensor is described in Ref. 3. If the sensor is mounted on the fingertip, the "sensitive volume" moves with and ahead of the fingertip and generates a voltage signal when the "sensitive volume" touches a solid surface.

In the control experiments the four proximity sensors' signals are presented to the operator as

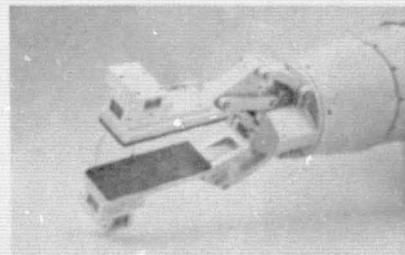
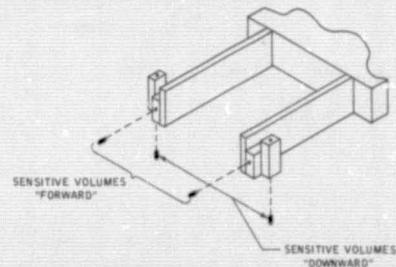


Figure 2. Parallel Fingers with Four Proximity Sensors

\*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.

stereo nor the mono view can provide a complete visual feedback to the operator under the described set-up. In particular, the visual feedback is highly degraded and obscured when the hand moves near solid objects.

The main point of the remote control experiments is that the operator can integrate the information content of the proximity sensor signals with an incomplete visual feedback and find control strategies to perform remote manipulator tasks which are very difficult or near impossible under the existing visual feedback arrangements. Typical tasks were: locate critical parts of the work scene (edges, corners, door openings, holes, blocks, etc.); pick up blocks and transfer them to designated places; put a pin into a hole, having 2 to 10 mm clearance; open a door; find a block in a box when the block is not visible to the operator through TV. As examples, Figs. 3 and 4 show two task scenes. In Fig. 3, the task is to put the block on top of the other block which is standing on the table, and align all four edges of the two blocks. The real situation is shown on the left part of Fig. 3, while the right part of the figure shows the actual visual feedback to the operator as presented to him by the mono TV camera in a side view. As seen, the side view visual feedback has only an incomplete information about the relative location of the two blocks. But using the proximity sensor audio feedback integrated with the incomplete visual feedback, the operator can solve the control problem quite easily. In Fig. 4, the task is to find and pick up the block in the box. As shown in the right part of Fig. 4, the operator cannot see in the mono side view display where is the block in the box. He has to search for it using the audio feedback of the four proximity sensors. The total clearance between the fully open hand and the block width is about 6 mm. In the average, it takes about 35 sec. to find and

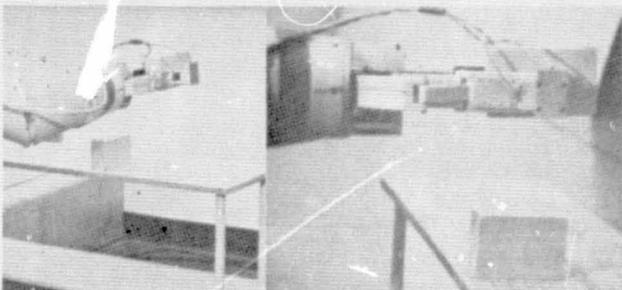


Figure 3. Task Scene: Stack Blocks

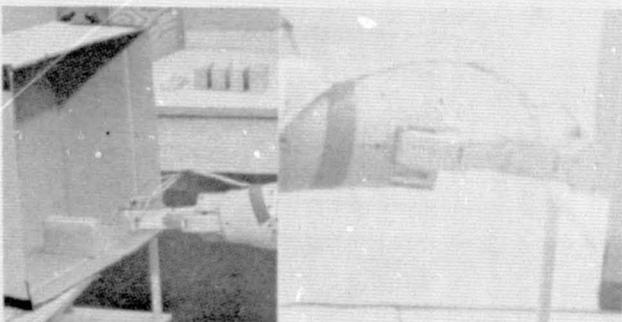


Figure 4. Task Scene: Find Block in the Box

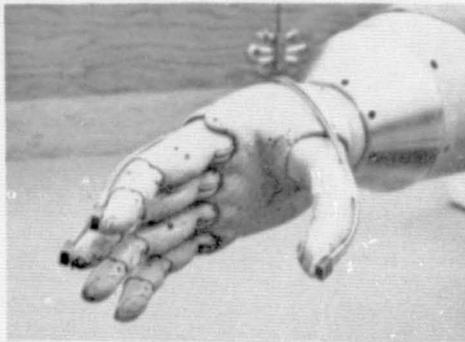


Figure 5. Humanoid Hand with Mini Proximity Sensors

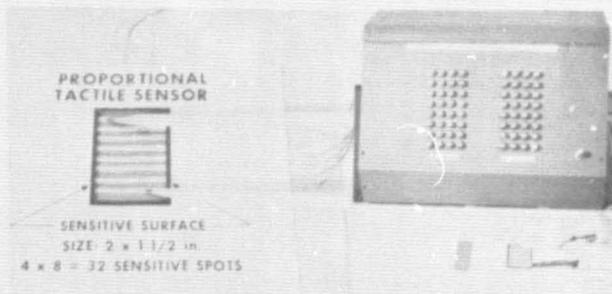


Figure 6. Proportional Tactile Sensor with Visual Display

pick up the block relying on proximity sensor feedback. Previous control experiments are described in Ref. 4.

The main conclusion of the control experiments conducted for a total time of about 25 hours spread over five weeks is that the error has been reduced by a factor of two using this proximity feedback, and that the operator can work more easily and confidently, and nearly impossible tasks can be performed. Task completion time does not seem shortened considerably when proximity sensor feedback is employed under nearly normal visual feedback conditions.

Fig. 5 shows an articulated humanoid hand equipped with miniaturized proximity sensors. This set-up is part of the ongoing control experiments. Fig. 6 shows the breadboard of a proportional tactile sensor with visual display. The sensor will be used in future control experiments in which direct human control inputs will be combined with computer control mode.

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## LOCATION AND ACQUISITION OF OBJECTS IN UNPREDICTABLE LOCATIONS

A. J. Sword and W. T. Park

Stanford research Institute, Menlo Park

Abstract

One of the advantages of augmenting a teleoperator system with a computer for manipulator control is the ability to combine the capabilities of both man and computer to accomplish a task. Such an augmented teleoperator system is described. This system allows objects in unpredictable locations to be successfully located and acquired. By using a method of characterizing the work-space together with man's ability to plan a strategy and coarsely locate an object, the computer is provided with enough information to complete the tedious part of the task. In addition, the use of voice control is shown to be a useful component of the man/machine interface.

Introduction

Between the two extremes of manual control, such as occurs in traditional master/slave systems, and computer control, such as in robotic systems, lies a continuum of control schemes in which computers play roles of varying importance. This intermediary region may be called "augmented remote control". By the use of augmented remote control schemes, the capabilities unique to both man and computer may be exploited to the fullest. Thus, tasks that neither man nor computer can perform alone, can be successfully accomplished when both are used. Many complex tasks can be performed by combining man's ability to interpret scenes, plan a strategy, and react to the unforeseen, with the computer's ability to save and accurately duplicate arm positions, remember sequences of positions, perform coordinate conversions in both hand and world coordinates, and interpret touch and force sensors. This combination of man and computer is particularly effective when used to remotely accomplish tasks presenting the following difficulties:

- A degraded communications link is present.
- The environment (in the short term) is significantly changing.
- The establishment of certain forces and torques is vital to task completion.
- The operator's view of the environment may become obscured in the process of performing the task.
- A manipulator (or other device) is used that is not anthropomorphic in nature or that has too many degrees of freedom to easily control.

This work was supported by the U. S. Army under Contract DAA15-74-C-0095 to Stanford Research Institute.

An example of a task where an augmented teleoperator control system may be used to best advantage is that of locating and acquiring individual M139 bomblet submunitions from an Honest John Rocket nose base section. (This task arose during disposal of obsolete ordnance by the Army.) This task requires surmounting many of the above obstacles, the most difficult of which is the unpredictability of the bomblet positions.

Each M139 bomblet is spherical with a number of small fins protruding longitudinally. The bomblets are tightly packed together in one of four identical quadrants of the rocket section, and because of the fins, any given bomblet may be interlocked with one or more of its neighbors. Thus when the extraction of an individual bomblet is attempted, neighboring bomblets may or may not be disturbed, and due to the orientation of their fins, may or may not be displaced. Even if displaced, the amount of displacement is not predictable, and because of the interlocking problem, retrieval of the topmost bomblet is not necessarily the best choice. Thus the bomblet positions are extremely unpredictable and the strategy must be reevaluated after each retrieval attempt. To circumvent these problems, a method was developed of characterizing the space within each quadrant. Thus, together with allowing the operator to specify to a very loose tolerance which bomblet to acquire, this method provided enough information to the system to allow the computer to finish the task during the automatic phase.

System Description

A functional system description of the bomblet retrieval teleoperator system is shown in Fig. 1. The heart of the system is the PDP-10 command computer. The majority of the software controlling both the manual and automatic control modes resides in this computer. All coordinate transformations are performed in this computer and various commands are passed to and data are received from the PDP-15 control computer, which acts as an input/output buffer channel to the PDP-10 computer. The PDP-15 computer services hardware interrupts, buffers joint commands to the Unimate, reads the manipulator status, passes commands from the PDP-10 to the NOVA and back, and reads the VIP 100 Word Recognizer.

The NOVA-1210 sensor processor is the key element in allowing successful adaptive automatic control. The NOVA-1210, when commanded, can activate various sensors, establish force and torque thresholds, and enter a mode in which the actuated sensors are continually scanned. If the output of a sensor is above (or below) its threshold value, the NOVA can quickly stop the Unimate via a hard-wired direct connection to the Unimate "hold" circuitry. In addition, the NOVA can provide the PDP-10 with

the 12-bit reading of any of the sensors, and can vary the speed of the Unimate by means of a separate analog output.

Vital to efficient manual control and serving as the man-machine interface is the VIP-100 Word Recognizer, and the television-based visual feedback system. The operator communicates with the system via a microphone headset. After training the VIP-100 to his voice and vocabulary, the operator merely "talks" the manipulator into place. The available commands were selected such that they are pertinent only to the operator's view of the remote environment in the television monitor. Thus, the operator does not need to control the Unimate's individual joints, he needs only to visualize himself sitting on top of the Unimate and moving right, left, up, or down related to where he is. This, in effect, places the operator on the Unimate's end-effector.

The final system component is the end-effector. The end-effector used in this work is part of a modular end-effector system shown in Fig. 2. More detailed system descriptions may be found in References (1) and (2).

#### The Subvolume Concept

The key factor in the operation of the system is the concept of the subvolume. Each quadrant was divided into 21 nonintersecting subvolumes, so that the center of a bomblet anywhere within the quadrant would fall within one and only one subvolume. Then, for each subvolume, the position and orientation from which the end-effector could most easily acquire a bomblet at the center of that subvolume was experimentally determined. Finally, since the bomblets did not in general lie at the exact center of a subvolume in actual operation, an automatic, touch-directed search procedure was used to find a bomblet within a given subvolume.

Since the shape of the nose base makes it impossible to lift bomblets vertically away from certain positions, we also had to determine experimentally the best direction from which to extract a bomblet from each subvolume.

The more subvolumes used, the smaller each is, and, therefore, less searching is necessary to find a bomb located in its subvolume. For the M139 bomblets in an Honest John nose base section, 21 subvolumes are sufficiently many to ensure a high success rate for the touch-directed search. With other objects and a container of a different shape, then more or fewer subvolumes would be appropriate, but, no matter what partitioning scheme and search algorithm the computer program might use, the operator would simply center an object on his television monitor and then let the computer handle the details of positioning the end effector, searching for the object, acquiring it, and removing it from the container.

A computer-augmented teleoperator system such as the one we have demonstrated is both extremely

general and easy to operate, and should therefore find wide application in situations where handling randomly positioned objects is required.

#### Coarse Localization-Manual Control

The success or failure of bomblet retrieval depends strongly on the ability of the operator to center the end-effector properly over the bomblet designated for removal. Even though the concept of the subvolume significantly reduces the accuracy required, care must be exercised in locating the bomblet because any misalignment somewhat reduces the probability of success and does increase the length of time required to acquire that bomblet.

The operator control station is shown in Fig. 3. The visual feedback consists of a television camera mounted on the Unimate, with shock mounts to absorb the vibration of the hydraulic system. The camera looks into a mirror mounted on the end of the boom, and from there into the nose base section. When in the manual control mode for coarse localization, the end-effector is vertically positioned so as not to obstruct the television view of the bomblets in the nose base. The operator then directs the Unimate via voice, until the desired bomblet is centered in the reticle on the television monitor. The available voice commands have been specifically designed to move the reticle around relative to the image of the bomblet on the monitor; i.e., when the operator says "MOVE RIGHT", the image of the bomb moves to the operator's left making the reticle appear to move to his right. The inset of Fig. 3 shows the direction in which the reticle appears to move for each command. A view of the monitor with the designated bomblet properly positioned in the crosshairs of the reticle is shown in the inset of Fig. 3. It should be noted that the bomblet is not centered; however, because of the adaptive nature of the system, a misalignment of approximately one-fourth of a bomblet diameter can be tolerated.

#### Precise Localization and Acquisition-Computer Control

The precise localization and acquisition algorithm is best explained by the flowcharts in Figs. 4 and 5. When the FINDBOMB algorithm is entered, the X-Y position of the designated bomblet has already been determined as a result of the manual coarse localization. FINDBOMB calls the algorithm TRYTOACQUIREBOMB. This algorithm is a recursive one, which means that it invokes itself as a subroutine as indicated in Fig. 5. Regardless of success (as is usually the case) or failure, the system returns control to the operator so that another retrieval sequence on the same or on a different bomblet may be initiated. The details of the algorithm are discussed in Reference (3).

#### Conclusions

An advantage of the present augmented teleoperator system organization is that it is usable on an item-for-item basis, i.e., it does not require that the quadrant of the nose base be full at the

start of unloading. Furthermore, the operator may partially unload one quadrant, switch to another quadrant, then return to the previous one without restarting the system or being obliged to "advance" it manually to the correct point to deal with the next bomblet.

The program is of an extremely general nature. In part, this generality is achieved by considering subvolumes. The subvolume concept allows the difficult bomblet-acquisition problem to be partitioned into two, more tractable, subproblems, neither of which requires accurate position information for its solution. This feature, coupled with the adaptive nature of the system and the ability to null out forces on the end-effector, provides the capability for accomplishing the task.

Another way in which the program is general is that it is "table driven". That is, all the information unique to the task is contained within tables. Thus, given an entirely different carrier packed with a different number of identical objects which could be other than bomblets, then all that is required to acquire these objects is a different set of tables.

A valuable technique that aided in implementing the algorithms was that of structured programming. The flowchart in Figure 5 shows evidence of the structured approach in the nesting pattern of the successive tests. This technique is valuable in writing software that is easy to debug and easy to transfer to a different computer system, when desired.

Finally, the technique of voice control was proven to be a useful one that greatly simplifies the control burden placed upon the operator.

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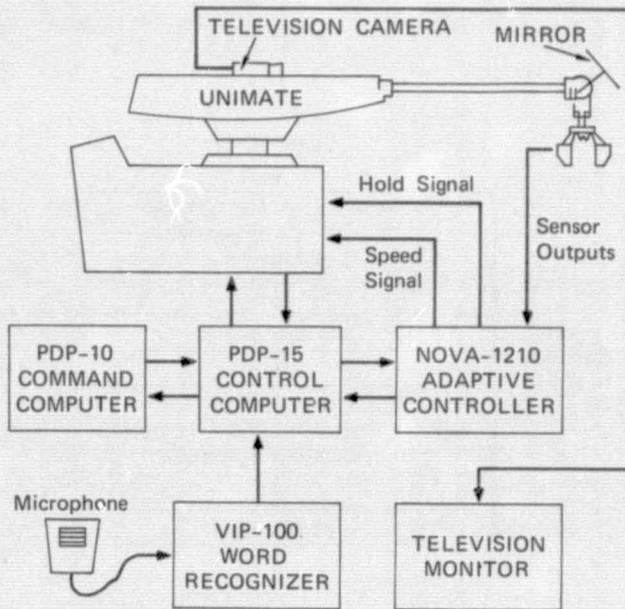


FIGURE 1 BOMBLET ACQUISITION TELEOPERATOR SYSTEM

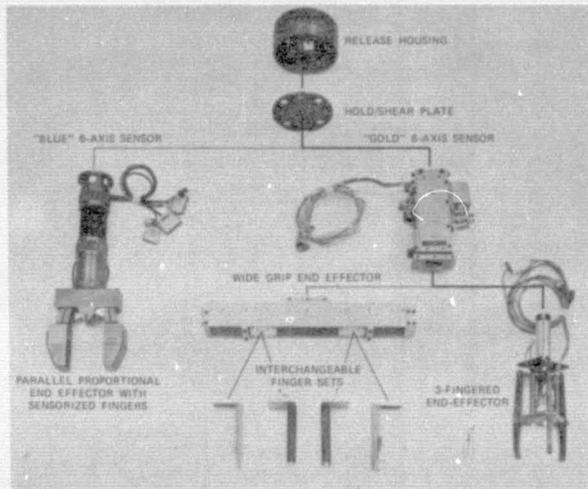


FIGURE 2 MODULAR END-EFFECTOR SYSTEM

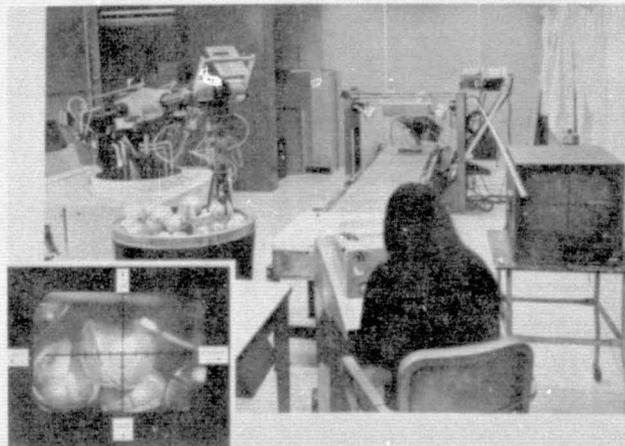


FIGURE 3 OPERATOR CONTROL STATION

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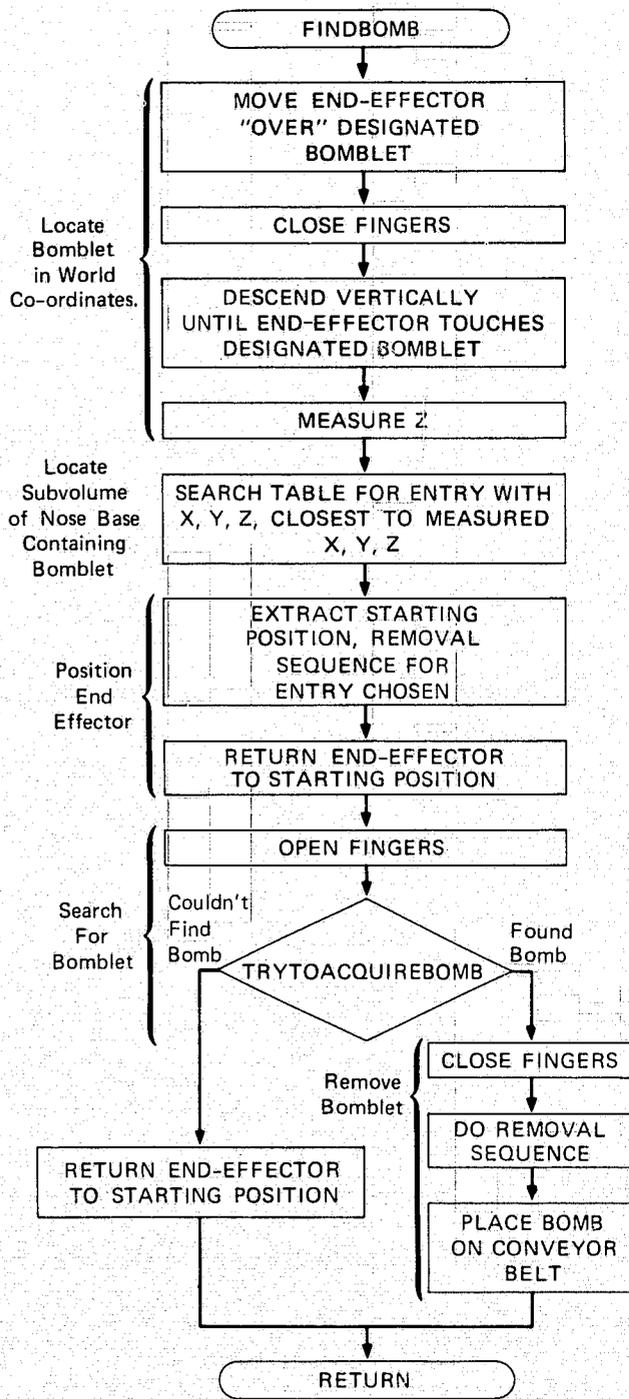


FIGURE 4 ALGORITHM TO PRECISELY LOCATE BOMBLET

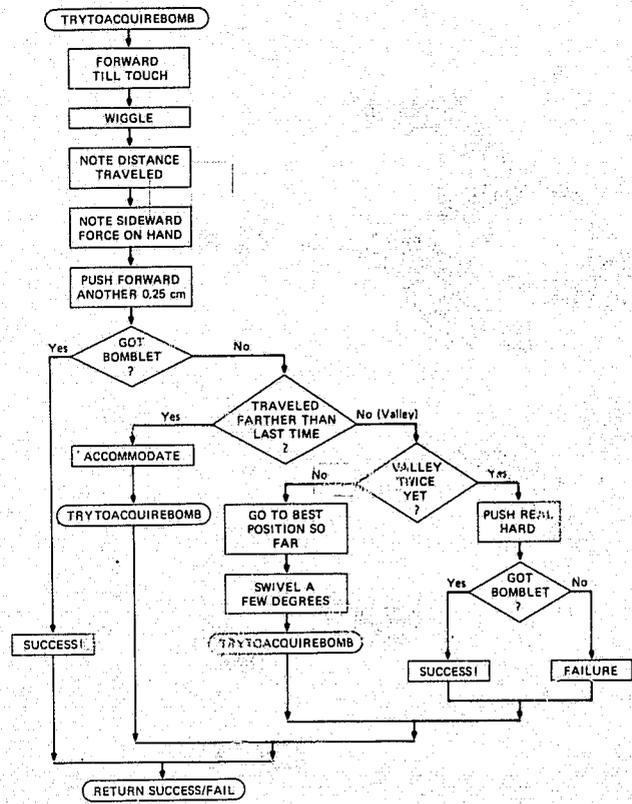


FIGURE 5 ALGORITHM TO ACQUIRE BOMBLET

**SESSION II**

**Advanced Technology**

## TV REQUIREMENTS FOR MANIPULATION IN SPACE

Larry A. Freedman

RCA, Astro-Electronics Division, Princeton, New Jersey

William H. Crooks

Perceptronics, Inc. Woodland Hills, California

and

Paul P. Coan

NASA, Manned Spacecraft Center, Houston, Texas

## ABSTRACT

This paper describes an analytical and experimental study to specify a video system for remote manipulation in space. The study was composed of three phases; they were: (1) analysis of basic manipulation tasks and visual requirements; (2) simulation testing to determine the effects of task, scene parameter, and type of video system on manipulation performance; and (3) video system selection and specification.

Analysis of the visual process began with an operator function analysis. Investigation of a variety of remote operation tasks resulted in derivation of a set of basic operator functions organized according to two characteristics: work volume and remote element relationship. These two dimensions define four manipulation tasks used in the simulation testing: large body docking, coupling the end effector to an object, manipulating a small object, and transporting a large body within close clearances.

A visual function analysis then extracted the basic visual functions required of the operator and listed the visual dimensions which might affect performance. Rather than attempt to deal with the large number of visual relevant factors, the analysis developed a set of elemental scene parameters which grouped the visual dimensions into major areas of influence. In this way, the large and unwieldy set of visual parameters was organized into a more manageable set of meaningful scene dimensions. Final scene parameters chosen were depth precision, object differentiation, scene reference, and scene dynamics.

Simulation testing was conducted with a four degree-of-freedom motion frame which allowed an operator to perform the four manipulation tasks using a simple toggle-switch control to minimize the effects of manual skill. For each trial of the experiments, the operator performed one of the manipulation tasks, using a particular TV system, with a specified combination of scene parameters. Four video systems were included in the simulation testing; these were a black-and-white and a color monoscopic system, a black-and-white two-view system, and a stereoscopic system. A sequential experimental plan first provided an overall analysis of the effects of tasks, scene parameters, and video systems. This was followed by a detailed experimental examination of the critical dimensions identified in the first experiment.

Performance measures included accuracy in positioning the manipulated object, number of contacts between the manipulated object and fixed objects, and task completion time. Additionally, each operator completed a subjective rating form for each trial and a final preference rating for the four video systems. The paper summarizes the performance and subjective effects of the experimental variables and describes the recommended video system. Selection of the recommended system was based on a weighted combination of the various operator experimental results and on system burden factors including weight, complexity, reliability, power consumption, transmitted bandwidth, etc.

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## GRAY-LEVEL TRANSFORMATIONS FOR INTERACTIVE IMAGE ENHANCEMENT\*

R. C. Gonzalez and B. A. Fittes

Electrical Engineering Department, University of Tennessee, Knoxville

Abstract

A gray-level transformation method suitable for interactive image enhancement is presented. It is shown that the well-known histogram equalization technique is a special case of this method. Experimental results which establish the superiority of the procedure over histogram equalization are also described.

## I. INTRODUCTION

Digital image enhancement techniques may be broadly divided into two principal categories: (1) transform-domain methods, and (2) image-domain methods. Approaches based on transform methods generally consist of computing a two-dimensional transform (e.g., Fourier or Hadamard transforms) of the image to be enhanced, altering the transform, and computing the inverse to yield an image which has been enhanced in some manner [1, 2]. Image-domain methods, on the other hand, operate directly on the image in question by means of algorithms that are usually based on gray-level content [2]. The procedure described in this paper deals with the latter method.

Suppose that an image to be processed is digitized to form an  $N \times N$  array of elements (called pixels), and let  $x$  be a variable which represents the gray level of each pixel. It is assumed for simplicity that  $x$  has been normalized to the interval  $0 \leq x \leq 1$ , where 0 denotes black and 1 denotes white in the gray scale. Attention will be focused in the following sections on transformations of the form

$$y = T(x) \quad 0 \leq x \leq 1 \quad (1)$$

which map a gray level  $x$  into a level  $y$ . The function  $T(x)$  is assumed to satisfy the conditions:

$$(a) \ T(x) \text{ is strictly monotonic in the interval } 0 \leq x \leq 1,$$

and (2)

$$(b) \ 0 \leq T(x) \leq 1 \text{ for } 0 \leq x \leq 1.$$

The monotonicity condition preserves the order from black to white in the gray scale of the enhanced image. In addition, condition (b) guarantees a mapping that will be consistent with the allowed range of pixel values.

## II. DEVELOPMENT OF THE TRANSFORMATION FUNCTION

The gray-level mapping method developed in this section is based on transforming the probability density function of the gray levels in an image to be enhanced. The density function of the levels in the original image will be denoted by  $p_x(x)$ , while  $p_y(y)$  will be used to denote its counterpart in the enhanced image. Although these quantities are in reality discrete functions for a digitized image, the following development will be carried out in continuous mathematics to simplify the explanation. The discrete equivalents are obtained from these results without difficulty.

The functions  $p_x(x)$  and  $p_y(y)$  are of fundamental importance in describing the physical characteristics of the original and enhanced images. For example, the average brightness of the original image is given by

$$\bar{x} = \int_0^1 x p_x(x) dx \quad (3)$$

while its variance (which is a measure of contrast) is given by

$$\sigma_x^2 = \int_0^1 (x - \bar{x})^2 p_x(x) dx \quad (4)$$

For a given image, we are interested in obtaining an enhanced image with a density function  $p_y(y)$  which has been interactively specified by the operator.

The transformation function  $y = T(x)$  and its inverse,  $x = T^{-1}(y)$ , are guaranteed to be strictly monotonically increasing in the interval  $[0, 1]$  by the conditions set forth in (2). Under these conditions, it is well known [3] that  $p_y(y)$  can be written in terms of  $p_x(x)$  and  $T(x)$  as follows:

$$p_y(y) = \left[ p_x(x) \frac{dx}{dy} \right]_{x = T^{-1}(y)} \quad (5)$$

The function  $p_x(x)$  is obtained from the original image,  $p_y(y)$  is specified, and the problem is to determine the transformation function  $T(x)$  which will yield the desired  $p_y(y)$ .

A very popular technique, known as histogram equalization [4, 5], is obtained from Eq. (5) by using the transformation function

$$y = T(x) = \int_0^x p_x(s) ds \quad 0 \leq x \leq 1 \quad (6)$$

which is the cumulative distribution function of  $x$ . The variable  $s$  in Eq. (6) a dummy variable of inte-

\*Work supported by NASA under contract NAS8-29271.

gration. From this equation we have that  $\frac{dx}{dy} = \frac{1}{p_x(x)}$  and Eq. (5) reduces to

$$p_y(y) = 1 \quad 0 \leq y \leq 1 \quad (7)$$

In other words, the use of Eq. (6) yields an image whose gray levels have a uniform density.

Although histogram equalization can be very useful in some applications, this particular method is not suited for interactive image enhancement since all it can do is produce a density function  $p_y(y)$  that is uniform. As will be seen below, however, histogram equalization can be used as an intermediate step in a transformation which will actually yield a specified  $p_y(y)$ .

Suppose that the gray levels  $x$  of an image are transformed using Eq. (6) to yield a new set of levels  $z$ , that is,

$$z = H(x) = \int_0^x p_x(s) ds \quad (8)$$

From the above discussion we have that  $p_z(z)$  is a uniform density function. If the inverse of Eq. (8),  $H^{-1}(z)$ , is applied to the  $z$ 's, we obtain the original image with  $p_x(x)$  back. It is noted, however, that if we specify a density function  $p_y(y)$  and apply Eq. (6) we would obtain

$$z = G(y) = \int_0^y p_y(s) ds \quad (9)$$

Although  $G(y)$  is in general different from  $H(x)$ ,  $p_z(z)$  is the same if either Eq. (8) or Eq. (9) is used. If we now apply the inverse function  $G^{-1}(z)$  to the  $z$ 's, the result would be a set of  $y$  levels with the specified density  $p_y(y)$ . In other words, if the  $z$ 's have a uniform density, the desired  $p_y(y)$  can be obtained by using the inverse mapping  $G^{-1}(z)$ . Therefore, if the original image is first histogram-equalized, and the new (uniform) levels are inverse-mapped using the function  $G^{-1}(z)$ , the result would be an image whose gray levels have the desired density  $p_y(y)$ .

The above conclusions can be expressed in terms of a transformation function  $T(x)$  from  $x$  to  $y$  by noting that  $y = G^{-1}(z)$  and, since  $z = H(x)$ ,

$$y = T(x) = G^{-1} [H(x)] \quad (10)$$

The histogram-equalization technique is a special case of Eq. (10) obtained by letting  $G^{-1} [H(x)] = H(x)$ .

The transformation procedure is summarized in Fig. 1. Figure 1(a) shows the original density function which is calculated from the image to be enhanced. Figure 1(b) shows the transformation function  $H(x)$  which maps  $x$  into  $z$ . Figure 1(c) is the result of this transformation. Figure 1(d) shows the inverse transformation from  $z$  to  $y$ . The result of this transformation, shown in Fig. 1(e), is the desired probability density function  $p_y(y)$ .

### III. EXPERIMENTAL RESULTS

In the results to be described below, the desired densities were specified by four parameters: mean ( $m$ ), height ( $h$ ) at  $m$ , left spread ( $s_L$ ) about  $m$ , and right spread ( $s_R$ ) about  $m$ . These parameters, which can be controlled by a joy stick with four degrees of freedom

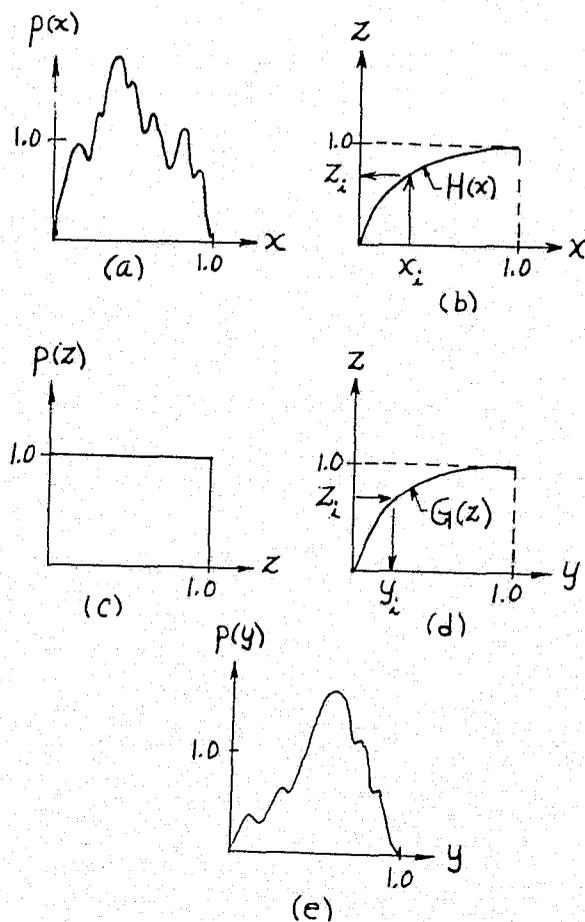


Figure 1

(see Fig. 2), are used to establish a piecewise linear approximation to the desired density.

Figure 3 shows the digitized image of a face, half of which is covered by a heavy shadow. In this particular case, the details of the hidden features could not be brought out by the TV controls. The histogram

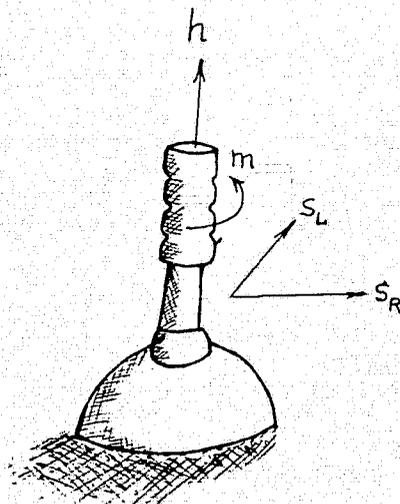


Figure 2

(i.e. the discrete equivalent of  $p_x(x)$ ) of the levels in this image is shown in Fig. 4(a). Figure 5 shows the histogram-equalized image and Fig. 4(c) shows its "uniform" histogram  $p_z(z)$ . The improvement of Fig. 5 over Fig. 3 is quite evident.

Figure 4(b) shows the specified density, Fig. 6 the enhanced image obtained using Eq. (10), and Fig. 4(d) the actual computed histogram. The difference between this histogram and the specified density is due to the fact that we are dealing with discrete rather than continuous levels. Comparing Figures 5 and 6 we see that the transformation given in Eq. (10) yields results which are a considerable improvement over the histogram-equalization approach. We have found this to be consistently true in a number of image enhancement experiments in which the two approaches have been compared.



Figure 5



Figure 3



Figure 6

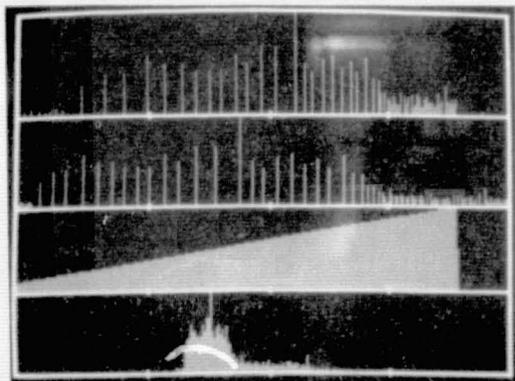


Figure 4(a) through 4(d) [from bottom to top]

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Yoram Yakimovsky  
 Jet Propulsion Laboratory, Pasadena

N77-29759

**ABSTRACT**

The sensory subsystem of the JPL robotics project has two types of inputs. The first sensory instrument is a pair of TV cameras, which provides a stereo view of the area of interest. The second is a laser range finder, which can be aimed in a requested direction and measure distances to a surface point that reflects the beam back. Both instruments are controlled by and are interfaced to a computer. The paper describes our calibration process and basic applications to obtain measurements of the external environment.

**SUMMARY**

The JPL robot is equipped with three remote sensing instruments—two TV cameras and a laser range finder (see Fig. 1). Problems of relative registration of the three instruments in three dimensions had to be solved before an effective use of the system could be made. The problems are nonlinearities in the scanning, drifts of scans as a function of time, and lack of thorough analysis of the internal properties of the instruments. To solve for the characteristic of the instruments with a minimum effort, semi-automatic calibration procedures of the instruments in three dimensions were developed.

Once the registration of the instrument is computed, the protocols of man-machine interaction must be defined so as to create an effective system. (The control monitors and teletypes are shown in Fig. 2.) This was done in our project with emphasis on achieving machine autonomy in the future. The goal of achieving machine autonomy calls for detecting objects and feature points, recognizing them, and measuring their 3-D properties. The elementary man-machine interaction is described in the paper. An example of a stereo display and cursors is presented in Fig. 3, and Fig. 4 shows verification by the laser range finder of the 3-D position of a surface point, computed by triangulation of the cursors' positions, of stereo TV pictures.

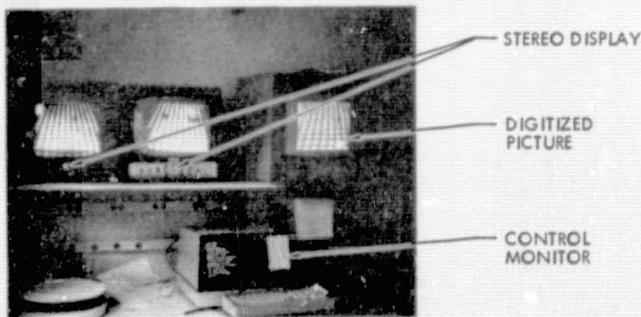


Fig. 2. Control monitors and teletypes



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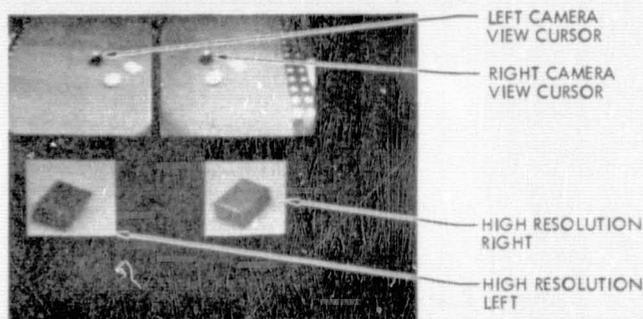


Fig. 3. Digitized stereo display and cursors

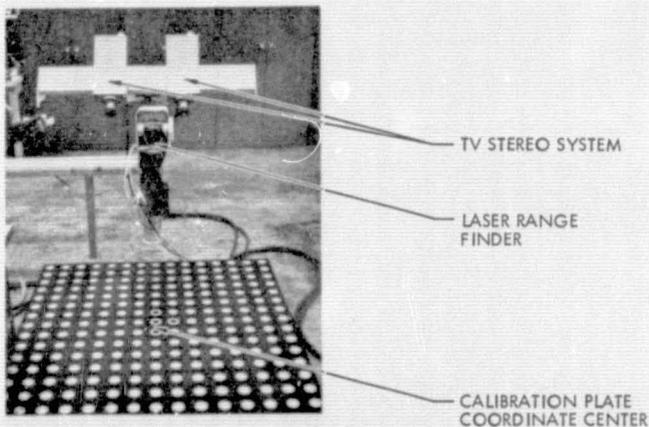


Fig. 1. Instruments and calibration plate

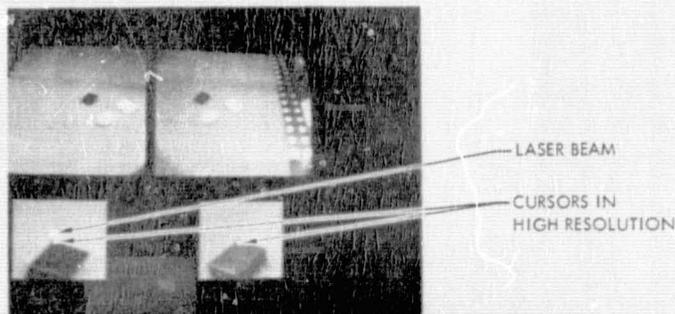


Fig. 4. Integrated use of stereo TV and laser range finder

<sup>1</sup>This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract NAS7-100, sponsored by the National Aeronautics and Space Administration.

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## PROXIMITY SENSOR TECHNOLOGY FOR MANIPULATOR END EFFECTORS.\*

Alan R. Johnston  
 Jet Propulsion Laboratory, Pasadena

Introduction

Optical proximity sensing techniques which could be used to help control the critical grasping phase of a remote manipulation will be described in this paper. Although manipulator technology is well developed, and has had many routine applications, one of the limitations in a remotely operated system is the lack of good sensory information to take the place of a human's sense of feel. Proximity sensors can be one means of simulating a sense of feel without requiring actual contact. They can measure the relative position of effector and object, and their output can be used for direct control of hand motion, if desired.

We feel that it will be desirable ultimately to devise ways of using the proximity sensor outputs in local control loops, leaving the basic relationship between operator and manipulator unaffected. The term reflexive control is useful to describe this concept, as its connotation is accurate. Reflex control inputs are visualized as supplements to the basic control loop involving the operator and manipulator. The operator would command the motions of the manipulator just as if the reflexive loop was not there. Sensor inputs would override or modify the operator inputs at critical points in such a way that his attention is not diverted from his visual display.

Earlier work has used tactile or touch sensing including investigations at Stanford Research Institute, MIT, and Stanford AI Lab. However, little work has been done with hand mounted optical sensors.

The proximity sensors described here use a triangulation geometry to detect a surface located in a predetermined region, a principle used in a larger sensor on the Shakey Robot at SRI, and also described in the literature by Benjamin and others.

The design of the proximity sensors themselves will be discussed, as well as their application to manipulator control with a local control loop, and possibilities for future development will be discussed.

\*This work was supported by the office of Life Sciences of the National Aeronautics and Space Administration under contract NAS7-100,

Sensor Description

The sensor concept is illustrated in Fig. 1.

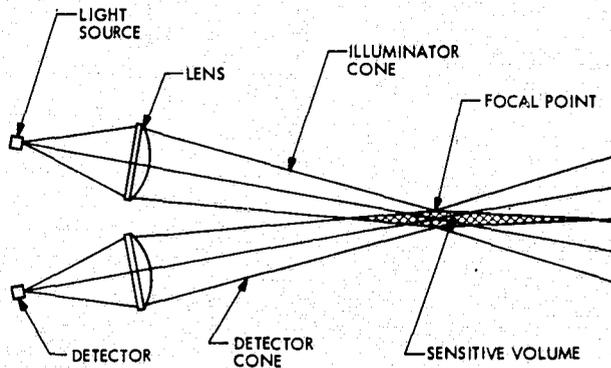


Fig. 1 Sketch Showing Principle of Operation of Sensor.

An illuminator and compatible detector are both focussed on a predetermined volume such that light diffusely reflected from a surface will be collected if the surface is located within the common focus or sensitive volume. If the surface is moved away from the region of focus, reflected light can not be collected because of the optical geometry used. The distance from sensor to focal point can be set by adjusting the convergence angle of the two beams.

The illuminator is a Gallium Arsenide LED, operated in a pulsed mode at approximately 1kHz. The detector is a silicon detector, and conventional phase detection techniques are used to extract the desired signal from noise. An appropriate optical filter is used to further reduce unwanted input to the detector, so that the sensor is insensitive to ambient light.

Both LED source and detector are roughly 1 mm in diameter and 1 mm long. Therefore it is quite easy to fabricate a device small enough that several can be mounted in the finger area of an effector. A photograph of a typical sensor unit is shown in Fig. 2, and in fact smaller sensors on the order of 3x5x5 mm have been built. A separate circuit card carries the electronics.

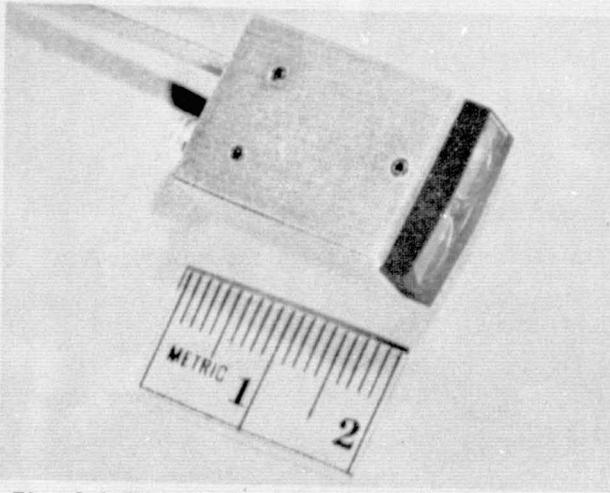


Fig. 2 A Photograph of The Proximity Sensor

The sensitive volume of the sensor can be shaped and the focal distance set by means of a replaceable lens mounted on the front of the unit. If the optics are sharply focussed, the sensitive volume can be made as small as 1/2 mm by 3 mm laterally, and roughly 2 cm in length at 10 cm focal distance. A larger sensitive volume is readily available with appropriate optics.

#### Manipulator Control Experiment

A pair of the sensors described above were used on an experimental manipulator to guide the effector into position for grasping under closed loop control. Lateral motion was controlled by the same two sensors to center the effector over the highest point of the object. The experiment was a simplified one mean feasibility of a concept, involving motion in two dimensions only. However, it illustrates how similar techniques could be extended in the future to three dimensional operations.

The sensors used were modified so that a proportional output was obtained over a 15 cm in nearly to contact. The two sensors were positioned such that the sum of their output indicated average vertical distance to the surface, and their difference was a measure of its slope. These signals were used to control effector motion in such a way that it was positioned directly above a local high point. Positioning was accurate enough to permit grasping of a reasonably regular convex object.

#### Discussion

It is straight forward to extend the experiment to three-dimensional control using four sensors, an effort to do so using the JPL NEVADA-Curv Arm is planned. The key to a successful application of these techniques, however, will be to devise acceptable ways to combine sometimes conflicting inputs from an operator, who may have limited vision, and the sensors, which have no judgement. Both techniques for automatic switchover and for mixing of signals should be considered.

In future work, the basic sensor will be modified to obtain a device specifically fitted to digital computer control techniques. By replacing the single solid state detector with a detector array, one can obtain a linear array of sensitive volumes. Each detector element would then sense a discrete position and would provide one bit of positional information. The sharply focussed optical configuration would be used in order to have each sensitive volume as well defined as possible progress on this idea and a cooperative optical proximity sensor will be discussed.

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## DESIGN FOR A THREE-FINGERED HAND

F. R. Erskine Crossley, Professor, and Franklyn G. Umholtz, Associate Professor of Mechanical Engineering  
University of Massachusetts, Amherst

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Design Rationale

At the start this question was posed: if an end effector of a manipulator arm is to be more than just a pair of parallel-acting jaws, what is the next step up? Should it have three or four fingers or jaws? Should it be anthropomorphic at all? The commission we received from NASA-MSFC (as interpreted) was for a general-purpose end-effector for use on the space manipulator proposed for the Shuttle program; moreover it should optimistically possess most of the capabilities of a human hand, and should also have peel-off value as a human prosthetic device, with this difference, that it must be separable at the wrist (distal to the wrist joint) from whatever arm it should be attached to.

A study was made of the capabilities of the human hand. It is known that mostly the hand is used for static gripping, and the present jaw-type device fulfills this reasonably well. We define a "manipulation" as an action (movement) of the fingers while holding something. The two most important manipulations for a garage mechanic were identified as:

- a) the pistol grip and trigger pulling,
- b) the transferring of an object from a finger-tip pick-up position to a firmly nested palmar grasp.

For both of these at least three fingers are necessary: two in apposition to hold the object, in the manner of parallel jaws; a third for the trigger or to retract the object held. (See Fig. 1)

Several controls are going to be necessary, and if these are to be operated successfully with television feedback an anthropomorphic form is desirable.

The design evolved through two mock-up stages. The final form is shown in the figure. It contains four electric motors. While thumb and forefinger bend, their ultimate phalanges maintain a parallel stance to one another. The grip centerline is at 45 degrees to the mounting base.

Design DetailsNew Finger Activation Mechanism

Several alternative mechanisms are in present use as finger activators. A crossed-four-bar linkwork design is used, for example, by Tomovic and others. All designs can be distinguished by the point at which the mechanism introduces the needed mechanical advantage. In the chain of the drive from motor to pressure surface the later that this velocity reduction can occur the better, for then the force-transmitting links can be lighter.

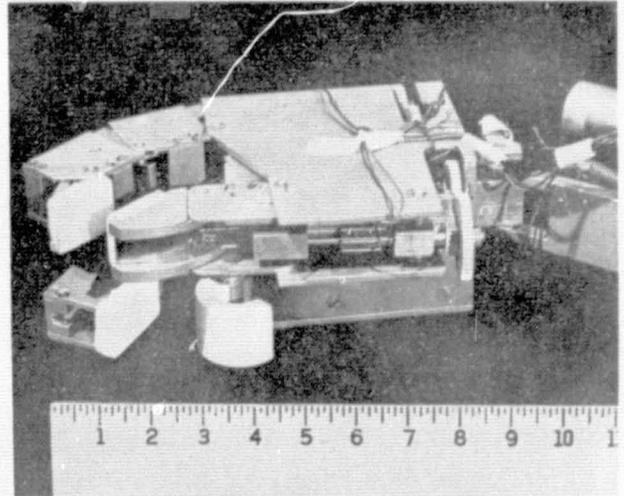


Figure 1

Photograph of A Three Fingere Hand

This design incorporates a new form of screw-operated turnbuckle to bend each interphalangeal joint. The screws are driven at an intermediate speed by electric motors.

The Thumb Nail

In tests on a preliminary model hand, the provision of a fixed thumb nail, projecting about 15 mm, with serrated and sharpened edge, allowed one to pick up certain objects otherwise very difficult, for instance a flat steel rule and a draftsman's triangular rule lying on a table. Because the extended nail would sometimes get in the way and hinder a simple grip, it was made retractable. An additional motor is needed to move it in curved guides. This adds to weight of course, and was probably a mistake: the fixed nail was better.

Controls

A set of button and switch controls were mounted on the hand of an exoskeletal master arm. These could be arranged on a joystick equally well. The controls were arranged in two sets: preset and run. Preset switches controlled whether thumb and forefinger moved together or independently, also whether the fingers open or close, also the thumb-nail motor. If the two opposing fingers run together, two buttons control when the motors drive the two or the third finger in the directions pre-chosen.

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THE LEMMA CONCEPT: A NEW MANIPULATOR

Dr. Leendert Kersten, Assistant Professor of Engineering Mechanics  
University of Nebraska-Lincoln, Lincoln

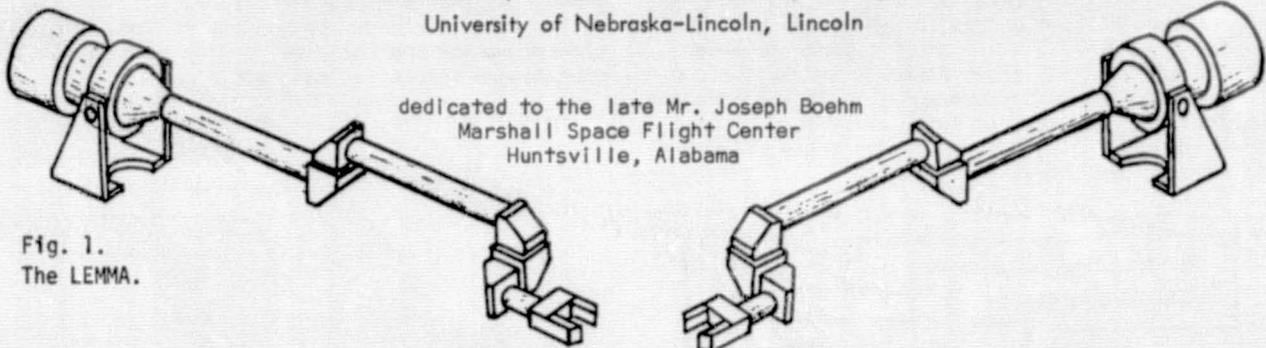


Fig. 1.  
The LEMMA.

In future space missions remote teleoperator systems will be applied in support of operations such as assembly, maintenance, repair, retrieval, hazardous activities, and other tasks. An important part of such systems is the manipulator arm and recent efforts in the design and development of such manipulators have resulted in some interesting, new and unique designs.

One of the stipulations for the required work-site manipulator modules states specifically that it shall have a working envelope similar to the human arm. With this requirement as a guide and trying to "borrow" from mother nature as much as possible, the LEMMA concept was born. The late Mr. Joseph Boehm\* christened the new idea with this name as it serves two purposes: 1. the concept took the D(=two) out of Dilemma by focussing on this proposal rather than an already existing arm and 2. such an action left LEMMA which is: "a preliminary proposition accepted for use in a demonstration," but more precisely defined as the Laboratory Engineering Model Manipulator Arm.

The analysis of the human arm establishes the workzone as the hemisphere; this axiom thus fixes two degrees of freedom at the shoulder (fig. 2) in order to reach the envelope of the hemisphere with the outstretched arm.

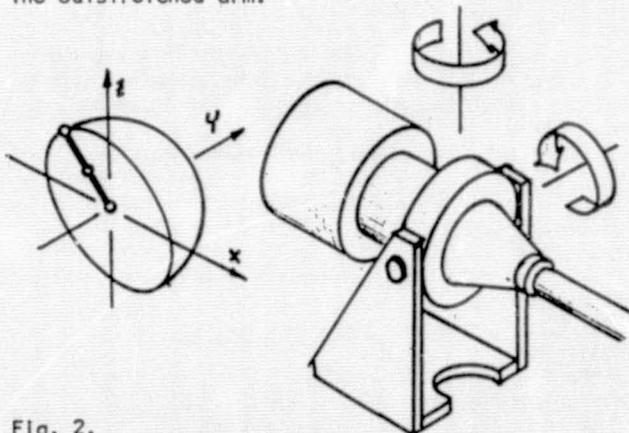


Fig. 2.  
Hemispherical Workzone for the Two Degrees of Freedom at the Shoulder.

\* Mr. Boehm came with Dr. Werner von Braun's group to the USA and has been with NASA until his death from cancer in December 1973.

To accomplish the touching of the shoulder by the end-effector, the upper-arm and lower-arm shall be of equal length, which requires one degree of freedom. A careful observation of the performance of a human arm reveals that the majority of elbow motions are of the yaw variety rather than the pitch variety. Most present day equipment utilizes the pitch movement in the elbow joint but Mr. Boehm's group decided to explore the more "human" motion of yaw. With the wrist motions remaining, and adhering to the six rules of sound kinematic manipulator design - especially rule 3: the last three degrees of freedom (exclusive of the end-effector) shall be as close as possible to the terminus and shall have mutually perpendicular axes - the yaw, pitch and roll sequence is accepted. The total number of degrees of freedom is 6 and has been illustrated in figure 3.

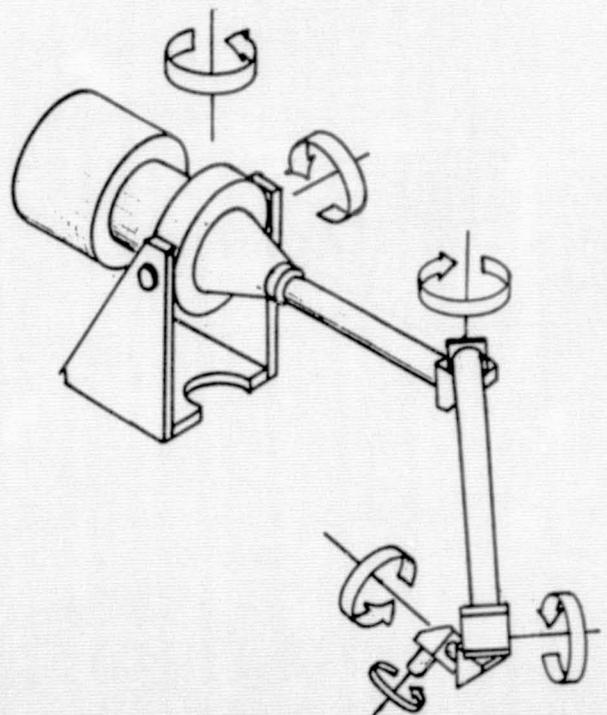


Fig. 3. Degrees of Freedom.  
Two in the Shoulder, One in the Elbow and Three in the Wrist.

A majority of manipulators feature drive mechanisms at the joints and this can be quite an obstacle when the work area of the end-effector needs to be seen via a television camera. To accomplish a minimum of joint obstructions, thus giving the maximum visibility, the bevel-gear configuration of the joints is utilized. This can not be achieved without a novel drive mechanism housed in the shoulder. Thus we see two separate ideas; 1. the differential drive assembly and 2. the concentric-tube arm configuration. In figure 4 we can observe the diagrammatic function of the drive assembly and figure 5 shows the assembly; figure 6 is an exploded isometric sketch.

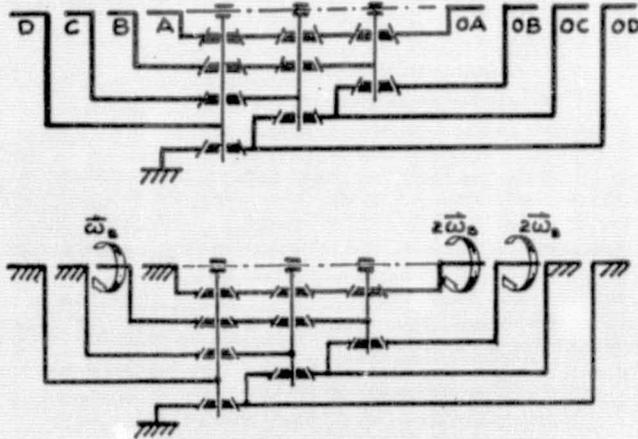


Fig. 4. Motion Analysis of Differential Drive

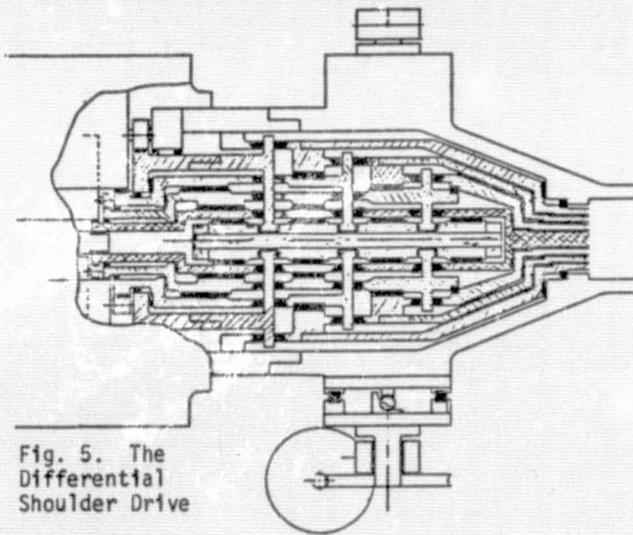


Fig. 5. The Differential Shoulder Drive

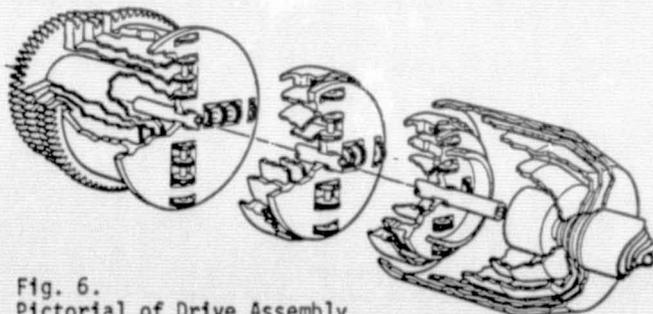


Fig. 6. Pictorial of Drive Assembly

The interesting feature of this kind of a drive unit is that it is a self-compensating assembly that maintains the relative position between various elements, unless specifically ordered to change the position between two related elements. The concentric-tube arm assembly utilizes the bevel gear arrangements as seen in figure 7. Here the roll motion is changed into a yaw motion. In a similar manner the roll-roll motion of figure 8 is transformed into a yaw-roll motion.

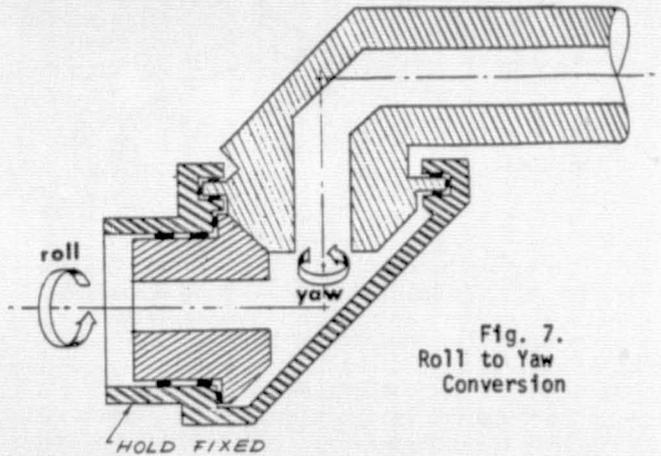


Fig. 7. Roll to Yaw Conversion

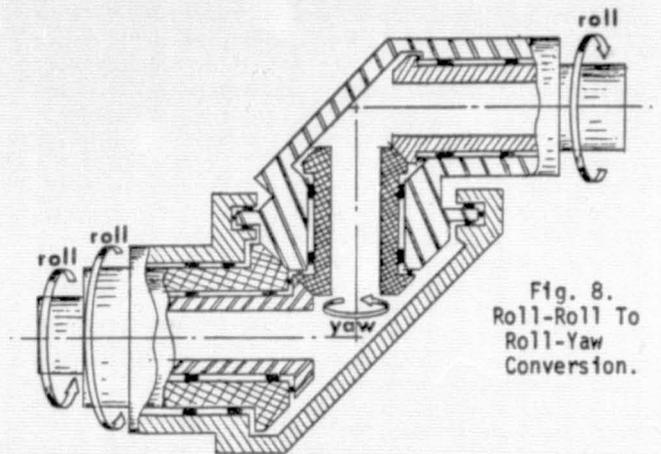


Fig. 8. Roll-Roll To Roll-Yaw Conversion.

A theoretical investigation of this arm has resulted in very encouraging data, showing that the required accuracy of the manipulator is certainly attainable.

The proposed Laboratory Engineering Model Manipulator Arm thus has become truly a LEMMA: i.e. a preliminary proposition accepted for use in a demonstration. The next phase will hopefully be the actual building of a prototype to prove under laboratory and field conditions the real feasibility of the concept.

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Leendert Kersten

Research Report 1973 NASA-ASEE

Summer Faculty Research Program

BER Report No. 165-94

## MANIPULATOR SYSTEM PERFORMANCE MEASUREMENT

M. Kirkpatrick, N. L. Shields, Jr., T. B. Malone

Essex Corporation, 11309E S. Memorial Parkway, Huntsville, Alabama 35803

## ABSTRACT

The research reported is part of a program to develop free-flying teleoperator technology for satellite servicing. The rationale for a series of manipulator system tests is presented. Data are reported on movement time in a fine positioning task using two different manipulator systems. The movement time data showed reliable effects of movement direction and index of difficulty. These data were considered to be baseline performance measures for the manipulator system used and modifications to the control and visual systems were suggested for future testing.

Introduction

The current paper presents research performed as part of an effort to develop manipulator system human factors requirements for earth orbital teleoperators. This work is being performed by NASA MSFC to provide data on man-machine interface criteria for free-flying teleoperator systems designed to service satellites.

The objective of the work reported here is to derive task requirements based on payload servicing missions, develop corresponding laboratory tests, and evaluate existing manipulator systems in terms of task performance. The manipulator system components being considered include:

- Manipulator arms
- End effectors
- Controllers
- Control laws
- Video systems

A number of manipulator systems may be constructed using various combinations of specific component types in the above areas. The data presented here are the result of testing selected manipulator systems on a task requiring fine position control with trained operators in the loop.

Test Approach

The test approach being employed is derived from requirements imposed on the manipulator system by the nature of satellite servicing operations. These tests were developed based on a survey of satellite servicing operations by Malone et.al.(1). The tasks and the manipulator operations they are designed to simulate are listed below.

- Fine tip positioning movements
- Cylindrical peg removal and insertion
- Position step input response

This research was supported in part by Contract NAS8-30545 from NASA Marshall Space Flight Center, Huntsville, Alabama.

- Attitude step input response
- Graded force application in one axis
- Opening and closing of fasteners
- Module removal and replacement
- Antenna extension

The rationale for the application of the tests to manipulator systems is that the tests are ordered in terms of difficulty and degree of specificity to servicing operations. The first five tests measure basic or general positioning, orienting, and forcing. The latter three tests are directly related to servicing operations. Manipulator systems are tested on later tests after having performed satisfactorily on earlier ones. During the process, changes in parameters are made based on test outcomes.

The present data were collected using the two manipulator systems described below:

## ESAM/Analog

- Five DOF Extendable Stiff Arm Manipulator
- Analog joystick controller
- Two orthogonal view video system

## RAM/TPC

- Six DOF Rancho Anthropomorphic Manipulator
- URS Matrix Terminal Pointer Controller
- Computerized resolved rate control
- Two orthogonal view video system

The minimum position change apparatus employed contained 16 conductive target contacts and one initial position contact. The end-effector held a stylus which permitted timing the movement from initial contact to target contact. Target size varied from 0.7 to 1.6 cm. and movement amplitude varied from 2.2 to 9.0 cm. The index of difficulty (ID) proposed by Fitts (2) thus varied from 1.5 to 4.8 bits. The task board was positioned near the center of the manipulator reach envelope and movements were required in 8 directions in the YZ plane. Five subjects completed all possible combinations of the 16 movements in 8 directions. To permit comparison of manipulator movement times to corresponding hand or manual times, each subject also completed the experiment manually by holding the stylus in his dominant hand.

Results

The movement times obtained were submitted to analysis of variance. All main effects--manipulator system, motion amplitude, target size, and motion direction were found to be significant at the .05 or .01 level. Interactions involving all four variables were also found to be significant.

For this reason, the effect of ID on movement time was assessed via correlation analyses applied separately to the manipulator system by motion direction combinations. The summary statistics resulting from these analyses are shown in Table 1.

Table 1 Movement Time Descriptive Statistics

	MD	MMT	$\beta$	r	TR
RAM/	0	53.8	14.5	.33 **	127.1
TPC	45	40.8	8.7	.28 *	96.4
	90	30.5	7.3	.25 *	72.1
	135	39.4	0.8	.02	93.1
	180	43.0	9.5	.29 **	101.6
	225	31.4	6.5	.24 *	74.1
	270	27.0	-0.1	.00	63.8
	315	32.2	4.3	.15	76.2
ESAM/	0	12.7	3.4	.37 **	30.1
Analog	45	9.3	2.6	.45 **	22.1
	90	13.7	1.4	.10	32.3
	135	9.9	2.5	.46 **	23.3
	180	14.0	3.7	.34 *	33.2
	225	9.8	2.5	.44 **	23.2
	270	12.7	4.8	.40 **	30.1
	315	9.0	4.0	.57 **	21.2

MD Movement Direction--degrees from north  
 MMT Manipulator Mean Movement Time--seconds  
 $\beta$  Least Squares Slope Coefficient--sec./bit  
 r Linear Correlation Coefficient  
 TR Ratio of Mean Movement Times--manipulator/  
 manual

\* p < .05  
 \*\* p < .01

Inspection of the mean time data shows that the task was completed more rapidly by the ESAM/Analog system than by the RAM/TPC system. Because a number of confounded differences exist between the systems, direct comparison is only tentative at present. One obvious difference is that the RAM arm contains one more degree of freedom than the ESAM. Further, the ESAM system is more amenable to command of one joint at a time. This may permit a strategy of independently nulling error in one axis at a time. This strategy would be difficult to implement with the RAM which requires coordinated joint action to achieve translation.

The two systems differ in terms of controller used. The test operators stated that the TPC controller had too little friction resulting in inadvertent cross-coupling. While the RAM arm has six joints, the TPC controller has only five outputs. This required the operator to achieve Z axis translation via a complex sequence of commands in the five controller axes.

The data should not be taken to necessarily support a five degree of freedom approach to the servicing mission. In the current test, the task board was placed near the center of the work envelope for both manipulators. If variation of the work in the envelope were present, the six DOF approach would presumably offer advantages in flexibility.

Table 1 also provides data on the relationship between movement time and ID. The relationship for the present data was assessed by obtaining the linear correlation coefficient as shown in Table 1. It may be seen that the coefficients are significant in most of the cases studied. The

data for the ESAM/Analog system show a generally higher degree of correlation between ID and movement time than do those for the RAM/TPC system.

The least square slope estimates are also shown in Table 1. These measure the additional time taken to process one additional bit of information. The slopes for non-significant correlation coefficients should not be taken as valid estimates. As would be expected, the observed slopes are many times greater than the .074 sec/bit value for manual movements reported by Fitts (2). In terms of comparison with values for other manipulator systems, Hill et. al. (3) reported a slope of little more than 1.0 sec/bit for a smaller scale RAM arm using direct vision and a master/slave controller. The increases over this value for the present systems presumably reflect the fact that these used hand controllers and video feedback.

Similar results were obtained for the manipulator to manual time ratio data. This measure was proposed by Vertut (4) who found time ratios ranging from 1.5 to approximately 100 for simple controlled movement and assembly tasks for a variety of manipulator systems. The current data show the time ratios for the ESAM/Analog system to be on the order of 20 to 30. The time ratios for the RAM/TPC system were found to be larger on the average and to show greater variability with direction of motion.

### Conclusions

The data presented provide baseline performance measures for two manipulator systems under the constraints of hand controller use and video feedback which are necessary conditions of remote teleoperator control from the shuttle. The data support the utility of the ID measure to quantify manipulator tasks and to generalize findings resulting from manipulator performance tests. Areas which should be incorporated into future testing include:

- Use of the TPC in conjunction with ESAM to determine controller effects
- Use of a 6 DOF controller for RAM
- Use of a two hand / two controller approach with RAM to eliminate cross-coupling
- Use of stereoptic video with both systems

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INERTIA FORCES IN ROBOTS AND MANIPULATORS

Michael S. Konstantinov, Professor

Higher Institute of Mechanical and Electrical Engineering, Sofia

Investigation of inertia forces in the linkages of robots and manipulators is closely related to the determination of the joint forces (loads) and therefore to the calculation of the actual joint sizes. Usually, the inertia forces in spatial mechanisms are determined by the matrix method, applied to the inertia tensors of the links. However, the use of that method calls for calculations associated with the acceleration of an arbitrary point (pole) on the link moving in the space, as well as with the angular velocity and acceleration of the link itself [1].

This paper deals with a method for the simulation of the dynamic behavior (inertia forces) of a solid performing a tridimensional motion, wherein a discrete system of mass points rigidly attached to the solid is used [2,3,4].

According to [2], three postulates are necessary and sufficient for dynamical equivalence: (a) the mass of the solid and the total of the concentrated masses should be equal, (b) the center of gravity of the solid and of the discrete system should coincide, and (c) the inertial ellipsoid of the solid and of the discrete system should be equal. These postulates are expressed by

$$\sum m_k = m \tag{1}$$

$$\sum \bar{r}_{m_k} = \int \bar{r} dm \tag{2}$$

$$\sum \{\bar{\rho}\bar{\rho}\}_{m_k} = \{JJ\} \tag{3}$$

wherein

$$\{JJ\} = \begin{Bmatrix} J_{xx} & J_{xy} & J_{xz} \\ J_{yx} & J_{yy} & J_{yz} \\ J_{zx} & J_{zy} & J_{zz} \end{Bmatrix}; \{\bar{\rho}\bar{\rho}\} = \begin{Bmatrix} x_k^2 & x_k y_k & x_k z_k \\ y_k x_k & y_k^2 & y_k z_k \\ z_k x_k & z_k y_k & z_k^2 \end{Bmatrix}$$

A specific model for general motion in the space is shown in Fig. 1. The point masses

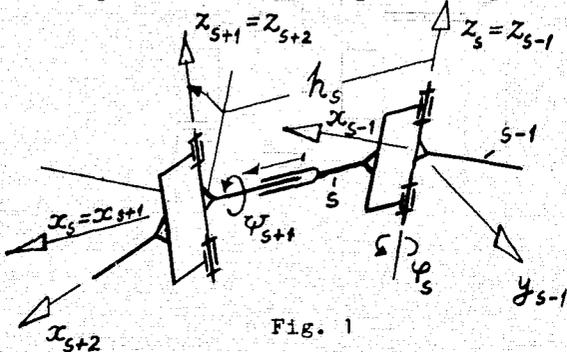


Fig. 1

$m_1, m_2, m_3, m_4$  correspond to the above conditions (1), (2), (3) reduced to

$$m_1 = m_2 = m_3 = m_4 = 1/4 m$$

$$x_1 = -x_2 = -x_3 = x_4 = x_0 = i_{xx}^0$$

$$y_1 = -y_2 = y_3 = -y_4 = y_0 = i_{yy}^0$$

$$z_1 = z_2 = -z_3 = -z_4 = z_0 = i_{zz}^0$$

Robots and manipulators mechanical arm/hand systems being, in fact, spatial mechanisms it is convenient to replace their links by point mass models [5]. Introduction of such models requires merely the identification of definite points on the link to be considered. The accelerations of these points are determined on the basis of a generalized three-link structure, illustrated in Fig. 2, taken

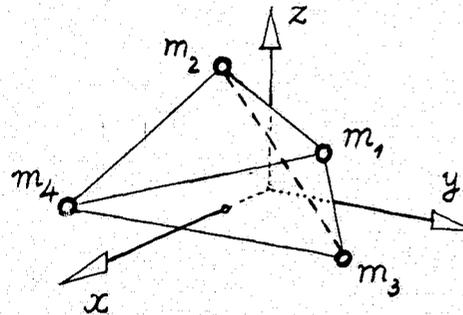


Fig. 2

as fundamental group, by the use of a vector-complex operator [6]

$$\begin{pmatrix} \bar{\lambda}_s \\ \bar{\mu}_s \end{pmatrix} = \begin{pmatrix} \bar{\lambda}_{s+1} \\ \bar{\mu}_{s+1} \end{pmatrix} e^{i\varphi_s}; \bar{v}_s = \bar{v}_{s+1} \tag{4}$$

wherein the conditional term

$$\bar{z} = \bar{\lambda} + i\bar{\mu} = \begin{pmatrix} \bar{\lambda} \\ \bar{\mu} \end{pmatrix}$$

expresses a complex vector.

The relative disposition of three adjacent links (S-1, S, S-1), pertinent to the structural composition, could be described by the recurrence operator algorithm

$$\left. \begin{aligned} \begin{pmatrix} \bar{\lambda}_{s-1} \\ \bar{\mu}_{s-1} \end{pmatrix} &= \begin{pmatrix} \bar{\lambda}_s \\ \bar{\mu}_s \end{pmatrix} e^{i\varphi_s}; \bar{v}_{s-1} = \bar{v}_s \\ \begin{pmatrix} \bar{\mu}_s \\ \bar{v}_s \end{pmatrix} &= \begin{pmatrix} \bar{\mu}_{s+1} \\ \bar{v}_{s+1} \end{pmatrix} e^{i\varphi_{s+1}}; \bar{\lambda}_s = \bar{\lambda}_{s+1} \end{aligned} \right\} \tag{5}$$

It is to note that (5) is a reversionary algorithm of the basic group shown in Fig. 2. Indeed, the algorithm of the accelerations is obtained by double differentiation of eq.(5). This is an acceleration operator.

In conclusion, it is demonstrated that the proposed operator is an appropriate means for the formulation of a computer program leading to the calculation of the inertia forces.

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## **SESSION III**

# **Remotely Manned Aerospace Systems**

## REMOTE SERVICING OF FREE-FLYING SPACECRAFT

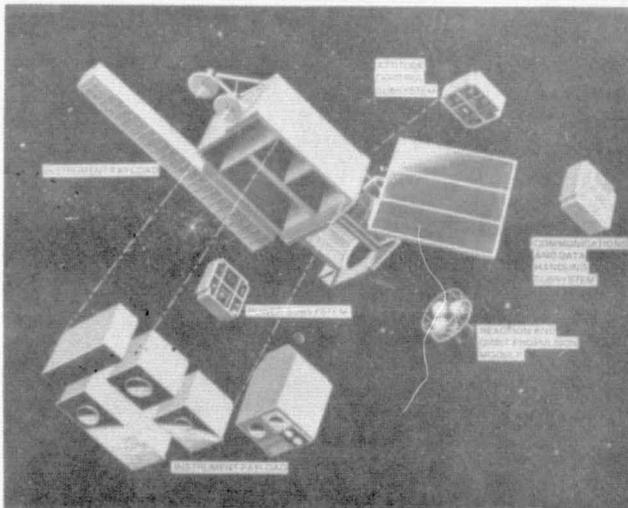
F. J. Cepollina  
Goddard Space Flight Center, Greenbelt, Maryland

J. M. Mansfield  
Rockwell International Space Division, Downey, California

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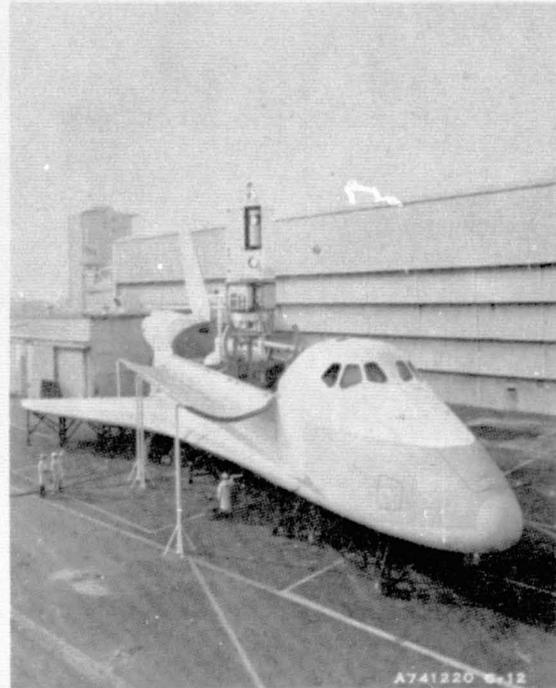
The Shuttle will provide flexible performance and many new utilities for potential users. Under contract to Goddard Space Flight Center (GSFC) in cooperation with Johnson Space Center, Rockwell International Space Division has conducted a ground simulation to demonstrate system compatibility by enacting satellite ground installation, orbit delivery, space servicing, and contingency retrieval with the space shuttle orbiter.

The basic configuration approach adopted by GSFC for the spacecraft (Figure 1) groups the standardized subsystems in the aft portion of the spacecraft and leaves the volume forward of the transition structure available for the mission peculiar equipment and sensors. The version used for this simulation is configured as an earth observatory with multi-spectral mapping and high resolution imaging sensors. Another version might have a gamma ray telescope or a collection of solar physics sensors. All modules including the propulsion package and the sensor modules are replaceable on orbit in the event of depletion, wear-out, malfunction, or the availability of an improved version.



Studies by Grumman, GE, TRW, and Aerospace have investigated the potential economic benefits of the modular approach selected by Goddard. They have consistently shown lower program costs with the utilization of the shuttle to support on-orbit servicing.

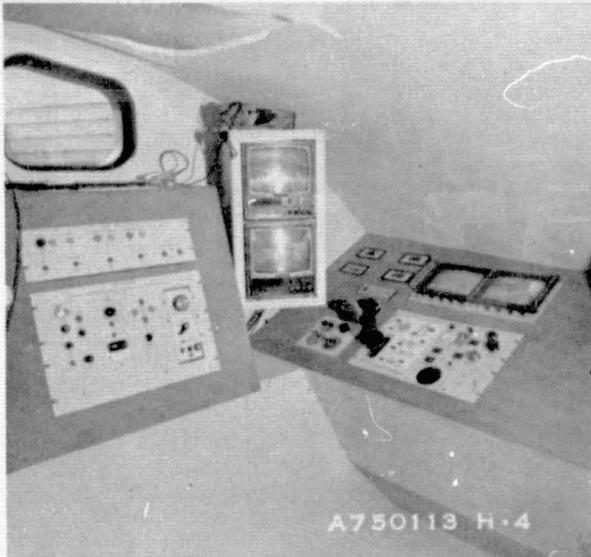
The spacecraft used for this simulation was an engineering model mockup assembled at GSFC. This particular unit is configured to be compatible with launch on a Titan vehicle prior to the shuttle era, with later servicing, retrieval, and relaunch on the shuttle. This spacecraft was installed in the shuttle orbiter mockup (Figure 2) together



with the full-scale engineering models of the retention, deployment, and servicing systems. These systems, collectively termed the flight support system, include a cradle to support the spacecraft, a positioning platform, a special purpose manipulator to perform the module exchange, and a storage magazine which holds the spare modules. The simulation illustrated the operations of these systems by performing a changeout of a subsystem module. The controls for the operation were installed at the same location in the shuttle cabin as the flight version would utilize (Figure 3). This permitted an assessment of the man-machine interfaces for this class of space operations.

The cradle is designed to provide the structural support of the spacecraft while it is stowed in the cargo bay. On a delivery mission, upon reaching the delivery altitude the positioning platform would be latched to the aft end of the spacecraft and it would then be erected into the vertical position. This allows it to be positioned and retained while it undergoes checkout.

The positioning platform also furnishes the functions of retaining and positioning the spacecraft for refurbishment missions. On a typical refurbishment mission the spacecraft would be captured by the remote manipulator system of the shuttle and berthed to latches on the positioning platform. The spacecraft is rotated to present the modules to be exchanged to the special purpose manipulator. This manipulator performs the exchange of modules between the spacecraft and the magazine. The module exchange magazine is a 4 degree-of-freedom device including a rotation in the pitch plane. This rotation is necessary to be able to address the modules in the spacecraft and to rotate them to the correct position for insertion in the magazine.



This simulation equipment utilized off-the-shelf hardware extensively and simplified designs to provide the basic functions at low cost. We feel that these activities have been highly beneficial in evaluating the basic engineering feasibility of utilizing the shuttle for on-orbit servicing of unmanned spacecraft. In addition, considerable insight has been obtained in the areas of ground handling and installation of payloads in the cargo bay, the simplifications permitted by utilizing man-in-the-loop, and the effectiveness of the basic shuttle TV to monitor details of operations in the cargo bay. The operations have been shown to be basically simple and easy to learn. A highly trained astronaut is not essential. Significant changes in the design of the module exchange elements have been identified well before the commitment to flight hardware. We feel that this project has been a good, early example of shuttle users and the shuttle program cooperating to get the most out of space for the dollars invested.

The module latches designed for the Goddard spacecraft utilizes a passive threaded shaft in each corner of the spacecraft opening and driven nuts on the modules themselves. Insertion is aided by guides and rails in the corners of each module. The concept for establishing the electrical connection is that the connector on the back surface of the module is driven into a receptacle on the spacecraft while the module latches are being drawn down tight.

After the module is replaced in the spacecraft and latches torqued down, the spacecraft is retained on the positioning platform while a checkout is performed. In a normal refurbishment mission the remote manipulator system would then attach to the spacecraft and move it to a safe distance from the shuttle so that it could resume its normal operational mission. In the event that the replacement of the module does not restore the spacecraft to its full operational capability, the spacecraft is rotated to its stowage attitude and lowered into the cargo bay. The whole system is thus stowed in the cargo bay for return to earth, rework, and subsequent relaunch.

Control of the whole simulation operation was under direct control of the operator in the cabin. The direct vision available from the cabin was found to be extremely effective in providing good controllability. The direct vision is supplemented by the baseline shuttle TV cameras. These include one that is on the tip of the remote manipulator system and one each on the forward and aft bulkhead. One of the examples of the use of direct vision to replace the complexity of feedback circuits and sensors is the rotational positioning of the magazine. It was found to be very simple for the operator looking directly out of the window of the shuttle cabin to position the magazine very precisely utilizing indexing marks.

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## ON-ORBIT SERVICEABLE SATELLITE DESIGN

Abraham Fiul

TRW Systems Group

Satellites can be designed so that failed or worn-out equipment can be replaced while the satellite remains on-orbit. Operation of satellites in this mode is found to be cost effective for long term satellite fleet operations at high altitude when compared either with satellite replacement or with satellite retrieval and ground refurbishment modes. The favorable economics result from a reduction in expenditures for hardware and from a reduction in the number of launches required to support fleet operations. Preventive maintenance cuts the number of satellite failures and launches.

Satellite on-orbit repair must be kept simple. This is particularly true when the satellite is in a high orbit where human skills cannot be applied. A practical approach is to modularize the satellite and to design the modules so that their removal and replacement can be effected by simple motions. On-orbit repair can be reduced to replacement of modules which contain failed or worn-out equipment. It is neither necessary nor even desirable to attempt to replace individual pieces of equipment. It is found that the economics are quite favorable even when the modules contain whole subsystems and only one or two pieces of critical equipment have failed. If the modules can be retrieved so they can be repaired and reused, additional savings accrue.

Satellite servicing is accomplished in high orbit by a service unit mounted on an upper stage which provides propulsion and guidance. The service unit contains a docking system (e.g., the Apollo type probe-drogue), a storage magazine to contain replacement modules, and a handling mechanism which effects the interchange of modules between the satellite and service unit. A system of arms and linkages holds the handling mechanism and positions it over the face of the satellite (or storage magazine) so that it can attach itself to the replacement modules. Control of the linkages and handling mechanism can be provided either by a stored program or by ground command. In the latter case, television cameras and a reasonably wide band communication link are needed.

The on-orbit serviceable satellite has a backbone structure to which replaceable modules are attached. An egg crate like structure is found advantageous in many applications. The modules are inserted into the openings and bolted to the structure. The backbone structure also carries a main wiring harness which provides electrical power and signal connections between the modules. The replaceable modules are structurally autonomous. They support the equipment they contain and transfer the launch loads to the backbone. The modules can be attached to the backbone structure by a three point support consisting of a system of cones and wedges. Fastening can be achieved by a single bolt. The on-orbit serviceable satellite is found to be heavier than the conventional expendable satellite primarily because of the less efficient structure.

The module attachment and fastening system permits a relatively simple design of the service unit handling mechanism. A bolt driver and a closely proximate latching probe is incorporated into the mechanism. The forces which must be exerted to engage or disengage the module fastening bolt are reacted locally and are not transmitted through the relatively long arms which are used to position the mechanism on the satellite or service unit magazine face. This concept permits a light weight service unit which can service large satellites.

Most of the equipment currently used in expendable satellites is directly useable for on-orbit satellites. Two changes in subsystem design approach are, however, desirable. These are in the electrical power and signal distribution systems. In conventional satellites, command and telemetry functions are implemented using a separate wire for each function. As a result the equipment which provides command dissemination and data collection have many hundreds of pins in their connectors. The requirement for simple replacement of modules appears to favor a reduction in electrical connector pin count both to reduce forces for making and breaking connections and also to permit the use of larger and more rugged connectors. A data bus which uses a time sequenced stream of data reduces this count to perhaps three pins. The system requires the addition of a remote terminal unit in each module to provide local decoding of commands and encoding of data.

The conventional electrical power control and distribution system also requires modification. It is necessary to design it so that power can be selectively shut down in each of the modules which are to be replaced. It is also necessary to shut down the entire power control system so that it can be replaced if necessary. This requires the addition of a circuit breaker system which is commandable from the service unit since it is mandatory that the satellite be powered up before separation.

It is also possible to limit power distribution to primary power and to provide secondary power conversion within each module. This approach further reduces connector pin count but at a slightly increased expense for power conversion.

The number of modules used in packaging the satellite avionics equipment is a design variable. Two contradictory factors operate. Satellite weight minimization (a desirable feature for deployment) is favored by using a few modules, say one per subsystem. On the other hand, preventive maintenance on a fleet of satellites is favored by using many modules since each is then lighter and more satellites can be visited when a service flight is made. The question becomes important when service tug performance is limited. It appears, however, that when module size permits visiting two to three satellites on a

single flight, a large fraction of the benefit from servicing is achieved. Avionic module weights of the order of 70 pounds on the average satisfy this condition even for relatively low performance tugs.

## ORBITAL SERVICING AND REMOTELY MANNED SYSTEMS

George W. Smith, Manager, Man Machine Systems, and Wilfred L. DeRocher, Jr., Departmental Staff Engineer

Martin Marietta Corporation, Denver

The potential of concepts and techniques of remotely manned aerospace systems to fully exploit the utility and benefits of orbital servicing is discussed in this paper. Many studies (1-5) have concluded that orbital servicing can significantly enhance the primary goal of the Space Transportation System (STS) -- to reduce the cost of space programs while satisfying their mission requirements. Orbital servicing in the form of module exchange enhances the STS goals through replacement of failed equipment, resupply of consumables, and updating of obsolete equipment. However, module exchange in space is an operation that is generally conducted at a distance, a situation where remotely manned systems can make a significant contribution.

### Orbital Servicing

The primary orbital servicing operation discussed, module exchange, has been shown to be economically and programmatically advantageous over expending the spacecraft (no servicing) or ground refurbishment (bringing the spacecraft to the ground for servicing and then placing it in orbit again). Studies led to the conclusion that spacecraft can be designed to be serviceable with some weight and volume penalties but with relatively low cost penalties. Modules can contain entire subsystems, parts of subsystems, experiment or mission equipment, can have all redundant elements in one module or can have them spread over several modules. The reasons for replacing a module are: (1) the module has failed, (2) the module has worn out (e.g., batteries), (3) the consumables have been expended (e.g., hydrazine tanks), and (4) the equipment requires updating (e.g., a new experiment design). For the STS missions, a review\* of the July 1974 SSPD (6) revealed 49 spacecraft types where orbital servicing deserves serious consideration.

A survey of servicing (module exchange) systems identified fifteen different system concepts described in the literature (1-5,7) that exhibited a range of versatility, complexity, and capability to accept a wide range of spacecraft characteristics. Those approaches (Table 1) were categorized as shown in the table and a single representative selected for each class based on level of definition available and design/utility superiority. The resulting seven then were evaluated for versatility, mechanical advantage, number of mechanical functions, docking mechanism dependency, stiffness, size, weight, reliability, application to both low- and high-earth orbit, variety of spacecraft types accommodated, dependence on docking mechanism type (central or peripheral), and access to multiple spacecraft surfaces. The result was that a pivoting arm, a general purpose manipulator, and the Orbiter cargo bay module exchange mechanism (discussed in a parallel paper) represented the range of useful orbital servicer mechanisms. This selection was primarily based on

\* This work was performed under NASA Contract NAS8-30820.

Table 1 Summary of Orbital Servicing Systems

McDonnell Douglas Astronautics Company Direct Access Aerospace Corporation
Bell Aerospace Cartesian Coordinate
Rockwell International Unmanned Orbital Platform A (External) Pivoting Arm
Rockwell International Unmanned Orbital Platform B (Internal)
Marshall Space Flight Center
TRW, Inc
Bell Aerospace Cylindrical Coordinate
General Purpose Manipulator
Rockwell International Geosynchronous Platform
McDonnell Douglas Astronautics Company External
Martin Marietta Corporation General Purpose
General Electric Advanced Geosynchronous Observation Environmental Satellite
Shuttle Cargo Bay Only
Marshall Space Flight Center
Rockwell International Earth Observatory Satellite
SPAR Aerospace Products, Ltd/Dilworth, Secord, Meagher & Associates Earth Observatory Satellite

need to give designers of on-orbit serviceable spacecraft the greatest latitude possible in number of modules, module size, module shape, module location, and module orientation.

The pivoting arm module exchange mechanism (Fig. 1) is a four degree-of-freedom (DOF) concept that removes/replaces modules axially from the end of a spacecraft. Shown in Fig. 2 is a seven DOF general purpose manipulator that removes/replaces modules radially from the outside of the spacecraft. An on-orbit servicer consists of the exchange mechanism to move the modules, a storage rack for the new and failed modules, and a control electronics assembly (CEA).

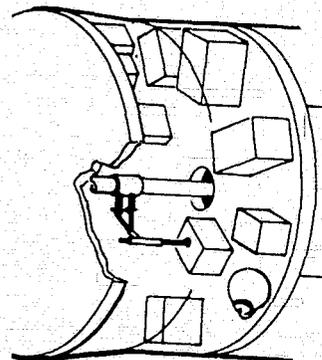


Fig. 1 Pivoting Arm Servicer Mechanism

Orbital servicing poses the control requirements listed in Table 2. The general task is to unstow the servicer mechanism, remove a failed module from the spacecraft, stow the failed module, locate the replacement module in the storage rack, place the replacement module in the spacecraft, verify that the replaced module is latched in place, repeat as necessary, and then restow the servicer mechanism.

### Control System Alternatives

Three control modes are addressed: automatic, supervisory control, and remotely manned.

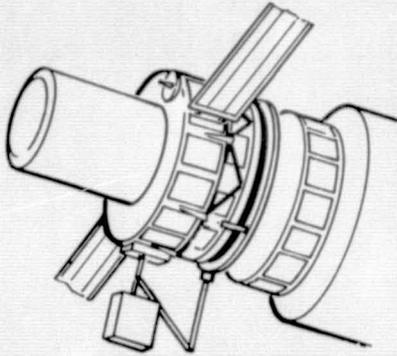


Figure 2 General Purpose Manipulator Servicer Mechanism

Servicing in geosynchronous orbit is our example case, though much of what is said also applies to operation in the Orbiter cargo bay.

Table 2 Control System Requirements

Exchange Modules One at a Time
Accommodate a Variety of Module Sizes, Masses, Locations, and Orientations
Operate with Different Spacecraft on a Single Mission
Up to 25 Module Exchanges per Flight
Provide Backup Modes
Generate Signals for Individual Mechanism Joints
Provide Required Accuracy and Repeatability
Compensate for All System Tolerances
Avoid Control Anomalies (e.g., Singular Points)
Provide for Hazard Avoidance
Provide Suitable Stiffness
Be Compatible with Structural Flexibility
Minimize System Data Rates
Accommodate Data Transfer Delays

The automatic mode involves a CEA that controls all of the module exchange activities including module trajectories, hazard avoidance, sequencing, activity completion indications, redundancy, and fail-safe aspects. The automatic mode can satisfy most of the Table 2 requirements. It particularly minimizes communication system data rates and the effects of data transmission delays. The difficulties lie in accommodation of system tolerances and the approach to the fail-safe/backup mode considerations. There appears to be no cost effective way to ensure fail-safe operation and to provide a backup mode for fully automatic operation.

The supervisory control mode involves a CEA that controls the detail module exchange activities including module trajectories, hazard avoidance, and some of the redundancy aspects. Man, through a command and data link, selects sequencing, acknowledges completion, and provides some of the redundancy and fail-safe aspects. To minimize communications data rate, it is assumed that the supervisory mode does not involve a television system. The supervisory control mode also can satisfy most of the Table 2 requirements. Supervisory control will require higher data rates and be slightly more affected by transmission time delays; neither effect is very significant. However, supervisory control is similar to automatic control in accommodation of system tolerances. It is possible to involve man in the measurement of system errors and their introduction into the CEA biasing scheme. With regard to the fail-safe and

backup requirements, the supervisory control mode is no better than the automatic mode unless the operator is provided with more data and control path alternatives.

The remotely manned mode involves an on-board CEA and sensor system, a two-way communication link, and an operator at a control and display station. The operator controls all of the module exchange activities including module trajectories, hazard avoidance, sequencing, activity completion acknowledgment, and fail-safe aspects. The redundancy aspects would still be a part of the machine. Module trajectories would be generated in response to the operator's control inputs. Multiple DOF hand controllers appear suitable for this task when used in a rate control mode. The use of inner-loop force feedback, where the forces at the end effector are measured, and signals generated to reduce the forces (and moments, in some cases) that are not in the desired direction to zero, may be very useful. Television is the obvious visual sensor for orbital operations. The remotely manned mode can satisfy many of the Table 2 requirements. It does require the highest communications data rates and is most susceptible to data transfer delays. Hazard avoidance in the remotely manned mode becomes difficult because the number of trajectories that might be commanded increases significantly. Backup modes can be provided for remotely manned operation.

#### Recommendation

Each of the three control modes appears to have both good and difficult areas; thus, it is recommended that a combination system be further investigated. It would consist of supervisory control with remotely manned backup as described in Table 3. The remotely manned system should also be considered for measurement of initial alignment errors so that these error measurements can be used, on-board, to generate exchanger mechanism bias signals. When the TV system is to be used only in a measurement and backup mode, it may be possible to use very low frame rates, say one picture per minute, and thereby significantly reduce the communications data rate.

Table 3 Recommended Control System Characteristics

Primary Mode - Supervisory Control
Backup Mode - Remotely Manned Control
Stored/Interpolated Module Trajectories
Hazard Avoidance
Supervisory - Precalculated
Remotely Manned - TV and Ground Computer Graphics
System Errors Measured by Man and Biased On-Board
Separate Translation and Rotation Hand Controllers
TV and Mechanism Position Displays
Mechanism Joint Control
Supervisory - Position
Remotely Manned - Rate
TV Refresh Rate - Three per minute

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## SPACE TUG SPACECRAFT/MODULE EXCHANGER (ON-ORBIT SERVICER)

Fritz C. Runge

McDonnell Douglas Astronautics Company, Huntington Beach, California

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On-orbit exchange of spacecraft modules containing experiment or subsystem hardware or consumables will be performed at geosynchronous altitudes with the Space Tug and at lower altitudes with the Shuttle. This unique service capability of the new reusable Space Transportation System will provide considerable benefits to future spacecraft programs. This paper addresses the remotely-controlled, Tug-based, on-orbit module exchanger service in particular.

On-orbit servicing offers two significant benefits, namely, (1) sustaining hardware performance and (2) changing of scientific or applications payloads for multiple use of a given spacecraft. Replacement of malfunctioning spacecraft or experimental hardware can result in substantial operational cost savings for the spacecraft. More significantly, the exchange of experiment hardware in orbit will permit an increased number of scientific experimenters and applications specialists to use a given spacecraft over the years in a given mission. Here, therefore, is a means for increasing the number of users of and thus constituency for space programs in general.

On-orbit replacement of spacecraft modules requires a servicer mechanism which incorporates high operational and volumetric efficiency plus high reliability. One promising concept for such a Tug-mounted spacecraft module exchange is the McDonnell Douglas Direct-Access Servicer. This servicer can also be used in low orbit, mounted on the Shuttle. In this concept, push-pull injector/retractor devices are combined with a rotating indexer to provide a minimum-complexity mechanism with a high capacity for coincident exchange of many modules. "Minimum length for the functions provided" is also a salient feature of this mechanism, which is important since length is at a premium when stages and single or multiple payloads are combined in the Shuttle cargo bay. The concept for this servicer is also uniquely cost effective in terms of resource utilization since it puts to secondary use (for the module injection/extraction) the available push-pull stroke of the Tug/payload docking mechanism. This concept can be put to widespread use in a number of programs for economy and standardization in the spacecraft community. It was designed to operate with at least three completely different types of spacecraft which were selected as representative of the heavy traffic in prospect of geosynchronous altitudes. Complementary serviceable designs for these spacecraft were developed in concert with the MDAC Servicer by General Electric and Fairchild Industries to confirm the integration feasibility of the overall approach.

This servicer concept was developed under Contract NAS8-29743 with the NASA Marshall Space Flight Center.

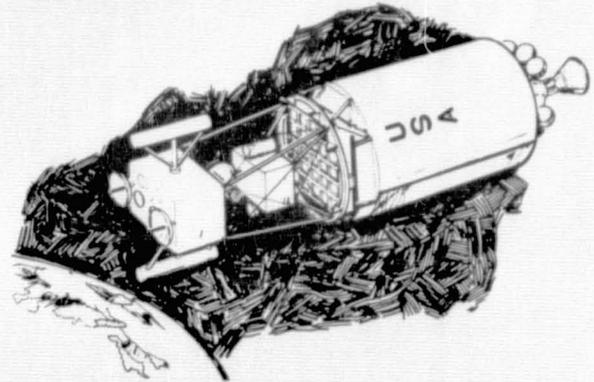


Figure 1. Module Exchanger (Servicer) Being Delivered Behind Two Satellites on Tug

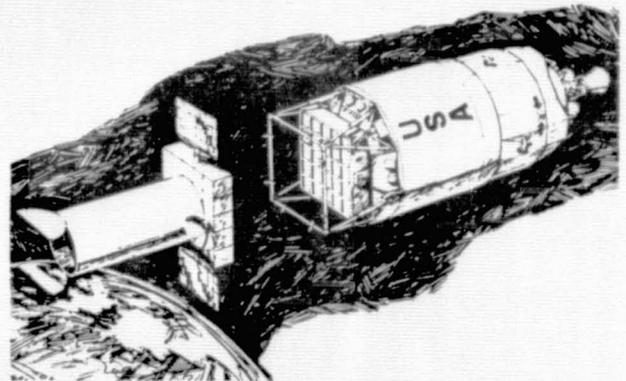


Figure 2. Tug Servicer Approaching Satellite to be Serviced

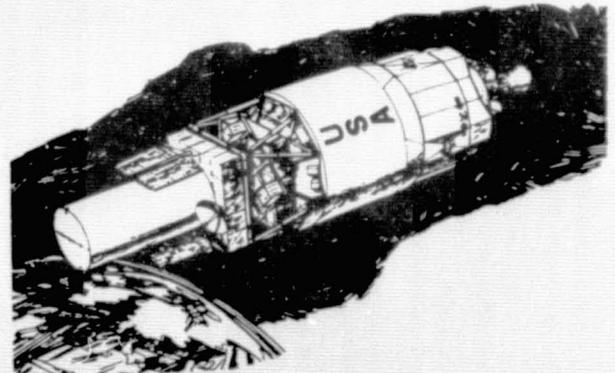


Figure 3. Satellite Being Serviced (Modules Being Exchanged)

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A USER ASSESSMENT OF SERVICING AT GEOSTATIONARY ORBIT

Gary D. Gordon, Senior Staff Scientist  
 COMSAT Laboratories, Clarksburg, Maryland 20734

A number of studies have concluded that orbital servicing will reduce the cost of space programs. Servicing has been assessed from the viewpoint of a commercial user of communications satellites at geostationary orbit. The need for servicing is emphasized by looking at the history of failures and defects occurring in communications satellites. The methods used in servicing have been evaluated in terms of the needs of a communications satellite user; most assumptions made in previous studies appear reasonable, but some different methods are suggested. A system that utilizes servicing has been studied, and some benefits in addition to cost savings have been identified. While this study has emphasized communications satellites, most of the assumptions and conclusions apply also to earth observation satellites at geostationary orbit.

Need for Servicing

To evaluate servicing, it is useful to look at past failures and defects that occurred on communications satellites (see Table 1). While this list is not complete, and the same failures will not occur in the future, the overall picture presented by these failures is probably applicable to failures in the future. Note that some satellites continued to provide service in spite of defects in some component.

In the column labeled "type," an effort has been made to classify failures in terms of reliability. 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 occurrence does not change the estimate of the component reliability. A "wearout" failure occurs late in the design life of the satellite; it may be an actual wearing out or some other expected failure such as fuel depletion. The column entitled "reparable" is an estimate of whether such a failure is serviceable; this depends on how much of the satellite is built to be serviceable.

A striking feature of this table is the large number of design failures. This makes servicing more attractive for two reasons:

- a. fixing a satellite early in its design life provides years of additional service, and
- b. often such a failure suggests servicing similar satellites in which failures have not yet occurred.

Suggested Methods of Servicing

Other studies have shown that, for servicing to be cost effective, the satellite must be modularized. Also, because it is uneconomical to send men into geostationary orbit, operations must be unmanned. It is further assumed that satellites will be body stabilized rather than spin stabilized. While several studies have maintained that servicing of spinning satellites is technically feasible, it is more cost effective for body-stabilized satellites.

Table 1. Typical Communications Satellite Failures or Defects

Satellite	Component Failure	Type	Reparable
SYNCOM, INTELSAT II, III	apogee motor	design	no
INTELSAT II	fuel lines	design	probably
INTELSAT IV	thruster	design	yes
INTELSAT III, TACSAT	structural bearings	design	difficult
NIMBUS	solar array bearings	design	difficult
INTELSAT II	solar array degradation	design	probably
INTELSAT II, III, TELSTAR	battery	random	yes
INTELSAT III, IV	earth sensor	design/random	yes
INTELSAT III	receiver	design	yes
INTELSAT III	transponder	random	yes
SYNCOM	telemetry	random	yes
TELSTAR, COURIER	decoder	design	yes
EARLY BIRD	fuel depletion	wearout	yes
RELAY, TELSAT	power conditioning	random	yes
DSCS-2	deployable structures	design	no
INTELSAT IV	telemetry beacon	random	yes
ATS-5	attitude control	design	no
INTELSAT III	low orbit	random	yes
INTELSAT IV	receiver	design	yes
WESTAR-1, SMS-1	low orbit	design	yes

This paper is based upon work performed in COMSAT Laboratories under Contract NAS 8-30849.

It is reasonable to assume that the satellite attitude control is functioning to the extent necessary to stabilize the satellite for rendezvous and docking. While this may not be always true, most communications satellites have a number of backup modes of attitude control. It is more cost effective to neglect the small probability of a complete failure in the attitude control system; should it occur, the satellite will have to be replaced rather than serviced.

Even with the Space Transportation System, the costs of returning modules to the ground for refurbishing or analysis are prohibitive. While exceptions are possible, the bulk of the modules should be left in geostationary orbit. (Returning modules to prevent litter in space is a separate consideration that should not adversely affect the concept of in-orbit servicing.) Failure analysis based on telemetered data has been adequate to diagnose most failures in communications satellites.

There are many communications satellites in operation in geostationary orbit, and the weight of the modules is small. To minimize costs, it is better to service several satellites in a single mission and to share the transportation costs of the servicer. The tug can perform a few servicing operations, although its time in geostationary orbit is limited by the cryogenic fuels used. A free flying servicer can be left in geostationary orbit, perform many servicing operations on different satellites, and be resupplied with fuel and modules periodically.

Satellites that are still operating should be serviced. Design failures can be eliminated, failed redundant components replaced, wear-out items such as batteries replaced, and fuel added. If only failed satellites are serviced, the probability of servicing a satellite is low; if the probability is low, then it is difficult to justify building a serviceable satellite. The possibility of servicing a satellite while it is operating needs further study. While there are problems involved in shutting off power to a module and in maintaining attitude control, they may not be insurmountable. Even if an outage occurs during the shock of docking, it may be preferable to switching the traffic to a spare satellite.

#### Benefits of Servicing

Most studies have concentrated on the average cost of a satellite system. A comparison of the figures with and without servicing shows a cost advantages for the former. Also of interest to satellite users is the possibility of decreasing costly overruns due to design failures or to statistical fluctuations in random failures. Even if the average costs were the same, servicing would be attractive if it can be shown that the 95-percentile point (costs

will be below this point 95 percent of the time) for servicing is substantially less than that without servicing.

In addition to cost, servicing offers the possibility of improved service. Commercial satellite systems need to have high reliability and availability, as demonstrated by the in-orbit spares that are maintained. System availabilities of the order of 99.99 percent are needed. Servicing a satellite can improve its reliability in many ways, and thus improve the effectiveness of the communications system.

THE ASSEMBLY OF LARGE STRUCTURES IN SPACE

George W. Smith and Shepard B. Brodie  
 Martin Marietta Corporation, Denver

This is a summary of a paper that discusses the work\* being done at Martin Marietta Corporation on the methods and techniques for orbital assembly of large structures. Two examples are used in the study; namely, a 200-meter diameter radio astronomy telescope and a 1000-meter diameter microwave power transmission system antenna. The microwave power transmission system (MPTS) is part of a solar power station satellite that will be used to convert orbital solar energy into ground electrical energy. The techniques developed for assembling the support structure for this microwave antenna will be discussed here.

The MPTS is a flat antenna that is to be operated in geosynchronous orbit. A baseline design is presently being developed by Raytheon and Grumman for NASA\*\*. We have modified the baseline design to make the structure more readily transportable by the Shuttle and more feasible to assemble in space.

Our design is made up of 2520 60-ft cubes. Figure 1 shows the support structure. A standard 60-ft cube is shown in Figure 2. This cube is composed of triangular horizontal beams and square vertical beams. This structure is self-supporting and there is no limit to the number of cubes that can be added to it in either direction. Adjustment points are built into each joint to allow continuous alignment as the structure is built.

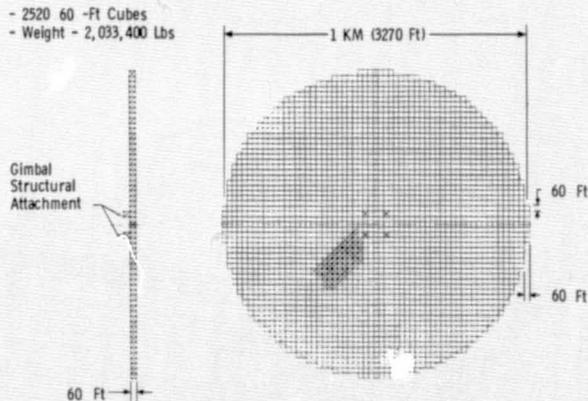


Fig. 1 Total Microwave Antenna Support Structure

We have investigated several techniques for attaching the structural mating joints. We have concluded that a permanent bond is required. Our present concept utilizes welding for joining the beam member pads. Small, electrically activated charges are imbedded in each attachment pad. After final alignment, these are activated and metal is fused between the pads at predetermined spots. Pyrotechnic devices are used to drive locking pins into the sliding tubes which serve

\* Orbital Assembly and Maintenance Study, NAS9-14319  
 \*\* Contract NAS3-17835

as tension members.

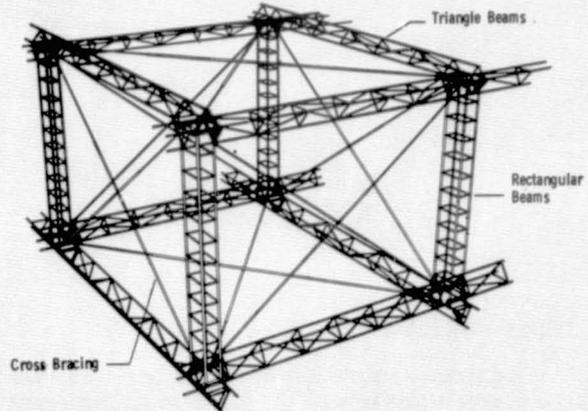


Fig. 2 Typical 60-ft Cube

The antenna is assembled in two phases. Phase 1 is done in low earth orbit with the use of the Shuttle Remote Manipulator System (RMS). Phase 2 is done in geosynchronous orbit using a mobile assembler.

During phase 1 a core assembly is constructed. Two Shuttle flights are required to bring a telescoping central section, sufficient beams to construct a core section and several attaching cubes, and two mobile assemblers. Figure 3 shows the Shuttle RMS completing the assembly of the core section. After this core section is completed,

Install Beam Packages on Holders  
 Complete 60 ft. sq. Core Assembly With Assemblers

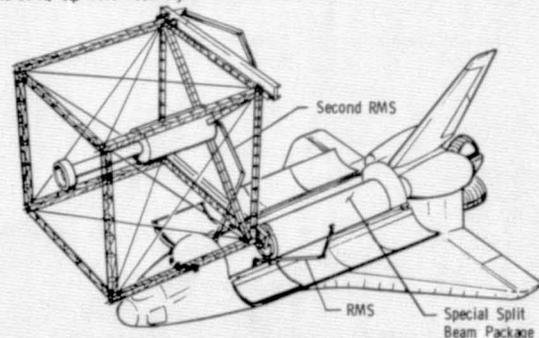


Fig. 3 Assembly of Core Section

the mobile assemblers begin building adjoining cubes. Figure 4 shows the core section and one completed adjoining cube. Two mobile assemblers are shown in the figure. These assemblers work in conjunction with beam pallets which store

remainder of the assembly takes place with the mobile assemblers being operated remotely from the ground using TV.

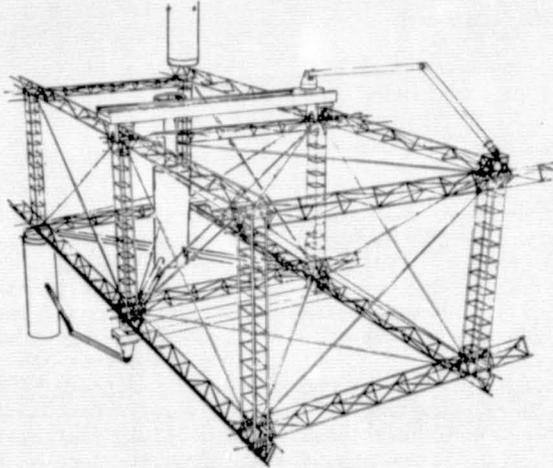


Fig. 4 Building Cube Adjoining Core Section

collapsed beams. Both the assembler and the beam pallets have similar mobile bases, which are supported at each end by four legs. These legs have end-effectors which grasp the intersection of the vertical and horizontal beams for maximum strength. To maneuver the base, the support legs on one end are retracted and the base is pivoted about the opposite end. A 90 degree pivot brings the end of the base over the opposite corner of the structure. Its legs are then re-attached to the structure. The assembler has a six-degree-of-freedom manipulator with a 60-ft reach and a 30-lb tip force. Electrical power is furnished from solar cells located on the manipulator or base. The manipulator extracts beams from the beam pallet and places them on the structure. The beam pallets are on mobile bases which are used to follow the assembler around during assembly. Figure 5 shows the mobile assembler and beam pallet. Figures 6 and 7 show two steps in the assembly procedure.

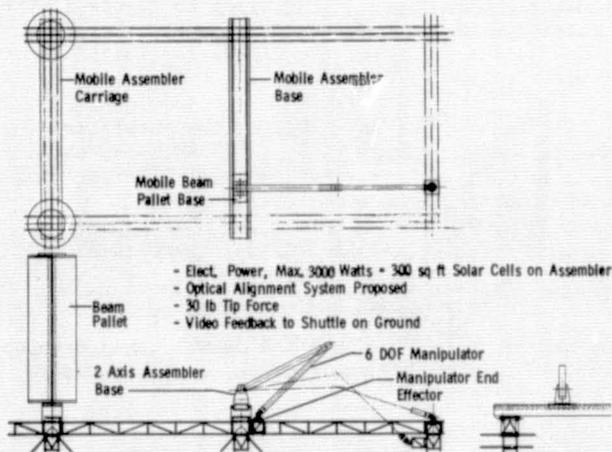


Fig. 5 Mobile Assembler and Beam Holder Concept

Phase 2 takes place in geosynchronous orbit after the central core and several adjoining cubes are boosted to the high earth orbit. There the

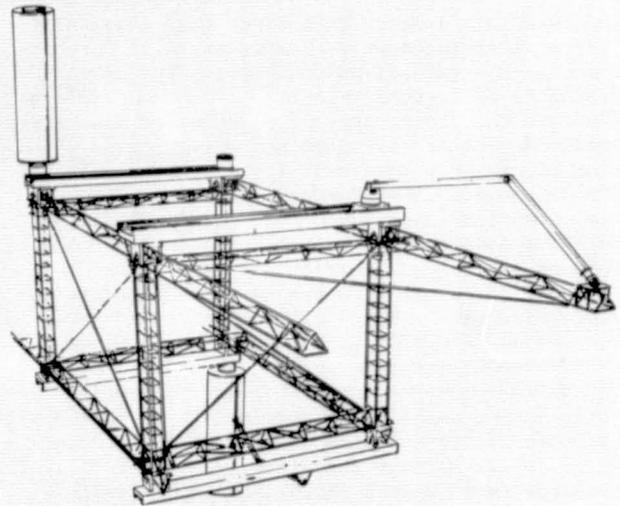


Fig. 6 Cube Assembly Sequence, Step 1

A method has been developed for folding the triangle beams and the square beams in such a way that one Shuttle cargo bay can hold 92 square beams, 192 triangular beams, and 288 (telescoped) tension tubes. Total weight of a Shuttle load with beam pallet is 37,870 lbs.

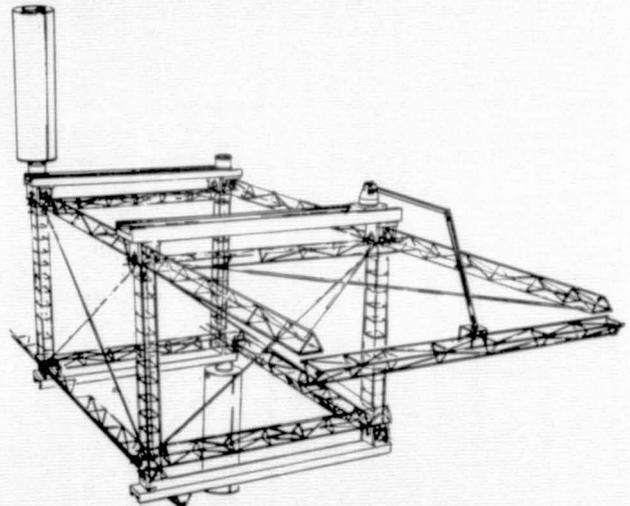


Fig. 7 Cube Assembly Sequence, Step 2

#### Acknowledgments

This paper describes work performed under NASA Johnson Space Center contract NAS9-14319. Gratitude is given to the following people for their efforts and ingenuity in carrying out the design and analysis related to the assembly of the Microwave Power Transmission System antenna: Gilbert Kyrias, Richard Skidmore, Jack Romback, Michael Salis, and Carter Lord. The Contracting Officer's Representative at NASA-JSC was Herbert Patterson. He provided valuable guidance throughout this work.

## CONTROL AND STABILITY PROBLEMS OF REMOTE ORBITAL CAPTURE\*

M. H. Kaplan and A. A. Nadkarni  
The Pennsylvania State University, University Park

## Introduction

Development of the space shuttle system will permit a whole new philosophy toward handling of payloads in orbit. The use of remote manipulators will provide the capability to deploy, retrieve, and repair satellites. Along with this new spectrum of capabilities comes a new set of problems associated with handling masses in orbit. Typically, a satellite to be retrieved can be expected to have some angular motion. Thus, retrieval schemes must be designed to anticipate such situations. Angular momentum must be eliminated before repairs or return can be effected. The process of nulling angular rates is sometimes called "passivation." Payloads which have been identified for potential retrieval operations include: (a) stabilized, normally-operating satellites which require periodic servicing; (b) freely tumbling or spinning payloads without active attitude control; and (c) satellites that have developed an attitude control malfunction and have resulted in some unanticipated state of motion. Typical satellites to be launched in the 1980's and 1990's have been tentatively identified in a previous study.<sup>1</sup> Of those identified the Research Applications Module (RAM) appeared to be the most demanding in terms of size and inertia for retrieval missions. Such a payload is of maximum size for the shuttle cargo bay and will require extremely precise handling. It is envisioned with a control moment gyro attitude system, which could cause random motion if a failure occurs during the mission.

The dynamic state of a satellite being retrieved could range from a completely stabilized one to a situation of general tumbling. A body is said to be spinning when angular momentum and angular velocity vectors are parallel. This corresponds to spin about the major or minor axis of inertia. To further categorize motion, spin about a symmetry axis may be called "simple spin" and about the transverse axis, "flat spin." A general state of "tumble" exists when angular velocity components about all three body principal axes are of the same order of magnitude. In many cases a body is said to be in "nutational" motion. This is characterized by having the angular velocity vector close to the major or minor axis such that transverse velocity is small. Although given enough time general attitude motion of a passive body will always degenerate into spin about its major principal axis, there are situations which require retrieval of satellites possessing nutational motion. The problem of docking with such a body is a complicated one. Special end effectors and multiple degrees of freedom are required of the grappling mechanisms.

Previous studies have considered requirements for shuttle attached manipulators<sup>2</sup> and free-flying teleoperators.<sup>1</sup> Specific objectives included retrieval performance for typical satellite configurations and dynamic states. One study<sup>3</sup> considered the problem of passivation of a spinning object with nutation assuming a complicated multi-degree-of-freedom arm. None of these studies considered effects of misalignment during capture. Furthermore, there are some basic stability questions that must be answered about the dynamics and control aspects of capture. A study of misalignment, stability, and certain control aspects are included in this work. The approach used is to allow differential angular rates and orientation between the object and grappier. Then control responses after capture are studied. The feasibility of nulling combined spin and nutation of a typical satellite is demonstrated by a Lagrangian formulation to establish a baseline situation. It is apparent that a free-flying teleoperator (FFTO) with a dynamically unbalanced grappier is not at all desirable because extremely adverse cyclic torques may be generated. A dynamic analysis of a combined teleoperator-satellite system was carried out assuming misalignments during capture. Related responses and stability evaluations are included.

## Approach and Capture Dynamics

When the FFTO reaches the vicinity of the satellite, one or two circumnavigations may be necessary in order to inspect the satellite and estimate its angular momentum vector. This information is essential for aligning the FFTO in the appropriate approach direction for docking. As indicated previously, the RAM satellite was found to be the most demanding for retrieval. Referring to Figure 1, the expected yaw,  $\omega_x$  pitch,  $\omega_y$  and roll,  $\omega_z$  rates for various failure modes of the RAM are estimated as follows:

- i) An abnormal shut-down of the satellite's attitude control system (ACS) followed by an extended period of satellite drift would result in:  $\omega_x = \omega_y \leq 0.025$  rad/sec,  $\omega_z \leq 0.1$  rad/sec.
- ii) A failure of the ACS about one axis:
  - (a) failure in roll would develop:  $\omega_x, \omega_y \leq 0.1$  rad/sec,  $\omega_z \leq 10$  rad/sec.
  - (b) failure in pitch or yaw would develop:  $\omega_x, \omega_y \leq 1$  rad/sec,  $\omega_z \leq 1$  rad/sec.

\* This work has been supported by NASA Grants NGR 39-009-162 and NSG-7078.

iii) A failure of the satellite ACS about more than one axis would develop:  $\omega_x, \omega_y \leq 1$  rad/sec,  $\omega_z \leq 10$  rad/sec.

The nutation cone angle  $\theta$  depends upon the ratio of the combined pitch-yaw rate ( $\omega_{xy}$ ) to the roll rate ( $\omega_z$ ). This coning angle is zero for a pure spin ( $\omega_{xy} = 0$ ). When the coning angle is small, the preferred approach for capture with convenience may be along the momentum vector to the end face of the satellite (end approach). However, when this angle is large, the preferred approach may be to the waist of the satellite at the center of mass (waist approach). The rendezvous phase ends with the FFTO about 20 to 50 feet away from the satellite along the final approach direction, as established by the inspection maneuver.

Before actual capture can take place angular rates and coning angle of the satellite must be estimated. Of course, it is not possible to achieve exact alignment for capture. Hence, the FFTO approaches the object along a direction slightly misaligned from its angular momentum vector. It then tries to capture the satellite with its grappling mechanism synchronized with a slight error. Motion of the combined body after capture is important, because instability could occur. The equations of motion for the composite body were solved via digital computer. After capture the teleoperator returns to the shuttle in the recovery phase. No complicated interactions between the two masses are anticipated.

#### Results

Figure 2 illustrates the grapppler configuration assumed here. This is quite similar to that used in Ref. 3. It has two-degrees of freedom in the shoulder and two in the wrist. It was found that of the many torque functions that could be applied, a constant torque would passivate the motion in its direction of application faster than other form of torque. For passivating the satellite motion simultaneously in all three directions, i.e.  $\psi, \theta,$  and  $\phi$ , it was found that the best method would be to apply a constant torque on all the three axes, discontinue the despinning torque  $\tau_3$  when the spin rate goes to zero, discontinue the detumbling torque  $\tau_1$  when the precession is nullified, and finally decone with the deconing torque  $\tau_2$ . This operation would not suit all satellites. A particular procedure of passivating would have to be developed after observing the approximate spin and tumble rates of the particular satellite to be retrieved. It was also found that some modifications in the design of the teleoperator are required for stability. These include addition of dynamic balancing masses.

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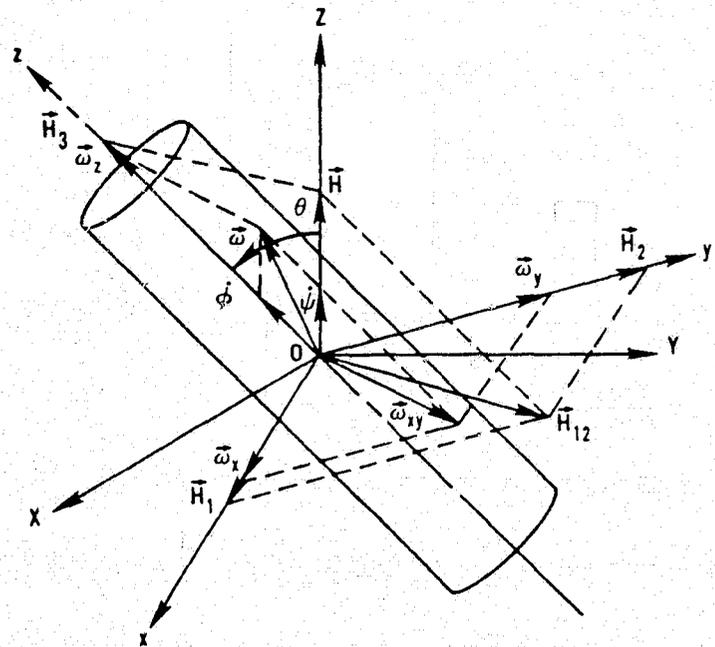
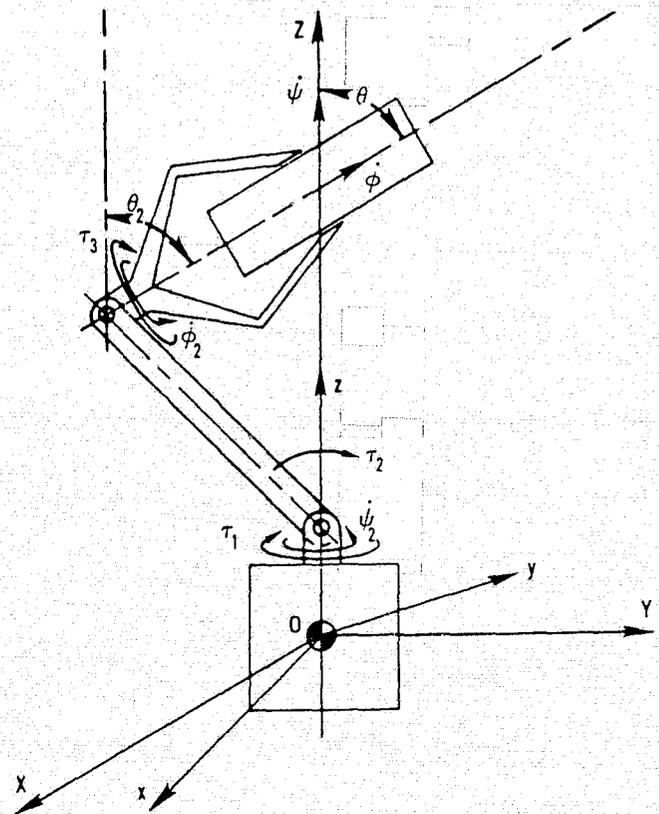


Figure 1. Research Applications Module



2. Grapppler Configuration Assumed

## REMOTELy PILOTEd AIRCRAFT IN THE CIVIL ENVIRONMENT

By Thomas J. Gregory and Walter P. Nelms  
NASA, Ames Research Center, Moffett Field

and

Jay Karmarkar  
Systems Control, Inc., Palo Alto

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Remotely piloted vehicles are of increasing interest to the military, as evidenced by the number of technology and development programs that currently are funded or planned. These programs have led to a number of test vehicles with significant capabilities, and future remotely piloted aircraft (RPA's) are forecast to become even more capable. As the size, weight, and cost of RPA's is reduced, the prospect of using them for civilian uses becomes more likely.

This paper will describe, briefly, several of the existing RPA programs, the technology of several important subsystems and the potential vehicle uses and operational concepts. Regulatory constraints and present and future study activities will be described that may lead to demonstration and then operational programs.

All the military services, the NASA, and several corporations have built RPA's for test and evaluation functions. Figure 1 shows one of these, the NASA Flight Research Center Mini-Sniffer, which will fly to altitudes in excess of 70,000 feet and sample the atmosphere behind supersonic cruise aircraft. This remotely piloted research aircraft is powered by a hydrazine engine and will telemeter data to ground stations. The vehicle weighs 145 pounds and carries 20 pounds of payload and instrumentation. It has a wing span of 18 feet and is launched from a catapult and recovered on a skid landing gear from a dry lake bed at Edwards Air Force Base.

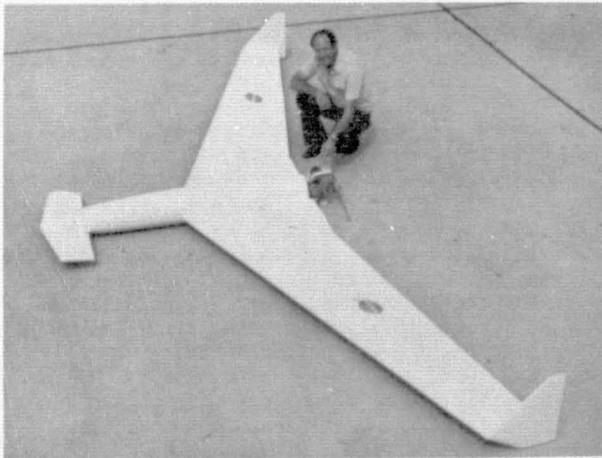


Fig. 1

This and other vehicles are demonstrating that current technology will permit relatively lightweight vehicles that fly for long periods of time and cover wide territory. They have demonstrated that with sophisticated sensors, they can provide useful image or other information in a test type of flight operation. This technology, or possibly next generation technology might serve civilian purposes on a regular operational basis.

TABLE I.- POTENTIAL CIVIL APPLICATIONS FOR RPA'S

<u>Airborne Research of</u>	
	Aerodynamics, propulsion
	Avionics & flight controls
	Remote sensing
<u>Monitoring &amp; Mapping of</u>	
	Weather, pollution, fires
	Snow & water depth
	Animals, birds, fish, vegetation
	Population, buildings, traffic
<u>Search for</u>	
	People & vehicles (lost or unauthorized)
	Fires, minerals, fish (tuna)
	Minerals, insect & disease damage
<u>Relay of</u>	
	Warnings (storms, obstructions, etc.)
	News & public broadcasting
	Commercial communications
<u>Transportation of</u>	
	Survival aids (radios, medicine, etc.)
	Crop dusts, sprays, fertilizer, seeds
	Fire retardants
	Mail
	Freight

Table I lists several potential missions that remotely piloted aircraft may serve in the future. The category at the top of the table, airborne research, is being conducted at the present time as described in the Mini-Sniffer program. These activities have demonstrated low cost and unique capabilities for testing ideas considered to be too risky with a pilot onboard. The next category in the list, monitoring and mapping of such items as weather, pollution, and traffic, etc. is currently done using other methods such as satellites, permanent ground stations and manned aircraft. Remotely piloted aircraft could conduct these activities very effectively, since the vehicles can be small and remain airborne for long periods with very little requirement for pilot action.

For the search function, RPA's with high resolution electro-optical systems can provide high quality image information transmitted to a ground based facility where image enhancement can take place on large-scale computers. Special algorithms and techniques to extract images having certain spatial and spectral features could vastly decrease the labor hours required to conduct search activities. Once detection was accomplished, the RPA has the unique capability to fly closer to the detected subject and verify recognition and identification. The last category describing transportation functions would require vehicles of increased size due to the weight and volume of the items to be transported. Certainly many of these civilian applications will not occur until remotely piloted aircraft have demonstrated extremely high reliability in either research type operations or in sparsely populated areas.

The question of if and how an RPA can meet the anticipated regulatory limitations that may be imposed by federal, state, and local governments are key issues that are unique to civilian RPA's as opposed to military ones. The next table describes the anticipated regulations that may apply

TABLE II.- RPA REGULATORY FACTORS

<u>Federal Aviation Agency</u>
License
Safety of flight
Vehicle certification
Operating areas
Enroute communications
<u>Federal Communications Commission</u>
License
Transmitter power
Frequency bands
<u>Environmental Protection Agency</u>
Emissions
Noise
Visual observables
<u>State &amp; Local Governments</u>
Approvals

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to the vehicles. The primary concern will be safety of the population and property overflown by the vehicles. Certainly the existing regulations were not drafted with remote piloting in mind, and hence may not be appropriate in many instances. An important factor influencing the rate of development and eventual use of RPA's will be the objectivity with which safety rules and regulations will be drafted and applied. Certainly, there will be incidents in which civilian RPA's cause isolated danger and damage, just as there is in today's operation of locally piloted aircraft. It will be essential that RPA technology provide vehicles that are as safe or safer than locally piloted aircraft as defined by some statistically finite measure. At this point there does not appear to be a technical reason why present or anticipated technology cannot provide safety and other features that will meet the requirements listed in Table II.

One of the key features for providing safety of operations will be an onboard computer. Computer technology is currently undergoing another revolution by the development of hybridized, large-scale circuit integration. Technology forecasts suggest that very small, low-power computers will be available in the 1980 time period that correspond to some of our present day powerful mini-computers. With such computer capacity, most, if not all, of the flight control, guidance, and navigation functions can be performed redundantly to provide very high reliability. Hence, the computer will be one of the key avionic elements to insure safety and cost effectiveness in RPA's.

Another key technology element in the remotely piloted aircraft will be the electro-optical sensor system. Again, solid-state electronic technology is the key factor leading to exceptional image capability at low cost. The next figure shows a present day solid-state imaging camera together with a small television monitor and a man's wrist-watch for size comparison. The charged couple, solid-state imaging device that is packaged inside the small camera has an active area of about 1/4-inch square. Many commercial systems now emerging from the development laboratories demonstrate that low-cost, high-quality image systems can be built

that will have capability beyond that of the human eye. These systems can operate at different wave lengths down to the infrared and can be selective in terms of bandwidth and resolution. Electronic stabilization of the optical system is being demonstrated in the laboratory and has been demonstrated in flight tests of military remotely piloted test vehicles.



Fig. 2

While the computer and the electro-optical system will be the key avionic elements in remotely piloted aircraft, a number of other important functions and subcomponents will be required. In many instances the functions that are now implemented on a separate basis will be highly integrated with the onboard computer, and hence not require as much weight, space, and cost involved with interface equipment. It is extremely important to reduce the weight and size of this avionics equipment, since they directly determine the weight of the vehicle by causing corresponding weight and size reductions in the airframe and propulsion system. Avionics weights and volumes are not nearly so significant in conventional aircraft. In the future we can expect vehicles in the 100 pound class to provide high quality image information and other sensor data for flight periods of 12 hours at ranges up to 200 nautical miles radius.

NASA is currently funding a small exploratory contract to identify future markets and vehicle concepts for remotely piloted vehicles. The study activity will emphasize first, identifying and establishing market potential with emphasis on those civilian uses that might occur first. A second phase of the study will be the definition of future vehicle concepts that may best serve these markets. The intention will be to identify areas of increased R&D emphasis that will be critical to RPA effectiveness and safety and to help focus research activity in these areas. An additional phase of the study will be to assess the safety and reliability aspects of these future vehicles.

When this study is completed, there may be further study activity to determine whether remotely piloted aircraft are the most cost-effective alternative for performing the missions identified. In the event these studies show good cost effectiveness with adequate safety, then demonstration programs in selected areas are likely to follow. These demonstration programs will occur under very controlled conditions so that the systems can be thoroughly tested and evaluated. After such demonstration programs, remotely piloted aircraft may find operational usage as their effectiveness and safety increase and their costs become less.

## **SESSION IV**

# **Remotely Manned Undersea Systems**

## AN OVERVIEW OF UNDERWATER REMOTELY MANNED SYSTEMS AND SUB-SYSTEMS

Andreas B. Rechnitzer, Ph.D.

Office of the Oceanographer of the Navy, 200 Stovall Street, Alexandria, VA 22332

The 1972 Remotely Manned Systems Conference offered a singularly effective opportunity to share technologies and experience in an area of engineering and science that transcends the application in space, laboratories, and undersea. This 1975 forum hopefully will be equally beneficial. A current overview of how the underwater facet of remotely manned systems has progressed since 1972, the current approaches being pursued and the success of the community, both foreign and domestic, is showing steady activity.

Underwater remotely manned systems development continues to progress in both technology and utilization. Both tethered and untethered systems have been advanced to stage of fieldable systems wherein the functional success of new innovations are being tested and evaluated under the constraints of ocean environmental factors. Field tests and operating experience has provided much satisfaction and valuable guidance to the design engineer. Few systems have evolved to the status of true prototypes and most are still considered by their creators as developmental systems suitable for continued refinement. Although the area of underwater remotely controlled systems cannot be described as a major area of technology development in any nation there has been a sustained interest and steady progress by a small dedicated cadre of individual effort in several countries.

The key driving forces for advancing the state-of-the-art in unmanned underwater remotely controlled systems are science, offshore commercial activities, search and recovery. It follows therefore that oceanographic institutions, the offshore oil and gas developers, and those responsible for locating inspecting, repairing and recovering objects on or from the sea floor are supporting or encouraging the development of new fieldable systems. Scientific investigations in automation are providing valuable knowledge and illumination of erudite methods that are expected to be adopted for remote system development.

The current status of U.S. underwater remotely operated systems technology will be covered rather thoroughly in this session. This overview of foreign activities shows that technical content reflects innovative concepts and approaches worthy of inclusion of foreign efforts here.

There exists an adequate historical record to show the progress of underwater remotely operated systems and the trend toward more advanced systems is steady

and unique because of environmental constraints and functions, and tasks successful solutions to undersea problems are likely to be suitable for technology transfer to other applications, e.g., space, research laboratories or industry.

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## AN UNDERWATER WORK SYSTEMS PACKAGE

Norman B. Estabrook, Senior Project Engineer  
Naval Undersea Center, San Diego

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The Work Systems Package (WSP) is being developed under the Navy's Deep Ocean Technology Program to help provide the Navy with a versatile work capability at ocean depths up to 20,000 feet. The approach taken in this effort is twofold: (1) to build a modular unit which can adapt to several existing deep submersibles to extend their working abilities, and (2) to use the system as a means for acquiring knowledge of components and techniques for working in the deep ocean environment. For the latter purpose, the system is designed to permit component replacement and modifications as information is accumulated from tests. Shown in Figure 1, the WSP is composed of an aluminum pipe structure on which are mounted two six-function grabber arms, a seven-function manipulator, tool suit, 1,000/lb. capacity winch, electrohydraulic power supply, electronics housing, lights, and television. The unit is currently designed to be operated by itself either remotely or with divers, attached to manned submersibles such as the ALVIN or the Navy's AUTEV vehicles, or mounted on unmanned cable-controlled submersibles such as the Navy's CURV III or RUWS.

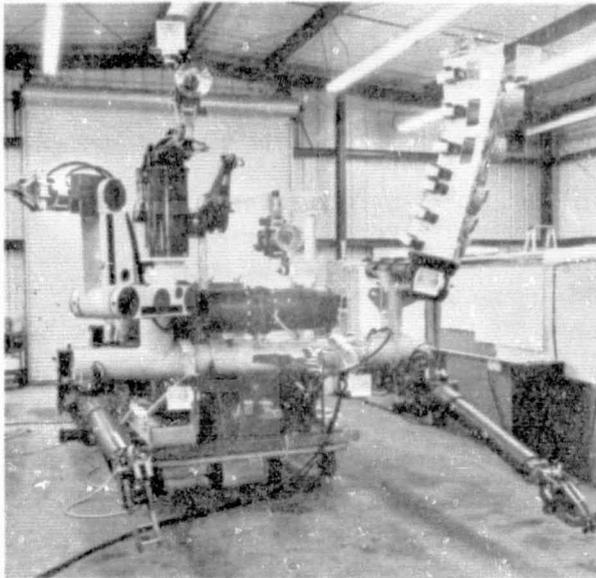


Fig. 1 Work Systems Package during assembly. Grabber arms can be seen extending from lower cross tube. Tool box, upper right, can be extended and retracted.

#### Power & Control

All working components on the WSP are hydraulically powered by an electrohydraulic converter containing a high-flow pump for tool operation and a low-flow pump for all other functions. Signals are transmitted using a time division multiplexing technique to minimize the number of individual wires to the system.

#### Manipulative Devices

The primary working arm is a seven-function, rate-controlled manipulator. It has been modified to pass hydraulic power through disconnects in its wrist to the various tools when they are grasped as shown in Figure 2. A linear extension function permits extraction and replacement of tools and performance of work functions requiring linear in-out movement such as drilling.



Fig. 2 Low-speed rotary power head and drill bit shown in grip of manipulator. Tool hydraulic connections are made when tools are grasped.

The grabber units, mounted on each side of the package, are intended as "strong arms" to stabilize the system while working or to assist the manipulator in performing various tasks. The grabbers lack only elbow functions to qualify as complete manipulators.

#### Tools

The tool box contains eight hydraulic power heads and six velocity-powered tools, all of which were selected to address work tasks commonly encountered without having to resurface for tool interchange. When used with the appropriate tool bit, the hydraulic tools perform chipping, drilling, wire brushing, sawing, torquing, synthetic line cutting, spreading, jacking, and cable cutting functions. The velocity-powered tools are stud guns and cable cutters.

Arrangement

The WSP was laid out with considerations of viewing areas, work area obstruction, trim and balance, and manipulator access in mind. The importance of the inter-relationship between operator visibility and manipulator was noted by positioning the manipulator in the same relative position to the viewport or center TV camera as the human arm is to the eye. Also, the tool box was located such that tool exchanges, long considered a difficult task, take place directly in front of the prime viewing area. After tool exchange, the box can be retracted to give unobstructed vision of the working area.

Preliminary Tests

Laboratory tests and some pierside tests have been performed with the WSP, including diver operation (see Figure 3) where the tools have been used to cut cables, drill holes in plates, tighten and loosen nuts, spread bars, and perform numerous other tasks on a test fixture. The package has been mated with the CURV III, maneuvered underwater, and checked out through the CURV cable.

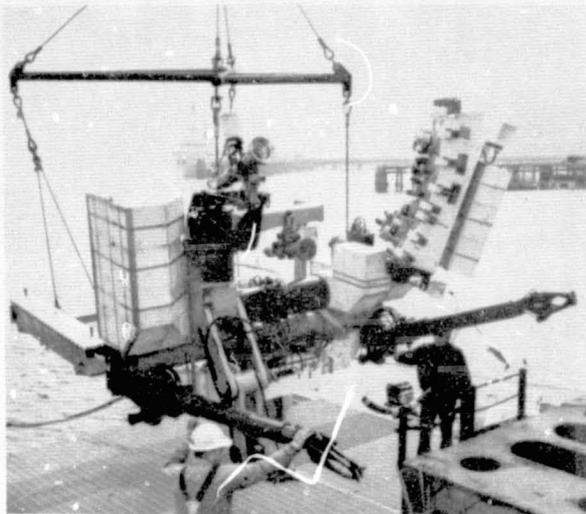


Fig. 3 WSP being lowered onto submersible platform for diver test. Test fixture is shown in lower right.

Future

Future plans call for quantitative evaluations of system performance by comparing relative times required to accomplish established scenarios when working in the various operating modes. The WSP will be fitted up to several submersibles in the near future, modified as needed, and hopefully provide much valuable information toward improving underwater work technology.

WSP Pertinent Data

Overall System

Weight: 3,200 - 10,500 lb depending on configuration for submersible mounting.

Depth: 20,000 feet

Current Operating

Mode: Diver-controlled, remote-controlled, CURV III and RUWS unmanned submersibles, Autec and ALVIN manned Submersibles.

Manipulator

Type: PAR model 3000US-H-7 function, hydraulic, rate-controlled.

Weight: 490 lb

Reach: 72 inches

Capacity: 7,000 in-lb on arm functions, 500 lb grip force.

Grabber

Type: 6-function, hydraulic, rate-controlled.

Weight: 260 lb

Reach: 82 inches plus 24 inches extension.

Capacity: 250 lb lift at max reach of 108 inches, 500 lb grip at fingertips.

Winch

Type: Piston-type hydraulic motor turning 8 inch drum through harmonic drive.

Weight: 21 lb

Capacity: 1,000 lb @ 2,000 psi

Tool Suit

Low Speed Rotary: 810 RPM, 275 in-lb torque.

High Speed Rotary: 1,575 RPM, 125 in-lb torque.

Impact Wrench: 1,289 RPM, 1,320 in-lb torque.

Reciprocating Knife: 525 RPM

Chipping Knife: 1,289 RPM

Hydraulic Cable Cutter: 2 inch wire rope, 23,000 lb force

Spreader: 13 inch spread, 2,875 lb force

Jack: 8 1/2 inch stroke, 19,000 lb force.

Velocity-Powered Cable Cutter:

Velocity-Powered Stud Driver: Anchor stud in mild steel up to 5/8" thick, max pull 500-2,000 lb depending on pull angle.

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# CABLE CONTROLLED DEEP SUBMERGENCE TELEOPERATOR SYSTEM

Jean Vertut

CEA, Saclay, France

and

Joël Charles

CERTSM, Toulon, France

## ABSTRACT

ERIC II, cable controlled deep submergence teleoperator system, is designed for remote observation, investigation and intervention from a surface ship, with a 6000 meters depth capability. The system is in development at CERTSM in Toulon Navy-Yard-France on contract of Ministère Des Armees; its main parts comprise first the heavy ancillary subsystems: cable handling gear, main cable, tether, PAGODE recovery fish, data and power transmission and second the ERIC II teleoperator fish and its control module. Special attention was paid at man-machine interface problems in the early stage of development and the result is the current development of "telesymbiotic" oriented hardwares: head mobility with T. V. and microphones sensory feedback, force feedback dexterous arms on sponsorship of CEA-Saclay-France, agility concept in the fish dynamic control with inertia feedback by kinesthetic motorized sticks also with CEA cooperation. First significative real world experience on underwater dexterous manipulative tasks was gained in late 1974 with great success. First experimentation of ERIC II is scheduled for early 1977.

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## USE OF MANIPULATORS FROM MANNED SUBMERSIBLES IN A DEEP-SEA MAPPING OPERATION

Dr. Robert D. Ballard

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543

After ten years of development, research submersibles are now capable of working on a routine basis in water depths in excess of 12,000 feet. In addition to a high reliability, submersibles now have manipulators, and precision navigation and data logging systems which permit scientists to make observations and collect samples within a frame of reference accurate enough to obtain unique insight into bottom processes. During the summer of 1974 three of the four submersible vehicles in the world capable of working in excess of 10,000 feet were used to carry out the most advanced underwater mapping program ever undertaken. During this program, known as Project FAMOUS, underwater manipulators were used to collect a series of precisely positioned rock, sediment and water samples. Since the exact position of the submersible was known as well as its orientation it was possible to recreate the orientation of the rock samples in the laboratory for subsequent analysis. The results of this program proved the value of manned submersibles operations and gave the scientific community a new tool with which to map the deep sea.

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FORCE FEEDBACK SYSTEMS IN UNDERSEA MANIPULATOR APPLICATIONS

Alan J. Pesch and William R. Bertsche  
Eclectech Associates, Incorporated

and

Clifford Winget

Woods Hole Oceanographic Institute, Woods Hole, Massachusetts

SUMMARY

We have begun an investigation concerning the application of force feedback in undersea manipulator systems in view of the lack of data which describes the operator's capacity for the utilization of force feedback information at various levels of fidelity and the anticipated benefit to undersea applications. Our objective is to investigate the manual control behavior of the operator with various levels of manipulator system complexity in order to determine the relationships among control system dynamics, certain base engineering variables, controller designs and system performance.

Previous research has defined "breakdown regions" of human performance in the spatial and temporal dimensions of manipulator operation. Examples include displaced vision studies (Smith, 1962), T.V. camera placement (Murphey and Wirta, 1963), and studies of time delay (Smith, 1966; Sheriden, 1960). Little research has been conducted in the energetic dimension which concerns the feedback of force and mass aspects of manipulator work. Since the fidelity of force feedback is often more variable across various existing manipulator designs than is the feedback associated with the spatial and temporal dimension of manipulator control this research appeared particularly warranted.

Efforts were directed to the identification of key engineering variables which most contribute to the fidelity of force feedback and which are amenable to study in a manual control context. Table 1 shows an abbreviated listing of selected variables from this analysis which illustrate the area of concentration in our current study.

Our initial concern has been with the variables which serve to create backlash in force signal. In order to study the problems of backlash the phenomenon was examined via a series of engineering tests which

describe the fidelity of the force-in/force-out relationship across a series of operating conditions. The result was a series of data files which define the continuous track of force through the system between the master/slave/master. An experimental manipulator system was assembled to conduct these tests. The system is a bilateral master/slave system operated hydraulically and connected only via an electrical system. The system has a payload of approximated 100 pounds and is designed for testing on applied tasks in an underwater environment.

Based on the engineering data, a set of general transfer functions were prepared to provide a mathematical model of the various levels of potential force feedback fidelity as a function of force backlash present in alternate engineering designs. The general form of the transfer functions is shown in Figure 1.

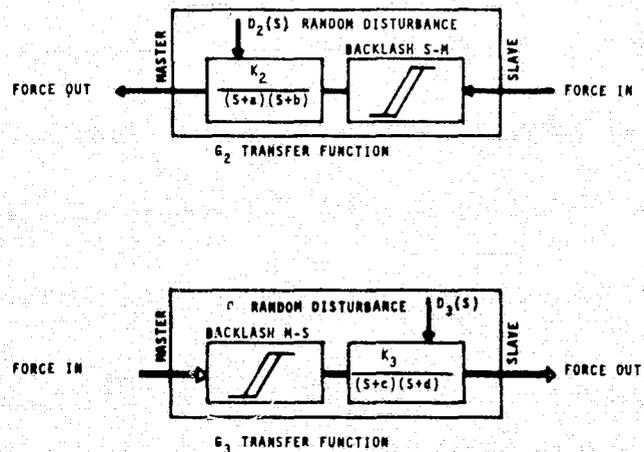


Figure 1. Bilateral Force Transfer Characteristics

Table 1. Key Engineering Variables

FORCE DETECTION METHOD	SYSTEM FORCE PROCESSING	TIME DOMAIN PROCESSING (positional & force)	SIGNAL CONDITIONING AND ENHANCEMENT
A. POSITION SERVO ERROR	A. COMPLIANCE:DROOP	A. RISE TIME	A. VELOCITY DAMPING
B. FORCE TRANSDUCERS	B. DEAD BAND	B. SETTLING TIME:	B. FORCE TO MOVE
-STRAIN GAGE	C. MOTION RANGE	OVERSHOOT	COMPENSATION
-LIGHT EMITTING DIODES		C. SLEW RATE	C. ELECTRONIC COUNTER-
C. MECHANICAL TRANSMISSION OF FORCE		D. TIME DELAY	BALANCING
-HARDWARE		E. FREQUENCY RESPONSE	D. COMPUTER WITH
-HYDRAULIC FLUID			SUPERVISORY CONTROL
D. JOINTS VS. X,Y,Z FORCES			

We are currently using the transfer functions to generate perturbations of the force signal in a series of operator manual control studies. The result of these studies will be a quantitative description of the operator's utilization of various levels of force feedback fidelity, and identification of "breakdown regions" of human performance traceable to specific engineering design characteristics.

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## CONTROL AUTOMATION IN UNDERSEA MANIPULATION SYSTEMS

Amos Freedy, Ph.D. and Gershon Weltman, Ph.D.  
Perceptronics, Inc., Woodland Hills, California

## ABSTRACT

This paper discusses the requirements for the successful use of automated manipulation in an undersea environment and establishes initial specifications for systems which share control between a human operator and an autonomous control element. Examples from the literature and the author's direct experience are used to illustrate the various areas of concern. These include: (1) Objectives of Automation; (2) Characteristics of the Underwater Task; (3) Hierarchy of Control Algorithms; (4) Man/Machine Interface; (5) Sensory Feedback; and (6) General System Organization. Special emphasis is placed on the solutions to the problem of controlling an undersea manipulator which is capable of performing certain automatic functions and implementing these solutions using current technology. The paper concludes with a summary of current capabilities for control automation and recommendations for applied development work.

Present-day undersea manipulators are controlled by on-off switches which supply power individually to the various joints. The operator of such a switch-controlled manipulator depends almost entirely on direct vision or TV to locate and define his work object and to position the manipulator's end-effector. Factors such as sediment, turbid water, failure of external lighting, or poor angle of view may prevent adequate visual information. In these cases, laboratory studies and practical experience have shown that performance is severely degraded, frequently to the point where it is impossible to proceed.<sup>1</sup>

Accordingly, it appears advantageous in the underwater case to point toward a more autonomous robot system, in which both the manipulator and its platform are able to automatically perform certain tasks.

A major limitation of present automatic robots is their inability to effectively sense the working environment and adapt their actions to changes in this environment. The latter may take the form of changes in the work-objects location, orientation, physical shape, etc.

Efforts are currently underway to equip robots with sensory feedback. This includes capabilities for tactile sensing, force grip feedback<sup>2</sup> and proximity sensors.<sup>3</sup> Additional work is being performed on robot control with visual systems for hand-eye coordination as well as

utilizing force feedback for "force steering programs."<sup>4,5,6</sup> This work involves both the development of special sensors, control programs, and the concept of producing and "intelligent" robot, where behavior is regulated by goal-directed programs and "closed loop" environmental feedback.

Although current sensor and software capabilities preclude the practical realization of a completely autonomous robot arm, it is possible to improve current undersea manipulator control through the utilization of shared man-computer control scheme. This type of approach employs the following elements.

1. A capacity for operator supervised task automation.
2. A capacity for synthesis of "natural" visual and force feedback in an underwater operating environment.
3. Facilitation of optimum control and a communications interface between the operator and the computer-manipulation system.

The integration of these elements provides a capability to transfer part of the control to the computer, to recreate some of the sensory feedback and to ease efficient control.

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OMIT

## ADVANCED TECHNOLOGIES FOR UNMANNED UNDERSEA SYSTEMS

G. L. Bane, W. J. Quinlan  
Autonetics Division, Rockwell International

The cybernetic approach to accomplishing missions in the deep ocean environment is investigated from both an economical and a technological point of view. Current technology is discussed with a typical deep water mission scenerio presented to highlight the practical advantages of such systems. The discussion concludes with a simple system mechanization and descriptions of available equipments/technologies that when properly integrated, result in satisfying basic mission objectives.

**SESSION V**

**Industrial Application Systems**

INDUSTRIAL ROBOTS IN EUROPE - MARKET, APPLICATIONS AND DEVELOPMENTS -

Dipl.-Ing., Rolf D. Schraft

Institute for Production and Automation (IPA) at the University of Stuttgart, Germany

Abstract.

A large number of work place analyses were conducted to define the requirements for industrial robots (IR).

On the other hand a survey of all IRs which are offered on the world market was made and a data base was established.

The market is already very large. More than 40 companies offer in Europe. The applications are 20 % coating, 20 % spot welding, 60 % loading and unloading machines and other handling tasks.

The developments go in two directions: on the one side to relatively sophisticated IRs and on the other side to modular systems.

1. Introduction

Research at the Institute for Production and Automation (IPA) at the University of Stuttgart in the fields of work-piece behaviour, work piece and material handling lead to the decision to further investigate the problems and opportunities created with the introduction of IRs.

In order to gather data on the requirements for industrial robots, work place analyses in different companies, involving a wide range of products and manufacturing processes were carried out. In the first stage of these analyses, the selection of work places was randomly done and the data presented today date back to these early investigations. Even though they include handling operations performed on punch-presses, forging-presses, die-casting machines, spotwelding machines, machine-tools, for cutting operations, spray painting a. s. o., these results should not be considered as giving a thorough survey over the full or even major spectrum of possible applications.

In Fig. 1 the method of analysis is roughly described.

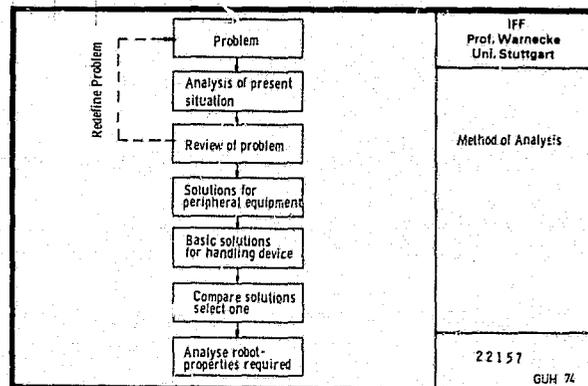


Fig. 1 Method of analysis

2. Market

In 1969/70 IRs were introduced on the european market.

We define an IR as an automatic handling unit which is freely programmable in several degrees of freedom. This means that the sequence of the motions of the different axis and the distances travelled in the different axis has to be variable. A great number of well known pick an place units, iron hands, tele-operators a. s. o. would consequently not be called IR.

But even when using this definition already a broad variety of IRs have been introduced on the market. According to our market-survey, there are close to 200 different models available. Certainly a good share out of these will never come beyond the prototype stage, but even then the number of robots actually applied for industrial jobs remains amazingly high.

In the meantime 42 different companies offer their products in Europe. All together about 850 models were sold till 1974. (see Fig. 2)

3. Applications

In the first time after the introduction a number of companies bought IRs to test their possibilities. This period is almost over and today the applications are well planned and have an economic background,

A main field of application is coating (20 %)

Manufacturer	Electrolux	Hawker-Siddeley	Kaufeldt	Trallfa	Unimation	Others	Σ
Country							
Germany	15	6	1	51	30	30	133
France	1		1	17	11		30
Italy	1		1	12	79		93
Sweden	30		80	28	25	1	164
UK		80	1	15	16	24	136
Various	15	39	33	11	14	21	283
Σ	62	125	267	134	175	76	839

	Robot Population in Europe (Total amount 839 in April 74)	22368 e RDS
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Fig. 2 Robot Population in Europe

The characteristics of the offered IRs are shown in Fig. 3, 4 and Fig. 5

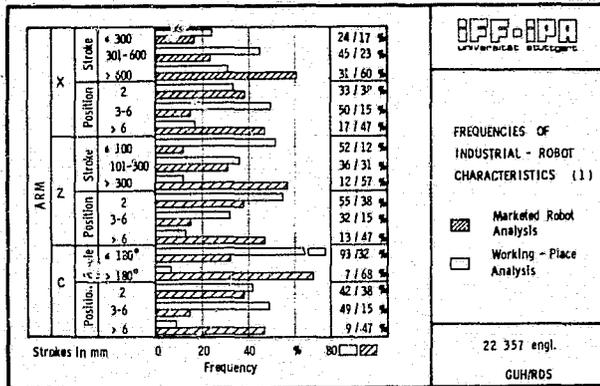


Fig. 3 Frequencies of IR Characteristics (1)

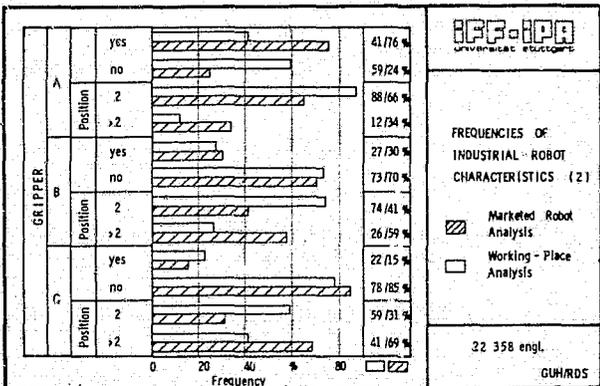


Fig. 4 Frequencies of IR Characteristics (2)

and spot welding (20 %).

Besides these applications a large variety of robots for various handling tasks are installed. The fields of application can be seen in Fig 6.

#### 4. Development

In the last few years a number of companies developed IRs. They cover the full range from simple IRs to highly sophisticated machines with computer control. Even

applicators like Volkswagen developed their own IRs. One can realize that electric drives and modular IRs gain on the market.

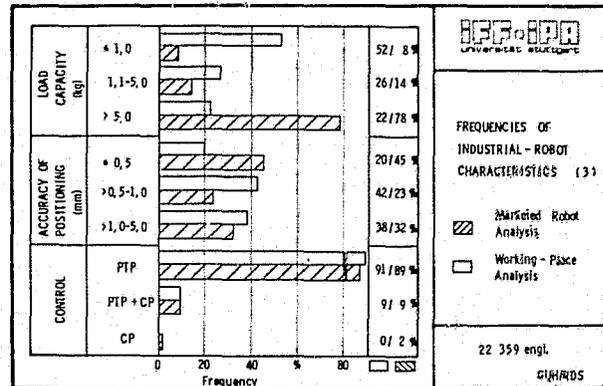


Fig. 5 Frequencies of IR Characteristics (3)

Application	%
Coiling	20,8
Welding	20,0
Handling (not specified)	14,8
Handling (presses)	13,0
Unloading of injection molding machines	11,2
Handling (cutting machine tools)	5,1
Unloading of die casting machines	4,8
Handling (glass industry)	4,5
Handling (forging presses)	2,4
Palletizing	1,6
Handling (chemical industry)	1,6
Unloading of investment casting machines	0,1
100% = 671 Industrial Robots	100,0

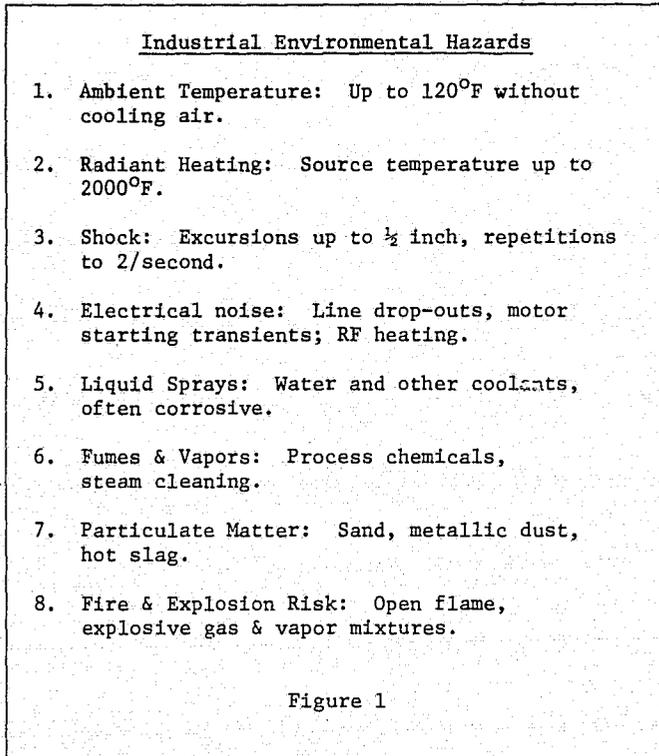
Fig. 6 Frequencies of IR Application in Europe

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SUMMARY

Drawing upon four million hours of industrial robot on-the-job field experience, a compendium of likely environmental hazards has been assembled. Figure 1 qualitatively enumerates these conditions.



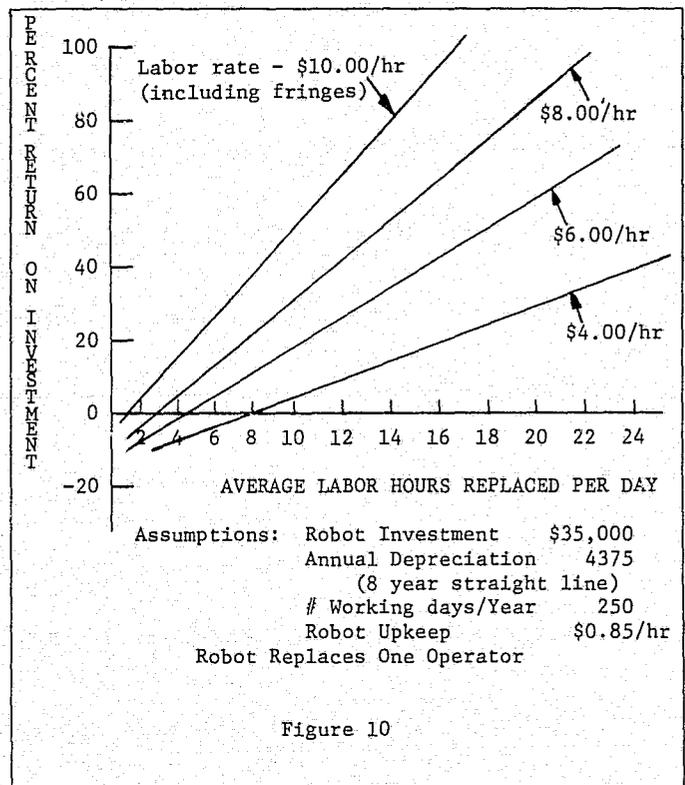
Given the working conditions, one must also consider just what is satisfactory performance under these conditions. Apart from doing the job properly, this involves demonstrating acceptable reliability and serviceability in the particular robot application.

Using the Unimate industrial robot as an example, data is presented as to the inherent reliability of the design and then this is used in a management system to bring the reliability performance up to a level nearing what is theoretically available.

The design analyzed has already paid homage to the requirements of Figure 1, and this design is then shown to be capable of a Mean Time Between Failure of 400 hours and an average up time of 98%. These standards compare favorably with that of human labor and Bureau of Labor statistics figures are indeed the source of the standard.

The paper will discuss some specific design decisions made in view of application requirements. Some of the more heinous jobs will be photographically presented.

The final constraint (which just might be classed as also being environmental) is economic. It is of no practical significance to build a robot which is not cost effective in comparison with human labor. Jobs are likely to bear wage scales that reflect how distasteful or unsafe the activity is. Figure 10 allows one to consider the level of expenditure for a robot which can be made for any worker pay scale, hours operated, and return on investment expected.



If a robot can withstand the industrial environment, maintain an uptime of 98%, endure 10,000 hours between major overhauls, and provide a return on investment in excess of 25%, it is probably a viable product.

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## TOPICS IN PROGRAMMABLE AUTOMATION

C. A. Rosen

Stanford Research Institute, Menlo Park

Background

Exploratory research and application programs in programmable automation are being conducted in a small number of laboratories.\* This development of software-programmable systems for application to materials handling, inspection, and assembly is based on the confluence of several technologies and areas of research:

- Numerically controlled and computer-controlled machining, which has become dominant in the fabrication of machine metal parts.
- Programmable manipulators, commonly known as industrial robots, which are becoming increasingly acceptable to industry as pick-and-place automations and for automated spot-welding, other welding operations, and spray painting.
- Machine intelligence, a branch of computer science devoted to the study and application of computers to emulate human-like capabilities, such as perception and interpretation, sensor-controlled manipulation, natural language understanding, modeling, and problem-solving, and finally, of integrated robot systems that make use of all of the foregoing disciplines.
- Large-scale semiconductor integration technology, which is growing explosively to provide powerful micro- and minicomputers and special electronic hardware, at a cost that is becoming increasingly less important compared to the costs of the software required to program for each application and to control the devices in a complex system.
- "Smart" sensor technology, which is beginning to provide us with the means for reliable measurements useful for autonomous control of manipulative functions. These means include torque, force, visual, velocity, and position sensors, whose outputs can be monitored in real time by using available microprocessors, thus facilitating asynchronous local computation without burdening the executive minicomputer which controls the whole system.

We are at the state of marrying elements of each of the foregoing technologies into integrated programmable automation systems. There follows a discussion of two topics: the role and development of training aids, and the potential application of these aids to augmented teleoperator systems.

Software Training Aids

There is reasonable basis for assuming that total hardware costs for useful systems will be economically justifiable to industry. It is less certain whether the cost of programming for each new job will not be excessive. The industrial robots now in use have gained such acceptance, in large part, because of the relative ease with which they can be programmed, by the present methods of "programming by doing." These methods have eliminated the need for formal coding and enable the robots to be "trained" by experienced factory personnel who are not computer scientists. It is indeed a challenge to extend this methodology to the far more complex programmable systems now in development. At SRI, a significant part of our total automation program is concerned with

precisely this issue. We are attempting to develop powerful "training" aids comprising hardware and software components, aimed at the minimization of formal coding by the factory user of these advanced systems. Experimental studies and implementations now in progress include:

- An interactive vision system that assists an operator to assemble a computer program that will execute an inspection function, by his selection of picture-processing and feature-extraction routines from a library of such routines, previously encoded.
- A program that automatically generates the decision strategy to recognize parts and determine their position and orientation. The operator "shows" samples of the parts to be differentiated to the visual sensing system and it automatically selects appropriate features and the sequence of their application to perform the desired recognition functions. This procedure has been termed "training by showing."
- A speech input system to supplement control of manipulators during training. At present, manipulator trajectories are generally programmed either manually, using switches and joysticks, or by coding instructions to be executed by computer. We are now using a spoken-phrase-recognition device, interfaced with the controlling minicomputer, to effect speech control of elemental low-level manipulative actions, or, more importantly, the control of more complex multiple-degree-of-freedom actions or sequences of such actions. It is assumed that assembly operations will ultimately require the use of several sensor-controlled manipulators acting cooperatively. It is envisioned that the programming of this complex system can be implemented by an operator interacting with the system via speech and manual control, while he or she is watching the performance of the manipulators in the actual factory environment. The operator will be able, via speech, to "call" specialized subroutines, set parameters, edit the sequence of events, and so forth. Although the operator will have to be trained to perform effectively in this mode, it will not be necessary for the operator to write code, and the use of teletyping will be minimized.
- Computer programs to implement automated path control. These control the manipulator, in real time, so that it can execute paths prescribed in a specified world coordinate system. These programs perform the coordinate transformation calculations necessary to control the multiple manipulator joints, simultaneously, so that the end-effector traverses a desired path, referenced to a chosen world coordinate system. Other programs are being developed to provide for insertion of constraints in path trajectories, and to optimize and smooth the actual paths to be executed after training. These programs will be stored as subroutines, callable by the operator via speech input during the training mode.

\*See references at end of paper.

## Teleoperator Systems

Several important applications of teleoperators require remote control of two manipulators acting cooperatively. Instances include the maintenance, repair, and modification of machinery in the nuclear power field, in space and deep sea applications, and in the disposal of dangerous materials. Although modern teleoperator systems include stereovision and force-feedback to provide "presence" to the human controller, complex operations are still slow and tedious and require considerable skill.

We believe that the above capabilities can be significantly augmented through the use of the visual sensing, speech input, and path control facilities being developed as programming aids for automated material handling and assembly. One can visualize an operator, while both hands were engaged with manual controls, requesting by voice input the execution of stored subroutines; the computer would accurately control the subsequent manipulator actions, such as the relative position, direction of travel, alignment, or velocity of the two manipulators. Other subroutines could implement fastening, unfastening, and fitting operations, with the operator providing supervisory control and "fine tuning" as necessary. Specialized routines could also be preprogrammed and made available for automatic implementation in instances in which particular sequences of required actions were repeated often. Further, visual sensing devices mounted in close proximity to the end-effectors could, by feedback control, effect precise positioning of the manipulator "hands" or tools at known sites of the workpieces or machinery. Image processing and interpretation programs, using salient features or painted "marks" could be developed for such control.

### Summary

The confluence of a number of disciplines has made possible the early development of programmable automation systems applicable to the material-handling, inspection, and assembly of batch-produced manufactured goods.

The development of software training or programming aids is a key element of this new work. Such aids are aimed at the reduction or elimination of formal coding by the factory user.

Ongoing work that is primarily aimed at implementing programmable automation appears highly relevant to the development of a new generation of teleoperators. By introducing a small but powerful computer into the man-machine loop, speech control, automatic sensing, path control, and accurate implementation of repetitive functions become available to augment man's capability for control of complex manipulation.

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INFORMATION AND CONTROL ISSUES OF ADAPTABLE-PROGRAMMABLE  
ASSEMBLY SYSTEMS FOR MANUFACTURING AND TELEOPERATOR APPLICATIONS

J. L. Nevins and D. E. Whitney  
C.S. Draper Laboratory, Inc., Cambridge, Massachusetts

### Introduction

The early successes of Ray Goertz in extending man's hands and sensors into hazardous environments with first his mechanical master-slave manipulators, then later with his electrical manipulators, was unfortunately never followed up. Some work was done by researchers in extending these simple devices and applying the techniques to underwater and rehabilitative engineering applications to the famous Mosher Walking Horse. Ed Johnsen has completed a very complete story on these activities.

At the Charles Stark Draper Laboratory in collaboration with the MIT Mechanical Engineering Dept. starting from the mid sixties basic research was started in these areas, supported by the AEC-NASA Space Nuclear System Office. This work attempted to identify the general research goals that would be required if significant changes were to be made in these systems. Significant developments were made for a computer-controlled-man-supervised-Multi-Moded Manipulator Remote Manipulator System.

The remainder of this paper will summarize the work performed for SNSO, its extension to industrial assembly systems, the importance of the National Science Foundation sponsored industrial assembly research to teleoperators, and finally recommend research projects that could be done on a fairly short time scale to make significant improvements in some present systems and permit their use in nuclear, mining and underwater applications.

### SNSO Supported Activities

The first of these activities was a computer-controlled-man-supervised system, in which man's role covered the spectrum from direct control to target identification and acquisition thru either single channel TV or optics, to a supervisor/planner. Supporting him in his visual tasks was a pointing system. Once a target and task site were located in some coordinate frame then a computer-controlled manipulator system could be called to perform assembly or disassembly routines. These routines were a combination of open loop position control to get to the target site and closed loop control organized about local force and tactile sensors.

A force sensor array and fairly simple control strategy was used to insert a 1.25 cm (0.5 inch) peg into a hole with a clearance of 1/80 of a millimeter (0.0005 inches). To achieve the desired end point motion a new control mode by Whitney called Resolved Motion Rate Control was implemented. To activate these new systems required new multi-degree-of-freedom hand

controllers. A 6 DOF force controller which requires minimum operator work volume was built. Finally, to avoid the trap of mobility system designs forced by designers' pet theories rather than the real requirements of the task or task environment, a number of design tools were implemented.

### Adaptable Programmable Assembly Systems - NSF Sponsorship

The SNSO sponsored work brought out the need to analyze manipulation tasks in detail, determine the information and control needed to accomplish them, and then design the required sensors, movers, controllers and displays. To describe tasks in the highly organized world of industrial assembly it has proved fruitful to distinguish tasks by the amount of uncertainty displayed by the parts and the devices used to assemble them. Midway between people ("machines" which can tackle tasks of great uncertainty) and conventional fixed automation (incapable of dealing even with uncertainty too small to disqualify the parts themselves) should lie adaptable machines with sensors and control strategies related to those described above.

Work currently under way involves expanding this point of view by carrying on research efforts in the following areas:

Assembly descriptors: Analyses of geometry of motions and forces of interaction between parts, detailed analyses of particular subassemblies to determine possible sequences and necessary tools, and a more general search for ways of delineating classes of assembly.

Information: Possible types and architecture of systems, types of sensors, and analyses of errors

Control: Dynamic studies of motion devices, the strategies for using the information to drive the motion device, and error analyses, which together allow prediction of assembly speed and repeatability.

Validation of the hypotheses via good experiments that can be repeated by many others is a virtual necessity for anything with scientific merit. The output of these studies are configuration definitions of systems that can be used in manufacturing.

### Assembly Descriptors

#### 1. Assembly Sequence — Macro Descriptors

A gearbox for a home automatic clothes washing machine illustrates the complexity of considering total assembly. 221 steps made up

of 17 distinct tasks, of which 9 are very similar, are required to deal with 34 parts that range in size from 0.64 cm (1/4 inch) to 1/3 of a meter (1 foot).

## 2. Geometric Analysis - Micro Descriptors

Pegs-in-holes can be categorized by the two dimensionless variables  $c$  and  $l/D$  where  $c$  essentially describes quantitatively a class of assembly tasks and  $l/D$  defines the wobble angle a peg would have as a function of  $c$  and the depth it is inserted into the hole. Two issues are important here. One is the totality of relative error sources, such as parts variation, and the repeatability of the mechanism used to position the part. The other is the range of values of  $c$  one is likely to encounter with certain kinds of parts. See Figure 1.

### Information

#### 1. Motion Regimes and System Levels

Configurations for assembly need be concerned with three things, namely: (a) fetching parts, (b) holding parts and (c) assembly of parts. These tasks define the degree-of-freedom available for consideration. There are many options. Two kinds of motion regimes have been defined - gross motion and fine motion. Fine motion is that motion associated with the actual assembly of pieces while gross motion is the fetching and moving of pieces.

In addition to the motion regimes, we have categorized systems into three levels of information use. The first level, level 0, is a system requiring no information from the environment with which it interacts. The so called "put and place" machines are of this kind. The geometric analysis described above indicates that even these crude machines can be used to accomplish specific classes of mechanical assembly. Violation of error constraints or lack of compliance would lead first to large contact forces and then to jamming. Level 1 systems contain force and tactile sensors for monitoring these forces. These systems, since their information is restricted to what they feel, can be described as capable of assembly similar to that performed by a blind person. Level 2 systems contain additional sensors, in particular, visual and non-visual imaging sensors. These systems allow a less structured environment.

#### 2. Sensor Technology

Two kinds of 6 degree-of-freedom force-sensor systems have been developed in support of this work: Wrist force sensors and a pedestal sensor.

### Control

In Level One or higher level systems, fine motion will be accomplished using some kind of force or touch feedback. A basic force feedback strategy of interest is called accommodation, a procedure by which vector motion commands in the  $x$  coordinate system can be deduced directly from vector force measurements reflected into that same coordinate frame. When it is realized that motions produce forces and strategies recommend motions based on those forces, it is clear that a loop has been closed

through the mobility device, the parts in contact, the force sensor and the motion control system. This means that any force-motion strategy must be designed carefully with its control servo implications in mind.

### Experiments

Experiments are under way to verify the above analyses. Commercial industrial robots have been used to assemble typical machine parts.

### Near Term Teleoperator Research Needed

The inadequacy of the earlier teleoperator systems has been well documented. To implement significant new systems we need to define a basic approach to the problem that allows us to employ scientific principles. Otherwise we fall into the easy trap of widget building or special mechanisms for each task.

The early analysis work performed for SNSO focussed on the specifics of the task(s) and the operational environment. The more thorough analysis performed for NSF on mechanical assembly has shown that tradeoffs can be made between task complexity (defined as increasing errors in the parts) and system configuration complexity. From these two previous activities three research tasks can be suggested whose results would help focus the research needed for new applications. The suggested tasks are:

1. A precise categorization and analysis of the tasks as illustrated in the previous section, oriented toward hazardous environments like mining or underwater exploration as well, where a much greater range of system accuracy and performance is needed.
2. Evaluation and testing of the new teleoperator modes proposed but not adequately tested.
3. Configuration studies based on items (1) and (2) to categorize the configurations of interest for the required tasks and to identify the information/control bottlenecks.

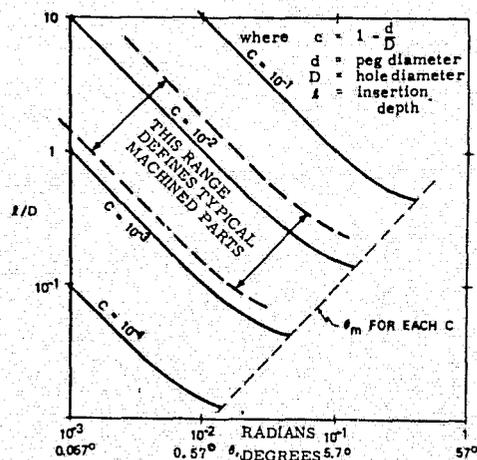


Figure 1.  
WOBBLE ANGLE vs INSERTION DEPTH

# PROFILES OF MECHANIZATION IN LONGWALL MINING

Larry N. Pearce, Ph.D., Director of Engineering  
T A B Engineers, Inc., Northbrook, Illinois

## Introduction

A flat, relatively level underground coal seam may be developed for longwall mining by driving parallel entries for a distance of 1000 meters into the seam. The entries, perhaps 150 meters apart, consist of ventilation and access passages, which are formed by removing coal in a grid pattern, leaving behind pillars of coal to support the overburden. Figure 1.

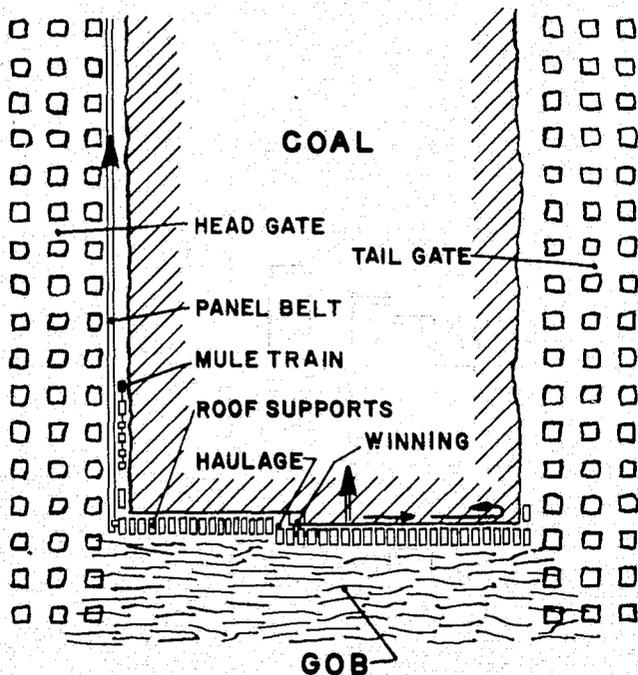


Figure 1. Longwall Mine-Plan

The basic equipment of a longwall coal mining machine consists of roof supports, haulage hardware and a winning (cutting) machine. Figure 2. Direct labor of about 12 people is required to operate a longwall machine. The face of the coal seam being mined by the machine might be 150 meters long and perhaps 1.5 meters high, and may yield up to 5000 tons of coal per day. As the winning machine travels along the face, the "won" coal falls into the face conveyor and is transported away. A roof support is quickly moved forward to support the exposed overburden. The roof collapses behind the roof support to form the "gob."

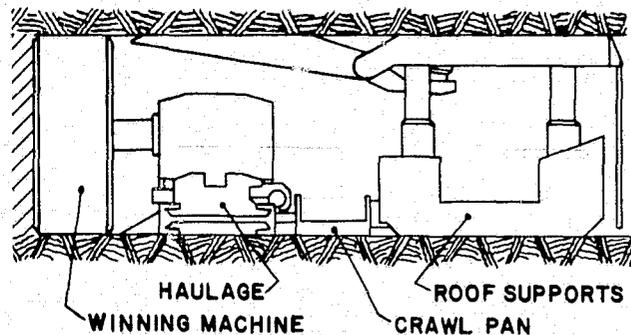


Figure 2. Longwall Equipment

## Remotely Manned Longwall Mining System

The remotely manned longwall concept has dual objectives: to increase production and to remove people from the face during production.

The concept of a complete integrated automation system has been lacking. Past attempts at longwall automation have tended to isolate one function and mechanize it. Since mine equipment manufacturers tend to specialize in a component (such as roof supports), each has tried to improve his product without much consideration for the other mining functions.

Evaluation of the results of previous mechanization attempts has varied widely, depending on the evaluator's commitment and understanding of the principles involved. The rigors of the mining environment have caused failure of subordinate hardware (such as valves and relays.) Problems caused by massive loads, dust, explosive gases and confined spaces have led to major design trade-offs that jeopardized performance.

## Mechanization Profile

Longwall coal mining involves a number of basic and elemental functions or operations or tasks. The coordinated combination of all elemental functions results in the "producing" of coal.

Each operation can be ranked on a scale from 1 to 17 that reflects the level of mechanization present in the performance of the elemental operation. At the lowest level (1) the operation is completely manual. At the highest level (17) the elemental operation is performed completely automatically, not requiring man's direct intervention.

A system chart can be created by listing every elemental operation in sequence as it normally occurs in the production process, and then plotting the appropriate level of mechanization that occurs at each operation. This technique was developed by James R. Bright in 1955.

Figure 3, Mechanization Profile, is a chart where it is convenient to record, for each elemental operation, the level of mechanization used in its execution. The levels are both numbered and described.

	CONTROL SOURCE	POWER LEVEL	LEVEL OF MECHANIZATION	OPERATION OR FUNCTION						
				1	2	3	etc.			
CLOSED LOOP	PERFORMANCE CONTROL RESPONDS WITH ACTION	M E C H A N I C A L	17	ANTICIPATE PERFORMANCE						
			16	CORRECT WHILE PERFORMING						
			15	CORRECT AFTER PERFORMING						
			14	IDENTIFY AND SELECT ACTION						
			13	SORT PER MEASUREMENT						
			12	CHANGE MOTION PER MEAS.						
			11	RECORD PERFORMANCE						
			10	SIGNAL MEASUREMENT						
			9	MEASURE CHARACTERISTIC						
			8	ACTUATE BY WORK PIECE						
OPEN LOOP	MECHANICAL CONTROL	M E C H A N I C A L	7	POWER TOOL REMOTE CONTROL						
			6	POWER TOOL SEQ. CONTROL						
			5	POWER TOOL FIXED CYCLE						
			4	POWER TOOL HAND CONTROL						
			3	POWERED HAND TOOL						
			MANUAL CONTROL	M A N U A L	2	HAND TOOL				
					1	HAND				

Figure 3. Mechanization Profile

#### Longwall Mechanization Profiles

A portion of a mechanization profile for an existing longwall operation shows the complexity of the manual observations performed by direct labor along the face. Figure 4. The portion shown is for adjusting the height of a shearer drum while cutting coal in order to control the cut to the contour of the surrounding

roof and floor. The height change is effected by push-button operation of a solenoid-controlled, pilot-operated, hydraulic valve that allows the adjustment by the movement of a cylinder piston.

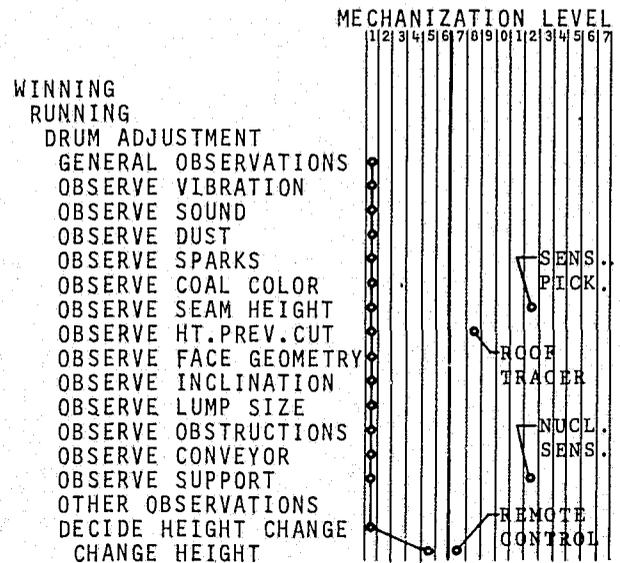


Figure 4.  
Partial Longwall Profile Shearer

There are currently four significant approaches to drum height control mechanization:

1. Remote control systems - umbilical and radio transmitter/receiver - operated manually up to 50 feet away.
2. Nucleonic sensing of coal thickness by differential coal/overburden radiation absorption.
3. Roof tracer sensing of the level of the roof from the previous cut.
4. Sensitized pick measuring cutting resistance when picks break through into a harder overburden.

Each of the four approaches greatly relieves operation duties but does not supersede his range of observations.

A systems approach is needed that will allow the removal of the operator from the face. The remotely operated longwall system must take into account not only the drum adjustment illustrated above but also all other winning machine function as well as all roof support and haulage functions.

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## SOME OPPORTUNITIES FOR TELEOPERATED MINING

E. R. Palowitch  
Bureau of Mines

and

P. H. Broussard, Jr.  
Marshall Space Flight Center

### ABSTRACT

The need to increase coal production and worker productivity while improving the health and safety of the coal miner presents some interesting challenges and opportunities for teleoperation.

Systems available for mining coal are described briefly in terms of fragmentation, materials handling, ground control, and environmental control subsystems. The need for automation systems, their requirements, and the state-of-the-art are explored. Technologic deficiencies of longwall mining--the system having the highest potential for full automation are discussed.

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# BILATERAL SERVOMANIPULATOR IN DIRECT MODE AND VIA OPTIMIZED COMPUTER CONTROL

J. Vertut  
CEA, Saclay, France  
and

P. Coiffet  
University of Montpellier, France

## SUMMARY

MA 23 bilateral advanced servo manipulator is designed as a general purpose arm to be adapted to various hostile environments, like undersea, space industry, medicine etc .. This system is in development at CEA Saclay in cooperation with university of Montpellier, La Calhène, and the French Navy at Toulon for the undersea application.

MA 23 is based on a light articulated arm with original zero backlash highy reversible mechanical reducers operated by DC torquers all located on the body.

An improved position - position servo loop operated only from the position error signal gives full dynamics and static force feed back in the range of 0,2 to 20 kg with accelerations over g and speed over 1 m per second.

The master unit can be a master arm in direct mode. An optimized computer control enables to improve that direct mode by dynamic simulation of the slave arm using only on the static and dynamic position error signal (ie force feed back). In particular the computer calculates the mass and center of gravity of the object being handled.

This computer subsystem can also works as a master and control any desired dynamic trajectory, to be generated from the environment analysis, to execute a high level command.

The system works now in direct mode and tape recording, the computer control is in development until middle of 76.

This system opens the use of bilateral manipulator system with no discontinuity from full time - manual control, to supervisory control and more autonomous operation associated with artificial intelligence.

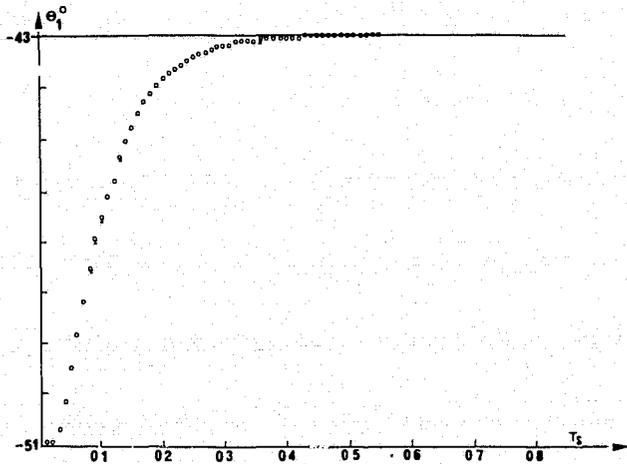


Figure 11

Simulation results:

"o" complete set of equations

"x" dynamic coupling terms removed

$$[(B) = (C) = 0]$$

Result for  $\theta_1^0$  with a maximum torque of 150Nm applied on the joint.

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AN EVALUATION OF CONTROL MODES IN HIGH GAIN MANIPULATOR SYSTEMS

D. R. Wilt, D. L. Pieper, A. S. Frank, and G. G. Glenn  
Cybernetic Automation & Mechanization Systems Section

Re-entry & Environmental Systems Division, General Electric Company, Philadelphia

Previous performance comparisons have been made between replica master and resolved rate control for small (man- equivalent) manipulators. This paper describes results for large load (100 lb.), and reach (14 ft.) manipulators.

Two types of tasks are studied. One is a pick and place task simulating removing parts from a conveyor and stacking them on a pallet (a two dimensional target). The second task simulates stowing palletized cargo in a container. This is also similar to space shuttle satellite stowage. It involves three dimensional positioning and demonstrates the value of compliance provided by a bilateral control.

Related experiments over the past several years, including those at Draper Lab and NASA/JSC are discussed and the results correlated to this work.

Over all results of the study show the bilateral master to have a distinct but less pronounced advantage with large manipulators than that demonstrated with small manipulators.

## **SESSION VI**

# **Rehabilitation Systems**

## ARTIFICIAL SOFTNESS SENSING - AN AUTOMATIC APPARATUS FOR MEASURING VISCOELASTICITY

I. Kato, Y. Kudo, and K. Ichimaru

Waseda University, No. 4-170 Nishiokubo, Shinjuku-ku, Tokyo, Japan

To realize artificially recognizing function of softness similar to human hands, it is not sufficient to recognize the object to be elastic. But we should recognize it to be viscoelastic. From this point of view we developed an automatic measuring apparatus for recognizing the viscoelastic characters. Now we can get the values of the viscoelasticity which constructs the main factor of human recognition of softness. There is the prospect that we can make the softness of the artificial sense similar to that of human hands.

#### Introduction

As for the present artificial sense of softness, the objects have been treated as the elastic solid which is subject to the Hooke's law. However we easily find several discrepancies between almost all objects we treat in our daily lines and those in Hooke's law. They show the viscoelastic properties in which stresses depend on their strains, strain rates and high degree time differential coefficients. Therefore they should be recognized as the viscoelastic bodies. Especially when we try to apply it to medical manipulators, the present way is neither applicable nor useful because of its rough approximate way. From these aspects we mentioned above, we have developed an automatic measuring apparatus so that we might realize the artificial sense of softness with similar function to human hands.

#### Synthetic Polymer Model

We produced synthetic polymer models for the two following purposes.

1. Investigate the relations between the viscoelastic coefficients and the human sense of softness, in the way of these models as the stimuli of softness for sensory evaluation.

2. Evaluate the apparatus, in the way of these models as test pieces for it.

Synthetic polymer models we selected are those of polyester and silicon. We actually produced ones of several degrees of softness. We investigated and learned viscoelastic characters in the standard creep test.

#### Sensory Evaluation

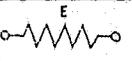
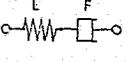
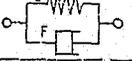
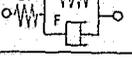
For the grasp of the human sense of softness, we did the sensory evaluation in the way of the synthetic polymer models as the stimuli of softness. (1) We used the psychophysical method of constructing the ordinal scale and ratio scale and analyzed them by means of psychophysical and empirical laws. (2) As the result of careful considerations about the factors which from the human sense of softness, we came to conclusion that main factors of the recognizing mechanism can be expressed by the viscoelastic coefficients.

#### Theory of Measurement

As the automatic measuring method of the apparatus, we use static one. Our method is to give the object the force of a step or a ramp pattern and to measure the strain as the creep compliance which is the function of time. Therefore we can get the solution of the dynamic analysis in the real force pattern and the form of hysteresis by the viscoelastic theory so that we could judge the viscoelastic model and calculate the viscoelastic coefficients of the object from the

creep compliance.(3)(4) In the dynamic analysis we ignore the transformation of the volume but when it comes to the form-transformation we define four typical viscoelastic models(shown in Table 1 )because of the appropriateness of the approximation and the difficulty of the analysis.

Table 1 Typical Viscoelastic Models

Model	Name	Differential Equation Stress $\sigma$ -Strain $\epsilon$
	Elastic solid	$\sigma = E \cdot \epsilon$
	Maxwell fluid	$\sigma + \frac{F}{L} \dot{\sigma} = F \cdot \dot{\epsilon}$
	Kelvin solid (Voigt)	$\sigma = E \cdot \epsilon + F \cdot \dot{\epsilon}$
	Three-parameter solid	$\sigma + \frac{F}{E_1 + E_2} \dot{\sigma} = \frac{E_1 E_2}{E_1 + E_2} \epsilon + \frac{E_1 F}{E_1 + E_2} \dot{\epsilon}$

### The Automatic Measuring Apparatus

This apparatus consists of two sections ,that is,the section of the measurement and of the data processing. The former gives the object the fixed pattern force and measures its creep compliance. The latter calculate electrically its viscoelastic coefficients from its creep compliance. The section of the measurement consist of the three mechanisms;that is,the driving mechanism,the measuring displacement mechanism, and the measuring force mechanism. The driving mechanism gives the force to the object. The measuring displacement mechanism measures without contact the displacement of the pellote optically. The measuring force mechanism measures the driving force by the strain gauge. The section of the data processing consists of two mechanisms, that is,the judging mechanism and the calculating mechanism. The judging mechanism recognizes the the viscoelastic model. The calculating mechanism calculates the values of the viscoelastic model already recognized. The flowchart of this apparatus is shown in Fig.1.

### Experiment of Measurement

Using this apparatus we measured the synthetic polymers and other various kinds of objects. As the result of this experi-

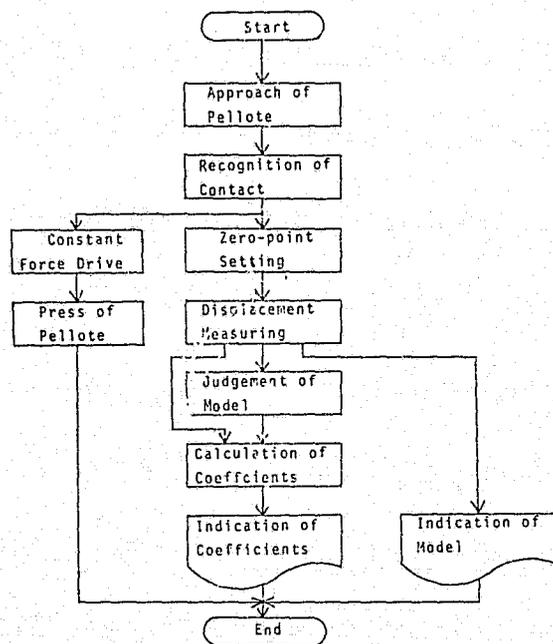


Fig.1 The flowchart of the apparatus measurement,we find out that if we remove the mechanical effect of the apparatus,we could get the considerably accurate values of viscoelastic coefficients. Accordingly it's quite possible that we apply this apparatus to the artificial sense of softness.

### Conclusion

Thanks to this apparatus we can learn the values of viscoelastic coefficients that form the main factors being recognizable human softness. If we think about these values in respect of human information processing,we can use this apparatus as the artificial sense of softness. therefore the first of realizing the artificial sense of softness has been achieved. However the problem to clarify the mechanism of human information processing and realize it artificially still remains.

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## SYSTEM INTEGRATION OF PATTERN RECOGNITION, ADAPTIVE AIDED, UPPER LIMB PROSTHESES

John Lyman, Ph.D., Amos Freedy, Ph.D., and Moshe Solomonow  
Biotechnology Laboratory, University of California, Los Angeles

This paper discusses the requirements for successful integration of a computer aided control system for multi degree of freedom artificial arms and establishes specifications for a system which shares control between a human amputee and an automatic control subsystem.

The approach integrates the following subsystems:

- (1) myoelectric pattern recognition
- (2) adaptive computer aiding
- (3) local reflex control
- (4) prosthetic sensory feedback, and
- (5) externally energized arm with the functions of prehension, wrist rotation, elbow extension and flexion and humeral rotation.

Under the proposed integration scheme, the realized configuration can be considered as a three level control system. These levels include the patient voluntary control level, the computer aided control level, and the reflexive control level. The patient level utilizes the voluntary control capability of the human and his ability to generate specific myoelectric patterns from multiple electrode sites. The adaptive computer aiding and certain reflexive elementary functions make up the two lower levels, i.e., the autonomous control capability of the system.

The concept of myoelectric pattern control is a means for efficient and compatible control (Wirta and Taylor, 1969; Herberts, et al., 1973), which involves the mapping of  $n$  electrode signal sources into  $m$  classes of patterns. Each pattern is used as a unique control signal to the total arm such that signals from the  $n$  control muscle sites are transformed into  $m$  prosthesis joint control signals, producing multijoint coordinated motions. This is in contrast to the conventional control approach where each control site is uniquely linked to an arm joint.

Unique to the approach considered here is the adaptive learning by a computer generated algorithm of the myoelectric patterns of an individual amputee and their utilization as a compatible control signal source. The technique is based on a trainable maximum likelihood network which makes up a personalized man/control system command scheme. The control functions that are generated by the computer occur in parallel with those generated by the human, and have the function of providing trajectories of motion or joint position commands (Zadaca, Lyman and Freedy, 1974). Reflexive control refers to arm output activity governed by a set of independent control loops that respond automatically to sensory inputs from the arm and the environment of operation. The addition of reflexive responses to the artificial limb control loop permits some direct

interaction between the hand and the environment, by-passing the human operator and the computer aided control.

Sensory feedback involves such information as grasp pressure, elbow and wrist angular position, etc. The objective of sensory feedback is to provide the amputee with sensations that describe the status and motion of the arm, and thereby decrease the amount of visual supervision and attention required to control the arm. For example, a fingertip pressure sensing system is included in the arm prosthesis in order to provide the operator/amputee with some sensation proportional to the pressure exerted by the fingers on various objects. The sensory feedback system includes a pressure transducer and a transformation network which generates the feedback signal configuration to the skin surface via contact electrodes.

In the process of realizing a successful system integration, a number of subsystem interface difficulties have had to be evaluated. Some of these difficulties and possible implementation options for reducing or eliminating them are developed in the full paper.

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## APPLICATION OF A POSTULATE BASED CONTROL THEORY FOR AN ARTIFICIAL ARM

S. C. Jacobsen and R. B. Jerard  
University of Utah

INTRODUCTION

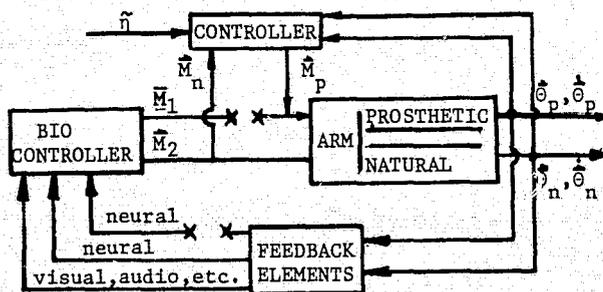
Strictly speaking, artificial arms may be considered as manipulators. However, there are several factors that cause artificial arm and manipulator design to be significantly different. The close proximity of the manipulator to its operator results in increased proprioception. Physical attachment of the machine to the man allows for force interactions which display manipulator loads to the amputee.

The performance requirements for artificial arms, however, are probably more severe than for manipulators. An artificial arm controller must allow high speed operation with sufficient accuracy to permit manipulator tasks which are coordinated with the rest of the amputee's body. The arm hardware must be lightweight, strong, fast, and totally self-contained. For example, the entire machine, including power supply for an above-elbow arm, should weigh less than two and one-half pounds.

At the University of Utah, we are developing an artificial arm for above-elbow amputees. The project involves construction of arm hardware and the implementation of a new theory for control. This paper will report experimental results of a preliminary application of the control theory.

ARM CONTROL THEORY

The controller for an artificial arm is shown below in block diagram form.



An important observation is that the controller, the artificial arm and the remnants of the natural arm form an interrelated and indivisible system. A controller cannot be defined without consideration of the entire system. The blocks in the diagram represent:

1. Biocontroller. The biocontroller consists of the brain, neuro pathways, and muscles which apply torques to the skeletal frame. Output from the biocontroller is a vector  $\vec{M}_2$  which represents the torques applied to

the natural remnants of the amputee's arm. The output  $\vec{M}_1$  represents the torques which would have been applied to the amputated parts of the arm now replaced by the prosthesis. Note that this pathway is interrupted by amputation. Inputs to the biocontroller are neural, visual, and audio information about the state of the arm-prosthesis combination.

2. Arm. The arm block represents both the natural portions of the arm and the electro-mechanical replacement for the missing arm. Inputs to the arm block are the torques which are applied to the natural and prosthetic joints by muscles and servomotors. Output of the arm block is the angular position and angular velocity of the prosthesis  $(\dot{\theta}_p, \theta_p)$  and the angular position and angular velocity of the natural portion of the arm  $(\dot{\theta}_n, \theta_n)$ .
3. Controller. The controller is essentially responsible for re-establishing communication in the interrupted signal pathway  $\vec{M}_1$  (torques which were applied to amputated portion of the arm). The controller inputs are the kinematic state of the arm prosthesis combination, the vector of torques which are applied by the musculature on the remnants of the natural arm, and the parameter  $\tilde{n}$ . The additional parameter  $\tilde{n}$  will be explained later. The output of the controller is the vector of torques  $\vec{M}_p$  which should be the same as  $\vec{M}_1$ . Note that the equations describing the controller may be derived from a fundamental postulate which will be discussed in the paper.
4. Feedback Elements. Feedback elements are responsible for monitoring the kinematic state of the limb and presenting that information to the biocontroller.

CONTROLLER DEVELOPMENT

Implementation of the controller requires completion of three tasks.

1. Equations for the controller must be derived from the fundamental postulate.
2. Develop the ability to monitor the vectors  $\vec{M}_n$ ,  $\vec{\theta}$ , and  $\dot{\vec{\theta}}$ .  $\vec{M}_n$  is obtained by monitoring electromyographic signals of selected shoulder muscles. The kinematic state of the limb  $(\vec{\theta}, \dot{\vec{\theta}})$  can be obtained by suitable goniometers.

3. Development of artificial arm hardware with performance sufficient to mimic the natural arm.

Our ultimate goal is to apply the above three steps to control a multi-axis artificial arm. We intend to control the degrees of freedom, humeral rotation, elbow flexion, and forearm rotation. In preparation for a multi-axis control, we are currently involved in a more limited, one degree of freedom experiment. We have derived the equations for control of elbow flexion. We have the capability to monitor  $M_n$  using nine EMG signals from shoulder muscles and we have developed an arm which can be utilized with one, two, or three degrees of freedom.

The paper will present results of the one degree of freedom experiment. Of particular interest will be the verification of the theory. Also of interest will be the stability and controllability of the system. The effect of variations of controller parameters will also be discussed.

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VOICE CONTROLLED ADAPTIVE MANIPULATOR AND MOBILITY SYSTEMS FOR THE SEVERLY HANDICAPPED

E. Heer and G. A. Wiker  
Jet Propulsion Laboratory  
and  
A. Karchak, Jr.  
Rancho Los Amigos Hospital

At present, there are nearly two million people in the United States with varying degrees of paralysis with an incidence rate approaching 1/100 annually. Nearly 2/3 of these individuals have severe deficiencies in manipulative and/or mobility capabilities.

During the past several years, NASA has invested significant efforts in the development of teleoperator and robot technology for space related programs. This technology can be applied to the benefit of the severely handicapped (e.g., quadriplegics) giving them greater self reliance and independence and offering many of them the possibility of leading productive lives.

A project jointly sponsored by the NASA and the VA has recently been initiated at JPL in July 1974. The primary objective of the project is to apply available teleoperator/robot technology to rehabilitate amputees and spinal cord injured patients with severe loss of motor, manipulative, and sensory capabilities in the upper and/or lower extremities.

As a first step, during the past few months a powered multipurpose manipulator has been developed and mounted on a standard Everest and Jennings Model 33 battery powered wheelchair as shown in Figure 1. Both the wheelchair and the manipulator motions are voice activated and controlled using an adaptive voice analysis and recognition system which has been mounted at the back of the chair. For comparative tests, which will be conducted at a later date, the wheelchair mobility can also be controlled through a VAPC two channel bidirectional proportional chinswitch; and both, the wheelchair and the manipulator motions, can be controlled through a RLA nine channel proportional torque switch controller. For emergency situations, the power to the motors can be shut off by means of a head switch attached to the rear of the patient's head support and can be activated by pushing the head backwards and slightly to the left.

The VAPC chinswitch is a joy-stick actuated switch assembly mounted on an adjustable bracket attached to the wheelchair. The chin-control assembly is positioned by means of the bracket in close proximity to the patient's chin. The patient controls forward, backward, and turning movements of the chair by similar movements of his head, which is linked to the chin control by means of the chin receptacle attached to the upper end of the joy stick.

The Rancho Los Amigos tongue switch control for the wheelchair and manipulator has a bank of nine bidirectional proportional lever-switches corresponding to six manipulator motors

(degree of freedoms), two wheelchair motors, and power on and off. A novel feature of this and the VAPC chinswitch device is another pair of switches positioned on one side of the head by means of a bracket attached to the rear of the wheelchair. This pair of switches, actuated by a lever, operates a small motor which swings the entire bank of control switches or the chin control switch assembly to the side and away from, or to, their normal operating position by an appropriate head movement.

The VAPC designed manipulator is a simple six degree-of-freedom mechanism with the motion capabilities: Horizontal ab- and adduction, shoulder flexion and extension, telescopic extension and retraction, supination and pronation, wrist flexion and extension, and grasping.

The Scope Electronics voice recognition computer recognizes 35 words with fair reliability and generates two binary coded decimal signals as output for each processed sound set. An interface system has been developed that processes the binary coded decimal digital code to develop a set of relay contact closures. The relay closures connect a set of preset twin resistors to the function to be controlled. In the case of the wheelchair two fast forward, two slow forward, and two slow backward, controls are connected to produce fast- or slow-forward, slow backward, right turn, and left turn resistance setting for input to the wheelchair motor controller in place of the two joystick controlled resistors. For the manipulator control functions, fourteen controls are provided to set the input voltages to the six linear power amplifiers which drive the six motors on the arm. All of the controlled functions are open loop at this time, so load variations or changes in battery voltage can change the motor speeds. This is especially true of the manipulator functions, since the manipulator motors are operating between ten and forty percent of design voltage and nearly at stall speeds.

The vocabulary for voice controlling the wheelchair/manipulator system is shown in the control display in Figure 2. The voice recognition computer is trained by the patient user in his voice and speech pattern by repeating each command about five times when the computer is working in the training mode. Switching to the execution mode enables the patient operator to move about or to perform simple manipulative tasks by giving the appropriate sequence of commands.

After turning on the computer and the interface system, it is good practice to give the commands "STOP" (01), "SLOW" (08), and "CHANGE" (07). This sequence insures that the system is in a static state. Then to set up the

Arm commands the following sequence of commands have to be recognized: "READY" (00), "ARM" (03), any of the Arm control words, such as, "UP" (11), "DOWN" (12), etc. Then to activate the stored Arm control the word "GO" (05) has to be recognized. The words "FAST" (09), and "SLOW" (08) can be used at any time to change the rate of an active control or to preset the desired rate of a control to be activated. To stop an active control or to change to another control function the words "STOP" (01), or "HALT" (02) have to be recognized. While in the Stop condition a new control can be set up if desired, then when "GO" (05) is recognized this new control will be activated. It is not necessary to change the control after a "STOP" or "HALT", the previous control is stored and can be re-activated with a "GO" (05) word.

To change over to the Chair control condition from the Arm condition it is necessary to have had recognized a "STOP" or "HALT" word then the "CHANGE" (07) word is used to reset the Arm select. The Chair control condition can be entered with the "CHAIR" (04) word. The "RESET" (06) word resets the Ready condition as well as any stored control. The only useable words in this state are "STOP", "HALT", "FAST", "SLOW", and "READY" (00). "READY" as previously stated is the start or enable word used to allow activation of the interface functions.

Although the feasibility of voice controlled wheelchair/manipulator systems has been shown, there are several areas which need improvement before the system can be released for clinical testing. The major ones include: (1) to provide a better match of motors and loads, (2) to provide locking for each manipulator degree-of-freedom when the power is off, (3) to provide position feedback for all degree-of-freedoms and force feedback for terminal device closing and manipulator lift, and (4) to provide a better match of speeds and control response time.

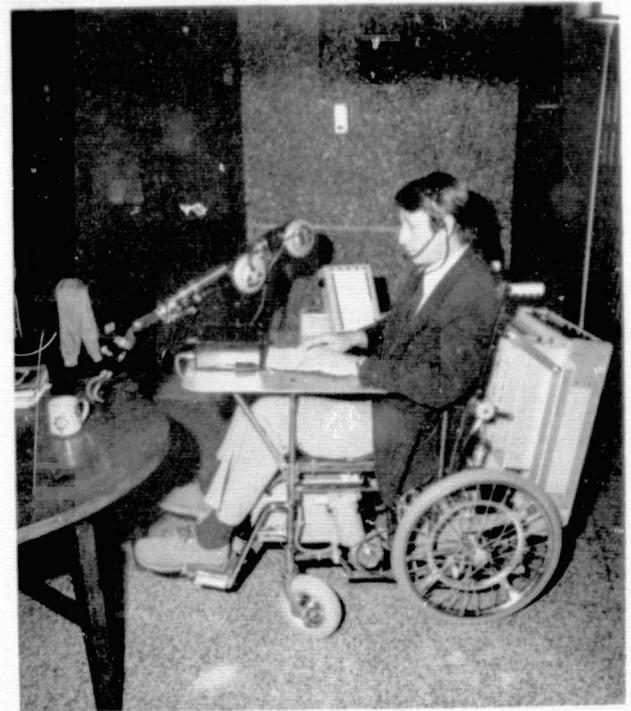


Figure 1. Voice activated and controlled wheelchair/manipulator system.

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GO	ARM (03)	READY (00)	(04) CHAIR	GO
UP (11)			(31) FORWARD	
DOWN (12)			(32) BACKWARD	
RIGHT (13)			(33) RIGHT TURN	
LEFT (14)			(34) LEFT TURN	
OUT (15)			(35)	
IN (16)			(36)	
SUPON (17)			(37)	
PRON (18)			(38)	
TURN (19)			(39)	
BACK (21)				
TILT (22)		GO (05)		
FLEX (23)		STOP (01 OR 02)		
OPEN (24)		RESET (06)		
CLOSE (25)				
(26)				
(27)			(09) FAST	
(28)				
(29)			(08) SLOW	

Figure 2. Control display panel showing the vocabulary and lights which light up when the corresponding command has been recognized by the computer.

## DESIGN AND CONTROL OF A MANIPULATOR FOR TETRAPLEGICS

V. Paeslack, Prof. Dr. med.

Forschungszentrum der Stiftung Rehabilitation, 69 Heidelberg, West Germany

and

H. Roesler, Dr. rer. nat.

Orthopädische Klinik u. Poliklinik der Universität, 69 Heidelberg, West Germany

Summary.

With the research project Medical Manipulators for severely Disabled Persons, sponsored by the German Federal Ministry of Research and Technology, the goal was set to produce a manipulative system which controlled by a disabled operator takes over tasks formerly performed by the upper extremities of the handicapped. During the work on a basic concept for the design of such an instrument it turned out that disability cannot be merely considered as a personal misfortune of the disabled, but is also evoked by an environment, the structure of which is exclusively adjusted to the dexterity of the normal fully able man. Disability in a more general sense means a mismatch between the functional capability of a manipulative system - either of biological or technical origin - and the structure of its environment. A concept for the design of a manipulator for tetraplegics, therefore, had to be based on the mutual adaptation of system determining properties of the disabled operator, the manipulator, and the environment.

The most important property of the disabled operator is his control ability. Because of the high lesions in the spinal cord movements of hand, arm, and shoulder are so unsteady that tetraplegics generally cannot use them for precise control. One had to fall back upon the movements of head and lips to derive control signals and it was decided to let them operate a

a control stick in three dimensions by lips and mouth.

With this rather poor information output of the disabled operator it was not advisable to design a manipulator complex enough to deal with tasks in a normal environment. A study in which a given set of activities was presented to tetraplegics with different heights of lesion showed that at least 15 degrees of freedom were required to perform approximately the half of all actions which occur in a normal environment. On the other hand the reduced control ability of the tetraplegics only allowed to control a maximum of three degrees of freedom at a time. So in a normal environment the disabled operator together with a manipulator he was able to control would be just a little bit less handicapped than without it. In this situation there is only one way out of the dilemma: to adjust the structure of the environment to the functional capability of the system disabled operator/manipulator.

At the present state of the research programm the following subsystems have been designed:

- 1) Threedimensional control stick
- 2) First prototyp of a manipulator
- 3) Control unit
- 4) Modells of an adjusted environment.

Rate control has been chosen for the manipulator. The control stick can be operated in six directions up-down,

left - right, forward - backward, and is kept in the neutral position by very soft springs which can be adapted to the force of the operator. Optoelectronic sensors are used as transducers. The control characteristic contains a backlash region, a range of creeping speed, and finally a range for proportional control. Different mouth pieces can be chosen by the operator.

A first prototyp of the manipulator has been built up from 3 joints for positioning a terminal device in the working space. The terminal device with further 3 degrees of freedom is still in the process of design. Each joint is composed of an electric motor with a harmonic drive reduction gear. A new principle was developed whereby an uncontrolled driving element is combined with an electronically controlled permanent magnetic brake.

In a first series of control experiments tetraplegics were asked to operate the manipulator with a direct coupling of the control stick's output to the various joints. The observation of each single joint, however, required too much concentration on the positioning of the manipulator and the results were poor.

In the control unit now two facilitations are combined to unburden the disabled operator from complicated control tasks. At first endpoint control was introduced. The movements of the manipulator endpoint follow the directions of a cylindric coordinate system (see Fig. 1) and the control stick is coupled to these directions. The transformation of the rate signals from the control stick into corresponding angular velocities of the different joints is presently performed by a PDP 11/40 computer. It will be taken over by a microprocessor in the next months.

A second facilitation, much easier to design than the first one, keeps the axis of the terminal device at a constant angle

to the horizontal plane while the manipulator is moved in its working space. A computer based learning system will be a further step into the direction of control facilitations.

The final goal of the research project is to set up a place of work with the manipulator where various disabled persons can be occupied. As was mentioned above this can only be achieved by designing a specifically adjusted environment. Fig. 1 gives an example of such a working place. From the wheel chair the disabled operator can easily reach the control stick and use the manipulator for the transportation of objects from and to movable shelves. Additional equipment, e. g. type writers with special key boards or page turners, which are operated by the manipulator but themselves perform sequences of rather complex actions, complete the adjusted environment.

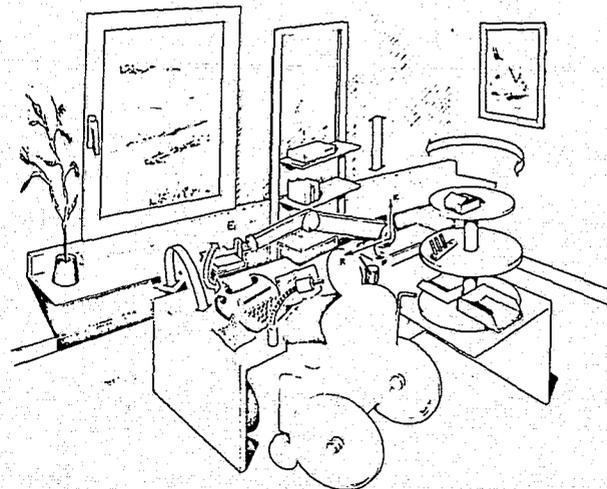


Fig. 1. Working place for handicapped.

MANIPULATOR FOR REHABILITATION

D.E. Peizer  
Veterans Administration Prosthetics Center  
and

J.R. Allen  
Rancho Los Amigos Hospital

Paper summary not available for publication.

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## LUNAR ROVER VEHICLE - AN IMPLICATION FOR REHABILITATION

Samuel R. McFarland  
 Southwest Research Institute  
 and  
 Gary R. Primeaux  
 Lyndon B. Johnson Space Center

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For the last three NASA Apollo missions of lunar exploration, a unique Lunar Roving Vehicle (LRV) was developed to extend the range of activity of the astronauts. Portions of the LRV concept have been evaluated as a means of extending the mobility of paralyzed persons, especially higher level spinal cord injury victims. As the astronaut was limited in his freedom of movement, balance, and force output capabilities, so the quadriplegic is constrained by impaired upper extremity function. The implications for adapting the control developed for one to the needs of the other are clearly evident.

Recognizing that independent mobility and self-maintenance are key elements in the rehabilitation and support of a growing population of spinal trauma victims, NASA, in cooperation with Southwest Research Institute, investigated the feasibility of adapting the LRV control concept to automobiles and vans for quadriplegics.

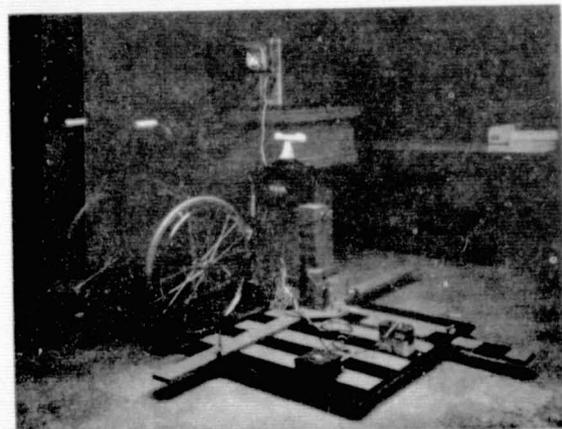
The entire program was preceded by a full-scale driving test of the LRV 1-g trainer by a C-5 quadriplegic volunteer. Using minor adaptive equipment and harnessing, the test subject was able to perform complex simulated traffic maneuvers with a minimum of practice. Based on that exercise, NASA has proceeded to expand its efforts by the program reported here.

Working in concert with the Veterans Administration, HEW, DOT, major rehabilitation facilities, automanufacturers, and handicapped driver control manufacturers, the investigating team has sought to define the

size and capabilities of the target population, legal and licensing requirements, the state of related development programs, and to specify the interfacing requirements for vehicle adaptation.

A functional capabilities testing device and interview program was developed for assessing a limited population of quadriplegics. Using a copy of the LRV control joystick, the simulator enabled investigators to sample control position preferences, control force output capabilities, and reaction times in both steering and braking modes. Data returned from these tests were used both as a comparison to functional parameters common in the literature and as quantities for design.

This paper will present a survey of the current state of automobile handicapped controls, a description of the affected population, and a design for interfacing the control system into a passenger vehicle.



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## NEW CONTROL CONCEPT OF ANTHROPOMORPHIC MANIPULATORS

M. Vukobratovic, D. Stokic, D. Hristic  
 Institute M. Pupin, Beograd, Yugoslavia

Control of active articulated mechanisms represents complex and specific problem of multivariable systems control. Solution of this problem (task) imposes very delicate question of the nominal regimes synthesis, i.e. the construction of the trajectories and corresponding driving forces (torques). Separate question represents the synthesis of the stabilizing algorithms for the compensation of large deviation from the nominal dynamic regimes.

Manipulator dynamics is attracting much interest with investigators in the last decade. Two procedures for assembling mathematical model deserve full attention /1,2/. The essence of these procedures consists in forming the dynamic equations of kinematic chains by using algorithms for automatic setting of differential equations using digital computers.

However, the synthesis problem of the nominal regimes themselves stays open, as well the calculation of the corresponding driving forces. These tasks, however, have in the case of manipulator anthropomorphic configurations their specificities, due to the presence of redundant degrees of freedom. The excessively complex optimization task of manipulators with redundant degrees of freedom led to unacceptable projects, containing among other items, very spacious and expensive control equipment. The first successful attempts in overcoming these difficulties were presented by the results of Whitney and Nevins /3/.

In order to overcome the problem of redundancy there are introduced two levels /4,5/

- level of prescribed (programmed) motion
- level of adaptation

The level of prescribed motion evidently has to solve the problem of basic motion (end point control), while the level of compensating motion should respond to certain dynamic demands, posed in every particular manipulation task.

It is clear, that in the phase of end point control, it is not necessary to include the total number of manipulator degrees of freedom. Taking into account only

the basic configuration of the anthropomorphic manipulator with three degrees of freedom, it is possible to perform end point control along its preselected trajectory. In this manner the problem of the redundant degrees of freedom is being avoided. The control task in this procedure can be formulated as follows: define the dynamic-control parameters of the basic manipulator configuration with three degrees of freedom, which should perform movements at N points of the working space. The task can be solved by forming programmed coordinated motion which have to realize the adopted tip trajectory.

In accordance with fig. 1, the following kinematic relations can be formed between the point M(x,y,z) and anthropomorphic degrees of freedom  $\psi$ ,  $\theta$  and

$$\begin{aligned} x &= f_1(\psi, \theta) \\ y &= f_2(\psi, \theta, \phi) \\ z &= f_3(\psi, \theta, \phi) \end{aligned} \quad (1)$$

Dividing the distances  $x_B - x_A$ ,  $y_B - y_A$ ,  $z_B - z_A$  between point A and B in space into equal intervals  $\Delta x$ ,  $\Delta y$ ,  $\Delta z$ , and assuming that they are sufficiently small, it is possible to get linear relations connecting them with appropriate increments of the manipulator angles  $\Delta\psi$ ,  $\Delta\theta$ ,  $\Delta\phi$ .

$$\left(\frac{\partial f_i}{\partial \psi}\right)_{\psi=\psi_0} \Delta\psi + \left(\frac{\partial f_i}{\partial \theta}\right)_{\theta=\theta_0} \Delta\theta + \left(\frac{\partial f_i}{\partial \phi}\right)_{\phi=\phi_0} \Delta\phi = \Delta q_i \quad (2)$$

where  $\Delta q_1 = \Delta x$ ,  $\Delta q_2 = \Delta y$ ,  $\Delta q_3 = \Delta z$

Manipulator tip motion, realized in that manner via precalculated angular trajectories of the points represents the prescribed motion level. This level evidently solves only one part of the manipulator task. For the complete solution of particular manipulation task it is indispensable to introduce the remaining manipulator degrees of freedom.

The synthesis of the prescribed motion of the manipulator basic configuration with three degrees of freedom can be utilized for dynamic control. The complete manipulation control task with the total number of degrees of freedom can be solved in this case based upon informations about the

forces, acting between the last manipulator member and the working object.

In this approach to the control of the manipulator the so-called "mixed" problem of mechanics and control is concerned. The prescribed trajectories to one part of the mechanism are imposed in order to realize particular movement of manipulator and by measuring the reaction forces acting between the last member of manipulator and the working object the control torques of the rest of mechanism are obtained. Thus, the motion of the system and the generalized forces are partially known and the dynamic control of complete mechanism can be performed.

In this way the angular trajectories of the third member could be obtained as function of the already imposed angles to the first two members

$$\begin{Bmatrix} \alpha \\ \beta \\ \gamma \end{Bmatrix} = f(\theta, \psi, \phi)$$

where  $f(\theta, \psi, \phi)$  depends on the particular manipulation task. However, fulfilling of these conditions in the control sense can be achieved by dynamic compensation via force feedback.

The minimal basic configuration with three degrees of freedom for some predetermined points in the working space has been realized, as the first project stage of the seven degrees of freedom industrial manipulator.

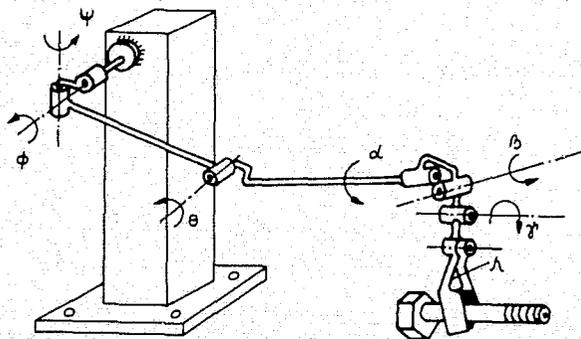


Fig. 1 Anthropomorphic Manipulator With Seven Degrees Of Freedom

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