TITLE: ROBOTIC AIDS FOR THE SEVERELY DISABLED, FEASIBILTIY ASSESSMENT

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NOTE: Portions of this manuscript appear in a complimentary paper (12).

ABSTRACT

In this paper we report results from our perliminary, largely qualitative, explorations into the feasibility of using a programmable robotic arm in the rehabilitation of severely disabled persons. Tests were performed with the Unimation 250 Electro-Mechanical Arm. A new multi-processor configuration has been designed which will include: 1) voice I/O; 2) mechanically switched safty overrides; 3) mouth controlled tracking functions; and 4) CRT situation displays. Practical systems are expected to be available in the late 1980s.

INTRODUCTION

Persons who are mentally alert but severely disabled physically need to control their physical environment independent of continuous assistance by other people. Environmental control may be accomplished by providing the disabled with a collection of special purpose devices or a single general purpose device. Special purpose devices are often relatively simple, are tailored to the patient, and are rather inflexible. The disabled, surrounded by a proliferation of rehabilitation gadgets, may be further isolated from the general populace and public spaces. An alternative approach is being studied by an interdisciplinary team from the Mechanical Engineering Design Division of Stanford University and the Palo Alto Veterans Administration Hospital Spinal Cord Injury Service. This new study program seeks to determine the extent to which severely disabled veterans might benefit from the application of robotics to their environmental control needs. The robotic aids (ROBAIDs) approach to environmental control is based upon the development of SMART ROBOTIC ARMS which can be programmed by the patient to perform virtually any manual task. This one high technology device promises to give the severely disabled person control of all the other gadgets in our society.

A number of recent technology advances make our studies feasible. A robotic arm can now be made with an integral microcomputer which accepts the simple command to move from point A to point B and then determines just how much each of 6 independent joints must be driven to accomplish the move in an optimal way (Unimation Model-250 Electric Arm). This same technology also makes voice command of the arm practicable. Over ten years of robotics research at Stanford and elsewhere has resulted in the development of control languages such as VAL which can compute the details of a move given the directive to move from A to B without changing the orientation of a hand which may be holding a cup of hot coffee. These developments in computer science also allow one to reprogram the arms operation while it is performing some other task. The development of new high strength, low weight, composite materials and very high performance electric motors has made it possible to build human scale robotic arms with performance characteristics approaching those of the normal human arm.

As is often the case when one attempts to recover lost human function, it is the interface between the machine and the human which is most difficult to reconstruct. Accordingly, our research efforts will be sharply focused upon the robotic command language structure, the feedback of arm performance information, and the assessment of patient, therapist, and physician response to the inclusion of a robot in the therapeutic process. Pretesting has been performed and we are confident that robotic aids can be utilized for daily living, personal clerical, and recreational tasks.

STATEMENT OF THE PROBLEM

We postulate that persons who are severely disabled physically, but who are mentally active, need to control their physical environment independent of continuous assistance by other people. We suggest that control of ones own personal space is an important component of human dignity and the quality of life. We propose to develop robotic aids which will give the disabled a degree of physical control over their environment. We will evaluate the efficacy of our work.

We are concerned with a class of robotic systems which must include:

1. one or more MECHANICAL LIMBS which can be moved about the physical environment and are capable of performing useful work
2. one or more MICRO-COMPUTER processing units which can mediate the operation of the limbs to execute complex behaviors upon receipt of natural language commands
3. one or more COMMAND CHANNELS which give the human user complete control of the robotic system
4. one or more FEEDBACK CHANNELS which give the human user awareness of the status of the robotic system at all times

There are three areas of application in which we propose to study the utility of robotic aids for the severely handicapped.

1. DAILY LIVING TASKS: food preparation; eating; personal hygiene; etc.
2. PERSONAL CLERICAL TASKS: telephone calling/answering; calculator use; appliance control; materials handling; information storage/retrieval
3. RECREATION: control of electronic games; manipulation in physical games such as checkers, chess, monopoly, etc.; avocational work

LITERATURE REVIEW

One witnesses a convergence of technology and philosophy in the following four fields:

1. Prosthetics

2. Orthotics
3. Telemanipulation
4. Robotics

From the most intimate man-machine interactions of a prosthetic device through robotic independence of man and machine, it is the information flow and control problems which dominate the evolution of useful systems.

A recent trend in prosthetics is exemplified by the papers of Hogan and Mann (1) and Graupe et al (2). Hogan and Mann have reopenned the argument in favor of cineplasty as a preferred means of controlling the prostheses of amputees. They do not rule out the usefulness of myoelectric control. They present a convincing line of reasoning to the effect that it is only through utilization of the human organisim's ability to internally a prostheses can be attained. The myoelectric control approach is uncoupled from kinesthetic feedback performance clues and thereby lacks an essential element needed for adaptive control. This is the case for reduced external signal processing, i.e. one must do everything possible to interface the prostheses on a mechanical level in order to preserve all aspects of the body's own control machinery.

The alternative trend, in this case exemplified by the work of Graupe et al, is to externalize the comand signal processing as much as possible. Their adaptive multifunction prosthesis control system is based upon external micro-computer processing of myoelectric signals from residual limb muscles. They are in effect trying to make the artificial limb system as smart as possible. To solve the remaining problem of performance feedback, Solomonow and Lyman (3), Kato et al (4), Prior et al (5) and others have sought to provide some form of tactile feedback to the user regarding position, force, or velocity. To provide usable feedback, it is increasingly necessary to provide the artificial limb with micro-computer signal processing and tactile display driving logic, Freedy et al (6). The external arm is again required to be smarter.

For the severely disabled, orthesis development has merged with the more general fields of telemanipulation and robotics. More generically, this is the field of remote manipulator systems (RMSs) in which one finds two distinct branches of investigation. The first places the human operator directly within the control loop. Such systems are often referred to as Master/Slave manipulators in the sense that each motion of the human limb is copied by a remote mechanical limb, Vertut et al (7). This mode of human participation is inappropriate for the physically disabled.

The second approach to remote manipulator systems places the human outside the control loop and physically uncoupled from the manipulator. The human user issues executive commands and supervises the performance of a robotic system which performs the task. Heer et al (8) have described a voice controlled manipulator for the severely handicapped which goes in this direction. At the time of their last known publication the system does not have computational capabilities for control of limb kinematics. The voice command subsystem can be trained to recognize new utterances and/or new speakers. There is no mention of a programmable controller for the mechanical arm. The system is wheelchair mounted and provides for voice command of chair motion. Seamone and Schmeisser (9), John Hopkins University, report using a system with six degrees of freedom. It is controller by mechanical switches and is moved one joint at a time. The authors suggest that the system is clinically useful but should include microcomputer based programming of limb motion.

To correctly place the disabled user of an artificial limb in a supervisory role, Ferrell and Sheridan (10). The user should issue commands and the mechanical a,m should perform the desired task without further attention. Shimano (11) and others have recently studied this problem. Shimano's theoretical work has been applied to VAL, a control language for the Unimation 250 Electric Arm (Figure 1). The user can program, edit, and directly control limb motions in terms of desired hand coordinates in three dimensional space (x,y,z) with three degrees of orientation control at the end of the manipulator (alpha,beta,theta).

HARDWARE SPECIFICATIONS

For feasibility study purposes, we have used a standard Unimate 250 Electric Arm with Microprocessor and Analogue Controller. The arm itself is entirely electromechanical. It has six independent degrees of freedom such that the hand can be positioned with any desired orientation for most points within the arms working space. The arm geometery is largely anthropomorphic and possess equal length upper and lower arm segments of 20 cm. Most points within a shoulder centered 0.9 meter diameter sphere can be accessed. The arm weighs less than 9 kilograms and was designed for light manipulative tasks in automation research. For assembly tasks the arm can lift objects having a mass of up to 1.5 kg. The system can perform most point to point motions within one second. Endpoint repeatability is approximately 1mm (this can vary as a function of usage). An analogue controller provides DC servo motor drive current, electromagnetic brake current, position sensor drive voltages, and velocity sensor drive voltages. Individual joints may be driven directly with the aid of a manual control console which acts directly through the analogue controller. A photograph of the arm, a kinematic diagram of the arm, and a system schematic are presented in Figure [1].

The analogue controller is interfaced to a Digital Equipment Corporation LSI-11 microcomputer. This 16-bit CPU system is configured with 24K words of static memory, an extended instruction set, analogue to digital converters, digital to analogue converters, digital input/output drivers, a serial terminal interface, and a mini-diskette interface. The computer is used to synchronously drive each of the arms six degrees of freedom according to kinematic computations which produce a fifth order least squares approximation to the optimum (minimum aggregate angular displacement) path between two hand endpoints. Distal arm segment displacements are given precedence. The VAL language executive which mediates these computations is entirely memory resident.

SOFTWARE SPECIFICATIONS

VAL is the Robotic Programming and Control System portion of the Unimate 250. It is a memory resident interpretive language with diskette file handling features. Most commands can be executed in immediate or deferred mode. Any program can be edited in the monitor foreground while program execution (including the program being edited) takes place in the background. Most instructions are self explainatory. Default conditions cover a large percentage of program steps. Programming can be done on the arm control computer or remotely with cross loading. The language is modular and new commands are easily added at any time. Subroutine nesting and diskette based subroutine library functions allow for rapid development of complex manipulation sequences. Control computations are performed in real-time such that a minimum of program and/or data storage are required. In practice, the VAL system has been reliable and relatively error free.

FEASIBILITY STUDIES

We have used a somewhat unorthodox approach to assess the feasibility of using robotic aids to perform daily living tasks for the disabled. In effect, we have used undergraduate Stanford University students to simulate the disabled and we have challenged them to perform useful tasks with the Unimate 250 Robotic Arm. The students were members of an introductory product design class. Typically, these students were in their second year at the University. Many were not engineers. A minority had had any computer programming experience. The students in this class were considered meaningful analogues of our ultimate user population in that they were:

1. non professional
2. non programmers
3. highly motivated
4. subject to time and energy constraints stemming from their already labored existences

Further, many more students (45 the first year and 53 the second year) were available in one place to perform the desired experiments. We also hoped that their resourcefulness and creativity might lead us to some insights. As able bodied persons, they also afforded an extra measure of safty during our initial experiences with the electromechanical arm and it micro-processor based controller. These studies were not intended to replace direct evaluation of the robotic arm with severely disabled persons, but, it has proven to be a very useful qualitiative measure of what can be done.

In each experiment the class was divided into groups of three students each. All groups were given the same task and required to perform the task within the subsequent two weeks. Evaluations were based upon task performance time, craftsmanship in hardware and software, and creativity. No student had had prior experience with the Unimation 250 system.

The first experiment was entitled "THE WORLDS FIRST ONE ARMED ROBOTIC CAKE BAKING CONTEST". The task contained the following constraints:

1. any prepackaged dry cake mix could be used
2. at least one fresh egg must be included
3. at least one liquid must be included
4. a maximum of six minutes was allowed to mix, bake, and serve the cake
5. a microwave oven was available for baking
6. penalties were assessed for human intervention

Figure [2] gives some indication of the results obtained. All groups were able to get a cake baked. There was a large variation in quality and the degree of human intervention. The best of the groups performed the entire task without human intervention, produced an edible cake, and introduced a good deal of theatrical invention. More hardware creativity was evident than software creativity. It was clear that while robotic cake baking was certainly feasible, there were a number of changes required in the Unimation 250 (as configured at that time).

The following conclusions were drawn from this first experiment:

1. hardware, jigs and fixtures, are as important as the arm control software
2. an extensive subroutine capability was needed for the VAL(1976) language
3. paper tape program storage was inadequate
4. position repeatability limitations required special programming techniques
5. liquids were deleteriors to the arms function
6. a world coordinate system was needed in addition to the arms own tool point coordinates
7. relatively slow manipulator speeds were required to prevent unwanted spillage and position overshoot
8. uninitiated persons could rapidly and effectively learn to program useful tasks
9. reliability was as, or more, important than high performance manipulator specifications

The second experiment (a year later) was run by non programmers, non computer users, and was entitled "THE FOUR STAR ROBOTIC MEAL SERVICE CONTEST". The students were asked to serve themselves a meal, using only the robotic arm, in a fashion equivelent to a four start restaurant. They were to perform the task under the following constraints:

1. serve at least one particulate food
2. serve at least one liquid
3. serve at least one food item which requires cutting

4. delivery each food item directly to the customer's mouth
4. demonstrate these services within five minutes
5. perform the service without human intervention
6. do no harm to the customer

An example of the results obtained can be seen in Figure [3]. As in the cake baking contest, all groups were able to perform the meal service. Speed, quality and human intervention parameters varied widely. The best 3 groups (out of 15) were able to execute near flawless performances. Hardware design and creativity were excellent. VAL(1977), with improved subroutine capability, encouraged good programming practices and we were impressed by the programming sophistication evident.

A number of new feasibility conclusions were drawn from this experience. Earlier findings were confirmed. The following considerations arose from our second experiment:

1. successful service was dependent upon having both good hardware and good software
2. the student/patients could be trained to use robotic devices by non experts (a single graduate student with two weeks experience provided the highest level of expertice available to the students or their instructors)
3. a flexible diskette filing system was needed to facilitate modular program development
4. while a paralyzed patient could be in some danger of bodily harm from an inadvertant arm motion, reasonably simple proceedural and mechanical constraints provided effective safeguards
5. command verification becomes increasingly important as individual commands invoke larger and more complex motion sequences
6. a facile means is needed to locate end points in both real world and tool point coordinates
7. both man-in-the-loop and supervisory control modes must be available to the patient
8. the foreground/background programming feature of VAL(1977) was particulary useful as a means of implementing heirarchial control strategies
9. a stronger and more versatile hand is required for the Unimation 250
10. a slip sensitive grasp reflex is required

PROGNOSIS

Based upon these experiences, we will proceed with clinical trials of the Unimation 250 Robotic Arm. Clinical trials will be performed at the Palo Alto Veterans Administration Hospital's Spinal Cord Injury Unit (Dr. I. Perkash, director). In qualitative experiments, C4-C6 level quadraplegic persons will be asked to perform daily living and personal clerical tasks rather like those performed above by students. In our initial studies, patient command will be simulated in that an able bodied experimenter will execute all command functions via a standard keyboard terminal. The experimenter will follow the patients commands except in those cases which might be harmful to the patient or the robotic system. It is the purpose of these tests to further assess the patients, therapists, and physicians response to the presence of robotic devices within their personal and professional environments. Quadraplegic persons have successfully, and eagerly, been retrained as computer programmers. They can earn a living as programmers and they have a means for written communication. Based upon this and other circumstancial evidence, we expect the robotic arm to be a welcome component in the rehab.litation of severely disabled persons.

Subsequent to qualitative clinical evaluations, we shall reconfigure the Unimation 250 into what we have tentatively called the ROBAID v1. This system is anticipated to have the following features, Leifer et al (12):

1. The Unimate 250 will be modified to incorporate digital position encoders
2. The VAL(1978) control language will be restructured into distinct heirachial levels.
3. A new hand will contain a grasp reflex
4. The system will first be integrated into a desk like work station
5. A multi-mode command subsystem will feature:
    a. Voice input for general programming and supervisory control
    b. Mechanically actuated head switches for system override functions
    c. A displacement transducing mouth peice for man-in-the-loop target tracking tasks
6. A multi-mode response subsystem will feature:
    a. Voice output for voice input verification
    b. Voice output for warning conditions
    c. A CRT display for programming and message communications
    d. A tactile feedback channel for grasp and proximity information feedback
7. A diskette subsystem will provide storage/retrieval

Attention is being directed towards the non device issue of patient performance evaluatior and the assessment of individual patient capabilities. Independent mobility for the robotic arm, robotic vision, and advanced tactile feedback systems are under consideration.

CONCLUSION

In summary, the feasibility of robotic aids for the severely disabled is assured. The timing of practical systems will be a function of the research funding available. A growing investment in industrial robotics and the diminishing cost of computer power are strong factors in our optimizim that perscription robots for the disabled will available in the 1980s.

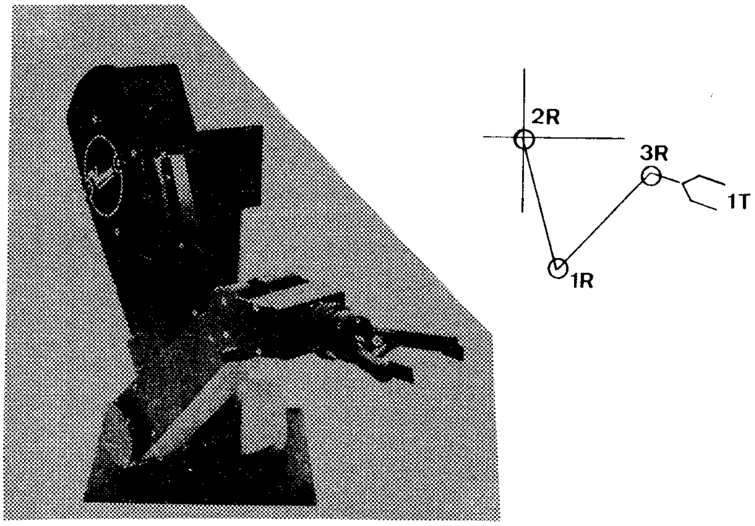

FIGURE 1a The Unimation 250 Electro Mechanical Arm, 6 degrees of freedom plus grasp, 6 revolute (R) and 1 translational (T)

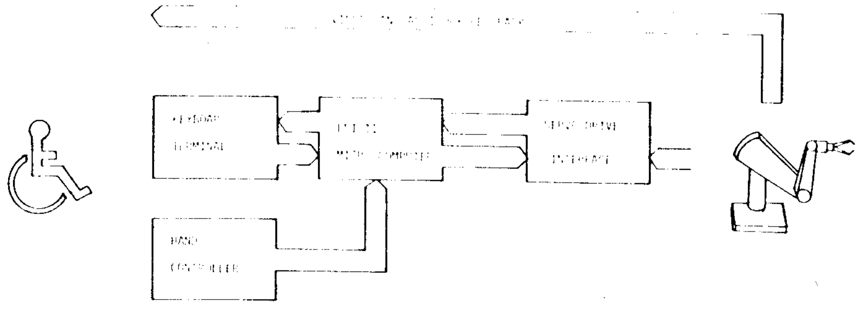

FIGURE 1b Robotic Arm System as used in the feasibility tests

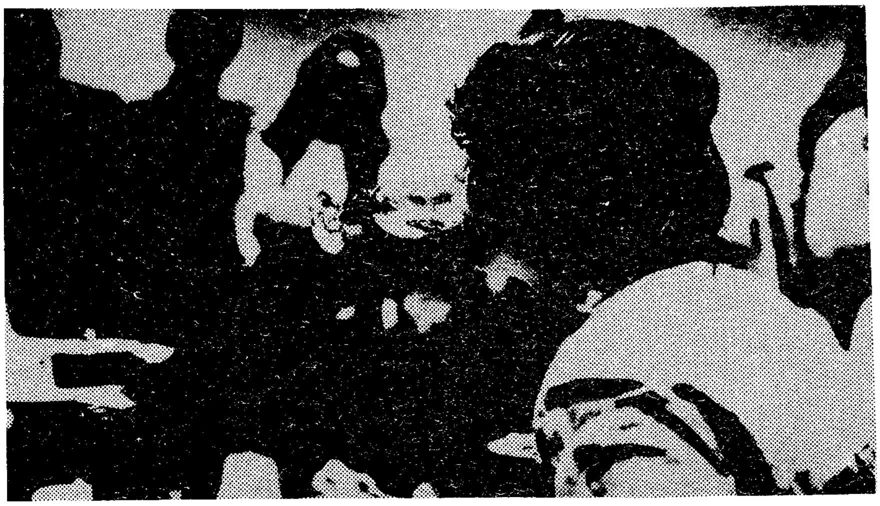

FIGURE 2 EXAMPLE from the ONE ARMED ROBOTIC CAKE BAKING CONTEST

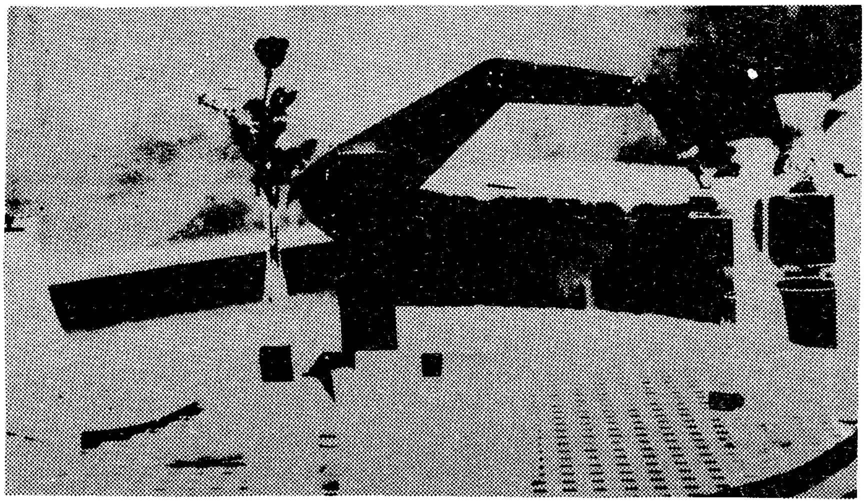

FIGURE 3 EXAMPLE from the FOUR STAR ROBOTIC MEAL SERVICE CONTEST

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