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ABSTRACT

The monograph is a collection of papers on the role of robotics in rehabilitation. The first four papers represent contributions from other countries: "Spartacus and Manus: Telethesis Developments in France and the Netherlands" (H. Kwee); "A Potential Application in Early Education and a Possible Role for a Vision System in a Workstation Based Robotic Aid for Physically Disabled Persons" (W. Harwin et al.); "Manipulative Appliance Development in Canada" (W. Cameron); and "Domestic Use of a Training Robot-Manipulator by Children with Muscular Dystrophy in the Netherlands" (A. Zeelenberg). Two U.S. commentaries by G. Fernie and J. Leslie address the above papers. The monograph concludes with eight papers from U.S. contributors, all of which were first presented at the 1986 Conference of RESNA-Association for the Advancement of Rehabilitation Technology. Titles and authors are: "Augmentative Manipulation" (C. Heckathorne); "An Independent Workstation for a Quadraplegic" (C. Fu); "Small Robot Arm in the Workplace to Aid in the Employment of Severely Disabled Persons" (L. Anderson); "Development and Use of a Robotic Arm System with Very Young Developmentally Delayed Children" (L. Hoseit et al.); "Evaluation of the APL/JHU Robot Arm Work Station" (W. Seamone, G. Schmeisner); "Development of an Advanced Robotic Aid: From Feasibility to Utility" (L. Leifer et al.); "CALVIN: A Robotic Control Language for Rehabilitation Robotics" (S. Minneman, T. Pham); and "Design of an Omnidirectional Mobile Robot as a Manipulation Aid for the Severely Disabled" (H. Van der Loos et al.). Appended is an issue of the newsletter, "Rehab Brief," which summarizes the information on robotic aids and the ideas on their place in rehabilitation contained in the monograph. (CL)

37 INTERACTIVE ROBOTIC AIDS—ONE OPTION FOR INDEPENDENT LIVING: AN INTERNATIONAL PERSPECTIVE

Editor, Richard Foulds

World Rehabilitation Fund
International Exchange of Information in Rehabilitation

MONOGRAPH NUMBER THIRTY SEVEN

INTERACTIVE ROBOTIC AIDS—ONE OPTION FOR INDEPENDENT LIVING: AN INTERNATIONAL PERSPECTIVE

With Editorial Assistance from
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and the Cooperation of
RESNA—Association for the
Advancement of Rehabilitation Technology

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TABLE OF CONTENTS

***NB**—All of the papers from U S contributors were first submitted to RESNA—Association for the Advancement of Rehabilitation Technology for presentation at that organization's annual conference

PREFACE AND ACKNOWLEDGEMENTS

It is the goal of the International Exchange of Experts and Information in Rehabilitation to share with the U.S. rehabilitation community information and ideas from other countries which enhance the rehabilitation knowledge base in the U.S. In addition to the publication of monographs on various topics of interest (see the back of this book for a partial list of monographs which have been published in the IEEIR series) and the awarding of fellowships to U.S. experts to study abroad, the IEEIR also selects certain monograph topics around which to hold meetings and conferences.

In 1983 Richard Foulds of the Tufts Rehabilitation Engineering program carried out an IEEIR fellowship study-visit. Shortly after that, Tufts was awarded federal funding from NIHR for robotics aid research. Because WRF's IEEIR had an interest in "importing knowledge" about robotic aids from other countries, Dr. Foulds was invited to participate as a monograph consultant. Experts in several countries were asked to author articles on research in robotics in rehabilitation. Four articles from the Netherlands, the U.K. and Canada were selected for publication.

In addition, the authors were invited to participate at the 1986 RESNA conference with a half a day devoted to their papers These arrangements were facilitated by Richard Foulds, and Larry Leifer to whom we are very grateful. Patricia Horner, Executive Director and Susan Leone of RESNA – Association for the Advancement of Rehabilitation Technology—are to be thanked for their whole-hearted cooperation.

Two individuals, not directly involved in robotics research Geoff Fernie and John Leslie, were invited to provide reaction to the three foreign papers at the RESNA meeting as well as to provide written commentary for publication in the monograph. Their commentaries are provocative and help to put robotics aid research in perspective.

Many individuals in the U.S Robotics Rehabilitation community have been supportive of this effort to communicate internationally and participated in the International session at the 1986 RESNA Conference.

The last eight papers which appear in this monograph were prepared by and presented first at the 1986 annual RESNA Conference by many of the top U.S. robotic aids researchers RESNA's cooperation makes it possible to publish them in this monograph.

Finally, without a grant from the National Institute of Handicapped Research for the international exchange of experts and information in rehabilitation, the WRF would not have been able to make this monograph available.

Diane E. Woods
Project Director

OVERVIEW AND INTRODUCTION

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Several years ago I had the experience of being exposed to the relatively new and very exciting use of human-scale robot manipulators with severely disabled individuals. In marked contrast to the science fiction androids popularized in the Star Wars films, these real life robots attempt to deal with the down-to-earth problems of employment, education, and daily living. Unlike fictional robots which are intended to replace human tasks, the rehabilitation robot serves as a direct extension of the disabled user in an attempt to increase the involvement and independence of that person.

After viewing the creative applications of a PUMA manipulator by Larry Leifer and his colleagues at the Rehabilitation Research and Development Center at the Palo Alto Veteran's Administration Medical Center and Stanford University, I was convinced that this technology would play a major role in the field of rehabilitation. Inspired by the Stanford projects, our own laboratory in Boston began a modest manipulator project. As we became more involved, we began to share ideas and thoughts with a number of other laboratories who were pursuing similar endeavors.

While on a World Rehabilitation Fund Fellowship, I had the opportunity to meet with Hok Kwee who had recently moved to the Netherlands to direct Dutch research efforts in rehabilitation robotics In our discussion, he impressed upon me the need for continuing dialog among the researchers and clinicians in this emerging area. This message found its way into my final report to the World Rehabilitation Fund (WRF). Following that suggestion, Diane Woods of the WRF and I began planning this monograph and the symposium at which the papers were presented

In developing the concept for this monograph, we sought to bring together both research and clinical ideas for an international exchange We sought out significant authors, Hok Kwee and A.P. Zeelenberg from the Netherlands, William Harwin from the U.K. and William Cameron from Canada, who would prepare papers covering their own work, as well as other major efforts in their own nations. We also coordinated our plans with the Special Interest Group on Rehabilitation Robotics of RESNA-the Association for the Advancement of Rehabilitation Technology in order to organize a Symposium on Interactive Robotics at the 1986 RESNA conference in Minneapolis, Minnesota.

In addition to the four invited papers on international rehabilitation robotics activities we have included the responses of two respected North American researchers to these papers We have also reprinted eight papers which were presented by U S authors at the RESNA Conference.

Several of the papers in this monograph present differing opinions on the level of technology applied to solve rehabilitation problems. There is no general agreement on the type of manipulator that will meet the needs of a disabled person. When one author argues for a powerful, device that is custom designed to meet the optimal needs of the user, another author just as eloquently justifies the use of low cost technology to satisfy economic demands. Similarly there is no consensus on the user interface to the robot Convincing discussion is given for preprogrammed robot motions to minimize the demands placed on the user, while equally compelling reasons are presented for maximizing the user control over the device. Such diversity of opinion makes this monograph an exciting forum for the unanswered questions facing the research community

These and other questions will of course only be answered as the results of clinical research are provided. While much more clinical evaluation is necessary, several of the papers present the results of users trials with a variety of manipulators and interfacing techniques. Several also attempt to define methods for measuring the effectiveness of a user/robot system.

The paper provided by A.P. Zeelenberg deserves special mention since Dr. Zeelenberg has as much personal involvement in his project as he has professional interest His paper describes his collaboration with his son who has Muscular Dystrophy. Together, they have explored the use of a manipulator as an aid to independence. Their discussion of the successes and failures they encountered provides a realistic assessment of the potential impact of this new technology.

The successful use of a manipulator will depend upon many factors that go beyond the design of the robot arm and the user interface. Several of the papers look closely at the tasks which user and manipulator will be able to consider. These include employment activities in both "white" and "blue collar" areas, educational and developmental applications for disabled children, and independent living tasks for the elderly

The philosophical issues of the ultimate utility of a manipulator in terms of its potential benefit to the user and its place within the overall rehabilitation service delivery system are addressed in the responses prepared by Geoff Fernie and John Leslie. These two individuals have not worked on robotic systems, but have used their extensive experience in rehabilitation to objectively assess the messages presented by the invited papers.

I am indebted to the World Rehabilitation Fund for providing the opportunity to organize the symposium and prepare this monograph. This exchange of ideas conveys a sense of excitement for the possible clinical benefits. There certainly appears to be a realistic expectation that manipulators will become useful aids to disabled individuals

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INTERNATIONAL EXCHANGE OF EXPERTS AND INFORMATION IN REHABILITATION

PEER REVIEW UTILIZATION PANEL (ADVISORY COMMITTEE)

SPARTACUS AND MANUS: TELETHESIS DEVELOPMENTS IN FRANCE AND IN THE NETHERLANDS

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Introduction

When man wants to gain access to a universe previously inaccessible to him, he has to create more or less specialized tools to do so Thus, special vehicles equipped with remotely controlled mechanical robot arms have been developed for outer space and deep-sea explorations, as well as manipulation in radio-active environments or other environments dangerous to human penetration In these applications, where man has to intervene in an unstructured environment, the human operator has to make the decisions and direct, or at least supervise, the control actions to be executed with the mechanical grippers.

This situation is very different from the one generally encountered in industrial robotics, where repetitive tasks have to be executed in a highly structured environment Here the task and each movement to be made can be precisely described, allowing a pre-programmed computer to replace the human operator as a controller and even to cope with relatively simple responses to be made to external conditions detected by appropriate sensors.

High-level quadriplegics and similarly disabled persons are confronted with a situation very close to one of the first type Therefore, many of the approaches developed in robotics, and in particular in its branch of telemanipulation, can be applied to solve some of the problems of persons who have lost their upper limb function.

Unlike the able-bodied human operator, the disabled person has very limited use or no use at all of his hands to operate the controls necessary to specify the movements of the mechanical arm, and in particular of its gripper. For these reasons, a major effort in this field has to be invested in the development of appropriate man-machine interfaces and control "languages." This aspect of man-machine communication appears to be a key factor in the success or the failure of applying robotics technology in the development of assistive devices for severely disabled persons.

Another important aspect concerns the mechanical structure to be used, which imposes the constraints on the classes of tasks that may be executed. It is also responsible for a significant proportion of the cost of the system, thereby forming one of the key factors determining the economical feasibility of its practical application Furthermore, it is the most visible part of the system, and its cosmetic appearance will be another key factor determining whether the user will accept it as an assistive device. The fact that it is not directly attached to his body, like a prosthesis or an orthosis, may facilitate its acceptance just as a tool.

The author was associated with the French "Spartacus" pilot project and presently directs the "Manus" project in The Netherlands Since the latter project also benefits from the experience gained in the former, this paper is drawn on the experience and the reflections of both projects, but with an emphasis on the results of the Spartacus project in view of its more advanced stage

The Spartacus project was a five-year robotics project, intended to stimulate industrial robotics in France, in which a "unifying theme" was selected to be a *feasibility study* aimed at the development of a telemanipulator controllable by persons with high-level spinal cord lesions. A telemanipulator system was realized in two phases. first as a simulation with a commercial arm used in nuclear research controlled by a mini computer (4) (fig. 1), and then by a specially developed manipulator, derived from the first one, with micro-computer control (19) (fig 2). From very early in the project, much attention was paid to control ergonomics, with the participation of a number of disabled volunteers in laboratory experiments (3, 4). After the formal termination of the project, studies with various disabled persons have continued in a hospital environment (6, 7, 8, 9, 10).

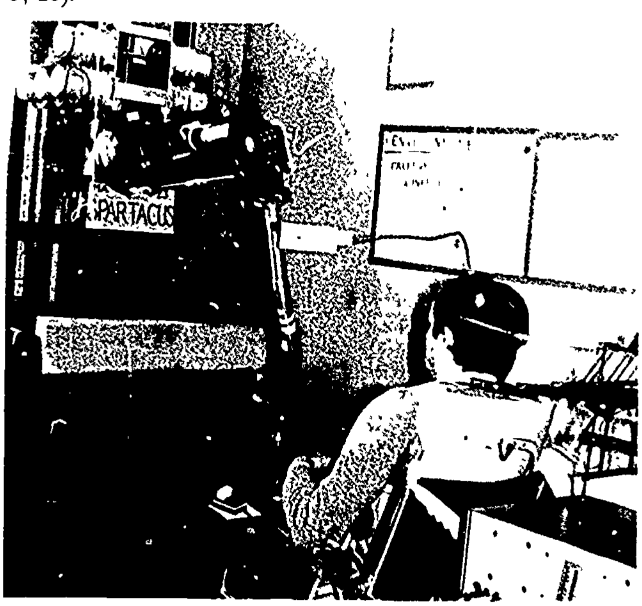

Fig. 1 The early experimental system of the Spartacus project, simulating a telethesis with a MA-23 nuclear telemanipulator controlled through a mini computer. The system is here experimented by a man with a spastic C6 tetraplegia Note the transparent screen which protected the user in early experiments The system is controlled through a two degree of freedom head movement transducer, an early version roller transducer and adapted push buttons

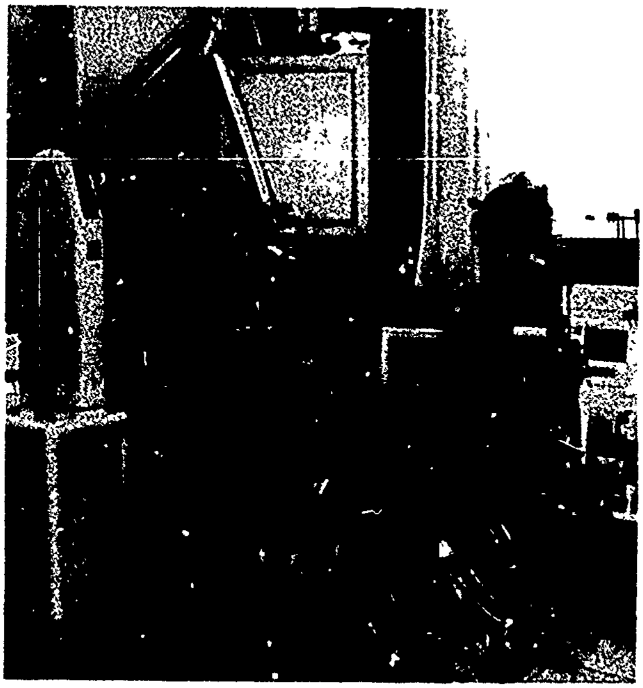

Fig. 2 The second model Spartacus MAT-1 telethesis in the experimental clinical situation, here used by a person with a C5/C6 spinal cord lesion to pour a glass of water. Control is by head movements (2 degrees of freedom) and rest functions of the right arm with a roller transducer and a flexible-bar switch (not visible).

The Dutch "Manus" Project is aimed at the development of a manipulator as a product which may be provided to disabled persons as an assistive device at an acceptable price (through some form of social security benefit). Following a one-year feasibility study, the Project officially started in 1984 with Dutch government funding for a two to three year period as a collaborative effort between four R & D institutes:

- Institute for Rehabilitation Research (Hoensbroek), principal contractor in charge of over-all project management problem definition and product specification, human factors, contacts with potential users and (para-)medical personnel, cost/benefit analysis, etc.;
- Institute for Applied Physics—TNO (Delft), in charge of system design, electronics and software development;
- TNO Product Centre (Delft), in charge of electromechanical hardware development, cosmetic design, and industrialization of the system;
- Netherlands Institute of Preventive Health Care TNO (Leiden), participating in a socio-economic cost/benefit analysis.

The product development is being realized by the first three institutes in very close interaction. This is necessary in order to optimize the over-all system, integrating mechanical, electro-mechanical and computer hardware, compromising between hardware and software solutions, and compromising between feasibility and costs of technological solutions on the one hand and user specifications (including functionality, cosmetics, safety and human factors) on the other hand.

The first phase of the project, now under way, will serve to realize a first model to verify the different hardware and serve to control concepts adopted and the acceptability of the compromises agreed upon. Further development towards a product will depend upon the outcome of the (technical) evaluation of this model, which will verify the feasibility of the objectives of the MANUS Project.

Mechanical Structures

The mechanical structures used in different projects can be classified in a number of ways (6). The first classification is according to their origin: designs derived from orthoses or prostheses (2, 17, 18), designs based on industrial robots (4, 11, 12, 13) or special custom designs (14, 15, 16, 19). A second classification can be made according to mobility. fixed working stations (4, 11, 15, 16, 17, 18, 19), wheelchair-borne arms (14) and independent mobile arms (2, 12, 13).

The option adopted for the French Spartacus Project, which was essentially a feasibility study, was that of a fixed work station with a specially-designed arm derived from nuclear manipulators (4, 19). It was felt that this configuration would impose the least constraint on the optimization of the performance, thereby allowing one to explore the limits of control feasibility and to avoid any failure due to mechanical limitations.

The mechanical arm of the second model Spartacus "telethesis," the MAT-1 (fig. 1), has six active (powered) articulations and a passive one, which mechanically maintains the gripper orientation constant with respect to the vertical axis, independent of the displacements controlled by the first three articulations (19). In addition, there is a powered gripper with two interchangeable fingers, compatible with nuclear telemanipulators.

The articulations are powered by electrical permanent-magnet cage-type motors, operating as torque motors, with a reversible cable-and-pully type transmission. This has resulted in an arm with a very low inertia, with movements that are inherently reversible and "soft," i.e. the arm yields when pushed against with a certain force. This flexibility is not normally encountered in industrial robots, which are designed to be rigid in order to offer very high precision and velocity. It is our experience that this reversibility is a nice feature indeed for a (medical) telemanipulator, giving it operating characteristics and compliance resembling more closely the ones of the human arm, and adding a large degree of safety (5). It does, however, require a rather bulky and expensive mechanical system for its implementation.

The articulated arm of the MAT-1 telethesis is mounted on a box-like base that contains its electrical motors, power supplies, control system, micro-computer and special transducer interface. Thus, with the exception of the control transducers, the system is self-contained.

The feasibility study preceding the Manus Project has led to the conclusion that the usefulness of a manipulator would be highly increased if it were mounted on the wheelchair. This corresponded with the comments collected from potential users who collaborated in the Spartacus Project. They also indicated, however, that they did not want to drive around all the time with a conspicuous robot arm on the wheelchair; so they wanted it to be both cosmetically acceptable and "disappear" when not in use. At the same time, it has to be able to reach high enough to fetch objects from shelves, and from the floor, and be strong enough to lift books and bottles, open doors and faucets, etc., and, be inexpensive. Among the various potential users interviewed, however, there was no concensus on the priorities to be given to the different aspects Thus, it was not possible to establish a unique set of specifications agreed upon by everybody from the start, except for wheelchair portability and modularity of its control structure. Both were adopted as a starting point. Finally, it was decided that the first nine months of the Manus Project should be a "specification phase," during which a first model had to be specified in an iterative procedure of designing and adjusting specifications according to technical possibilities, costs, and expressed or inferred user wishes. Numerous full-scale plastic "sight models" were realized in order to evaluate the consequences of various options for arm configurations and make it discussable for a mixed public including potential users, therapists, laymen and designers. At this time it is still too early to report what the final model will exactly look like, but the following options have been agreed upon for the mechanical system:

- The system will be wheelchair-mounted rather than a fixed working station, as stated above;
- An articulated arm with 6 degrees of freedom will be used. We strongly feel that versatility would be severely impaired with fewer degrees of freedom by the need to make more adaptations to the environment;
- The arm will be designed to work on a lapboard on the wheelchair, which may be designed to match the possibilities of the arm, but it should also be able to work on a table reach shelves somewhat above eye-level and the floor over a small area next to the wheelchair;
- It should be capable of lifting objects with a mass of 1.5 kg;
- Since gripper movements are to be directly controlled (or at least closely supervised) by the human operator, we feel that there is no need for a high absolute precision, but we do require a good resolution (better than 2 mm with extended arm) for the execution of precision tasks;
- Although directionally-controlled compliance would be a desirable feature, it will probably not be possible to incorporate it in a compact mobile system at a reasonable cost, except for compliance in gripper closing.

Man-machine Interface

The control by a physically disabled operator of a mechanical structure such as the ones described in the preceding chapter is a complex operation. Early projects reported in the literature required the operator to directly control each degree of freedom of the mechanical arm. More recently virtually all projects have adopted some form of computer-assisted control to facilitate his task. The computer is charged with the detailed control of the movements of the arm's articulations or telescopic movements, while the operator may specify the operations to be executed in a more global way which is better adapted to his mental representation of the movement of a hand in space.

In spite of this assistance, the interface between the operator and the (micro-)computer remains a particularly delicate aspect since it depends directly on the remaining control functions left to the user, which vary with the type of impairment and thus are not the same for all disabled operators.

For persons with high level spinal cord lesions, the initial target group of the Spartacus project, many of the efforts have been concentrated on remaining head functions: switches or joysticks operated by the mouth, breath-operated switches, eye-movement control, chin-control of joysticks and switches (14, 15, 17), various versions of head movement transducers (4), hum-control (4), melody-control (1), voice control (11), etc In the Spartacus system a modular bus type interface has been used, accepting a variety of transducer imputs, with special preprocessing cards for specific transducers if necessary. Thus, the control structure may be adapted to the needs and the remaining functions of the individual user. Although the flexibility provided by this system proved to be excellent for this experimental system, it is also rather bulky and expensive, and a simpler solution will be sought for the portable Manus system to implement modularity of its interface.

Control transducers that have been particularly useful in our experiments with the Spartacus system are.

- Two-degree-of-freedom head movement transducers capturing head movements axes perpendicular to the frontal and sagittal planes of the head (4)(figs. 1, 2, 6, 7);
- A three-degree-of-freedom head movement transducer capturing, in addition, head rotations about a vertical axis (6, 7) (figs. 4 and 5; see p. 10);
- A one-degree-of-freedom joystick to capture elbow abductions (fig 7; see p.11) (3, 4);
- A "roller" type transducer, consisting of a soft foam plastic ball mounted on the shaft of a potentiometer, allowing it to be controlled by global arm movements (fig 3), chin movements (figs. 9 and 10), etc. It provides a soft but rough contact surface with a high friction for easy control and strong sensory feedback upon slippage (important in cases of diminished sensation from the skin), while having a low inertia to prevent potentiometer damage when run into the end stops at high speed (by non-disabled users!). Initially, a multi-turn (5 or 10) potentiometer was used, occasionally necessitating it to be reset when a limit was reached. Later, it was replaced by a single-turn potentiometer without end stops but with two cursors offset at 180°, and the computer switching back and forth between them to remain within the continuous part of the track (while also taking care of computing a continuous signal);

- A three-degree-of-freedom joystick, including a rotation of a knob about the shaft as the third movement, modified to move with very little resistance and without springs. In addition, on top of the rotating knob a shaft extension has been added to facilitate control of x-y movements without inadvertently rotating the knob. This unit has been developed for persons with weak hand movements as rest functions, such as in cases of advanced muscular dystrophy (fig 8; see p. 11);
- Commercial track balls have recently been used instead of two-degree-of-freedom joystick in the Manus project, and offer an interesting alternative, which is still awaiting a better evaluation;
- Various types of switches, in particular an industrial flexible-bar limit switch (figs. 3, 9 and 10), a commercial large-size push button, and a mercury drop switch (fig 8);
- Switch alternatives in the form of an EMG-signal (when possible captured from ear movements with electrodes behind the ear) or a humming signal, captured with a laryngophone (figs. 4 and 7) and processed by the EMG-amplifier.

For direct control of gripper movements we have emphasized the use of proportional mechanical control transducers, rather than the use of e.g. voice control. We have based this on the hypothesis that the use of physical *movements* to control gripper movements in space may both give a closer match with the mental representation of movement control and take advantage of any sensory feedback left to the user in operating the transducers. It also facilitates the use of multiple degrees of freedom simultaneously to control composite movements in a coordinated way.

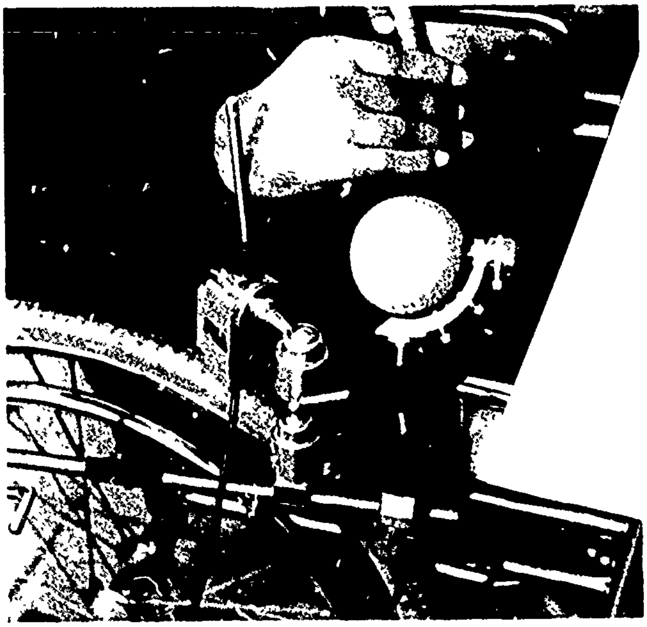

Fig. 3 A later model roller transducer and a flexible-bar switch used by the person of Fig. 2.

Fig. 4 A 20 year old man with a C3/C4 lesion in a learning situation using "H-elements" Control is by head movements (3 degrees of freedom) and a laryngophone hum switch, later replaced by a foot switch

Fig. 5 A man with a C4 tetraplegia fetching a cup from a cupboard in a laboratory experiment He is using the three-degree-of-freedom head movement transducer and a switch controlled by the elbow

Fig. 6 The person of Fig. 2 drinking. He is using a special drinking mode, controlled by the roller only, combining a rotating and lifting movement of the glass to simulate a natural drinking movement.

Fig. 7 A 27-year old man with a C3/C4 tetraplegia using the simulated system of Fig. 1 to turn the pages of a telephone book; first many at the time, then one by one as shown here. He is using the two-degree-of-freedom head movement transducer, a one-degree-of-freedom joystick controlled by elbow abduction, and a laryngophone hum switch.

Fig. 8 A 22-year old man with a Duchenne muscular dystrophy using the system to paint. Control is through a three-degree-of-freedom joystick and a mercury-drop switch, using minimal finger movements. He is using a battery-powered respirator on the wheelchair.

Fig. 9 A 10-year old child with athetoid cerebral palsy in a block building task. Control is by the roller under the chin and the flexible-bar switch operated by the left hand.

Fig. 10 The boy of Fig. 9 cutting a cake with a roller (pizza) type knife.

Control Language

The control "language", with the man-machine interface, defines the effectiveness of the communication between the operator and the mechanical arm. With the introduction of computerized interfaces, a large variety of procedures may be adopted. These may be classified according to their similarity to the actual movements of the mechanical arm, i.e. according to the task-shaping between man and machine:

- At the lowest level, the operator directly controls the natural movements of the mechanical structure, and no real need exists for computer assistance;
- At the second level, the operator can control a selected set of movements in a reference frame adapted to his spatial representation In general, some form of end-point control of gripper movements will be used, and a large selection of reference frames and control modes is possible in theory;
- At the third level, the same operations as in the second level are used, but in addition the system may respond to external conditions in a "reflex" type way, e.g a "soft touch" reflex may limit downward forces, thereby facilitating such tasks as writing, telephoning, page turning, etc., or sensors on the gripper may facilitate the grasping of objects;
- At the fourth level, the system uses a number of preprogrammed operations, each executing a specific task in a stereotyped way when activated by the operator. Thus, a complete sequence of fetching a drink, pouring it into a glass, and serving it may be executed upon one command, but under the condition that the environment is completely known to the computer. A human intervention, such as changing the place or the size of the bottle, may lead to failure of the operation. A more limited use of preprogramming consists of the execution of partial stereotyped movement sequences facilitating the execution of repetitive tasks;
- The fifth level extends much higher and may call for the application of powerful procedures of artificial intelligence For example, the user may speak to the system in natural language and the system proceeds to execute the order the way a human attendant would, charging itself with the interpretation of the request, planning of its execution, asking further information if necessary, and execution of the task in an autonomous way, while taking into account the constraints imposed by the environment.

To a certain degree, all levels are represented in different projects today, often with a mixture of different approaches. However, there is a clear difference between them in their emphasis either on direct control or on preprogrammed control. Our own approach has been one emphasizing the possibilities of direct control, since we consider that this one best replaces the human's hand as an extension of his brain, restoring his freedom to act in his own way in an unstructured environment Therefore, our first efforts have been directed toward the development of computer assisted procedures to facilitate the task of "talking to the gripper" We do acknowledge, however, that the addition of some stereotyped preprogrammed procedures or sequences may be useful to facilitate and speed up certain tasks, and the Manus system will include a limited number of programming possibilities which are yet to be specified in detail.

In our direct control approach we offer the user the choice of a number of control modes of preprogrammed *characteristics* (transfer functions) of the manipulator, i.e. the way the system responds to the limited set of control signals emittable by the operator. The choices to be made are what are the gripper movements to be controlled, in what reference frame, by which operator control signals, and how should each of the latter ones influence the gripper movement controlled (i.e. control of gripper, *position*, *velocity*, or *force* and its ratio or "*gain*" factor). This leaves us with a very large number of potential solutions that, moreover, are not necessarily the same for each subject, depending on his particular disability and the configuration of the control transducers used

For these reasons, the computer program has also been organized in a modular way, but such that a specific configuration can be realized without a profound knowledge of computer programming as long as no new modules are required. In the Spartacus system the whole configuration can be specified by defining the essential parameters in a number of tables, and seven of such configurations may be stored in memory if the system is to be used by different persons. This modularity has permitted us to experiment with many different control configurations, both in the laboratory and in a clinical environment (4, 6, 7), and to establish a number of control modes that seem to offer a reasonable compromise between many conflicting constraints

A typical control configuration consists of a loop of four sequentially-selectable basic control modes. Each one using three (or less) proportional signals to control certain gripper movements in a selected reference frame. Together, they permit the operator to control gripper position, orientation, and opening and closing a semi-sequential way, with access at no more than three variables at the time. A judicious combination of simultaneously controllable parameters in a minimum number of control modes is an essential element in the design of a functional system. In addition, a number of special-purpose modes may be added in a parallel loop to facilitate specific tasks, such as drinking from a glass or turning pages, without increasing access time to the four basic modes.

Furthermore, each mode has been doubled through the use of a "[illegible]tch" function, an essential element permitting one to uncouple the controls This leaves the operator free to move without provoking unwanted gripper movements, and to couple at any value of transducer signals and gripper position, thus permitting him to shift his "zero" position, both for comfort and change of range of control (explained in more detail in the references 4, 6, 7, 8, 9, 10).

Mode selection and switching between coupled and uncoupled modes are visualized on a display located on the arm near the gripper, with the operator functioning in a single-switch scanning mode. With the display mounted near the gripper, the operator usually has both the display and the task being executed within his field of vision. This is particularly important when he is controlling gripper movements by head movements. Another method of selection that has been experimented in a direct selection by a melody code (1). The recognition rate was not yet high enough with the available equipment. A voice recognition system may also be useful here, but recognition rate may also be a problem here, in particular if a respiratory impairment exists.

In view of the very limited motor function available to the target group of users, it will be necessary for mobile systems to combine the control of gripper movements and the control of mobility. Thus, the Manus system will include special modes to control wheelchair movements through the same controls as used for the manipulator For some advanced wheelchairs it might even be possible to combine wheelchair displacements and arm movements in order to obtain a global control of gripper movements in space, but this remains to be studied.

The Telethesis and its Environment

A working station for the human operator has to satisfy certain criteria of ergonomy in order to permit him to work in an optimal way. These criteria are even more severe in the case of the disabled operator. A telethesis is one of the adaptions that may render the environment more accessible However, the mechanical arm has its own constraints, more restrictive than those of the unimpaired human arm. Therefore, the working environment of the operator and his telethesis has to be adapted in order to optimize their shared performance. The need for such adaptations is all the more important as the capabilities of the mechanical arm are more limited. Thus, the lack of a degree of freedom on the arm imposes as specific direction of approach when fetching objects with the Heidelberg arm (15, 16) This has led the Heidelberg group to organize the environment accordingly, and even to add motorized rotary shelves to assure the right orientation of books to be fetched. Similarly, the use of completely preprogrammed actions requires a stable environment, with each object at its allocated place, for the system to be effective (2).

For these reasons, all projects working with a manipulator at a fixed work station have to organize the environment to some degree, and in particular the Heidelberg (15, 16) and Baltimore (17, 18) groups have studied this aspect, creating working stations in which the telemanipulator is but one of the elements. The Spartacus system was aimed at working as much as possible in an environment organized for the human operator, and with its six degrees of freedom, besides its gripper opening and closing, it can approach objects from any direction, thus reducing the need for pre-oriented objects The fact that thus far no pre-programmed actions have been used has also limited the need for structuring of the environment. However, careful placement of shelves and objects at the periphery of the operating range has been necessary in order to cope with the limited range of reach. Further structuring will be necessary when a growing number of different tasks must become independently executable by the operator and more objects have to be stored within range.

For mobile systems like the Manus system the range is enlarged due to their mobility, but adaptations to the environment, at least similar to those required for paraplegics, will remain necessary. In addition, for the Manus system the privileged work station will be the wheelchair lapboard, which may be optimized for its use in conjunction with the manipulator.

Safety Considerations

User safety is a major concern in the design of a manipulative aid that must function with the user within its range of action. There will necessarily be a conflict between functionality and absolute safety. Decisions will have to be made about the level at which the user should be responsible for his own safety and where the system should be inherently safe. The trade-offs between safety and functionality may in some respects be adjusted to the user, and evolve with his changing needs and dexterity in using the system as he gains more experience. In the design at least three levels of safety may be distinguished:

Passive Safety

Under worst-case conditions "passive safety" largely depends on the [illegible]o-mechanical design.

- Low inertia of the moving elements to limit the impact of collisions Thus, in the Spartacus system all motors have been placed in the fixed base structure and light-weight materials (including carbon fiber casts) have been used in the arm The "pay-load" of course has to be added to the inertia, and safety aspects should be taken into account in specifying the loads that can be handled;
- Maximum velocity attainable, which determines the maximum kinetic energy which can be accumulated in the inertial elements. If everything goes wrong, maximum velocity is limited by the maximum tension which can be applied to the motors (if we consider DC-motors);
- Maximum static forces that can be applied, determined by maximum motor currents at stall;
- The effect of any uncontrolled movements can further be limited by a design avoiding sharp edges and protrusions, avoiding any dangerous pincning gaps (scissor effects), exposed gears, etc., and by padding if necessary;
- It should be possible to move the arm passively even if all

control is lost, i.e. it should be possible for an attendant to push the arm away without excessive force. This implies a design with either a reversible transmission or the use of elements like slip couplings or shearing pins,

- The system should be fire resistant to withstand overheating due to electro-mechanical failures.

Supervised Safety

Under normal conditions, another level of "supervised safety" should be active to increase the safety level, to reduce the nuisance of being out of control, to protect against system damage and to compensate for certain user control errors. This level relies on the system computer and/or special circuits to check critical parameters such as forces, velocities, accelerations, proper functioning of the program (check points), penetration of forbidden territories including electro-mechanical ranges and imposed functional restrictions, etc. If any risk limits are exceeded, the program should take the appropriate actions either to stay within limits if possible, or to shut off the system in a "friendly" way. This level should also include a self-check of safety provisions at start-up. User and service friendliness would be enhanced if some form of status feedback and diagnostic error messages would be given when start-up conditions are not satisfied.

Interactive Safety

Some of the variables of the second group may be specified, within certain ranges, in the set-up of a specific user configuration. Therefore, another level of safety needs careful considerations at this time, which we may call "*interactive safety*" or the avoidance of "*control-blocking conditions*." With this we mean that for some reason the user may loose functional access to his control transducers. In its simplest form, a transducer may get out of reach due to a change in posture which cannot be corrected by the user himself. Thus, a weak hand may lose its grip on a joystick and lack the strength to get back to it.

In this respect, particular attention should be paid to the possibility that control might be lost due to the mechanical interaction between a moving gripper (or manipulator segment) and the control transducer in a direct or indirect way. For example, a hand may be pushed away from a joystick by the gripper. The movement of the gripper pushing the joystick may even reinforce this in a positive feedback loop condition.

A similar condition, with potentially more dangerous consequences, may occur when a control by head movements is used. In order to avoid such a positive feedback condition when using head movement control with the Spartacus system, we have used an inverted control action. pulling the head backwards causes the gripper to pull away from the head. The price to be paid for this safety feature is a more difficult control situation, in particular during the learning phase. We have considered it worthwhile, however, in particular since it permits a safe and even more convenient way of approaching the face, such as in eating, drinking, cleaning, etc.

Another cause of control-blocking conditions should be considered when using non-contact transducers such as ultrasound or optical transducers. Here, the mechanical arm, or an object held in the gripper, might interpose itself between the transducer and the user, thus making him lose control.

Interactive safety aspects are the most difficult to ensure in a uniform way, since they rely for their implementation on the person setting up a configuration for a specific user and are not under complete control of the design team A good understanding of these aspects is therefore a prerogative for anyone to be allowed to change a user configuration In addition, the user himself should be taught to understand and avoid control-blocking conditions

Finally, it would be desirable for the user to have access to some independent form of alarm, asking for human help if everything else fails. It may be difficult, however, to find an adequate way of triggering such an alarm if only minimal motor functions are available. Therefore, the system should be safe enough that the user could wait for spontaneous human help, which will always be available within a reasonable time to persons with a disability severe enough to justify the use of a manipulator.

Configurations for Case-studies

The case-studies briefly reported here are all drawn from the Spartacus experience. In this project various disabled persons have participated in laboratory experiments from very early in the project (3,4), starting with the system simulated with MA-23 nuclear manipulator (fig 1) and further elaborated with the MAT-1 system (fig. 2). Thus, the concepts have developed in an interactive process of design and experimentation. In a later phase, the MAT-1 has been installed in a fixed work station in the occupational therapy department at the Raymond Poincaré Hospital at Garches (fig. 2) In all cases experiments have been carried out under "supervised" conditions in a close collaboration between engineering, medical and paramedical personnel As a result of these experiments, a gradually expanding library of control configurations has been constituted, generalizing the concepts developed for a specific case to a whole group of potential users.

The actual MAT-1 experimental system, designed as a flexible system to study the *feasibility* of the use of a multipurpose telemanipulator by severely disabled persons, did not yet allow its unsupervised use for prolonged periods of time. This was due to the fact that the user had no access yet to a procedure to reinitiate the system when the automatic safety surveillance shuts it down (usually due to the exertion of a force exceeding a preprogrammed limit).

For tetraplegics with different residual functions, four different configurations of control modes have been developed and experimented. three for control by two head movements plus global arm movements (left or right, controlling a one-degree-of-freedom joystick or a "roller transducer" and a switch) (figs. 1, 2, 3, 7), and one for control by three head movements (figs. 4, 5)(7, 9). The switch signal is required to select control modes and control a "clutch" function. In figs. 4 and 7 the switch signal was obtained from a humming signal picked up by a laryngophone.

A similar control configuration using two head movements and a roller type transducer was used for a 19-year old man paralysed by poliomyelitis at the age of three, who still could use the fingers of one hand. The adaptation posed no additional problems in this case.

More effort was required to realize a configuration for a 22 year old man with an advanced muscular dystrophy, under continuous respiratory assistance on his wheelchair (fig. 8). He had no head movements, and only very weak finger movements were available. For him a special control box was developed with a modified three-degree-of-freedom joystick, which could be moved with very little effort. It was supplemented by a light-weight mercury switch, attached to a finger of the other hand. A special configuration was developed for him and added to the library. Due to his very restricted range of movements, his installation was quite critical, both to obtain the correct position of the controls and to assure an optimal range of vision.

A very different situation was encountered when we were confronted with a 10-year old boy with athetoid cerebral palsy affecting both upper limbs (figs. 9 and 10). He used a head stick to type or use a Canon communicator and was of a normal intelligence, but could not express his full potential due to his neuromuscular impairment. Our first trial to have him control by head movements using the configuration of fig. 2 failed due to the fact that he was not able to actuate the mode control switch without moving his head, causing unwanted movements of the gripper. This problem was finally solved by using the roller transducer, controlled by chin movements. Having the possibility to release the transducer before hitting the switch with an extension movement of his arm (a movement already used to control other devices), he could now avoid making unwanted control signals. A new configuration was developed for him, using the roller and the switch to control only one degree of freedom of the gripper at the time. This configuration was gradually developed from one with only four modes (x, y, z and gripper opening and closing) to one t aling eight modes. In additional to complete control of gripper orientation in space (three modes), he could then also control the displacement of the gripper into the direction it is pointing. This last mode, also used as one element in the "piloting" mode (3, 4, 6, 7, 8) but now used on its own, allowed him to move the gripper into any direction in space without requiring a tedious "staircase" type of approximation. In fact, with this configuration of a sequential control of one movement at the time, we compensated for his impairment of *coordination* by having him first *select the direction* of the movement to be made and then allowing him to control only this single movement, thereby eliminating any "parasitic" movements.

During its development, this last configuration was also adopted for a 5 year old boy who, in addition to a peri-natal C6/C7 spinal cord lesion, had also suffered brain damage, causing learning problems and a retarded development. For him, the objective of the use of the manipulator was not primarily to provide a manipulative function, but to use it as a device to aid his cognitive training. The possibility to confront him very gradually with an expanding set of movements, acquired and trained one at the time, proved to provide an effective tool for this purpose.

Training and Experimentation

During the clinical studies we have continued the development of teaching aids and procedures for manipulator control (7, 8). In particular the use of a set of 'H-elements" (fig. 4) has proved to facilitate teaching due to the simple way in which the tasks can be explained and gradually modified to require the control of more and more degrees of freedom. Typically, a person using one of the first configurations described can learn in the first session to combine the use of three basic modes to poor water from a bottle into a glass. In the other cases it may take some more time to try out different adaptations to find the most adequate configuration. Few cognitive problems have been encountered with this method.

Although the basic training was conducted in a rather structured way, l r sessions were more and more adapted to the possibilities, desires and therapeutic exercises for each individual. Nevertheless, a number of tasks were executed by several or most users among those who continued for prolonged periods of time. Among these tasks we find (10):

- Pouring liquids or "pla ing with water" as mentioned above (fig. 1);
- Fetching objects from shelves (fig 5);
- Opening of cupboard doors, either requiring to pull it through a spring-closing mechanism or to turn a key and pull it;
- Eating food held by the gripper (cookies, etc.);
- Eating with a spoon or a fork;
- Cutting a pie-shaped cake with a roller (pizza) type knife (fig. 10);
- Lighting a lamp;
- Drawing or painting (fig. 8);
- Drinking—using a special mode which combines tilting and lifting of a cup or glass, simultaneously controlled by a single signal (fig 6) This task was considered a "landmark" since it showed that a certain level of confidence and dexterity in controlling the system had been obtained;
- Turning pages of a journal or a book, also facilitated by a special mode, giving access only to gripper pitch and yaw (fig. 7);
- Using a standard dial-type telephone;,
- Lighting a (large size) cigarette lighter and light a candle

("playing with fire");

- Using an electric range to heat water and prepare a pot of coffee;
- Playing games;
- Making (large-size) LEGO constructions;
- Shaving with an electric razor;
- Playing with "Rubik's Cube" or opening and closing a bottle, using a second motorized gripper (an Otto Bock electric hook mounted on a special support which may be moved and oriented with the manipulator gripper). With this "second hand" objects could be stabilized when acted upon by the main gripper;
- Using the gripper to make physical contact with other persons (teasing the therapist, "fighting"), dropping objects, etc., as a means of personal expression and communication.

Several case studies were documented on film and a summary edited on video is available to give a compact visual account of some representative clinical experiments (9).

Discussion

The supervised conditions under which these experiments have been carried out also presented an occasion for more intensive social interactions, which have certainly contributed to the motivation of several of the subjects. Nevertheless, they have given results of which some were beyond our expectations, increasing our confidence in this approach of telethesis-assisted manipulation. Not surprisingly, the highest motivation has been encountered by those persons with the severest impairments, obtaining the highest relative benefits from the use of this manipulative aid. This observation, which we have reported earlier for persons with high-level spinal cord lesions (7), has since been confirmed by the case studies involving the person with advanced muscular dystrophy and the boy with athetoid cerebral palsy. In particular, it has allowed the latter to execute many of the tasks for the first time in his life. In spite of this he has shown no problems either in spatial representation or in planning of gripper movements.

One aspect which must be noted is the time expansion in the execution of tasks with the aid of a manipulator as compared with its execution by an able-bodied individual. To the latter, such an expansion may seem difficult to accept. To a severely disabled person, used to waiting for things to be done for him, the fact of being able to do it at all, by himself and at the time of his choosing appears to be a strongly motivating aspect in several of the cases we have encountered. In fact, on several occasions motivation increased gradually as the user got more skilled and began to use the potential offered in his own way. This aspect of time expansion, used as a measure of performance in conjunction with nuclear manipulation tasks, may merit its further development as a means to evaluate performance of manipulators in rehabilitation.

The final test of user acceptance will only come from the use of these manipulative devices under actual living conditions. It is difficult to predict its outcome due to the multitude of factors involved. This will be one of the aspects ultimately to be considered in the cost/benefit analysis within the Manus project. The same holds true for the economical aspects of cost/benefit relations, where equipment costs must be weighted against savings, among others, on more specialized devices (such as page turners, etc.), fewer adaptations to the living environment, better coping and reduced need for attendant care. Although the Heidelberg experience (16) has cautioned us to moderate our expectations, the progress made thus far has strengthened the author's view that with a telethesis periods of several hours of unattended autonomy should be within the realm of possibilities, even for severely disabled persons. Of course, intermittent human care will remain necessary for more demanding ADL tasks, such as those related to dressing, personal hygiene, transfers, etc.

Acknowledgements

The author wishes to dedicate this report to the memory of Jean Vertut who contributed many of the basic ideas that guided the Spartacus project. This project was launched and financed by the "Institut de Recherche d'Informatique et d'Automatique" in 1976, transferred to the "Agence de l'Informatique" in 1980, with its personnel detached to the "Université Paris XII" at Evry. Among the numerous persons who have contributed to these studies the author wishes to thank his colleagues R. Barbier, J.P Gaillard, G. Cristeau, M. Dupeyroux, V. Dupourqué, F. Eyrault, S. Galerne, J. Guittet, N. Quétin, M. Temprement and J. Yclon Among the persons having collaborated in the clinical experiments at Garches the author is in particular indebted to F Galmiche, S. Pannier, F. Pélicant, S Pétrequin, J Randani, M. Tramblay and M.F. Vinceneux. Particular thanks are also addressed to all those persons with various disabilities who have contributed to shape our ideas, often in many hours of experimentation, in spite of the fact that they may not benefit of it personally.

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A POTENTIAL APPLICATION IN EARLY EDUCATION AND A POSSIBLE ROLE FOR A VISION SYSTEM IN A WORKSTATION BASED ROBOTIC AID FOR PHYSICALLY DISABLED PERSONS.

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The United Kingdom Perspective

Over recent years several projects have started in the U.K., born from a plethora of low cost robots and an ideal to put these to work for the disabled Many of these projects have been short lived because of the mechanical inadequacies of the robot or the low data rate of the user when operating a robot as a manipulator(1). There are, though, several active projects in this field, representing widely differing approaches to the problems of using robots with physically disabled

Dr B Davies at Imperial College London is working on a low-cost, purpose-built and dedicated feeding device with 3 axes, an end effector with clip-on attachments such as a spoon, large key pad inputs and safety approach based on inherent weakness This type of purpose-built device for disabled must aim to have a low cost since the demand is limited making mass production impossible. The operation of this device relies on the environment to be structured and it aims to fulfil one specific need in a small category of users (2, 3). The robot has an estimated eventual cost of £300.

A high quality teaching robot is currently used by M. Hillman at the Bath Institute of Medical Engineering (BIME). This robot has stepper motor drives and 5 degrees of freedom in a 600 mm range and a load capacity of 1 kg(4). An educational computer both drives the robot and runs the user interface consisting of menus operated by two switches This system is currently undergoing clinical trials and has an estimated final price of about £2000. A wider range of applications are possible with a more powerful device such as this but either the user must have patience to provide manipulator style commands or the workspace must again be structured.

At the Cambridge University Engineering Department we are investigating the use of robots to assist in the devel opmental education of handicapped children. The robot used in this project is the RTX manufactured by Universal Machine Intelligence LTD, London. The robot is based on a SCARA format and is, to our knowledge, the only robot with design considerations given to applications for disabled in addition to those of light industry. It has a full 6 degrees of freedom, a 1000 mm range and a load capacity of about 2 kg(5) A vision system is added to the robot as are gripper sensors and we hope for an eventual cost of about £10000. Although this cost is comparatively high it is justified to keep flexibility and safety in a wide range of potential applications. The intention is to keep a flexible range of user input systems and use sensors and vision to minimise the information that must come from the user

These three projects are all in developmental stages so success cannot be measured by commercial sales, however other indicators are possible.

Two past workers in this field gave cautionary advice about the acceptability of robotic systems, and projects initially showing great promise, failed in clinical trials as the robot was unacceptable to the user. (6, 7) In addition a survey conducted by the BIME on applications of robots for physically disabled notes that most people who could benefit from a device of this type have either full-time or part-time care(8). Thus a reasonable criteria of success would be given if a user can achieve an intended task using a robot in a time comparable to summoning assistance, or the task can be seen by the user and the assistant to be beneficial if completed alone.

A robot based device must be shown to fulfil a need or needs and thus criteria such as frequency and efficiency with which it is used, its reliability and cost are also important. It is unlikely hardware costs of this type of system will fall in the same way as microcomputer costs but a long term possibility is that safety levels and the range of applications will increase as computers become more sophisticated.

Safety Concerns

Where a mechanical system must operate close to humans questions about safety must be raised A programming error early in our project became a self destruct mechanism for the industrial robot we were using and remains a telling reminder of the level of safety we must achieve before a robot can be considered safe for a disabled user who would not be able to hit the "panic button."

A robot can be made safe in three ways, limiting its strength so even in failure it cannot conceivably injure the person using it, keeping all concerned outside the robot's envelope, or monitoring the robot's environment with sensors and using software able to act correctly on this information.

To limit strength to a completely safe level would restrict the applications to an extent where all advantages of using a robot are lost and a purpose-built aid would provide a more appropriate solution Denying a person access to the robot's envelope again restricts potential applications and does not account for a third party straying into the robots environment. The most promising alternative is to use a system of sensors However, running a robot with complete confidence about safety requires a high sensor density and sufficient computing power to decide appropriate responses in real time. Such technology does not exist at present.

Our philosophy is to use a combination of all three methods in varying degrees. The strength of the robot is kept low and a load of 2 kg should be sufficient for most practical applications. The RTX robot allows for further force limitations and we hope to exploit this in future versions that use the minimum force required for each stage of movement.

At present the user does not need to enter the robot's envelope, although some predicted applications will require physical contact between the user and end effector tools. In such cases a reasonable safety can be achieved by positioning the user at the extreme of the robots movement However, we hope a more appropriate solution can be achieved by using sensors in a dual role to monitor environment and maintain safety.

When it becomes possible to operate a robot with a safety record comparable to that of an electric wheel chair, one could consider that a sufficient level of safety has been achieved.

Applications

The most commonly cited application is using a robot to give food or drink and two of the three projects described above are intended mainly for this purpose. However, applications are wide ranging and linked with the needs and intelligence of the people likely to use robots, thus expectations will vary according to disability. A user who has had normal function would try to use a robot to regain independence, thus feeding may be a major application. A person who is born disabled will use a robot to explore and experiment in an unknown environment.

Applications in daily living are cited in the BIME survey(8) which cites possibilities for a low cost robot-based aid ranging from meal preparation, cooking, reaching to shelves, loading a cassette and even to opening cans of beer.

User input system

The needs and abilities of people who could potentially benefit from the use of robots is wide ranging and as a result so are the applications. A chief advantage of a robotic system is its inherent flexibility. This should not be compromised because a user cannot provide input in a correct form or is more able than an input system expects. At Cambridge our initial approach was to dedicate a computer to interpret the commands from the user and pass these across to the control system in serial form(9, 10). This proved successful and allowed us to interchange quickly between inputs such as a membrane keyboard, a special access keyboard, head switches and two large area switches.

It would now seem more appropriate both to run the outline application program and interpret the user information in a computer dedicated to each user or class of users, keeping the responsibility of collision avoidance, safety, local location of objects, environment details and vision system in a general purpose computer (Figure 1). Multitasking techniques could be used to keep the application and the input independent(11).

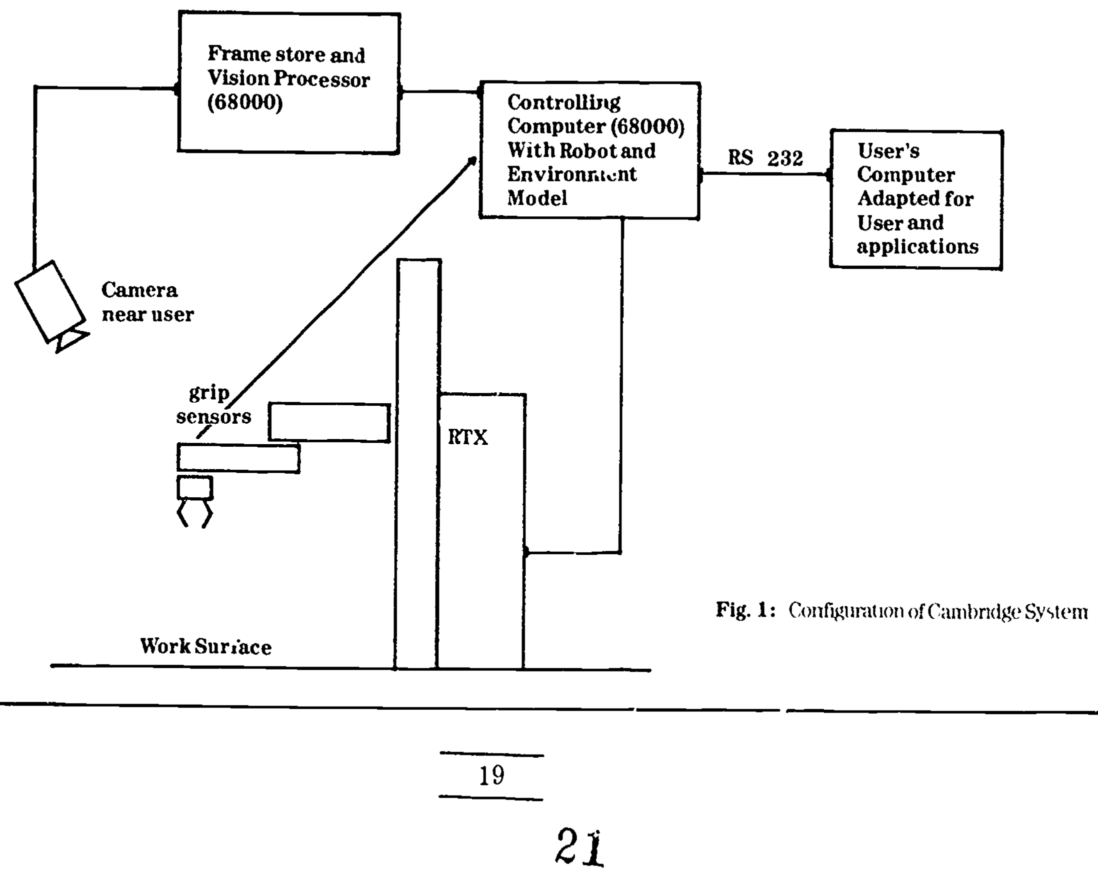

Fig. 1: Configuration of Cambridge System

There seems little doubt of the potential of a robot-based aid for physically disabled However, the cost of this technology is potentially high, safety is a major problem and expectations by users usually exceed the abilities of the robot. This is equally relevant to vocational applications and activities of daily living as it is to our work on educational possibilities at Cambridge.

Use of Vision

Because it is unrealistic to structure a domestic environment it would seem worthwhile to use a vision system both to identify objects and to locate their coordinates This information would be passed on to the robot. However, all current vision systems are feeble in comparison with the resolution of the human eye and processing power of the brain. So some

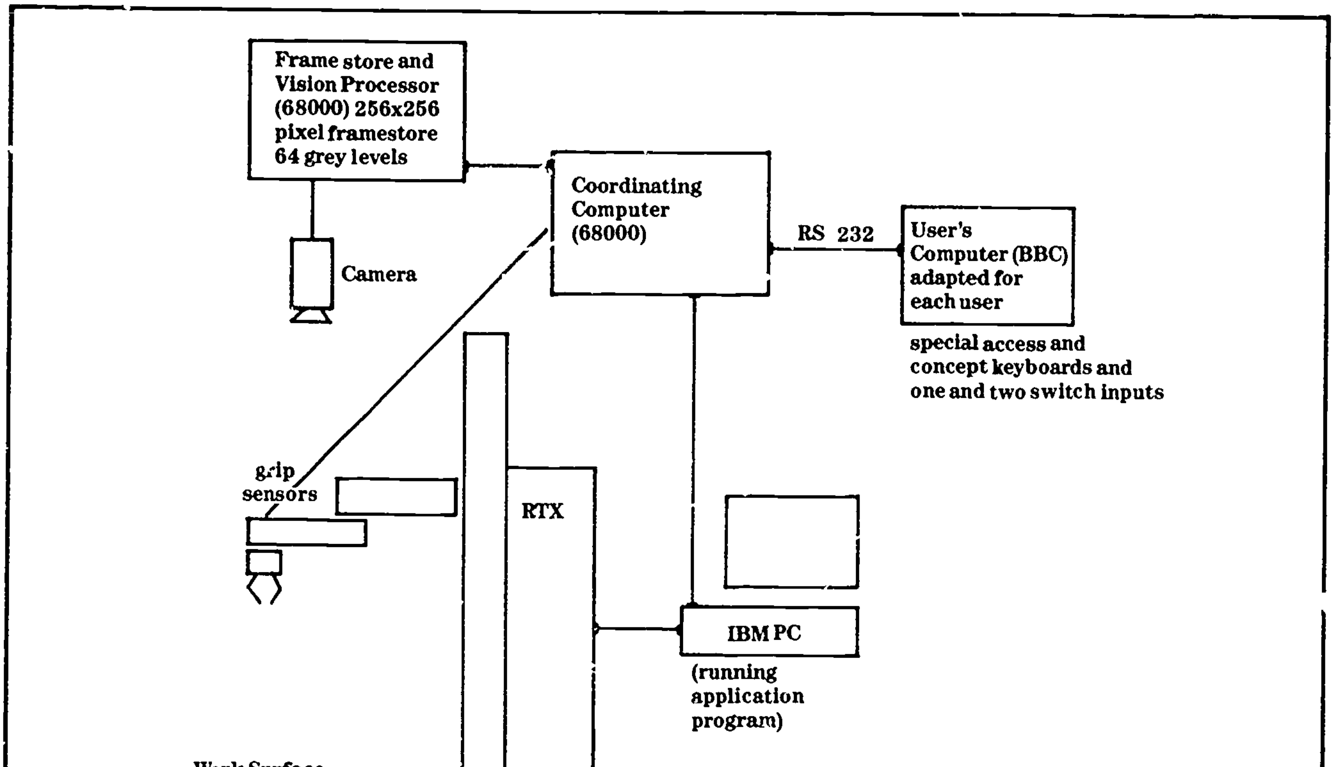

Fig. 2: Cambridge Robotic System Including Computer Vision

Robots in Early Developmental Education

One of the objectives of our project was to work closely with a school for disabled children. It was natural, therefore, to concentrate on educational applications and provide a facility for a disabled child to manipulate an environment This allows for tasks such as examining the size, colour, relationships and shape of objects There may also be scope for creative work based on art and craft work allowing for different levels of users.

The arrangement of the system is shown in figure 2 and shows a camera mounted directly above the work area.

This arrangement gives a direct measure of the 0, x and y coordinates if an object is recognised by the vision system. There is also an option for the user to indicate an object with a cursor on the vision system screen. However with the camera in this position we found it difficult to match objects in the picture with their physical positions and concluded that a child with less concept of space would find this impossible Until the camera can be moved to a position near the user we will not use a screen cursor to identify objects to the robot.

simplification is required if the above objectives are to be realised using current techniques

Industrial vision systems are highly simplified by using controlled lighting conditions and structured backgrounds. In addition much research in computer vision is not constrained by the need for real time processing. A combined robot and vision system for the disabled can enjoy neither of these advantages However, exploiting the fact that a finite number of objects will be manipulated repeatedly in this application, it would be possible to label these objects using a set of coded markers rather than identify the objects directly. This reduces the problem to identifying markers in an unstructured environment, reading their coding, and calculating their position and orientation. Using the coding, relevant information about the object and how it must be handled is read from a data base

Our image processing hardware consists of a 256 by 256 pixel frame store encoding 64 grey levels and in the memory map of a 68000 processor. Processing the image consists of three stages, preprocessing, feature extraction and identification, and calculating position and orientation.

Preprocessing detects all pixels that may correspond to marker boundaries and codes. As each pixel has to be scanned, the algorithm must be simple and efficient to minimise the execution time. Conventional techniques failed because of the wide range of lighting levels and unstructured environment that are encountered, so a new method based on finite state machines now carries out the preprocessing task(12) All possible marker boundaries and coding dots are detected and classified into "channels," reducing the data from 64K to a few hundred bytes.

Line segments are extracted from the reduced data and the algorithm tries to merge these line segments to form closed contours If successful it splits the contour into straight line segments to find out the number of sides. If four sides are found the algorithm assumes a marker has been found, works out the equations of the best fitting straight lines through the data points and solves these to obtain the coordinates of the four corners of the marker. Coordinates obtained in this way are more accurate than those read directly from the image.

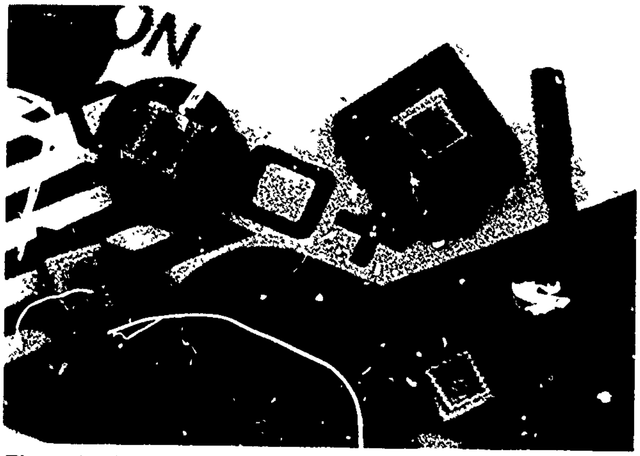

Figure 3 shows a photograph of the image with the marker boundaries detected and highlighted.

The coding is read by placing a grid on the image of the marker. We use a 3 by 3 equi-spaced grid to read up to 9 dots. Allowing for rotational symmetry 140 codes are possible. It is worth noting that on a 4 by 4 equi-spaced grid 16,456 distinct combinations are possible making error checking and correcting codes feasible.

For the initial trials the camera was mounted overhead fixing marker position in 2 dimensional space and giving the rotation along the third dimension. Overall accuracy for the robot and the vision system is within ±2mm The size of the marker can be used to estimate the depth, indeed, the image of a square marker contains enough information to calculate its position and orientation in three dimensional space[13] thus giving all necessary information without using structured lighting or multiple view points.

It takes approximately 10 seconds to analyse a scene, too slow for a closed loop control but more than adequate in an open loop configuration To maintain good positional accuracy a ratio of 1 pixel to 1-1.5 mm is needed As the aspect ratio of the system is 1 47:1 the resulting field of view is about 300 mm by 200 mm. This restricted field of view limits the usefulness of the vision system. Further the pixel geometry of a vidicon camera is not sufficiently accurate to estimate depth but CCD cameras and windowing facilities should overcome these problems.

Gripper design

Extensive use of infra-red sensors is made on the gripper or end effector. The end-effector we are using is a modification of the standard supplied with the robot. In future versions we hope to design a gripper specific to our needs. Since the end effector is central to the robot's operation, eight binary sensors are used to give information about the gripper's local environment and maintain safety in the area of the gripper. Four of the sensors point forward and allow a limited estimation of range They are also used to determine depth, as this is not yet available from the vision system.

A marker based system implies a semi-structured environment where markers must either be placed on an object, the object holder or a block fixed to the object. The control program must have a data base on the item associated with these code that influences safety, orientation and grip procedures. 3×3 Coding in a square marker uniquely defines the orientation in 120 out of the 140 codes.

Potentially a cursor can be placed on the vision screen and controlled by the user to identify an object If an object is located by this method or the robot is commanded to move directly towards the object, the robot must approach the object with care Although a local search can be made for a grip point, the robot must await confirmation from the user.

Case Studies

One substantial clinical trial has been made so far in which three learning tasks were investigated. Two of the tasks were suggested as basic developmental tasks that are not achievable by children with severe physical disability yet are central to their education. These were a routine to stack bricks in a pile and break the pile once built, and a routine to sort bricks into boxes depending on their shape or colour.

The third task was the Tower of Hanoi puzzle that consists of a tower of discs with decreasing diameters which must be moved to a second location with the rules that only one intermediate location can be used and at no time can any disc be placed on a smaller disc. The robot enforced these rules but gave the user control over moving discs.

Stacking and breaking

The vision system is used only to identify the position of the bricks and passes these coordinates to the robot The robot locates and brings each br. k in turn to a stacking point in front of the user. Once built, the robot will then break the tower and ideally could then rebuild it. In practice the software cannot deal with bricks that are too close or bricks landing on top of each other when the tower is broken.

A typical person using this program was a severely disabled 17 year old with cerebral palsy, spastic quadriplegia, no speech, who had recently begun to use head switches.

The user's level of interaction in this process was gradually increased, initially he provided signals to start the robot on the task and command the robot to break down the tower. The next stage was to segment the building process into stages corresponding to locating the brick, grasping it, moving it t the stack point and placing it on the pile with the user initiating each stage in this process. Timr l.d not permit extending this to allowing a choice over the order in which blocks were stacked and whether in the final stage the tower was broken by the robot or dismantled brick by brick.

Sorting on colour or shape

The sorting task used the vision system to locate the bricks and read the code contained within the markers. This code uniquely identifies each brick. The robot picks up each block in turn and presents it to the user to identify either colour or shape. Once the user has indicated that he has seen the block the robot tries to sort the brick, either on a scanning basis where the robot goes to each bin in turn and waits for a 'yes' or 'no' response from the user, or by direct selection where the user can indicate each sorting bin. The robot ensures the brick is eventually sorted correctly, thus if the user has given a wrong command the robot's response is to appear to try the brick in the bin but refuse and give a negati ·e sound before continuing with the program.

A typical person using this program was a severely disabled 12 year old with cerebral palsy, spastic quadriplegia and single utterance speech. He spent most of his time with this program and managed to sort colours using the scanning system with help to identify the correct switch. Several switch combinations had to be attempted before he could operate them reliably. Our intention was to reduce the problem to a direct selection using only two colours and coloured labels to associate the switches, but again time did not permit this.

Figure 4 shows the robot above one of the sorting bins waiting for a user's response. Items in this scene correspond to those identified by the vision system in Figure 3.

The Tower of Hanoi Puzzle

The third task was devised because one user found no difficulty with the stacking and breaking task, and sorted the blocks on colour and shape using scanning and direct selection modes. To maintain his interest we adapted the Towers of Hanoi problem. He was a 15 year old with cerebral palsy spastic quadriplegia, limited speech and severe learning difficulties.

After the explanation he managed the problem using two discs on the first attempt. Later he was given a tower of three discs. He tried solving the puzzle using a trial and

† Masculine form used throughout

Figure 4

error approach and became conversant with the rules as a result Over the trial an increasing amount of planning strategy was used and after several successful attempts the user achieved the solution by the optimal path.

Conclusion

Everyone enjoyed working with the robot and it would appear to have a potential impact on someone who would not normally have done such tasks. The robot provided experiences about sounds and dimension in life. We believe this shows a potential for robots in education and would like to suggest a similar configuration for other applications. Future work hopes to expand the vision to increase field of view and possibly use it to identify unmarked objects to the robot A more sophisticated robot control language is envisaged that would take advantage of sensor information and information in a data base.

Acknowledgements

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MANIPULATIVE APPLIANCE DEVELOPMENT IN CANADA

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Canadian Perspective

Industrial robotic use in Canada is very modest and is primarily concentrated in the manufacturing province of Ontario. The most advanced robotic research has been fostered by the National Research Council of CANADA development and the commercial production (1) of the "Canada Arm" used in the U.S. NASA space shuttle program and projected for use in the space lab construction. Canada also boasts major achievements in deep sea research and has successfully developed and marketed submersible manipulators for more than ten years. (2) Significant remote manipulation technology has been developed over the past twenty years in atomic energy of Canada's CANDU nuclear reactor development program, (3) and in the service program of the world's largest cyclotron. (4) A bold attempt to produce a robotic arm mounted on a wheelchair was undertaken by the Ontario Crippled Children's Center and Spar Aerospace in 1979, but the results were less than satisfactory. A true "medical robot," believed to be the world's first surgical robot is in clinical testing in Vancouver for manipulation of the knee joint in arthroscopic surgery. (5)

Two other projects in Canada have contributed to a better understanding of the problems to be solved by a robot. These are the Canadian Paraplegic Association (6) which monitors closely all known paraplegics or quadriplegics in Canada (not exclusively spinal cord injury), and the Neil Squire Foundation (7) which delivers microprocessor based technical aids training to institutionalized or homebound severely physically disabled adults from coast to coast.

Robotic technology can be utilized for the severely disabled for many services ranging from recreation, cognitive retraining, physiotherapy, hygienic and personal servicing to physical transferring, but the really significant role seems to be liberation from dependency on others, or the attainment of some small degree of independence.

Technology and Consumer Independence

In 1985, the Neil Squire Foundation taught more than seven hundred severely physically disabled adults how to access and use the personal computer as a technical aid to independence. Many of these people were able to write letters, return to education studies, even to speak, for the first time in years—in some cases in their lifetime, yet almost none of them gained *any* increase in independence! There was still a barrier. They still had to be set up, to be handed a book, to have pages turned, to find the correct diskette, to adjust the monitor. There is always a barrier to that last step to independence. One of the students now works for us. She is a ventilator dependant quadriplegic woman with enough residual movement in one hand to operate an electric wheelchair. She cannot show up at the office and do a day's work without help. The barrier is always there. We know solutions to overcoming this barrier lie in technology. Voice commands can unlock and open the office door. The manuals can all be loaded on hard disk. The diskettes can be stored in a sip and puff actuated carousel. The consumer oriented solution to this multitude of problems lies in the programmable manipulator.

In applying existing technology to breaching this barrier, one is faced with a wary, conservative, underfinanced market that is highly structured and institutionalized (resistant to change). This indicates that a first model should be a relatively small, simple, reliable, inexpensive appliance performing non-threatening tasks. We envisioned three stages of development:

First version. Robot work station, low powered (for safe interaction), reliable components, roughly human sized to do human-like tasks, extremely user friendly, inexpensive (heavy reliance on software rather than hardware).

Second version. Addition of sensors, gross positioning (relocation of work envelope ie; travelling on a track or pivot).

Third version: Addition of artificial intelligence allowing for unstructured mobility.

The user input for activation and program selection is open to any established computer or environmental control input system. Single switch, dual switch, special code, voice, or scanning systems are all viable and interchangeable. The user input for master control, either one to one or with any gain factor desired, is a more complex problem. In the first version we use an attendant to do the trajectory teaching, with the disabled user being able to call up programs, and make minor timing or trajectory modifications if desired. In the second version, an expanded master control capability will be introduced. This presents a whole area needing intensive research and development, as master control systems relying on single switch scan, morse code or voice key board emulation for direction control are currently all very slow and lack dexterity. After establishing a "wish list," we defined the following factors:

- The envelope location, or zone of manipulation, (in front of face and body, beside head, to bookshelves above workstation, below desk). The "floor" tasks were not considered.

MANIPULATIVE APPLIANCE "MOM I" WISH LIST

Work Center	Programmed	Fingers	Max Master	Min. Master	Max Dexterity	Min Dexterity	Zone
Handle paper, notes, etc	x	s	x			x	1
Load Printer, Typewriter	x	s				x	1
Load cassette, disk	x	s				x	1
Stamp envelopes	x	s			x		1
Handle telephone	x	L					3
Apply cosmetics	x	s		x		x	4
Handle electric razor	x	L					4
Play cards (holder)	x	s		x		x	1
Pour	x	L		x		x	1
Turn pages	x	s	x		x		1
Turn knobs	x			x		x	1
Operate environmental controls	x	s		x		x	1
Serve a mouthstick	x	s		x			3
Feed	x	s		x		x	4
Handle drinks (stir)	x	L		x			4
Wipe face	x	s		x			4
Clean teeth	x	s					4
Shelved items (books)	x	L	x			x	5
Handle cash			x		x		
Handle hat	x			x			
Operate spray bottle	x			x			
Open doors	(x)		x			x	
Unlock doors			x		x		
Wall Switches	(x)		x				
Operate appliances	(x)		x				
Operate faucets	(x)			x			
Dial telephone	(x)		x			x	

- The practicality of programming the task
- The gripper finger length (long or short)
- The dexterity required for the task (maximum or minimum)
- The master control capability required (maximum or minimum)

The wish list was further broken down into three mobility requirements (workstation, mobility required, or both). From this wish list the first version of the robot was determined to satisfy the work station or work station and mobile wish list requirements.

Economic Considerations

The cost/benefit and the self-esteem questions are really philosophic. In Canada, the investment/pay-off syndrome is clouded since the original investor agency is not the agency that reaps the eventual savings. We have found that discussions of economic reductions in staff and attendant care costs are bottlenecks to progress. We prefer to address the prospects for improvement in quality of life through increase in independence, knowing full well that better health, attendant care cost reductions and income earning potential are all going to occur as a natural result. How could one possibly give an economic comparison of recreation benefits or improvement in self-esteem? If we were proposing development of the automobile we would be smothered in the figures showing economic chaos for harness manufacturers, blacksmiths, feed distributors, carriage makers and glue manufacturers. In Canada we have an economic disincentive program that is different (better? worse?) than the United States. The benefits to the disabled in Canada tend to be marginally better, thus the disincentive to break out of the system is less. All these factors call on the Canadian robot designer to downplay the economics and to concentrate on the self-esteem. However, the small market base in Canada and the limited funding available for the use of non-traditional equipment in institutions or for personal use by individuals on welfare does require us to optimize design by fabricating techniques to achieve a reasonably priced serviceable reliable product.

Programming the Manipulator

An early scenario in the design stage is the discussion over the availability and use of computers by the disabled user. One argument claims that by the time the robot is marketed most disabled potential users will be computer smart and will be able to do their own programming. The other extreme is the potential user may have no desire to learn to use a computer, and are computer illiterate. We favor the computer illiterate approach in our solution. No knowledge of programming dictates either "Lead by the Hand" teaching, or master/slave mode programming, both of which require some unique technical solutions. We feel instruction should be simple and only involve implementation, termination and modification of programming, guidelines for gripping, awareness of safety systems and understanding of diagnostics. A typical guideline would be on picking up a hot drink, to have the program pause and await a "cognitive" command after picking up the drink, so that the user can visually assure himself that the container is properly gripped.

Design Specifications for Manipulator System

The Foundation robot project started in 1982 with a thorough study of the history of medical robotics, followed by six months of data collection, mostly through interviews, with many severely disabled, rehabilitation professionals, workers compensation and insurance claim groups and extended care workers.

The specifications for the first model are:

1. Mass produced sales price of arm and stand-alone control electronics under $5,000
2. Both master/slave and programmed operating modes.
3. Programming to be done on any home computer. An Apple II was selected for the first prototype, and an IBM pc is being prepared for the second.
4. Complexity of service and maintenance to be kept simple enough to allow for local consumer audio or computer agency servicing.

5. Operation to be extremely "user friendly," with no operator training being required. Specifically, no knowledge of computer programming will be necessary, and no computer keyboard will be used.
6. The co-ordinate envelope is approximately human-sized.
7. The appliance must be portable, with total weight to be less than 20 kg.
8. Lifting capacity at worst geometry of 1.4 kg, and at most geometries of 2.3 kg.
9. Use in industry in light manufacturing to be underscored.

A six degree of freedom robot to satisfy the general specifications has been developed over the past three years by Cameron/Birch for an appliance that will allow disabled people with severe physical limitations (eg. quadriplegia, arthritis, amyotrophic lateral sclerosis, cerebral vascular accident, multiple sclerosis, muscular dystrophy, cerebral palsy) to independently manipulate items in their environment. As this human sized arm was also appropriate for performing tasks under master control in a hazardous environment, it was adopted by TRIUMF, a sub-atomic particle research center at the University of British Columbia and funding was provided to complete three prototypes with a well developed PID controller (Proportional Integral Derivative), a master control input, and a simple gripping capability. One of these units is available for continuing laboratory development and one will be available for field testing in an extended care environment. The Neil Squire Foundation has developed in parallel a supervisory or host-computer control (programmed) capability, has an on going end-effector (gripper) development program, and is developing a lead-by-the-hand (back drive) programming mode and safety interrupt routines.

Machine for Obedient Manipulation

The robot (M O.M., a Machine for Obedient Manipulation) is designed as a work station manipulator in which the disabled user travels to the workstation (by wheelchair) and the arm operates as an attendant. M.O M is mounted at about eye level (to one sitting down) and can, by program, perform manipulations for tasks such as:

- picking up a manual from a bookshelf and placing it in front of the individual,
- turning pages;
- picking up, serving and replacing a drink;
- serving up a mouthstick;
- loading a diskette in the computer,
- picking up an electric razor and shaving a person,
- brushing hair;
- brushing teeth.

One version of M.O.M. can be bedside mounted with the arm swung over the bed to be facing the user when called into service. User input control can be by either voice, code, scan select, or computer keyboard.

Technical Realization of M.O.M.

The basic reasoning that led to the geometry was to create a manipulator that could perform similarly to an attendant, and in human size scope. This led to mounting the arm on a horizontal bar which allows travel sideways over a work table or bed. An examination of the "Wish List" (Appendix B) indicated that most tasks involving a lot of disorder, that consequently created problems for programming, were associated with wheelchair mounting. These were mainly the same tasks that require good master slave control, and the long reach required for retrieving articles dropped on the floor. Consequently, the wheelchair mounting was ruled out and will await a "second generation" model which can incorporate some artificial intelligence.

In following the specifications, cost is minimized by using standard extrusions, cable (pulley) drives, standard stock precision gears, a single model of a standard robust (reliable) motor and only two standard sizes of high reduction gear boxes for all 6 degrees of freedom. Potentiometers are used for all servo feedbacks and velocity is controlled by backwards difference calculation software rather than tachometers. In the hand-lead-through-teach routine, clutches have been eliminated by the use of a unique software back-drive development. Software torque limiting in designated zones is used as a safety adjunct. The PID control algorithm is digitally processed by a low cost 8 bit Motorola 6809 that has 16 bit arithmic capability. Although any computer with an RS-232 serial port can be employed, an Apple IIe is currently being used for supervisory control since it is most commonly used by the disabled.

Servicing and repair is kept simple by supplying separate printed circuit boards for the 6809 CPU, the A to D and D to A circuits, the power amps and the serial ports. The hand-lead-through-teach pendant allows simple programming with a numeral keyboard supplying the taught program number and a LED display showing the status. The human sized envelope is enhanced by a change-by-program end-effector (hand) to provide short fingers for dextrous object and paper handling, and long fingers for large objects as books, mugs, etc. The end effectors carry their own servo motors (model airplane servos—lightweight and waterproof). The horizontal travel and arm extension can be selectively changed for special installations with only tubing, cable and software control limit modifications Three degrees of gross positioning (microswitch limit) is provided at the table or bedside mounting, so the manipulator may work at the table, and then shift to work at a new area such as an adjacent bookshelf The manipulator is lightweight and easily removed and replaced from its stand (as with a bed mount, for making the bed). Although the capacity lift in the first prototype is limited (3-5 lbs.) it is adequate for most jobs on the wish list. Greater power at this time creates the possibility of physical damage to the disabled person.

Other safety precautions are incorporated in the design as well.

User Control of the Robot

Historically, robotics started as master/slave devices where an operator pushes buttons or manipulates hand controls to control a slave arm in its motions. These are typically used for one-time jobs in under-sea operations or for handling hazardous materials. This technology requires skill and training with the hands for the operator to learn how to properly control the master to correctly manipulate the slave.

In the past twenty years industrial robots have been developed that are programmed with a reusable memory so a task may be repeated many times consecutively or on command.

The problems encountered in developing a manipulative appliance for severely physically disabled persons with no hand control capabilities have been many. The primary difficulty has been to combine the industrial robot programming capability with a master/slave control device to allow for complete trajectory control. The desire is to develop a robot that is easy to use with pre-taught complex manipulation trajectories but which can also function in a non-structured environment with the user determining the trajectory. With such a system the goal is to combine the two control methods so that the user will not become overly frustrated by the lack of physical input capability and the robot will be able to perform satisfactory tasks in an acceptable time and manner.

The TRIUMF/NEIL SQUIRE robot development to date has leaned toward fully programmed tasks with standard environmental control interfaces. It is our goal to find a suitable combination of disabled user control and programmed control that will provide performance that is user-acceptable.

Evaluation of User/Robot Performance

There seems to be no established protocol or historical precedent for a prototype human-interactive machine development evaluation (interactive robot) in Canada, Japan, or the U.S A. and probably not in Europe. The Canadian Government regulates safety and efficiency of some products directly through Consumer and Corporate Affairs, Canada and indirectly through the Canadian Standards Association, but there seems to be no standard protocol for evaluation of prototypic rehabilitation technical aid products.

Our procedure will be to establish both subjective (user) and objective assessments of all tasks. Subjective feedback from the users will be formally acquired through carefully designed questionnaires which will ultimately allow for objective measures. These questionnaires will include such issues as the level of anxiety while accessing M O.M. (using the State and Trait Anxiety Inventory), improved mood (using the Beck Depression Inventory), attitudes to use, perceived problems and benefits by the user, adaptability and utility. From an objective point of view we want to strive for the ideal of simple input to perform complex tasks. The assessment of this will be based on following type of measurements.

- time to execute a given task
- number of times user input is required during the execution of a given task
- number of commands that are required to initiate a given task
- statistics on the number of times that given tasks are executed, the length of time and the number of times that the arm is used during a given test period, and a definition of scheduled verses unscheduled usage.

Subjects Involved in Field Testing

The Neil Squire Foundation in 1985 worked on a one-to-one basis with more than seven hundred severely physically disabled clients from coast to coast for at least 12 weeks of training the use of computers as a step towards independence. This experience in over forty extended care units, ten special group homes and several private homes in ten provinces, has given us an enviable position in understanding the interface problems with control systems for all types of severe physical disabilities. The ages of our clients have ranged from 18 to 80.

This work has also allowed us to identify disabled users that are particularly motivated and who are comfortable with computer based technical aids. We will involve these individuals in the early stages of field testing so that initial feedback is more directly focused on the manipulator system itself. We will group all user populations into voice input, mouth input (tongue or pneumatic), head control, gross hand movement, fine finger movement and direct hand access. Ages will vary from 19 to 80. We intend to financially reimburse the disabled participants for their time on the project. User training procedures will be established and evaluated.

Field Testing Procedure

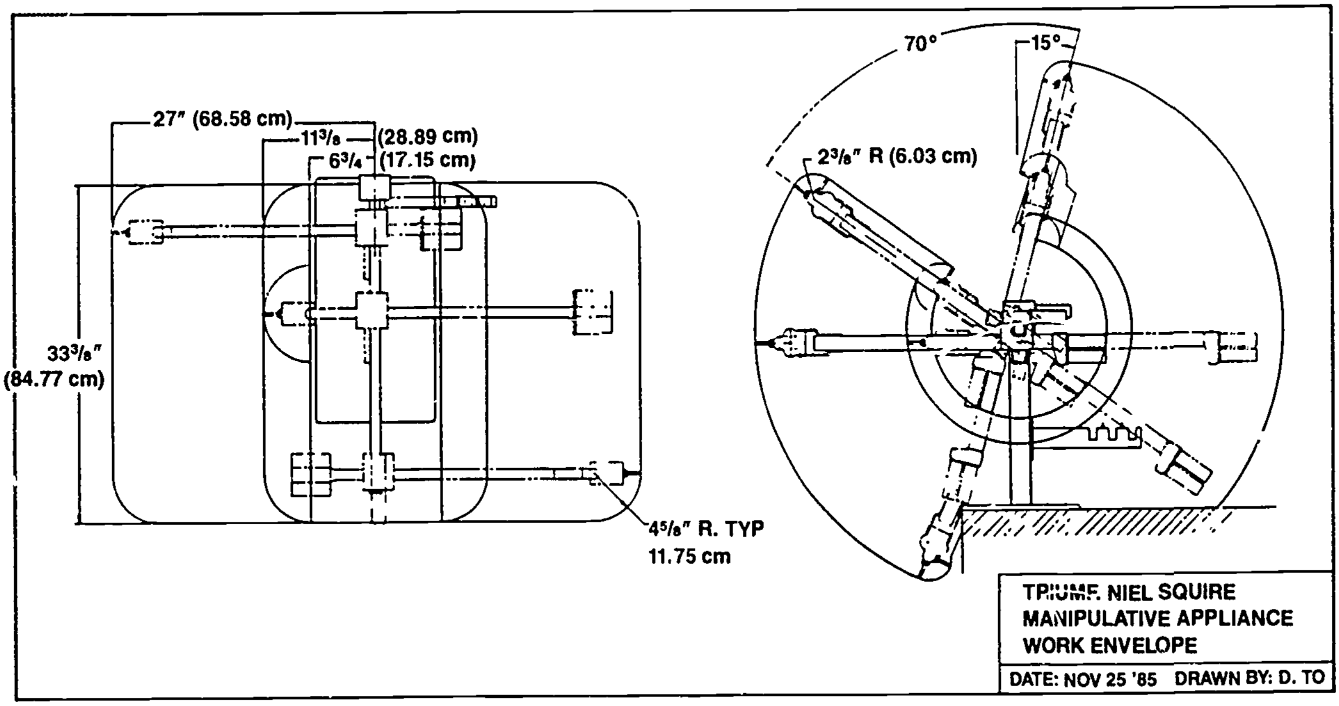
The first laboratory testing will take place in the University of British Columbia School of Medicine Medical Engineering Resource Unit at Shaughnessy Hospital in Vancouver. When the development staff is satisfied (this will include single component failure analysis) with M.O.M.'s operation, disabled testers (5-10 different users) will be brought into the lab. Some simple programmable tasks such as bringing a drink (with drinking straw) to the mouth, and placing a floppy disk into a disk drive will be first used with the testers.

The next stage will be to repeat the procedures with more difficult tasks such as placing a book in a book holder and turning pages, or shaving with an electric razor.

The following stage will be to repeat the procedures to develop interrupts so that the user, for instance, may interrupt shaving to talk with someone and then continue without having to restart the whole program. The fourth stage will involve developing some limited master control for such tasks as picking up a book from a bookshelf, so one program can be used for any one of several books by master select override. Continual development will be carried out on providing the capability for the user to "tweek up" a program to accommodate for problems such as shifting of body position. There will also be continual development to improve fundamental system aspects such as velocity control, accuracy, repeatability, end effector dexterity, user interface, safety features, master and hand-lead-through teach software.

This ongoing concurrent testing and modification is essential in a project of this nature. Unanticipated problems to be solved will be frequently encountered and close constant inter-reaction of the disabled users and the technical developers will allow for the creation of a practical solutions.

When satisfactory performance on such tasks, as given above, has been achieved, M.O.M. will be moved into Pearson Hospital (a 186 bed long term care facility for physically disabled adults, average age 42) for data collection in the field. These test periods will be relatively short (probably 2-3 weeks) periods of time and will only involve one test user at a time Again, five to ten different users would be employed, over a twelve month period, in this stage of testing. The final stage of testing will take place at "Creekview", a co-operative apartment, housing six young adult, high lesion respirator-dependent quadriplegics In this case the manipulator will be placed in that setting for an extended period of time (2-3 months) At this stage the equipment will be instrumented so that it can provide a time and usage history. The system will be used mostly on a "want-to use" basis under conditions of minimal supervision from the development staff This final stage will require six months.



(Detailed specifications can be obtained by writing to the author or the World Rehabilitation Fund)

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5. Andronic Devices Ltd., Vancouver, B.C.
6. Canadian Paraplegic Association, Toronto, Ontario
7. Neil Squire Foundation, Vancouver, B C

DOMESTIC USE OF A TRAINING ROBOT-MANIPULATOR BY CHILDREN WITH MUSCULAR DYSTROPHY

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Summary

A private initiative to provide a wheelchair-mounted robot to my son disabled by muscular dystrophy has resulted in experience on the daily use in the home situation over a period of three years. The remaining slight finger function of the person with Muscular Dystrophy allows a more direct control than is possible for high level quadriplegics. The relatively low cost of these training robots makes them suitable in this situation. Examples are presented of results with these simple robots. Desirable improvements are ranked in order of user preference. User qualifications for successful application are discussed as well as the necessity of informing social and health authorities at an early stage of the benefits, the costs, and the alternatives of these aids.

Introduction

Most of the reports published[1] on the use of manipulators for the severely disabled originate from specialized institutes. They are mainly considering quadriplegics who have been disabled by an accident. Technically this subject constitutes a very difficult but rewarding research problem. Lesser difficulties in the use of a manipulator by people disabled by muscular dystrophy is at the best only mentioned[2] in passing. It is surprising that this fact has not been used as a stepping stone in the development of more intricate systems since with the muscular dystrophy patient the control can be performed by very light switches closely grouped together. Blow-suction devices or voice command are not needed, when slight remaining finger function is available. Muscular Dystrophy, especially the most prevalent and severe form, that of Duchenne, is a progressive disease which successively incapacitates the skeletal muscles. The loss of walking and the transition to a sedentary life occurs at about the age of 9-10 years. Nowadays, this transition is well supported by the provision of electric wheelchairs enabling the children to attend school, enjoy wheelchair-hockey and to participate in many independent and personal activities. Possibly as result of the better living conditions and improved healthcare the life expectancy has risen from about 15 years, two decades ago, to about 20 years at present. No adequate treatment has yet been discovered, but it becomes increasingly well known that assisted ventilation[3,4] can safeguard their lives considerably and in a quite acceptable way. An increasing number of rehabilitation centers do provide assisted ventilation not only in emergency cases, but also as precautionary measure. A personal robot assistant would be a great asset for these people.

The slow but ongoing progression is in sharp contrast to the accident that the quadriplegic has suffered. In muscular dystrophy, the gradual loss of the hand- and arm function creates an increasing dependence without a distinct breakpoint at which aids become necessary. The required assistance can become excessive. Since the disease is located in the muscle tissue, all the nerves, especially those associated with sensation, operate flawlessly. Thus every misadjustment of garment or body position will be noticed and lead to a request for correction. Any activity the person can do himself is not only to the benefit of his surrounding, but also keeps him mentally busy. In these cases some technical aids can already be provided: pageturning devices, electric typewriters, eating aids or remote controls. However, a simple multi-task manipulator seems preferable, not only in terms of cost, but also with regard to spatial efficiency and ease of change. Most of the publications however, impressed the public more by the tremendous cost and complexity of the manipulator than that they promised a cost effective application.

Basic Philosophies

It is possible to distinguish different design philosophies of the various investigators:

A *Fixed location:*

The manipulator is located on a bench[6] around which various accessories are arranged, such as book shelves, typewriter, wireless and environmental controls. This set up can be optimized for a specific disabled person, but his expressive possibilities are restricted to the location of the manipulator.

B *Freemoving or tethered.*

The manipulator is a free moving or tethered robot[6], that follows or accompanies its master in the wheelchair and that operates as a butler, even on voice commands. It is important that the user remains the master in all situations and not the machine. The situation is roughly comparable to the one in which a trained animal, monkey or dog, is employed for helping a disabled person. Some prefer the last possibility over the cold and impersonal technical aid (not in the least for the affection a living creature could give). Although we do not agree, this aspect has to be taken into account but cannot be quantified easily.

C *An exoskeleton:*

The paralyzed limbs are moved by an external system which envelopes the human body[7]. However, people do not always accept such imposed movements, if these deviate even slightly from the normal directory.

D *A powered helping hand mounted on the wheelchair:*

This possibility[8] appeared to us the most attractive one for use by those affected by muscular dystrophy. It resembles quite closely to a toy crane or a small dragline, that is attractive to many youngsters. The small size, power, speed, and above all expected price, favoured an experiment on its suitability

Our Situation

After the diagnosis had been established as muscular dystrophy we have acquired a reasonable knowledge about the prospects and limitations that could be expected. Both by keeping our son active, avoiding fatigue (swimming, cycling on a tandem) and by offering him in an early stage technical toys (Meccano. whistle controlled Lego train, radio-controlled boat and car etc.) we tried to find ways for the fullest development of his skills. Our work in a large research establishment also offered a good opportunity to keep track of new developments, like the work on robotics. At the time that our need for a supplementary manipulator increased (1982), robotic research had advanced so that some training robot-manipulators appeared on the market for the instruction of industrial robot programmers. At this moment we are aware of over 20 different types and models that could be considered for use by disabled people. Unfortunately, few fundamental improvements have been achieved in the mechanical setup in the latest models. Those models that operate on 12 or 24 V (wheelchair batteries!), have a reach of 50 cm or more, have a lifting capacity of at least 250 g, and a low weight of their own seem suitable for installation on an electric wheelchair. Such types are e.g. the English Armdroid, its German derivatives, the Cobra series, (all very analogous to the American Microbot). The direct control with a 12 push button control box for the 6 motors is most suitable for an introduction and also feasible with regard to the remaining finger function. The addition of a computer on the wheelchair for automatic routines initially seemed certainly overly complex for a willing amateur. Thanks to some personal contacts, a Cobra-RS1 kit could be made available for a certain duration and a colleague devised and built, on short notice, a direct control unit without microprocessor **(Figure 1)**. Later on, we started an evaluation of the potential use with a better and stronger manipulator. In the mean time, other reports appeared, dealing with such manipulators[9].

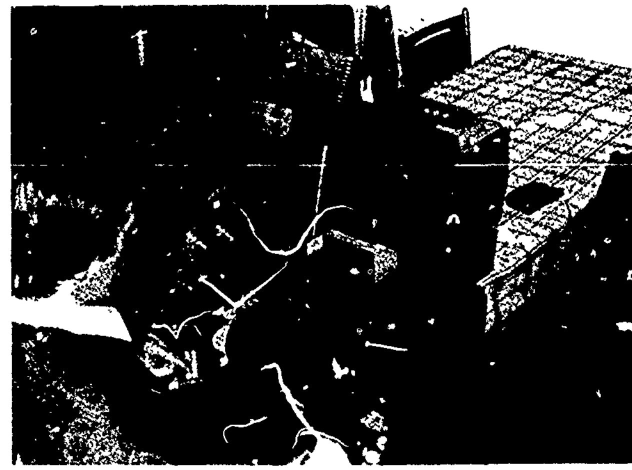

Figure 1: Cobra Manipulator is controlled by user's left hand using specially designed interface.

Individual Applications

After the equipment was available our son could start his part of the investigation and explore the possibilities and shortcomings, while we observed his willingness to operate and the reactions of outsiders. He mastered the three dimensional positioning of the gripper and its orientation in a shorter time than other people need to obtain their (two-dimensional) driving license. He developed a kind of helicopter-view similar to that of a crane operator in a large shipyard. His most frequent activities are eating of pre-cut slices of bread, hot meals and soup (for which a spoon has been bent into a special shape). The rubber tip on the gripper made the manipulator also a page turning device, but with the ability to pick up a book from a table or put it aside in a book shelf. For large newspapers the manipulator base on the wheelchair tray is in the way. A number of controls for wireless operation of a TV set, doors, and appliances were already in use but had to be brought into his finger reach of about 5 cm diameter. Now he can pick them up himself with the manipulator **(Figure 2)**. More-

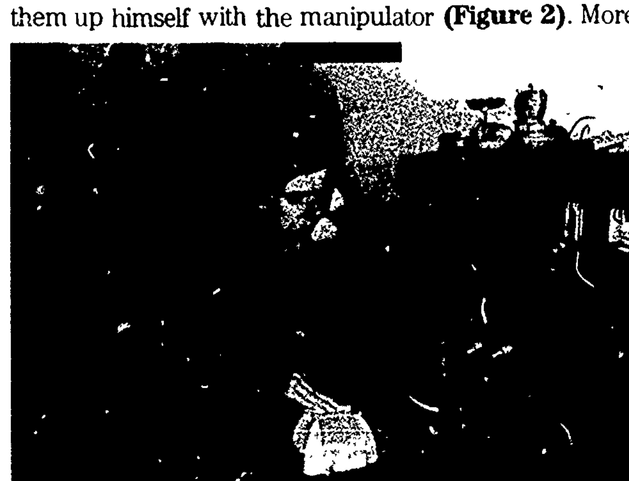

Figure 2: Use of the telephone with the lap board mounted Cobra

over it is possible to manipulate light switches, cassette tapes, compact disks and floppy disks The control is accurate and fine enough for tuning a broadcast station by turning the potentiometer On vacation he can do without his remote control for the TV set. Operation of electric switches that are often located high on the walls can now be reached by using a stick in the gripper of the manipulator. Also, most plugs can be connected to electric outlets, however, the heavy and closely fitting European safety earthed plugs require more force than is available. Going out and ringing a door bell can be done again. In the bathroom the water tap was already adapted, but could no longer be operated as it was too far away and required too much force. Now he can tap water independently when no one is around Pressing the button in an elevator or in the municipal metro is within reach with this aid. The opening of interior doors in the house and moving a small table on castors through the room is at the limits of the capabilities. It can be done by good coordination between the right hand driving the wheelchair and the left hand operating the manipulator **(Figure 3)**. In the last example it proved to be advantageous to switch off the power to the motors, letting them move free, enabling the manipulator to follow the movements imposed by the excursions of the wheelchair. This feature is otherwise only present in technically much more advanced systems. Also, in the recreational and hobby sphere, the manipulator has proven its value. During a game of chess or draughts the opponent can of course move the pieces as directed by the disabled person. By studying exemplary games or solving problems it helps if the stones can indeed be moved to their new positions. The alternative to using a computer with a suitable program is not quite comparable. It is more acceptable to play with normal pieces. The manipulator has been used in such activities as divergent as drilling holes in electronic printed circuit boards, soldering components onto them, and sandpapering wooden components for shipmodels. Many tools can be used if the weight is not too large. Nowadays, a large variety exists; for instance electric scissors. Objectivity requires us to enumerate the things he cannot do; not with the present manipulator and probably also not with the best manipulator to come within foreseeable future. This

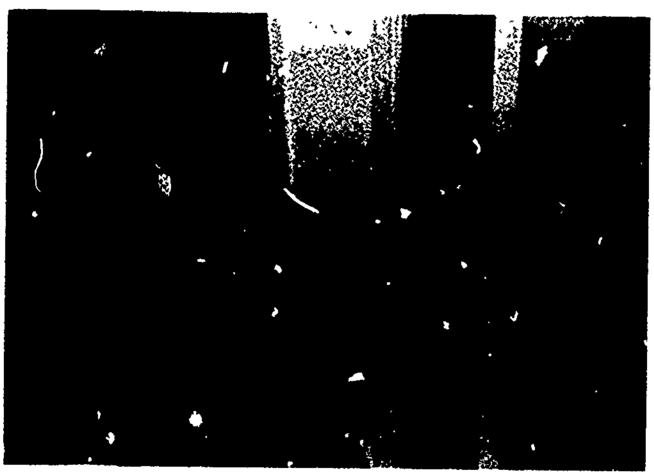

Figure 3: Opening a door requires coordination of the robot and the wheelchair movements

includes among others: dressing, washing, turning oneself in bed or in another place, and even all those actions that require the use of two hands or more fingers in a concerted way. Also other activities, like preparing food, opening a bar of chocolate are impossible. Nevertheless we are relatively happy that we can offer him a degree of independence and are sure many other children in similar situations would also welcome such an aid

Figure 4: User control of the movement of chess pieces

Favourable user group

Our group of muscularly disabled children represents, for several reasons, a population that could benefit more easily from existing and commercially available manipulators because of the lower price and the lessened requirements.

The following points may be mentioned:

- Manual control by pushbutton is still possible, with direct control or simple optional partial routines.
- Visual feed-back does not require special sensors and interfaces.
- Low speed suffices and is even advantageous for safety reasons.
- Position accuracy can be easily fulfilled, some slip or loss of increments can be overcome by visual feedback.
- Exact linearity is not essential.
- Even the low lifting power is already sufficient for a number of actions.

This does not mean that our group will not benefit from technical improvements, they are eagerly awaiting better manipulators. Our enthusiasm for these simple manipulators stems also from other aspects. The first aspect is the attitude of the person himself. He is physically handicapped, but mentally he is on a par with us all. Various attitudes may be encountered from a blunt refusal to even try, to a disappointed return after a short trial that did not make him the famous musician after two attempts, as he possibly had dreamt. Even the direct control can be too complicated if you have no experience and motivation in moving things in space and if attendants take care of it quicker than you can do yourself. So it is suggested that the complexity of the tool grow with the experience and teach first the simple lessons. A direct involvement of disabled persons in the further development of aids is more often advocated than effectuated. The high level of dependence that those people can develop on these devices can stimulate their participation and all day thinking on improvements or alteration. It would be unwise not to profit from their involvement, not only for their own sakes, but also for other applications. An essential condition is that the "teething troubles" have to be overcome. They have sometimes encountered so many disappointments, that any new trouble can absorb their willingness to participate.

Getting the Manipulator

Another major aspect deals with the social and health authorities which in a welfare state decide whether or not somebody is eligible for any provision. After we had gained our first positive experiences and understood the prospects of the manipulator, we applied, under the Dutch laws, for the permanent provision of a manipulator. Previously the Dystrophy Association had notified the R&D department of the GMD (the official General Medical Service which advices the funds providing aids) on the potential of the robot-manipulator and sent them the report on the evaluations. Nevertheless, their first reactions were very disappointing and even now, after three years, little progress has been made. Ignorance and unwillingness to be involved in potentially very expensive aids for an unknown number of people and for an unknown number of years are the most likely reasons, but officially we have heard different reasons for the denials. At the same time, however, equally expensive items like electric wheelchairs, pacemakers and assisted ventilation are provided relatively freely because these items have passed the decision stage. In this phase the contacts with the technical institutes were very stimulating and rewarding. Professor Stassen from Technical University Deft showed us the results of Stanford University, while TNO helped us, amongst others, with a literature survey. The best day was when we received the message that the Institute for Rehabilitation Research (IRV) in Hoensbroek would start a project. The worst day was when the Prinses Beaux Fund turned down (after 23 months of deliberations) the application for a grant for a manipulator for evaluation purposes with the affected members of our association A step forward was also the decision by the authorities involved to start an evaluation and the provision of the Cobra-RS2 almost one year later. Our general experience is that the technically and research minded are quick in understanding both the problem and the solution. The administration people have considerable difficulty in arriving at an understanding level and even more so at a conclusion or a decision. The attitude often seems to be. let us wait, perhaps they will die and then we have no longer a problem. Still we have to live with this situation, probably on both sides of the ocean, and define a policy. Either we try to introduce a relatively simple manipulator at low cost and gain experience on how to develop a better one, or we go for a very expensive, but almost almighty robot, that can be made available to only very few people independent of the opinion of the providing services. In the latter case, later on simpler versions can become available for more people. Both approaches have their own benefits and shortcomings From the point of view of the potential user, we would like to state that the point has been passed of only reading about the wonderful future possibilities, and that a test of the admittedly immature product is eagerly awaited In any case we would advocate a more intense dissemination of suitable publications, not only to the relevant authorities involved but equally well to the associations representing the potential users. This could obviate the present situation of being ridiculed when lodging a serious application.

Desired Improvements

Every time this manipulator, or occasionally another one, (Microbot, Movemaster, CS111) was tested by other potential users with muscular dystrophy it was placed on some distance from the operator. They soon requested to place it on their wheelchair as this makes the operation more akin to that of their own arm. Sometimes they would even like an arrangement like the four-armed god Siva, with the manipulator mounted at their shoulders, and no obstacles on their desk. The need for two arms readily becomes apparent when they are not able to open a box or pot with only one gripper. An additional fixing device is necessary, even more so than the extra degree of freedom in the wrist. A higher force, a larger reach, and increased speed are considered a priority as the proficiency in use increases For our group with muscular dystrophy it can become necessary to attach a respirator to the wheelchair with its implied power requirements on the batteries. Thus the isolated situation of a wheelchair can become a problem because of limited power. The stepping motors of the manipulator use power continuously even in stationary positions. The possibility of storing a number of positions for later recall at the press of a button is appreciated as is that for small repetitive programs. Interrupts for "manual" fine-adjustments are then needed for those activities as eating and turning pages. It becomes clear very soon that small subroutines like stirring cannot be transferred to another location without unintended changes. This requires another system of coordinates to be controlled. For the control itself alternative solutions have been proposed. joystick for more degrees of freedom or a number of positions, and a trackball. A mouse is, however, improper because the necessary movements are not available. Simultaneous control of more motors even during manual control is of primary importance. Much thought was given to the availability of an emergency stop If the user's hands are shifted from the controls during a programmed movement there is no way to stop or to recover. A simple voice control can give a partial solution, but will not replace the hand upon the control buttons.

Conclusions and Recommendations

A commercially available training-robot can be used as an aid for persons with a severe form of progressive muscular dystrophy. These manipulators are economical and easily adapted (compared with those for quadriplegics) because the muscular dystrophy patient retains residual finger function. Both the attitude of the persons involved, and the moment at which the manipulator is introduced, are important for the degree of success. The availability is influenced negatively by the unfamiliarity with these aids and/or misconceptions on their potential, among officials of the Services providing aids and the patient associations. Experience with these manipulators has shown that involvement of the disabled themselves in designing improvements is fruitful.

Acknowledgement

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ROBOTICS—A COMMENTARY FROM THE PERSPECTIVE OF APPLICATIONS IN GERIATRICS (or "Can Robots Help People Help People")

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I am told that traffic lights in South Africa are called robots. They earned this name because they replaced a human subject standing in the middle of the road waving his arms to control the traffic. Of course, they do this now by red and green lights and do not have a simulated human arm. One might say that they control motors without motor control.

In contrast, the papers from abroad that are presented in this monograph describe working robotics where the emphasis is on the development of a mechanical arm that will reach, hold and manipulate. Sometimes the systems are placed at static work stations or, alternatively, it is suggested that they will be mounted on wheelchairs or mobile work stations. Whilst this emphasis is appropriate for quadriplegic users it is inappropriate for geriatrics.

Reduced upper limb function does not rank as one of the most significant problems facing elderly. It is generally agreed that symptoms that are broadly classified under the heading of confusion are more common and more problematic than physical difficulties. The confusion may range from very mild to very severe and will include varying degrees of memory loss, cognitive dysfunction and disorientation. For these subjects the human function that must be replaced is not an upper limb but is closer to the function of the traffic light. Metaphorically speaking, the robot should give the elderly user a green light when everything is in order and a red light if an inappropriate or dangerous action is being taken or something has been forgotten. The robot would therefore have as its two most important functions, monitoring and reminding. A couple of examples might help illustrate this role.

Fires on the kitchen stove are a very common consequence of the forgetfulness of confused elderly persons. In some cases the elderly are so anxious that they will forget something is on the stove that they will choose not to use it or anxious care givers will remove the fuses. Presumably, a robot would monitor this situation and provide appropriate reminders. Falls are the commonest cause of accidental death of the elderly and frequently lead to injury that needs medical assistance. A robot that could watch for this circumstance and send for assistance by telephone might occasionally save a life and would certainly be a comfort to the family as well as to the elderly person.

William Cameron, in his paper, describes a manipulative robot which he calls "mom" This brings to my mind images of a robot that can actually do things for you whereas the reminding and monitoring function of the geriatric robot might be more aptly likened to the stereotypical "mother-in-law".

Most commonly significant loss of independence results from limitations in lower limb function rather than upper limb function. Frequently walking aids are used such as canes and walkers to provide additional support and stability. One of the most difficult tasks is to stand up and sit down. Additional assistance to get out of an armchair or to transfer to a toilet is frequently required. A robot that would emphasize assistance with mobility would therefore offer great potential value in the elderly. One imagines a device that would provide a good safe hand hold and would act as a sophisticated walking aid. The robot would be particularly helpful if it could carry things such as food and drink from the kitchen to the living room since this is always a difficult task when both hands are required to use a stable walking aid. This carrying function would not require a six or seven degree of freedom arm but would simply require a surface that would be adjustable in and height which objects could be slid onto and off from various other surfaces. This one degree of freedom "arm" might also be helpful to assist the user to rise up from a chair. Certainly, this would necessitate a much higher force capability than is commonly specified for the multi degree manipulators. It would have to be strong enough to provide assistance in rising from the chair, carry the supper and to carry loads such as the pot from the commode.

Finally, the geriatric robot should emphasize augmentation of the elderly person's diminished sensory function. For example, it might be very helpful if it had "eyes" that would enable it to also serve as a reading machine.

The sketches contrast the geriatric robot with the manipulative robot. Whether such a device is practical and cost effective is yet to be demonstrated. Certainly we are beginning to see the function that might be performed by this robot included in intelligent devices that are distributed throughout the house. There may or may not be benefit to combining these in the form of a single multi purpose mobile device. This question must be pursued by creative minds in an imaginative way.

The project area is glamorous and appeals to the public imagination. Care must be taken that it does not receive a level of funding that is disproportionate to the funds that are available for less attractive but equally or more important areas of technological research for the elderly. On the other hand, the demands of conservative bureaucrats for the researchers to demonstrate the cost effectiveness of their inventions at a premature stage must also be resisted. It is worthwhile remembering that the first wordprocessor would not have compared favorably in an evaluation when compared to the cheaper, more reliable, easier to operate and more portable mechanical typewriter.

The second major criticism that is levelled against research in robotics is the issue of people versus robots as helpers.

Certainly robots have taken over many of the unpleasant, dangerous or repetitive tasks that have been done by people in factories. This has caused and will continue to cause the loss of many jobs Some of the manufacturing jobs may be replaced by service oriented jobs where versatility and personality skills are of greater importance. The result of this trend is that robots would seem to have a natural place in factories and that people would have a natural advantage in caring for other people.

However, we know that if the elderly are in a situation where they need help for routine functions such as bathing, toileting and feeding then they tend to resent this instrumental dependence. Similarly, relatives and helpers often resent being relied upon for these essential functions. The situation is particularly delicate because of the fact that the elderly are generally relying on volunteers and relatives rather than the paid attendant that may be available to some of the younger disabled Technical aids, maybe including robots, that reduce this dependency for routine function will improve the nature of the relationship between the elderly and their helpers and are likely to increase, rather than decrease the level of social support and interaction. In contrast to industry, the question is not robots versus people but it is really *can robots help people help people?*

A REACTION TO THE PAPERS ON "INTERACTIVE ROBOTIC AIDS—ONE OPTION FOR INDEPENDENT LIVING: AN INTERNATIONAL PERSPECTIVE"

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I began reading the three articles with a great deal of trepidation However, this skepticism soon turned to happiness because each of the authors. (1) did not present robotics as a panacea and (2) mentioned the concept of cost effectiveness. I think there is a tendency in the rehabilitation engineering profession to over sell technology as the answer to all problems confronting severely handicapped persons. Additionally, we are in love with concepts without assuming the subsequent responsibility of considering the cost of acquisition of the device and its lifetime maintenance. I generally found that the articles were well written from a technical point of view. I learned several things relative to new applications and I appreciated the authors' pragmatism.

However, with the above statements as a frame of reference, I must make several comments based upon my experience in an independent living environment. The Cerebral Palsy Research Foundation of Kansas, Inc. (CPR) provides a variety of rehabilitation services to over 50 persons who can be classified as severely physically disabled. In my opinion, a device (robotic or otherwise) must satisfy two tests in order to have practical use in a service delivery environment. First of all, the utilization of the device must result in a cost reduction to the overall system funding base and (2) the device must improve the quality of life for the handicapped individual. An organization that I am affiliated with, The Timbers, a 100 unit housing project, provides aide and attendant care to handicapped people to the extent of 1,160 hours every two weeks at a cost of $7 per hour. Any potential cost savings from the utilization of robotics would result in significant savings to the Title XIX, Medicare/Medicaid system which provides the majority of this funding. However, the Kansas Department of Social and Rehabilitation Services, the organization administrating Title XIX funds in Kansas, specifies that certain client/staff ratios must be maintained for the purposes of safety and security. Therefore, even though a robot might reduce staff and, therefore, reduce the number of billable hours, client/staff ratio restraints may not result in a subsequent linear reduction in cost.

Additionally, since staff are not busy 100% of the time, they can use downtime for multiplexing, such as filling out reports of client usage of services, processing billing for services to appropriate funding agencies, etc. In other words, the flexibility of a human being compared to that of the robot is important in an independent living environment where a considerable amount of aide and attendant care is provided. The fact that staff can be theoretically utilized 100% of the time whereas the robot may be idle a large percentage of the time is an important element in cost consideration.

Relative to quality of life, it goes without saying that the utilization of a robot to control one's environment has got to improve a handicapped individual's self-esteem. In many of the cases, a robot manipulation may be the first time a handicapped person may have affected his or her environment. This issue is certainly significant and a strong reason for the continued development of robots for independent living. However, many handicapped people have been institutionalized for large segments of their lives. They have not had the normal human interactions with able-bodied people. It is imperative that the handicapped person have relationships with his able-bodied peers in order to develop normal social skills. The replacement of human beings by robots, in the strictest sense, would eliminate this human interaction and thus have a regressive influence on the human growth of the disabled person. Additionally, many handicapped persons are overcome by the "halo effect" when dealing with technology. They want to be cooperative to assist the researcher in developing assistive technology. However, their true feelings are not expressed and when a device becomes the "modus operandi", the researchers became disappointed due to the lack of its use by the persons who have a great need for it. The elimination of the human element in aide and attendant care must be an independent variable considered by all workers in this field.

Pragmatic issues, directly or indirectly associated with those outlined above, which might hinder or help the utilization of robots in an independent living environment include the following elements. Cost is an important factor because handicapped people are typically "poor" people. The developmentally disabled population served by CPR is extremely poor. It is anticipated that only the "super funding" agencies such as the Veterans Administration or third party insurance payers would be able to afford to provide a robot for a handicapped person in an independent living environment. Studies by the Electronic Industries Foundation (EIF) and others indicate that from 50% to 75% of the handicapped persons who need technology cannot afford it. Additionally, most handicapped persons are funded in an independent living situation by Title XIX, Medicaid funding. Qualification for this funding varies from state to state. The definition of a robot as a durable medical good and whether or not Title XIX would pay for it is an issue which I seriously question.

An element related to cost is reliability. Since handicapped people are "poor" people, they not only cannot afford to buy robots but routine maintenance would be a severe problem for them. All researchers are encouraged to consider lifecycle costs inherent in the design of their devices If cost is ignored, the researcher simply is not recognizing reality. The concept of "wear and tear" should also be considered The cerebral palsied population is extremely hard on technical devices. I can envision a robot mounted on a wheelchair lasting only several days because severely disabled cerebral palsied people are not good wheelchair drivers Lack of inexpensive service facilities and spare parts must also be taken into consideration, due to poverty of the people needing the service Any research effort must encompass a significant cost analyses and the development of reliable funding bases. In many cases, it is not a matter of how much, but who pays for anything.

A satellite issue is the development of constriction standards for the utilization of robots in an independent living environment. Many handicapped people in the United States live in HUD Section 202/Section 8 housing. This housing is typically built on a low-bid basis responding to loose standards developed by HUD. The design of mobile robots requiring standard room layouts, doorknobs, fixtures, cabinets, etc. would simply be impossible in the current HUD system without the development of related technical standards.

Liability issues must also be examined in detail. If an individual has a malfunction of his/her robot resulting in medical jeopardy, who is responsible? I would suspect everyone would get sued, the manufacturer, the wholesaler, the dealer, and the service provider. Liability issues are ones that will confront the rehabilitation technology movement for the next several decades to come.

Finally, robotics should not only be designed from the standpoint of use by the young physically handicapped person but as possible servants for the elderly population. I am convinced that if the cost of devices is to be reduced, the device has to have a potential use for elderly people. Elderly persons are large in number, they have considerable political clout. Therefore, marketing and cost strategies can be developed for supply and demand bases much greater than that of the disabled population. This potential of marketing to the elderly must be taken into consideration in the development of future robotic devices.

Is it all "doom and gloom" for robotics applied to independent living? No, I do not think so. In my opinion, robots can provide great benefits to handicapped people in the areas of. recreation, learning by the development of hand/eye coordination, and vocational applications in which the cost of the devices can be amortized. Relative to activities of daily living, a robotic system could be utilized as a backup during scheduled peak periods of utilization of human aid and attendants. In other words, a robot could provide those aide and attendant functions not requiring sophisticated human interaction. Additionally, a robot could be used as a "weaning" method to transition people from post-trauma environments to independent to independent living settings. This would allow the handicapped person to become acquainted with the robot during the early stage of his disability. Therefore, his reluctance to the utilization of technology may be reduced. For all the applications indicated above, it might be well to consider the concept of shared cost among handicapped individuals in order that no individual would be burdened with the total cost of any one device.

As in most cases with the utilization of new technology, robotics is a "mixed bag." In the independent living environment, there are issues that seriously restrict the utilization of robotics at the current time. However, we must look to the future. I am convinced that this technology can provide what all handicapped persons so desperately need, the chance to be a productive human being

U.S. PAPERS ON ROBOTIC AIDS

AUGMENTATIVE MANIPULATION

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ABSTRACT

Advancing technology is increasing the number and types of manipulation aids available to the person whose disability involves upper-extremity impairment. Achievement of effective manipulation depends upon an understanding of the attitudes and characteristics of the user, the characteristics of the aids and their functional relationships, and the properties of the manipulated environments. The term "augmentative manipulation" is proposed to identify a holistic approach to supplementing manipulation skills.

Introduction

At one point in the movie *Blade Runner*, an android, one of several designed for space exploration, is challenged by a genetic engineer to demonstrate his skill at chess. The android scoffs in reply, "We're not computers, Sebastian, we're physical."

Like that android, we, as human beings, have been designed, whether by evolution or divine intervention, as physical beings. We learn by manipulating the physical world, and later, as our thinking gains in sophistication, to use our physical manipulations as metaphors to achieve insight into abstract concepts. We use the environment as a tool to act on ourselves—physically, mentally, aesthetically. We shape ourselves by shaping our environment. The more control we have over manipulating our environment, the greater are our opportunities for reshaping ourselves.

The principal media through which the physically intact person manipulates the environment are the hands. From dealing with objects, to accessing information, to maintaining personal hygiene, the hands serve as a versatile physical and sensory extension of the mind. So closely is the control of our hands coupled to our minds, that we are rarely aware of the subtle manipulations we perform as we carry out a task. When working through our hands, we almost never think about our hands, but rather about the work "at hand."

In the case of a disability affecting manual skills, much of a person's rehabilitation is centered on substituting or compensating for the loss of physical and sensory abilities mediated by the hands. A variety of devices, primarily used in occupational therapy, have been developed to assist in specific manual tasks (such as hygiene, dressing, meal preparation, and writing) where some residual hand/arm function remains. The total or severe impairment of hand function, however, requires a range of assistive devices because the disability more broadly affects manipulation of the physical environment. Some devices are needed to extend the individual's intact sensory abilities into the environment—to "couple" the user to the objects being acted upon. Some are needed for action at a distance since severe physical impairment frequently includes impairment of mobility. Some devices are needed to facilitate tasks requiring continuous interaction between the user and the object or objects being manipulated. Other devices are needed for momentary tasks which do not require close involvement of the individual.

The following sections will describe some of the basic characteristics of manipulation aids, offer comments on factors which influence their relative utility, and finally propose that a holistic approach, emphasizing the functional relationships between the user, the manipulation aids, and the environment, be fostered in the supplementation of manipulation skills.

The challenge of augmentative manipulation: to supplement or replace the impaired physical and sensory abilities of the upper extremity by a set of complementary manipulation aids and manipulation strategies.

The delineation of aids and of factors influencing their utility is not intended to be all-encompassing, but is presented to promote an awareness of the relative functions of different aids and to provoke thought about the design and application of manipulation aids.

Manipulation Aids

Manipulation aids can be divided into two categories. those that are task specific and those that more generally assist in manipulation The former category would include aids for eating, for perso al hygiene, for dressing—aids which perform a speci... function within the context of a task, but which have no function outside that context In the category of general purpose aids, I include hand orthoses, mouthsticks, headpointers, environmental control systems, upper-extremity prostheses, remote manipulators and robotic devices, and other persons in the environment —manipulation aids which each can be used for a variety of tasks.

In this discussion, the concern is with general purpose manipulation aids.

Hand orthoses stabilize the hand and wrist for pushing and pulling objects close to the body or for holding down an object that is being manipulated. The orthoses also provides a platform for the attachment of task specific tools, such as eating utensils or writing implements. And, if powered by body movement or external actuators, a hand orthoses can provide basic prehension.

Mouthsticks and headpointers, like hand orthoses, can be used to push objects about which are close to the body. They are especially useful for activating push-button devices (such as keypads of electronic calculators, telephones, and appliances; keyboards of typewriters or computers; elevator buttons; and push-button environmental control systems). With interchangeable tips, they can also be used for writing and artwork. Some commercial and custom mouthsticks and headpointers also provide a mechanism for tip prehension, for grasping and positioning relatively small and lightweight objects.

Environmental control systems serve as interfaces for the control of a variety of electrical and electronic devices. They provide action at a distance. For the individual who may be relatively immobile at times or whose energy is better spent than maneuvering from one appliance to another, the environmental control system extends the range of control.

Upper-extremity prostheses do not have direct application to the mo or-impaired individual without an amputation; howe , many concepts developed in the contro nd design of prostheses may be relevant. Much of the work in prosthetics has dealt with substituting control sites to compensate for the amputated joints. And many schemes have been developed to expand a small number of control sites into a greater number of control signals for the operation of multi-joint prostheses. The motor-impaired individual is in a similar situation requiring both substitution of control sites to compensate for the affected joints and an expansion of the remaining control sites or movements to increase the repertoire of function. Upper-extremity amputation also results in significant sensory deficits which have been the focus of extensive research on sensory substitution and feedback. This body of work is already available to those dealing with the deficits of motor/sensory impairments, such as result from injury to the spinal cord.

Remote manipulators and robotic devices hold the promise of a general manipulation instrument. They can provide action at a distance. They can be used in unstructured environments or carry out pre-programmed tasks within highly structured environments. They can be used to manipulate larger and heavier objects than an individual could handle with body-actuated manipulation aids. And they can be provided with the ability to accommodate ce: ...in characteristics of the environment, supplementing the commands of the user. The key to the fulfillment of this promise is the control interface between the user and the manipulator/robot.

The most versatile manipulation aid is, unsurprisingly, another person. People are generally readily available. A sufficient number of them are responsive to requests for assistance. And enough of those have adequate intelligence to carry out carefully worded instructions. In addition, the en...onment and objects within the environment are peculiarly suited to manipulation by people. Regardless of whatever other manipulation aids an individual may have available, emphasis should be placed on mastering the ability to direct another person to carry out any task that may be required. Having this skill is both a pre aution against the failure of an assistive device and a necessity since many tasks are impractical or impossible for a severely disabled person to perform.

Comments

Locus of Control and Control "Coupling"

One aspect when considering the relative role of a manipulation aid is the perceived locus of control, i e. whether the aid is perceived as an extension of the body or as a remote effector controlled by, but not closely coupled to the user. The degree of coupling affects t e mental loading of the manipulation aid, i.e., the am unt of mental effort expended in controlling the aid. Hand orthoses, mouthsticks, and headpointers are examples of closely coupled manipulation aids. Because of their intimate mechanical coupling to the body, they serve as physical and sensory extensions of the body. In the case of a hand orthosis, forces exerted on the hand are perceived by the sensory apparatus of the most distal intact joint. For the mouthstick, the skin and proprioceptive senses of the mouth and neck are extended to the tip of the mouthstick much as the sensory apparatus of a blind individual's hand and arm is extended to the tip of a cane. The sensory apparatus of the head and neck are extended through the headpointer

The wealth of sensory information available through these body-extending mani ulation aids greatly improves the control of these aids. The user has a mechanical sense of the effect of his or her actions on the objects being manipulated and does not need to rely purely on visual inspection. Little mental effort is expended in the control of the aid, allowing the user to concentrate on the task.

Switch or voice-operated manipulation aids, on the other hand, may not take full advantage of intact physical control abilities or of intact proprioceptive senses. Because the aid is mechanically uncoupled from the user, control of the aid requires closer attention by the user and external supplemental feedback, such as command confirmation, to insure proper transmission of control commands. The mental loading is higher when the user is uncoupled from the manipulation aid because the user's attention must be divided between control of the aid and performance of the task. The aid, in effect, becomes an intermediate object to be manipulated.

Continuous or Momentary Interaction

The influence, on performance, of coupling through the control interface will depend to a great extent on whether the interaction is continuous or momentary. In the fields of human factors and control, it is generally considered more effective for machines requiring moment-to-moment adjustments to be controlled as extensions of the operator. Examples would include driving a car, piloting an aircraft, or handling nuclear materials or chemicals with remote manipulators. The operator is able to respond more quickly to errors in control or changes in the environment and is able to more accurately grade the response in proportion to the need because of the feedback afforded through the mechanical coupling.

Likewise for the motorically impaired individual, tasks requiring a series of manipulations, as in setting up books and notes for studying or in preparing a meal, might be performed more quickly and efficiently if the controller of the manipulation aid extends the physical control and sensory abilities of the individual. If, however, the task is momentary, requiring only brief attention from the user, such as turning an appliance *on* or *off* or initiating a preprogrammed set of actions of a robotic device, than the advantage of a physiologically-coupled controller is less. Other types of controllers (switch-type or voice activated) may serve just as well for these situations.

Influence of Control on Tasks Selected

Although remote manipulators and robotic devices may have the mechanical characteristics to carry out a variety of tasks, the types of tasks mediated through these devices are likely to be chosen based on the type of control used. As has been learned from the design of multi-function upper-extremity prostheses, control needs to be natural, or intuitive, and the system be highly responsive to that control, otherwise, the mental effort expended in the control of the device in a continuously interactive manner overshadows the benefit of the task performed through the device.

If the control interface of a remote manipulator or robotic device provides the physically impaired individual a natural extension of intact physical and sensory abilities, the individual will be more likely to use the device interactively in novel situations and unstructured environments. If, on the other hand, the control interface is such that a significant degree of planning and attention are necessary for successful use, the individual is more likely to use the device for repetitive tasks which can be pre programmed and which are carried out in a highly structured environment.

View and Viewpoint

Other factors, such as the view of the object being manipulated will influence utility of a manipulation aid for certain tasks. In upper-extremity prosthetics, hook-like terminal devices are frequently recommended over hand-like devices for individuals with bilateral limb loss. Although the hook-like devices offer a greater variety of prehension patterns, they also, because of their slender frame-like construction, present the user with less visual obstruction of the work area and of objects being manipulated.

The tips of mouthsticks and headpointers offer little visual obstruction. But a hand in an orthosis may obscure the work area because of the restricted range of approach to the work resulting from the impairment of wrist and elbow function. As with the terminal devices of the bilateral amputee, the orthotically supported hand cannot be easily repositioned to approach the work from a different angle. Instead, an extension to the orthosis may be needed in order to set the hand back from the immediate work area, but maintain a mechanical link between the objects being manipulated and the individual.

Remote manipulators and robotic devices may be positioned so as to place objects in clear view while they are manipulated. But whereas the user of a hand orthosis, mouthstick or headpointer has a body-centered viewpoint from which to manipulate, the user of a remote manipulator or robotic device may have to adopt the perspective of the manipulator or robot when issuing movement commands. (This type of problem is encountered in the operation of radio-controlled cars. When the car is traveling toward you, the car's movements are opposite those of the control stick, and you must adopt the car's perspective, opposite of your own, as you turn it right or left.)

Other Considerations

Additional factors affecting the use of a manipulation aid include. *transportability* (an easily transported device can be used in many environments), *set-up time and effort* (if an individual requires assistance in setting up the manipulation aid, such as donning a hand orthosis or arranging objects within the reach of a remote manipulator, the individual might be more inclined to simply ask the one assisting to perform the intended task), *the degree of structure in the environment* (regardless of the type of manipulation aid used, the more structured the environment is with respect to the physical abilities of the individual, the more efficient the individual will be within that environment—the properly structured environment itself can be an aid to manipulation; *training* (manipulation aids, even as seemingly simple as a mouthstick, require time and practice to be used deftly); *down-time and repair* (an aid which is susceptible to frequent breakdown impedes the acquisition of skill and contributes to frustration and a sense of dependency), *use of a powered mobility aid* (a mobility aid, such as a powered wheelchair, enables the person to independently and appropriately position him or herself with respect to the objects being manipulated); *seating and positioning* (stable support of the body is particularly important for efficient use of body-extending manipulation aids).

Summary and Proposal

Manipulation of the physical environment is a multifaceted problem. Techonological advances are providing new systems and techniques, increasing the options for supplementing manipulation skills. More versatile mouthstick and headpointer systems are becoming available. Traditional orthotic support of the hand and wrist is gaining from advances in lighter weight, more durable materials and in body and externally powered actuators. Functional neuromuscular stimulation of the hand and wrist may eventually complement the use of orthoses. "Universal" environmental control systems, capable of learning the control codes of remotely actuated electronic appliances, are appearing in the commercial sector. Remote manipulators and robotic devices are being developed experimentally and commercially, specifically as aids to assist in manipulation by motorically impaired individuals.

However, no one manipulation aid will be most efficient for all tasks. Just as the individual who has a speech impairment may use, in combination, gestures, signs, vocalizations, a passive letter board, and an electronic communication aid, depending upon the circumstances and nature of the message to be communicated, the individual who has a manipulation impairment should be able to draw from a variety of manipulation aids, selecting the one most appropriate to the physical constraints of the task and degree of personal involvement with the task.

The effective use of these devices depends on careful assessment of the user's abilities, the characteristics of the environments the user will need to manipulate, and the characteristics of the manipulation aids. Psychosocial issues will play a significant role, particularly in the early phase of intervention. The attitude of the individual toward reliance on assistive devices, especially in the case of impairment resulting from traumatic injury, must be taken into account. The appropriate time to encourage the use of a particular device should be chosen in the context of the person's interest in achieving the task. Procedures should be developed to respond to changes in the individual's attitude over time and experience.

In short, the successful supplementation of manipulation skills can be best achieved through a synthesis of intervention strategies, drawing upon technical advances and a sensitivity to the individual's self-concept and manipulation needs.

Language reflects thinking, but also influences thinking. The term "augmentative communication" defined and encouraged an approach to communication in terms of its function and how the function of communication might be facilitated by a synthesis of strategies and assistive devices. To foster like thinking with respect to the function of manipulation and the synthesis of a variety of approaches to achieving manipulation, I suggest the term "augmentative manipulation". The focus of augmentative manipulation being not on the hardware, but on the actor and the act, and on the facilitation of action by a set of complementary manipulation aids and manipulation strategies.

Acknowledgement

The author wishes to thank the many individuals—designers, therapists, users, and "everyday" folks—who have stimulated the ideas expressed.

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AN INDEPENDENT VOCATIONAL WORKSTATION FOR A QUADRIPLEGIC

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ABSTRACT

With today's technology, people who have impaired mobility can make use of their mental talents and join the mainstream of working force in our highly computerized world. This paper briefly describes the Boeing voice-activated microprocessor based workstation which allows a physically limited individual to manipulate data electronically and conduct business activities naturally. With the aids of the voice driven robotic arms mounted on a specially designed furniture, the quadriplegic can perform the physical tasks required in an office and become independent of frequent external assistance The paper also discusses the difficulties encountered in the available technology, the safety issues, the human factors and how we have dealt with them to ensure independence for an individual in an office environment. It also briefly touches on the future enhancements planned for this workstation in intelligent robotics and machine understanding

Background and Motivation

Of the physically impaired individuals, the majority are quadriplegic, caused by disease or injury. It is believed that they constitute a pool of intelligence and highly self-motivated resources.

Boeing has several reasons for sponsoring this project Most importantly, it is felt that the experience gained in our developing speech understanding applications can be applied to industrial situations and the company's aerospace work. Of course, Boeing is, as ever, interested in recruiting qualified, dedicated computer professionals locally in a what has become a very competitive market. Boeing sees this as an opportunity to tap this pool of largely conscientious and talented workers, while performing a community service.

Phase 1 of this project, which began in early 1984, initially focused on providing a speech controlled workstation that could be used by programmers and analysts and on voice control over data later in October. We believe that if a workstation can be built for a programmer, others might be able to adapt it to satisfy the specific needs for other professions such as financial analysis, engineering and manufacturing.

Phase II of this project, started to consider that a quadriplegic individual when using the workstation might impose a burden to co-workers in the environment in which the unit was to be placed. The physically limited person could not handle such routine functions as referring manuals, retrieving printed output, loading diskette into a disk drive without assistance, etc. The voice controlled robotic aids were then added to the workstation.

Workstation and Speech Components

The workstation that is in use now has a microcomputer system that supports and is driven by two voice recognition products and a voice communication product.

The microcomputer is an IBM PC XT. This unit is capable of emulating different terminals which give access to multiple vendors' mainframe products Besides, there is also a greater freedom of selection amongst voice products for the IBM PC.

The voice communications product comes from Dialogic, and the voice recognition products from Keytronic and Microphonics. The following explains why two voice products are being used.

The Keytronic 5052V keyboard unit was initially programmed so that voice could be used to simulate a full keyboard. When text editing and spread-sheet software were added, the functions of the Keytronic product were expanded to substitute spoken commands for keyed command sequences. While the keyboard entry method could be used to perform the required tasks, to achieve the entry rate of an experienced keyboard operator, single commands were needed which produced the equivalent of multiple keystrokes.

Keytronic, at Boeing's request, modified the product so that up to 160 command words or phrases were supported at one time. But 160 words were not enough when the user was called upon to employ graphics, support multiple programming languages, and to obtain access to different networks. The vocabulary reached nearly one thousand words. While the 5052V supported multiple syntax structures, the available vocabulary limitation did not meet the requirements of this environment

Microphonics approached Boeing with the request to assist them in testing their OTO-1 product (now called "Pronounce") This product permitted the saving and downloading of different files each containing up to 128 words or phrases. It was decided to marry the two products together by using the Keytronic unit to emulate the keyboard and initiate the downloading of different application vocabularies to the Microphonics board The products were also set up to logically turn each other off and on.

Since the user is dependent on phone communication, a voice communication product is also required. The Keytronic product provides the commands for dialing; and the Dialogic DIALOG/2 product, the phone interface—dialing, answering, recording conversations, note-taking and messaging These functioning additions necessitate, of course, additional equipment (e.g. an expansion chassis and 25 Mbytes of hard-disk storage).

Robotics Requirement

The functions of robotics aids include such diverse tasks as handling manuals, floppy disks and individual sheets of paper. Use of a robot in an office environment requires cleanliness and minimal noise. Robotic control by means of the IBM PC is desired to provide local control. Other requirements include relatively smaller size, at least 4 ft. of reach, a 10 pound payload, programmability by the operator, force sensing (for safety) and (again) low cost.

As a result of the search for a low cost robot which met these requirements, Universal Machine Intelligence, Ltd. (UMI) of London, England, brought the robot to our attention. Two RTX arms were ordered by Boeing and delivered in March, 1985.

Tasks laid out for the robotic aids to perform are as follows:

Display reading material on the reader-board.

Manuals and books (weighing up to 10 pounds) are placed in the specially designed book shelves. The robotic aids will retrieve them from the shelf, display them on the operator's reader-board, turn pages and return the materials to the requested location.

Handle filing in a file cabinet.

The robot arm will open/close the file cabinet, insert, retrieve documents from file folders, and assist the operator in searching for document folders.

Handle floppy diskettes.

Most of the commercially available business packages used by the microprocessor require their key diskettes to be loaded in the floppy disk drive while processing. The robotic aid is to pick up a requested diskette, load it into the floppy disk drive and return it to the requested disk storage slot—when instructed.

Adjust printer according to the operator's commands.

The robotic aids are to load printer paper, retrieve printed pages and display them on the reader-board. The printing function, however, creates several difficulties. There is a need to produce diverse types of output—graphic, standard and condensed print, draft and letter quality. Paper handling can be especially difficult for the robot. Loading paper, removing single or fanfold sheets and alignment can not be accomplished without a great deal of engineering, programming or vision. To overcome this difficulty a Quadram laser printer is used. This printer collates the output so that multi-page reports can be stacked in the proper order.

Perform miscellaneous support activities.

The robotic aids can place materials in the waste basket, on the user's lap, retrieve or place materials in the user's back pack or an in/out tray.

Furniture Consideration

In this application the location of the robotic aids becomes more than just a functional consideration. Safety of the operators becomes critical. Maneuverability of the operator is limited. The operator's attention is frequently on the computer monitor or the reader board. The robot is expected to carry out assigned tasks without attendance and without posing a hazard to the operator.

The robot's placement determines the design of the workstation. The robot must be able to access the disk drive(s), printer, reader-board, file cabinet, book shelves, in/out tray, waste basket, diskette storage, user's lap and back pack. The implementation of the robot demonstrated that a single arm could not be positioned to perform all these functions unless mounted on a track. The track may be added after other requirements (which will be discussed later in the paper) are satisfied, but two arms are now needed to perform all the tasks.

File cabinets present another problem Manufactured vertical and horizontal cabinets have been rejected. Horizontal cabinets demands more space than is available. Vertical ones do not furnish the kind of access required by the robot. A vertical file that has a 10" x 11" footprint and is divided into 4" shelves has been designed so as to make it an easy access to the robot.

Manuals and books are stored in specially designed vertically partitioned book shelves. Each partition contains one book or manual.

Peripherals Support Consideration

Diskette loading and unloading require a modification to the drive face. Floppy diskettes sag when supported from the edge. Care must therefore be taken not to crash them against the drive face or crush them in the gripper. A tray is used to align the diskette both vertically and laterally to facilitate the loading and guide removal.

The operating system is a multi-tasking environment to permit independent activities (e g. robotics, telephone management and applications). Microsoft WINDOWS is employed to manage the multi-tasking function.

Robot Programming

The robotic tasks are divided into four categories—task, ad hoc, teach and system.

The task operations involve directing the robot to perform a sequence of retrieval, storage and manipulative instructions. The computer or the robot controller must remember prior placement location of several elements of the system. The workstation is also called upon to remember what to do with materials after their retrieval.

These knowledge operations are part of either the "source" instruction set or the "destination" set. The source memory activities include knowing the starting position of the arm, where the material is stored, etc. The destination activities involve remembering if the space where the material is to be placed is already occupied (like the disk drive) so that accidents will not occur. Other destination movements embrace transport of the material from a fixed position (manual partition) and return the arm to "home."

Several manipulative tasks concerning a fixed sequence of operations are performed—i.e. reset the printer, turn a page, etc. The emergency stop sequence is always available to permit the operator to halt operations and restart with several options.

The ad hoc category of operations deals with the movements of the arm in world coordinates—left, right, up, down, in, out, pitch, yaw, roll, open and close. These are used by the operator for non-routine activities.

"Teach" operations are simple commands to the system to store ad hoc movements in a reference set so that the robot can be instructed to perform new routines (tasks) that are reproducible. "Remember" is the only word added to the ad hoc command syntax.

All the above are under voice control.

There are also some computer system controlled tasks. Included in this category are such actions as return to home before shut-down or initialize the robot when the system is started up. System emergency stops take place if an obstacle is encountered.

Looking into the Future

The above takes this project through Phase 2. All the tasks were completed in April 1986. There is an intent to integrate the speech controlled robotics with further developments in Real-Time Systems Research at Boeing's Artificial Intelligence Center. The following possibilities are being considered.

One of the Real-Time programs is sensor development. Gripper feedback, for example, has a variety of capabilities. Amongst them are. shape determination, thermal sensitivity, reflective surface awareness, resistance detection and awareness of the center of gravity Force sensing is already included in the arm, but not yet in the gripper.

Interchangeable grippers have been proposed by UMI which has not yet, however, forecast the modification of the arm to support this capability.

Voice response is now under consideration to provide feedback from the robot and emergency situations when the robot is performing unattended activities. Upgrade of voice functions (speech recognition, response and communication) are also among the items to be considered, as the results of the research and evaluation in Speech Understanding prove to be applicable.

Summary

By April, 1986 the workstation and its operator are fully functional in a business programming environment. The operator is completely independent of supportive aid from co-workers. We, at Boeing hope that our work will provide an example and encourage others to continue on many fronts to help the handicapped to overcome their physical limitations.

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SMALL ROBOT ARM IN THE WORKPLACE TO AID IN THE EMPLOYMENT OF SEVERELY PHYSICALLY DISABLED PERSONS

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ABSTRACT

The Rehabilitation Engineering Center in Wichita, Kansas, has, as its emphasis, research in the area of finding means to place severely physically disabled persons in the workplace through the use of technology. A project to investigate the use of small robotic arms to assist the disabled at work has been underway for three years at the time of this writing. Several types of devices were investigated and evaluated prior to purchase. Two such types representing two distinct operating and programming criteria were purchased and have been in use on the job Descriptions of the robotic arms, examples of workstations chosen, and relative merits of device types are presented and discussed.

Introduction

The Rehabilitation Engineering Center (R.E.C.) in Wichita is federally funded by the National Institute of Handicapped Research and is under the sponsorship of the Cerebral Palsy Research Foundation of Kansas, Inc., with a cooperative relationship with the College of Engineering at Wichita State University. Center Industries in Wichita is a company which employs disabled persons in the "real world" environment of non-sheltered employment. Center Industries has been the laboratory at which research activity has been carried out in the area of using small robotic arms to aid the severely physically disabled worker on the job. Considerable research has been carried out in the choosing of robot devices and of identifying suitable workstations to be operated using a robotic arm. Price considerations, of course, were a most significant factor. Considerable information has been gathered and the Center has experienced success to this point in the project.

Methods

Choice of Robotic Arm Devices

The project objectives called for the choice of a small robotic arm in the $2,000 to $4,000 category. It was hoped that if a suitable device could be found in this price range that it would be affordable to the employer and, perhaps, even to the employee as a tool. Several sources were found that offered such devices. However, all devices in the desired price range were intended for classroom use in the teaching of robotics to students and none were considered by their manufacturer to be of industrial quality. That is, they were not intended to be used on a continuous basis on the job. To satisfy budget constraints in the first year of the five-year project a teaching robotic arm manufactured by Microbot, Inc.[1], was chosen and purchased. The price was less than $3,000 and it can be seen in Figure 2. In the third year of the project a robotic arm of different operating technology and programming procedure was purchased. This device is manufactured by Feedback, Inc.[2], and can be seen in Figure 3.

Choice of Workstations

The purpose of the project was to choose a workstation which would be suitable for robotic application in the area of manipulation of workpieces, but, would also require the support of a worker in the area of quality control inspection and indexing of workpieces for the start of each operating cycyle. The worker should also be able to stop the operating cycle should problems arise. It was anticipated that a severely physically disabled person could then work at this station utilizing the robotic arm to perform the precise manipulations of small parts while, at the same time, exercising quality control (inspection) and the indexing of parts for the operating cycles.

A contract with the Boeing Company in Wichita calls for solder tinning of the electrical leads of small components prior to insertion into circuit boards. The operation requires the picking up of the part, dipping the lead in a liquid flux, then dipping the lead in molten solder (holding for three seconds), inspection of the lead for uniform solder coating, placing the part at the side for cooling in air, and, finally,

FIGURE 1: Tinning operation by hand

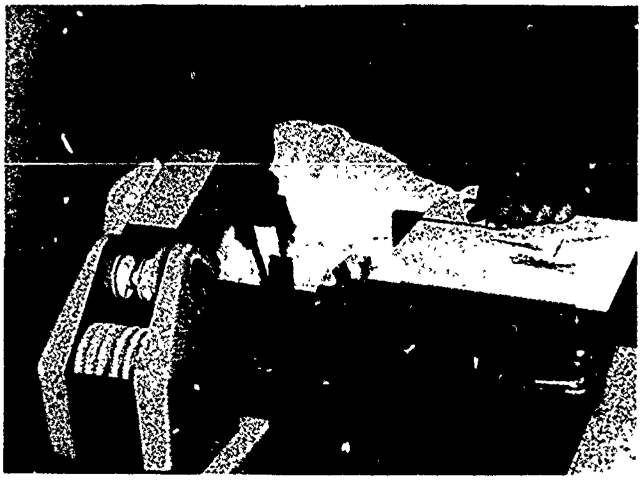

FIGURE 2: Tinning operation using robotic arm by Microbot, Inc.[1]

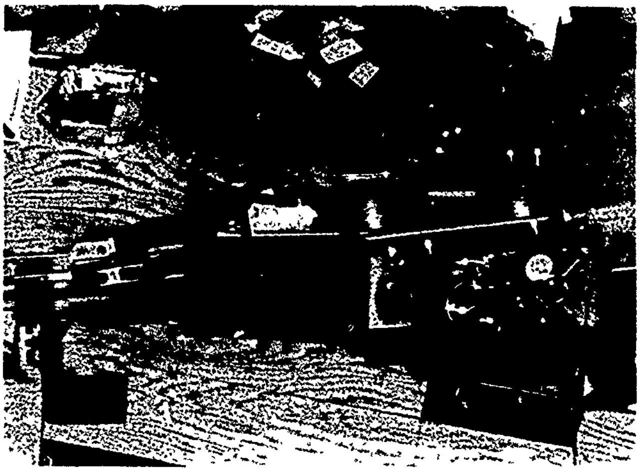

FIGURE 3: "Armatrol" by Feedback, Inc.[2]

placement of the part in an alcohol bath. The manipulation of these small parts in this operation was difficult, at best, to do for persons with unsure hands. One of these workstations was chosen for the first application of robotic arms in the research. The workstation as performed by an able-bodied worker by hand is shown in Figure 1. The workstation as set up with the Microbot[1] can be seen in Figure 2. Note that considerable support for the workstation in the way of fixtures was required to allow the worker who has cerebral palsy to properly index the parts and perform the other duties of the job. To date, this contract and activity at Center Industries, has provided the best choice for the opportunity to employ the use of small robotic arms in keeping with the original intent of the project. The robotic arm called the "Armatrol" by Feedback, Inc.[2], can be seen as it picks up the indexed part in Figure 3.

Discussion

All robotic arms do not provide for the same level of articulation and each must be investigated as to particular need on the job. The model by Microbot, Inc.[1], called the "Teachmover" provides for shoulder, elbow, and wrist movements with the additional function of wrist "roll" or twisting of 360° each direction from center position. All of

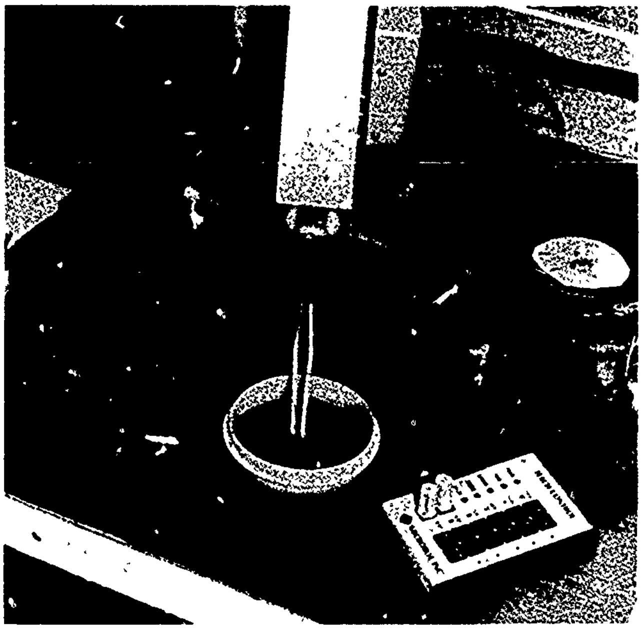

FIGURE 4: Programming by Teach Pendant

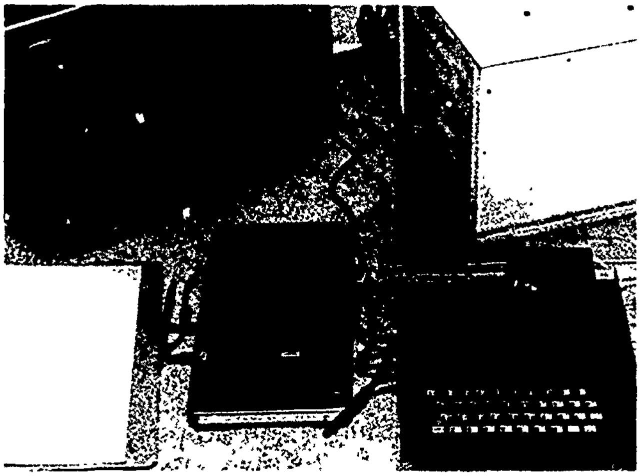

FIGURE 5: Programming by Computer Keybaord

these movements can then be utilized as rotation takes place around the base. The "Armatrol" model by Feedback, Inc.[2], provides for all of the above motions except for "roll" of the wrist, which means that the workpiece cannot be "turned over" in the work cycle. Simple "picking" and "placing" tasks may not require rotation of the "arm" about a base. The research project goals were to investigate devices that provided for the most articulation so that fine motor tasks could be investigated. The workstations that were chosen require the capability of the fully articulated "arm." Therefore, a more thorough investigation of robotic arm capabilities was possible.

Robotic arms can be programmed to function in a repeatable cycle in three basic ways. 1. Use of a teaching pendant —a small console with push buttons to control the arm and enter programmed positions (see lower R.H. corner of Figure 4), 2. Entry of programming data through a computer keyboard requiring separate computer and monitor (see Figure 5), 3. "Lead by the nose" programming which requires the placing of the robot's "hand" manually and recording each placement by keyboard input. Methods 1 and 2 were utilized by the Microbot Teachmover and the Feedback Armatrol, respectively. Method 3 was not investigated by the project.

Costs

At the time of purchase, the Microbot Teachmover that was first purchased cost $2,670 including a hard shell carrying case. An additional $870 was invested in a Radio Shack Model 100 computer for the purpose of recording programs for permanence that had been created using the teaching pendant. One year later, a Microbot Teachmover was purchased at a cost of $4,019 which had additional programming capacity plus the added feature of non-volatile memory. That is, the microprocessor would retain a program in its memory after power had been turned off, eliminating the necessity of "dumping" the program from the microprocessor to a cassette tape through the use of the computer.

The Feedback Armatrol was purchased at a cost of $1,890 including a 10% discount from the manufacturer. This purchase price included a Sinclair computer (see Figure 5). A black and white televison set was purchased for $65 to use as a monitor (necessary to visualize computer inputs).

Conclusions

At the time of this writing the research project has consumed three years of an originally proposed five year time period. Much has been learned and investigated. The following observations have been made by the research staff.

1. The small robotic arm is most definitely a useful tool which can be utilized to place a severely disabled person doing a complicated task.

2. The robotic arm not only is capable of performing fine motor tasks but acts as an excellent "pacer." It forces the worker to be "ready" for the next cycle of operations. Members of the research staff have found "pacing" to be a difficult concept for many to grasp without some external indicator.

3 Programming by the teaching pendant seems to be the preferred method when teaching the worker to program the device for a new cycle of operation. Computer programming of the devices requires knowledge of mathematical criteria which is beyond the majority of disabled blue collar workers.

4. Tasks can be found that require the human element for judgement in addition to the handling of workpieces by the robotic arm, eliminating the possibility of a "token" employee.

5. A programmed repeatable cycle is the only form of use that a robotic arm can be productive on the job regardless of physical capabilities of the worker. Manipulation of the "arm" manually simply is too time consuming and inaccurate to be reasonable on the job, especially if production rates are required.

6. "Pick" and "place" tasks do not always require the articulation of a full "arm." Highly accurate devices are available with less than whole-arm capability.

7. In the day-to-day operation of a workstation at which a robotic arm is utilized it is most desirable that there be a known, or "stored", "home" position. That is a position known to the microprocessor in the robot from which all operating steps can be referenced. The Microbot Teachmover does not have such a known position. Robotic technology to date uses two principles of mechanical operation; air or hydraulic pressure coupled with actuating cylinders and electric motors. The two devices investigated are operated by electric motors. The Teachmover operates using electric stepper motors (the microprocessor simply counts the "steps" through which each of the operating motors rotate). The Armatrol utilizes servo motors coupled with encoders and offers the known "home" position. A pre-stored program will not operate the robotic arm through steps which must touch locations precisely if the reference point, or "home" position, is not precisely the same for each initial startup (i.e. at beginning of the day of operation).

8. The robotic arms that are sold for educational purposes and are the least expensive ($2,000 to $4,000 and even up to $10,000) are not suited for the rigors of day-to-day continuous operation of a workstation. The mechanical and electrical components of these devices simply are not industrially rated for that kind of demand.

The author and other researchers on this project have concluded that the concept of employing severely physically disabled persons by the use of small robotic arms has been shown to be viable.

The Microbot company now offers an industrially rated robotic arm called the "Alpha." The project has recently purchased one of these models (retail value $14,000). Sophistication of operation is at a much more technical level with approximately five times the programming capability. Staff is currently learning operating procedures of this device It is anticipated that problems that have been encountered in the area of maintenance will be curtailed.

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DEVELOPMENT AND USE OF A ROBOTIC ARM SYSTEM WITH VERY YOUNG, DEVELOPMENTALLY DELAYED CHILDREN

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ABSTRACT

A robotic arm system has been developed and used to foster environmental interaction in very young developmentally delayed children. The system includes hardware and software for training and playing back movements, and collecting and analyzing data. Children as young as 5-6 mo. (MA) will use the arm as a tool.

Introduction

Handicapped children often display a lack of responsiveness to their environment. This is the result of an inability to interact with the environment rather than an inherent characteristic of the individual. It may be avoided if early intervention takes place.

Cognitive development is dependent on early physical interaction with the environment. Sophisticated cognitive and language abilities are all dependent on early consistent interactions with both people and objects. Physically disabled infants frequently cannot interact with their environment in a meaningful manner. Consequently, they may not develop cognitive and social skills and be responsive, interactive individuals.

The goal of this project is to provide a computer-controlled manipulative system which will increase the control disabled children have over objects and social events in their environment.

Robot System Hardware

We have carried out a preliminary study using a robotic arm (the MiniMover-5,[1] with a group of developmentally delayed and able-bodied young children. The anatomy of the robot consists of 5 main structures: a stationary base, a body, an upper arm, a forearm, and a 2-fingered gripper. Not only is this robot arm anthropomorphic in its structure (1/2 adult human scale), it also moves like a human arm in its articulation. The arm can rotate at its base, extend and flex at both its shoulder and elbow, pitch and roll at the wrist, and, open and close at its gripper (hand).

Two ways of teaching the robot to execute a desired movement are included in the system: teaching-by-text (the operator uses textual commands) and teaching-through-guidance (the operator uses a guidance unit to lead the robot along the desired path) During the guidance, the path data are stored so that the arm can later play back the movement.

The guidance unit is a 4"x 4"x 6" box that houses a joystick, 4-buttons, and interface circuitry. The joystick is a four DOF discrete- output device. Movements include: forward/backward, left/right, up/down, & clockwise-twist/anti-clockwise twist. The first three pairs of joystick activations will move the robot arm in the direction of activation. Twisting will cause the gripper to close/open. Pitch and roll of the gripper are controlled by two pairs of buttons at the four corners of the unit. A tool coordinate system is employed.

Robot Arm Control Software

We have chosen FORTH[2] for this development since it has many of the desirable characteristics of a robotic programming language[3]. These include extensibility, structured language techniques, unrestricted variable names, English-like syntax, and extensive subroutine nesting. FORTH is also able to manipulate transform equations, and it can be interpreted as well as compiled. It is also faster than compiled BASIC. The most important characteristic of FORTH is its extensibility. For example, the implementation at present can allow one to define actions such as REACH and PICKUP:

```
: REACH 200 FORWARD 150 DOWN ;
. PICKUP CLOSE-GRIPPER 100 UP ;
```

When REACH is called, either from the keyboard or within a program, the arm will move 2 inches forward, and then 1.5 inches down. When PICKUP is called, the gripper will close, followed by the raising of the arm for 1 inch. Also, a new word REACH-AND-GRAB can be constructed as a combination of previously defined words:

```
: REACH-AND-GRAB REACH PICKUP ;
```

When REACH-AND-GRAB is called, the entire movement described above will be executed by the arm. The following is a list of currently available 1-D movement directives and their syntax.

1. Microbot, Inc , 453-H Ravendale Drive, Mountain View, California 94043.

2 Feedback, Inc , 620 Springfield Avenue, Berkeley Heights, New Jersey 07922.

Forth Word	Syntax	
FORWARD	n FORWARD	
BACKWARD	n BACKWARD	
UP	n UP	
DOWN	n DOWN	
LEFT	n LEFT	
RIGHT	n RIGHT	
FLIP-UP	m FLIP-UP	(+P)
FLIP-DOWN	m FLIP-DOWN	(-P)
ROT-CW	m ROT-CW	(+R)
ROT-CCW	m ROT-CCW	(-R)
OPEN	n OPEN	
CLOSE	n OPEN	
CLOSE-GRIPPER	CLOSE-GRIPPER	

n=inches x 100 m=degrees P=pitch R=roll

For example, to move the arm left 2.5 in. n=250. and the correct command is: 250 LEFT.

Our system allows a therapist to teach the robot arm to execute movements (the trajectory through which the arm traces, including both the displacement and orientation of the gripper) which are relevant to an individual child. These movements may then be stored and recalled later in appropriate situations.

Based on a careful evaluation[4] we have found this system to be easy for a therapist to use, and also capable of producing movements which the therapist feels are appropriate to a child.

The robotic arm control software of the system consists of the following principle modules: the guidance module which makes possible teaching through guidance, the edit module which allows editing of a movement after it has been taught, the playback module which replays a taught movement, a management module which allows parameter changes, and a directory module which allows changes between system functions such as training the arm, playing back a movement, recording data or using other contingencies such as toys or graphics.

The teach-by-guidance method is implemented by the guidance unit together with the guidance module written in FORTH. This guidance module repeats the following cycle until terminated by the ESC key: it first reads and translates the input, calculates the robot parameters (backward transformation) and stores them into a data array. Finally, the motor driver is called to move the arm. Within the guidance mode, the therapist can use the arrow keys on the Apple computer keyboard to trace back and re-teach that portion of the movement. In tracing operations, a forward trigonometric transformation is used to convert the vector in tool coordinates so that updating of tool coordinates is possible.

A movement editor is also included so that a previously taught movement can be modified and given a new name. This is useful when a slight variation (e.g. opening the gripper a little more for a larger object) of an original movement needs to be made. With this editor, a segment of a movement can be deleted, replaced, appended, or inserted.

The playback module replays a taught movement when activated from the keyboard (for therapist) or from the baby-switch (for the infant). The baby playback routine allows interaction between the baby and the system, thus playing a central role in contingency intervention programs. At present, the switch activation can be set in a one-hit or continuous mode, each controlled by different software routines. In the one-hit mode, an assembly routine QUIK-MOVE-ARM plays back the entire movement from the beginning to the end without interruptions. In the continuous mode, a routine written in FORTH reads the switch and moves to the next position if it is activated.

The management module allows the therapist to change parameters of interest. These parameters include the name of a movement, its speed, the increment size, and the activation mode of the baby switch.

The directory module handles the saving and retreiving of data between the disk and the RAM memory. To the user, movements are indexed by their names and this module is responsible for keeping track of what movements exist on the diskette, and where they are located.

Experimental Control Software

Our experimental system also has provision for labeling a button or key as corresponding to each of the observable (but not directly detectable) behaviors. The observer will press the appropriate key when a behavior is noted (e.g. directing eye gaze to the object being controlled or to the screen, expressing fear, interest, boredom, etc.). The computer also has a clock, and it automatically records the time of occurence along with the coded behavior. At the end of an experimental session, the computer can be used to combine the manually entered behaviors with those directly sensed (e.g. switch activations, robotic arm movement actions controlled) and display the matrix of behaviors. A hard-copy of these data may be obtained using a printer.

The test control module coordinates all the functions pertinent to robot arm movement, switch detection, and data storage and processing for an experimental session with each subject. Choices of visual graphics or toys (including a tape recorder) as alternatives to robotic arm movement are also included. The switch detection module provides a software interface to the switches connected to the system switches. After configuration by the test control module, the switch detection module monitors switch closure times and durations.

The data collection and processing module stores the data format and raw data to disk for later retrieval. Running averages and totals for the data can be accessed and displayed for such items as switch closures, switch closure durations, and patterns of switch activation and observed behaviors during the course of the interaction with the subject.

The data display module accesses the data stored on disk following data collection and allows the preparation of a variety of reports. These reports may take the form of statistical analyses and plots Either video or printed data formats may be used.

Evaluation with Young Children

The present robotic arm system has been used in a preliminary study with 7 very young (CA < 36 months) developmentally delayed children in an infant development program and 3 able-bodied children matched in chronological age. Based on interview data from the program director and parents, we began with a period of familiarization during which we played with the child, and determined what their typical responses were to things they like, dislike, are fearful of and are bored with. These were coded for data collection using the system. We then used either a battery operated puppy or cassette tape recorder which was activated by a switch. This allowed us to establish whether cause and effect between the switch activation and toy movement was understood and to determine the best anatomic site and switch for each child.

For all these children, the hand/arm was the best anatomic site. Most used the Zygo tread switch and one used the Zygo leaf switch attached to a piece of yarn. The latter switch was used because it was similar to a task in which the child used the yarn to retrieve a toy.

After we had established reliable switch cause and effect, we trained the robotic arm to make movements which the program director and parent thought would be of interest to the child. The child was then presented with the switch and asked to hit the switch to see the arm move. Continuous and single press modes were both used.

We found that the continuous mode, used with a movement which had a payoff to the child, was the most effective. For example, we trained the arm to pick up a cracker which was out of the child's reach and bring it close enough to be taken with their hand. Each of the children demonstrated understanding of the cause and effect between switch activation and arm movement by first looking at the cracker, then looking at the switch and pressing it, then looking back at the arm as it moved. Sometimes they would reach for the cracker before it was close enough to grab. When this happened, they all reactivated the switch to bring the cracker closer, and then attempted to reach it. This sequence continued until they could reach the cracker.

The degree to which this type of interaction occurred was called the correspondence criterion for interaction. We also determined the degree to which a sequence was repeated (the repeatability criterion). Based on an analysis of these two criteria, we found that children with a developmental age greater than 5 to 6 mo. would interact with the robotic arm system as a tool.

Conclusion

This preliminary study established that the children were interested in the arm, were not frightened by it, and were bored unless the arm did something "useful" for them. The use of continuous switch activation to complete the movement proved to be valuable in determining if the child understood that the arm would eventually bring the desired object within his/her reach. All of the children and their parents were very interested in the experiments.

Acknowledgements

American Microscan loaned the MiniMover-5. Microbot provided the Apple to MiniMover interface, and the Placer Infant Development Program (Roseveille, Ca) assisted with the clinical trials.

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EVALUATION OF THE APL/JHU ROBOT ARM WORK STATION*

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ABSTRACT

A robot arm/work table system has been designed at APL/JHU and evaluated at VA Medical Centers as an assistive device for the high spinal cord injured person The goal of this system is to provide some level of independence to the disabled individual who possesses little or no manipulative function. The robot arm is a 6 degree-of-freedom device which is controlled by a low cost computer with both individual joint control and up to 48 preprogrammed motion sequences This paper will describe the overall system and discuss alternative control input modes for the highly disabled person. Controllability and safety are two important issues which have commanded a high priority in the design. Testing has been conducted with over 20 volunteer quadriplegics and results of this clinical evaluation will be highlighted.

Background

The APL/JHU robot arm/work table system has been designed to enable high level quadriplegics to execute certain manipulative tasks with little or no attendent assistance This research program, has now reached a stage where a manufacturing prototype has been fabricated and is in the final stages of evaluation. This system is designed to provide manipulative capability for a variety of tasks for the high level quadriplegic. Such individuals, with little or no upper and lower limb functions represent one of the highest needs in rehabilitation engineering

This work station has been designed with the specific goal of meeting total task accomplishment in complete safety and with little or no attendant assistance. The latest model incorporates a low cost computer (6809 microprocessor) with adequate flexibility to permit programming a number of useful manipulative tasks on a structured work station. The robot arm is a 6-degrees- of-freedom, computer controlled anthropomorphic limb. The individual degrees of freedom may (if the user so elects) be directly controlled by selection of the desired joint to be moved. Alternatively, the user may select preprogrammed motions to perform tasks where such structured trajectories can accomplish a task. Picking up a book and placing it in a reading stand or adjusting printer controls are examples of task compatibility as shown in Figure 1.

Input Modes to the Robot

Throughout the course of this research program many control input methods were examined as possible input modes to the system. Safety in operation and ease of user control were important goals of the input device. Chin motion input was selected after evaluation of alternatives because of its positive control and good resolution capability. The chin motion sensor may be a dual purpose controller as part of the wheelchair controller or may be a

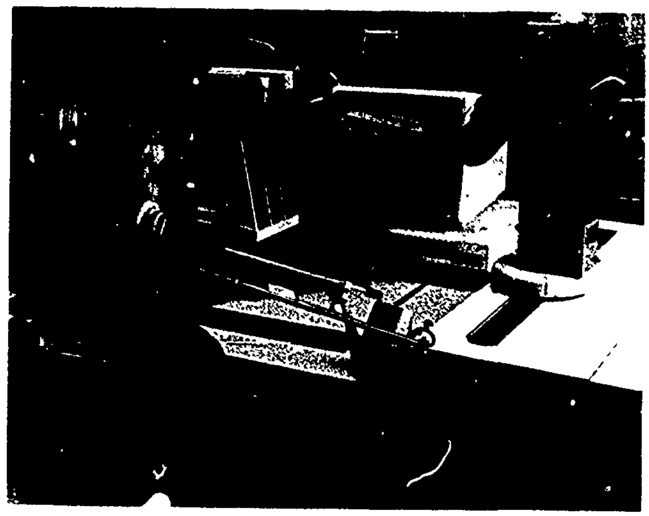

Figure 1: Workstation with Reading Materials and Computer Setup

stand-alone device mounted on the workstation. Small up and down chin motion provides proportional control of selection of individual joint motion or prestored motion sequences while a single pulse activated by slight rocking fore and aft causes an event to start or stop. For systems employing the dual mode wheelchair controller, steering control of the wheelchair is achieved by lateral motion of the chin controller. Torque of the motors, hence wheelchair motion, is controlled by how far the controller is depressed. The chin control apparatus is very small and obscures very little of the face. Once the user maneuvers in front of the workstation, an optical link transfers signals to the robot arm and the chin controller is now used to input the robot arm.

Individual users who have their own wheelchair controllers and choose not to use the APL/JHU dual mode wheelchair chin controllers may utilize a stand alone chin controller. This table mounted controller is operated in an identical manner as the wheelchair controller. For those individuals who cannot input a chin controller, a sip & puff controller is available. Thus, the APL system addresses the needs of a wide range of users by providing alternative control methods of inputting the system.

The Workstation Concept

The workstation concept is based on placing components in fixed locations on the work table such that the robot arm may use manual step-by-step motion or prestored computer controlled motion trajectories to carry out the desired functions. The system not only provides for basic manipulative functions within its 6 degrees of freedom motion, it has demonstrated that complex functional tasks such as self-feeding, handling a variety of reading materials, use of a telephone, and a computer system may be accomplished with minimal attendant assistance.

As an alternative to direct control of any single axis-of-motion, the user may select one of many prestored trajectories to accomplish a specific task. The following tasks, which are only a partial list, use prestored application programs in the current model of this robot system:

1. Move mouthstick or morse code keyer into position for use
2. Pick up the telephone and earphone; hold it next to one's ear
3. Hang up the telephone
4. Pick up Kleenex tissue
5. Eat sandwich from a plate
6. Eat with spoon in plate; and
7. Eat from a bowl
8. Turn the computer off-on
9. Input the computer printer controls for draft or letter quality print

An important tool used in conjunction with the robot arm is a mouthstick. Manipulative functions such as putting a magazine in place for reading are accomplished by the robot, which page turning is accomplished by use of the mouthstick

The work station may be configured for the task environmental needs of individual users. A typical desk-work station layout was shown in Figure 1. Prestored trajectories may be readily preprogrammed to accomplish new tasks as needed. The programming keyboard is designed to be used by either the therapist or an experienced quadriplegic user. The functional keys define BASIC like language element for easy specification motion sequences Commands exist for motion to a point, stimulation and sensing of external devices, jump to other motion sequences, and more

Clinical Evaluation

An important tool in the evoluton of a practical system design is the conduct of clinical testing with quadriplegic volunteers. Conceptual ideas which look good on paper may often be discarded after realistic day-to-day testing. Clinical testing can contribute much to overall system design, since it exercises the system under realistic environment. Since January 1983, two experimental robot arm work stations have been included in part-time evaluation testing at VA Spinal Cord Injury Centers at Richmond, Virginia, Cleveland, Ohio, and Hines, Illinois. These tests have shown that the system concept has merit for certain highly disabled persons yet still needs some "fine tuning" to make the system of practical value(1).

Involved in the clinical evaluation were 20 male quadriplegics between 21 and 60 years of age Their levels of injury ranged from C-2 to C-5. Individual accumulaton of time working with the equipment ranged from 1 hour to over 100 hours, over 300 meals have been eaten by these individuals using the robot arm. The self-feeding arrangement is being demonstrated by the design engineer in Figure 2.

Figure 2: Workstation Self-Feeding Arrangement

About one half of these individuals found the equipment gratifying to use, especially for self-feeding. There were no safety problems encountered throughout the test program. The most frequent and significant problems were.

1. Incompatibility of the system with a reclining user,
2. Inadequacy of this early version of the chin controller to compensate for posture changes in a wheelchair, and
3. Incompatibility of the work station with other wheelchair controllers

Since these clinical tests were conducted, a new chin controller with self-adjusting features was designed to compensate for the patients' change in position during the day. A table mounted controller option was added to the system to allow the use of a broader range of existing wheelchairs. Additional tests are being conducted at a VA Medical Center to further evaluate these changes.

Manufacturing and Producibility

The APL robot arm work table system was selected by the VA for transition to a manufacturing prototype model. Such a model has been designed, constructed, and is undergong acceptance evaluaton testing. Upon completion of these test, it is expected a small number of units will be ordered and placed in VA Medical Centers for long-term utilization by quadriplegic patients in these centers.

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DEVELOPMENT OF AN ADVANCED ROBOTIC AID: FROM FEASIBILITY TO UTILITY

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ABSTRACT

Many severe physical disabilities, such as quadriplegia, are characterized by a greatly reduced capacity for manipulating the environment, a condition often exacerbated by a reduced mobility. The Veterans Administration is sponsoring a continuing effort to develop a robotic manipulation aid that can be controlled by severely disabled individuals to provide functional restoration of lost motor skills Hardware and software systems have been implemented for a mobile manipulator and its stationary control station.

Introduction

The psychological and economic importance of access to, and control of, one's surroundings has long been recognized by the disabled and by rehabilitation professionals[1,2,3]. This need can only be partially addressed by human attendants, trained animals, and the use of specific technology-based solutions such as environmental controllers[4]. While robots can also offer only a partial solution, their true value lies in their ability to serve as a general-purpose manipulation tool, capable of being applied in changing or unpredicted situations, capable of mobility, and under the complete command of the user.

The Incentive

At this time, effective care for physically disabled people is labor intensive. The incentive to apply robotics technology is thus economically similar to the situation in industry. The cost of human labor averages $15/hour and is increasing. Robot costs average $5/hour and are decreasing[8]. Furthermore, robots are most effective when applied to multiple shifts per day as would be the case for robots in human service applications.

Kalsbeek, et al.[6] estimate that the average cost per year (44% direct costs, 56% indirect costs) for all *new* head and spinal cord injury cases in the U.S. is $2.4 billion. In 1983 there were over 16,000 cases of spinal cord injury treated in the VA alone, with a direct cost of $1.5 million over the estimated lifespan of each of these individuals, the total cost to the VA will be $4.5 billion[5]. Is it worth investing in research and development? Bowe[7] has estimated that every dollar spent for rehabilitation research returns $11 in cost benefits to society

The Problem

The feasibility of our approach to robotics has been demonstrated through the development of two first-generation proto type Robotic Aids[9], one for clinical evaluation and one for technical evaluation. Each is composed of a Unimation PUMA-250 arm that can be controlled by spoken commands, a joystick, stored programs and rudimentary hand sensors Clinical evaluation and analysis of the capabilities and limitations of the system[10] have helped us define the areas of research and development we are now pursuing to move robotics from *feasibility* to *utility*. Specific problems are outlined below as elements of the current research and development program:

1. A communication manager is needed to facilitate human-machine interactions by sustaining an effective "conversation" between the user and the computer.
2. Sensor-driven reflex control loops are needed to reduce the operator's work load and assure rapid response to grasp and obstacle-avoidance problems.
3. Intelligent motion planning is needed to reduce the system's dependence on a highly structured environment, and to reduce the operator's work load.
4. A vehicle is needed to extend the Robotic Aid's working volume beyond the fixed tabletop environment.
5. Instrumentation and a formal strategy are needed to measure utility objectively

Project Objectives

To define specific research projects, we first compiled a set of tasks from spontaneous, unsolicited comments made by disabled users during training sessions with the first Robotic Aid. We then identified an associated set of **capabilities** that would be required to assist in the performance of these tasks [Table 1] **Capabilities** were generated by breaking down each task into the fundamental functions requisite to its performance. Finally, we determined the **devices** and **algorithms** needed to implement the desired capabilities. The capabilities are explained below.

1. COMMANDS are discrete transactions between the user and the robot. They are, for instance, words

spoken to a speech input system or items selected from a menu.

2. CONTROLS are continuous variables, of controllable magnitude and duration, used by the operator to refine commands and do real-time piloting The operator could use a joystick, mouse or head-position detector to move a screen cursor or the mobile base.
3. COMMUNICATION MANAGEMENT is a set of procedures and rules designed to assure that effective two-way communication is maintained between operator and machine.
4. AUTONOMOUS PLANNING is performed by the machine when sensed data are operated on by applications programs, with the result that the machine makes navigating (or equivalent) decisions These decisions are subject to human supervision and veto. Trajectory planning for the mobile base and switch toggling on an appliance by the robot hand are two examples.
5. GRASP is the property of a robot that allows objects to be selected, positioned and oriented. It is typically associated with "hands" and includes a variety of functional attributes, such as detection of slippage and evaluation of object geometry for stable holding
6. MANIPULATION is the capability to move objects from one place to another while maintaining a correct orientation of the hand and avoiding collisions with stationary objects.
7 PROGRAMMABLE REFLEXES are designed to protect the operator and/or the robot from adversity They act quickly and do not require human supervision
8. MOBILITY extends the Robotic Aid's working volume beyond the desk-top workstation environment. In this project it also includes vertical "mobility" to facilitate access to floors and shelves.

The laboratory version of the first Robotic Aid was the starting point for these goals. Two general problems that were solved at the start of this phase are the design constraints of the mobility system itself[11], and the requirements of the computing environment[12]. Both of these topics have been addressed satisfactorily to proceed with the problems enumerated above.

Current Research Status

The project is one year into its current phase. A companion paper in these Proceedings discuss individual areas of endeavor within our rehabilitation research project This section outlines recent results and ongoing efforts

Human/Machine Interaction

We continue to emphasize speech input as the primary communication medium A recently acquired Kurzweil 1 1 recognition system, combined with improved software support, should significantly enhance the speed, accuracy and facility with which the Robotic Aid accepts and processes words. Specifically, we are implementing a new computer-based Dialog Management System which recognizes and analyzes commands given in the form of simple English sentences "Pick up the cup," for instance, would be translated to appropriate low-level robot specific commands. The user is informed, via synthesized speech through a DEC Dectalk unit and a visual display, of the commands passed on to the robot controller Since the user exercises a supervisory role, the system provides a real-time color image of the internal state of the control system, and the state of the computer's current world model, currently on an IBM PC/AT equipped with a Professional Graphics Display

TABLE 1

To live independently, one must be able to perform a variety of TASKS. These can be correlated with generalized CAPABILITIES needed to get the job done in minimally structured environments.

- = don't need ○ = should have • = must have

FUNCTION

TASK	COMMAND	CONTROL	DIALOG	PLANNING	GRASP	MANIPULATION	REFLEX	MOBILITY
MAINTENANCE								
Food Preparation	•	•	○	○	•	•	○	•
Food Service	•	•	○	○	•	•	○	○
Personal Hygiene	○	•	○	○	•	○	•	○
Personal Grooming	•	•	○	-	•	•	•	○
Clothing Management	○	○	○	•	•	•	○	•
Appliance Usage	•	•	○	•	•	•	○	•
VOCATION								
Storage & Retrieval	•	○	○	○	•	•	○	•
Equipment Operation	•	○	○	○	•	•	•	•
Assembly	•	•	•	•	•	•	○	○
Word Processing	•	○	-	-	○	○	-	
Computing	•	-	○	-	-	-		-
Materials Processing	•	○	○	○	•	•	•	•
RECREATION								
Reading	•	○	-	○	○	○	○	-
Film/Video	•	-	-	-	•	•	○	•
Performing Arts	○	•	○	○	•	•	○	•
Graphic Arts	○	•	○	○	•	•	○	-
Sports	○	•	○	•	•	•	•	•
Social Interaction	○	○	•	-	○	○	○	•

Mobility

We have chosen to extend the range of the Robotic Aid by mounting the arm on a unique three-wheeled base that allows the unit complete three-degree-of-freedom mobility. left/right, fore/aft, and rotation are all possible simultaneously. This design is discussed more completely in a companion paper [Van der Loos et al.], and the computer architecture and control software is reviewed in another [Michalowski et al.].

Machine Autonomy

We assert that a degree of autonomy is crucial if the Advanced Robotic Aid is to lessen the control burden on the operator, defined by the amount of time and the degree of focussed attention needed to complete a given task. The emphasis is on a "symbiotic" structure, in which necessary control functions are shared between the operator and the robot's supervisory computer. We have identified those aspects of the manipulation process most advantageously assigned to the robotic system. They fall into two categories, **reflexive** and **strategic:**

Reflexive Functions

In the first version of the Robotic Aid, the movements of the arm were determined directly by the user, who had to rely on a single mode of perception—vision—to guide the arm through such elementary operations as gripping and obstacle avoidance. But it is clear that visual (i.e., position) information alone is inadequate for the control of certain important tasks. User fatigue and frustration can be traced, in part, to the fact that direct control of the robot s movement requires constant, conscious attention. Our Advanced Robotic Aid is endowed with the sensory capabilities appropriate to alleviate this burden.

We label as "reflexive" those functions that result directly from sensory stimuli. The user's role is limited to initiating the function and monitoring its successful execution.

Consider the bumper system of the base. While providing physical protection to the base, it also provides contact-point localization and the capability to "bounce-off" any obstacles, given that the user has invoked that procedure, and not the one used to shove boxes across the room. This provides an example of two reflexes appropriate to one sensor system. Two additional systems, an ultrasonic ranging system and a laser-scanner for absolute position detection, are currently under development.

The hand on the robot is equipped with proximity sensors to deal with objects at distances of 1-2 centimeters, for object detection during grasping and collision avoidance during piloting. Additionally, the arm is equipped with a force sensor at the wrist to facilitate tasks such as placing a grasped object on a table and operating a push button. These two sensor systems are discussed in a companion article [Park et al.].

Strategic Functions

The term Strategic Functions refers to manipulative tasks that require some overall knowledge of the environment, and are preceded by a planning phase. Examples are. meal preparation, light assembly, navigation in a confined space. The autonomous execution of such tasks in an industrial setting is the focus of considerable activity within the fields of robotics and artificial intelligence. A rehabilitative application is complicated further since the robot is meant to function in an unstructured, everyday environment. We believe that the participation of the disabled user provides a unique opportunity for overcoming and circumventing some of the more intractable problems associated with environmental modeling and task planning.

In the Advanced Robotic Aid, the user and robot work together to complete a task. The role of the operator is that of a supervisor. Commands are no longer *motion-specific* (for example, "forward",) but *task-specific* ("pour from the bottle into the cup") To assist the user in strategic planning applications, the Robotic Aid must be endowed with the following specifics. which we are currently implementing:

1. it must be able to *acquire* data about the environment;
2. it must interpret the data in terms of an *internal representation* (or *model*) of the environment;
3. it should be able to *plan* and *execute* simple manipulative motions;
4. it must have a means of *communication with the user* to present the results of data-taking, analysis, and planned motions;
5. it must be *safe*, in that the user must be able to stop any planned or ongoing motion at any time

We are applying these general principles to the specific case of manipulating medium-sized objects on a table and maneuvering in a typical room environment.

Evaluation

Since our goal is the increased utility of the Robotic Aid, a formal evaluation process is being pursued to extract qualitative and quantitative measures of success. We maintain a Laboratory System (located at the Center for Design Research at Stanford University) to develop new hardware and software features, and a Clinical System (located in the Spinal Cord Injury Service of the Palo Alto VA Medical Center) Specific evaluation objectives are discussed in a companion paper [Glass et al], and are summarized below.

1. To train disabled users of all ages in the use of the system. A companion paper [Holloway et al.] describes the training manual produced for the first Robotic Aid. With an advanced system, the features themselves could lead one to predict a higher degree of learning difficulty, however the concomitantly enhanced user-interface should instead serve to *simplify* the use of

the system.

2. To develop applications for the robot. The robot is being studied in specially-prepared environments, using commercially available components, such as domestic appliances

3. To assess device performance under realistic conditions. Every new feature of the Advanced Robotic Aid is being evaluated through a series of time-to-completion studies of selected tasks, including a comparison with baseline measurements performed on the first Clinical System.

A major goal at this stage of research is for the laboratory development process to receive feedback from the evaluation effort, tightening the design loop and creating a more useful system for our user population.

Conclusion

We believe that robotics technology, carefully and sensitively applied, can help bridge the gap between physically limited individuals and their environment in a cost-effective manner. The current phas of research is advancing on well-defined fronts to shape a useful manipulation tool, one that utilizes the ability of people to organize, plan, see, and supervise, and complements that with the strength or machine sensing, motion, and control

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CALVIN: A ROBOT CONTROL LANGUAGE FOR REHABILITATION ROBOTICS

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ABSTRACT

A new control language has been developed for use with small, microcomputer controlled robotic manipulators. The language was specifically designed for use in rehabilitation settings. Particular attention has been paid to the user interface, programming environment, portability of programs, and extensibility The language has been introduced and well accepted for use at two clinical sites investigating occupational applications of small robotic manipulators Application program development time has been drastically reduced and the language has permitted the robots to be used with clients for whom a suitable interface could not previously be found.

Introduction

The application of remote robot manipulators has tremendous potential in the field of rehabilitation. A robotic arm may allow a severely disabled person to have increased control over the physical environment. The concept of allowing a person to interact with an electromechanical arm is not new. A number of existing research efforts have demonstrated that the use of modern robotic arms controlled by minicomputers can be programmed to perform important and necessary tasks for disabled persons [Corker et al., 1979; Leifer, 1981; Leblanc and Leifer, 1982]. While there has been the promise of large gains in independence, a number of issues have prevented the potential of robotic arms from being realized.

One of those issues is the lack of a robot control language suitable for rehabilitation robotics [Buckley, 1983]. This problem manifests itself in numerous ways in the various contexts of contemporary rehabilitation robotics. Examples are the difficulty of developing interactive application programs, obstacles to trying out new interface devices or control strategies, and having to start over when a new robot is purchased. The specifications of CALVIN address these particular needs and provide a flexible environment for rehabilitation robotics development.

Robot Programming

While a large number of robot control languages exist, they can all be grouped into three categories [Lozano-Perez, 1983]. Guiding languages wherein the user leads the robot through the motion to be performed, robot-level programming in which the users write a computer program specifying motion and sensing, and task-level programming in which the user specifies operations by their desired effect on objects. A brief examination of some characteristics of the existing languages will provide a useful context for consideration of the features that are desirable in a robot control language.

Robot Guiding

Robot guiding, also known as point to point guiding, remains the most common type of robot programming available on the market today [Snyder, 1985]. The robot is programmed by saving a series of points obtained by guiding the robot through task positions, usually with a teach pendant. Robot guiding is best suited to applications such as spot welding, painting, and simple material handlings While the limited capabilities of guiding can in no way serve the complex requirements of rehabilitation robotics, the playback mode of programming may be useful

Robot Level Programming

This type of robot programming language allows the user to program a task in terms of robot motions and sensor states without actually guiding the robot through the desired motions. For instance, a robot can be instructed to move to a defined position, close its gripper, and if it detects an object in its hand do one thing, otherwise do another Languages of this type can be further divided into two categories: unstructured languages and structured languages.

Unstructured languages provide simple conditional branching as their primary form of flow control. A well known example of an unstructured robot language is VAL™. The sensor interfacing capabilities and robot motion control sophistication of these languages vary widely [Bonner, 1982].

Structured programming languages such as KAREL™, RAIL, and AL incorporate structured flow control into the robot language This will generally result in more readable, maintainable code. The structure and syntax of most of these languages such as PASCAL or PL/1 [Lozano Perez, 1983].

Task Level Programming

These languages allow programming in terms of desired effects on objects, effectively concealing low level decision making from the user An example of an executable statement in such a language is "place block A on block B." Languages of this type being developed include IBM's AUTOPASS®, and LAMA at MIT [Lozano-Perez and Wilson, 1977]. Obstacles to successful implementations of task oriented languages are collision avoidance and emergency decision making [Lozano Perez, 1983].

Most low-cost, microcomputer controlled robots come with a limited robot-level programming language [Eshed, 1984; Sandhu, 1982] These languages are geared toward the educational function of these manipulators; some are small subsets of industrial control languages. A more advanced language, ROBOTALK®, was recently developed as a $500 option for the Rhino Robot [Sandhu and Schildt, 1985]. Each of these languages are only compatible with the robot they came with, effectively prohibiting program portability

The SCORBOT ER-III™ used while writing CALVIN is supplied with an interpreted language called SCORBASE® (for SCORBOT BASIC) that is written for the IBM PC™. It is a menu-driven environment for program development limited to 100 previously defined positions for motion specification and 400 lines of program code. This language, representative of teaching languages, was a major obstacle to the development of useful rehabilitation applications using the SCORBOT.

Implementation and Description

CALVIN was designed and implemented at a time when progress on a major project was being impeded by its absence. This created an atmosphere of constant conflict between expediency, elegance, and robustness. However, numerous goals existed for the final product from the outset:

- That the language be usable by and useful for clinicians, application programmers, researchers, and the disabled users themselves.
- That support for additional interface peripherals and sensors be extensive and easy to implement.
- That the language be compatible with a number of candidate robots (Rhino, Scorbot, Microbot, UMI, etc.).
- That the language support and simplify the interactive development of interactive tasks.
- That the language be structured so as to create readable, maintainable code.

These will be addressed as they come up in the development process outlined below.

CALVIN is written on the IBM PC entirely in C and uses the YACC (Yet Another Compiler Compiler) utility to construct the parser. YACC takes a description of the grammar of a language and produces C source code for the parser [Kernighan and Ritchie, 1978]. This has the effect of simplifying the process of extending the language. Adding some of the simple commands that have been requested by the sites has taken as little as 15 minutes. Creating a version of CALVIN for a particular robot for which primitives have been written is accomplished simply by linking the particular object file to the core of the language.

CALVIN incorporates features from Logo and C. Logo encourages an inquisitive, modular programming style and has been successfully used as an instrument for teaching computer programming [Papert, 1980]. The C programming language has powerful flow control and a convenient, compact syntax.

CALVIN was implemented as a programming environment. A user is provided with all the facilities needed to do program development, run programs, make listings, etc. The user has a full screen editor (a commercial editor being run as an executive process), an interface to the disk operating system, and a powerful interpreter for commands and application programs.

CALVIN is first a fully functional language with complete mathematical and trigonometric operators, program flow control (if-else, for and while statements) and input-output routines. Statements are parsed into code that is then "run" on a simple software stack machine. While this software machine is much slower than compiled code, speed has not been a limiting factor due to the comparatively slow speed of the manipulator.

CALVIN commands may also be combined into procedures that can be executed at a later time. As a procedure is being parsed, the generated code is placed onto a program stack. Procedures on the program stack can be called in the same manner as the built-in routines or primitives.

The core of the language is augmented by a set of robot-specific driver routines for communication with the robot controller. This allows the language to move the robot joints, query the robot about move status, and any additional features supported by the particular controller (e.g. external switch inputs). The controllers of each robot for which CALVIN is being implemented communicate with the microcomputer via an RS-232 link. The major portion of the work of implementing CALVIN on a new robot involves writing of these routines.

These primitive robot driver routines are combined in the language to provide the user with more convenient methods of describing the results that are desired from a program. Positions may be referenced in a cartesian coordinate system, names, stored and recalled. Motions can be expressed in absolute terms or relative to the current position. The size of an object in the gripper can be found. These routines contribute to a powerful system for describing desired robot motions.

A number of routines are present to support user interface hardware such as joysticks, a speech recognition and synthesis board, a digitizing tablet, etc. Robot tactile sensors, workspace instrumentation, and possibly a rudimentary vision system interface could also be implemented in this manner.

As a very simple example, the following procedure would make the gripper repeatedly move in squares each having sides 10 mm less than the previous one until the side length goes negative:

```
define square (side) [
    if (side > 0) [
        moveup(side)
        moveleft(side)
        movedown(side)
        moveright(side)
        square(side - 10)
    ]
]
```

The ability of a routine to call itself is called recursion, this feature can be very convenient in certain programming situations. This procedure is then available just like a primitive and would be run by typing a line like: **square(100).** The incremental method of program development supported by this transparency of the primitive/procedure distinction permits granular construction of applications covering a wide range of complexity [Papert, 1980, Harvey 1985].

Programs may be written with what are being referred to as robot independent routines. These routines are a subset of the CALVIN primitives that refer only to world coordinates, and use only controller queries that are universally implemented. These programs will possess a maximum amount of portability. It is not possible to say how useful these routines and practices will be until additional experience is acquired.

An important aspect of CALVIN that is currently being investigated is what might collectively be called environment sensitive routines. These routines will monitor the position of the robot and objects in the world as the language knows it. These routines will provide much of the safeguarding that can done for interactive robotic users as well as protecting the robot itself from commands given by the user that may cause damage to the robot or workspace.

Discussion

The CALVIN language already meets many of the presented design goals. The clinical testing sites are a constant source of suggestions and critiques. As expected, many of these changes and additions are simple to effect, others are considerably more difficult.

One major change involves the implementation of interrupt service routines to improve the real-time behavior of the language. It is imperative, for safety reasons, that there be reliable ways to stop the robot in the event of an imminent or detected collision, or upon receiving various types of imp . from the user. These routines may be complicated by the issue of communicating with the controller via an RS-232 link.

Another change that may prove challenging is the incorporation of inverse differential kinematics (straight line routines) routines into the language. Not only do these routines involve a great deal of calculation, they also require velocity control of the motors, a feature seldom present on inexpensive robots. Nonetheless, approximations of these routines can be implemented using many through points and/or the limited velocity control provided [Paul, 1981; Brady, 1983]

Conclusion

CALVIN is a fully functional robot control language that offers its users numerous benefits over the languages traditionally supplied with the purchase of a microcomputer-controlled manipulator. Clinical trails are demonstrating that the language is robust, easy-to-learn, and extremely useful for developing rehabilitation robotics applications.

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DESIGN OF AN OMNIDIRECTIONAL MOBILE ROBOT AS A MANIPULATION AID FOR THE SEVERELY DISABLED

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ABSTRACT

The design of a robot intended for human-service applications, which is the case for the Rehabilitative Robotic Aid under development at the Palo Alto Veterans Administration and Stanford University, is under different constraints than either an industrial robot or a classic telemanipulator system. Rather, an **Interactive Robot System** has unique design requirements stemming from the need to perform certain operations autonomously, yet at all times be responsive to human intervention to redirect the progress of a task. This paper will investigate the design issues, report on the current status of the project, and offer our solutions and thoughts about future system enhancements for discussion.

Introduction

The Veterans Administration/Stanford University Robotic Aid Project (VA/SU RAP) is currently developing a mobile, omnidirectional vehicle with a 6-axis robot arm mounted on it. The three-wheeled base and the arm are outfitted with an array of sensory subsystems to allow the unit to interact in a nondestructive and useful way with the environment it is intended to operate in, that is to say, a home or clinic where severely disabled individuals perceive the same needs to manipulate their personal space as the able-bodied, but would require human assistance to accomplish them. The RAP project seeks to develop a tool that can be commanded and controlled directly, by voice, by head-motion, and by residual limb movement, to perform certain typical manipulation tasks in such situations, and thus restore a significant measure of independence and privacy to the person who wishes to express himself thus

Background

The process leading to the design described below was initiated in 1979, with the start of the first phase of the VA/SU RAP The four years of this phase saw the development of a table-top Unimation PUMA-250 arm, enhanced by a host processor managing voice I/O units, diagnostic displays, a 6-axis joystick, and the robot arm itself[4]. The programming of the real-time aspects of the control of the arm was instrumental in guiding current software work.[1]

Over the past two years of this phase, the system underwent clinical trials, during which the system evolved in response to exposure to quadriplegic users at the Palo Alto VA's Spinal Cord Injury (SCI) Center. Additionally, a user and training manual was produced[3], and studies were performed to assess the success and viability of the voice-recognition unit as a control device[8]. This effort, in conjunction with continuing technological development, has led to the current phase of work[5], which centers on the implementation of an omni-directional mobile base, on the design of sensor systems, and on more sophisticated software to control the device Within several months, we will implement comprehensive performance assessment procedures with members of the intended consumer population at the SCI Center. This paper will concentrate on the design criteria and sensor sysem development.

Design Issues, Criteria and Choices

While proceeding through the various aspects of the design, one criterion should be reiterated: this is an interactive, semi-autonomous device that moves about human environments and is not only controlled by, but also in close proximity to, its principal inhabitants.

Mobile Base and Drive Train

The mobile base is intended to exist in a home or clinic environment, and must not itself be handicapped in maneuvering in such a space A wheelchair, hampered by the inability to crab sideways, is at a major disadvantage in places such as elevators and kitchens. An omnidirectional design by W. La[1] has been implemented for our vehicle. It consists of three motorized wheels mounted at 120°, each carrying a circumferential ring of rollers [see Figure 1]. The fact that the wheel shafts are fixed to the base greatly simplifies the turning problem, in that there is no steering gear per se, the rollers, intrinsic to the wheel design, allow for any combination of moving and turning. To move in a certain direction with a certain rotation requires only that the three wheels be driven by their motors in the prescribed manner.

This configuration represents the elegant minimum of wheels and motors for true omnidirectional locomotion. In addition, no suspension is required to keep all the wheels on the ground, as would be the case with four or more. The stability of the system is not significantly compromised, with the tip-over angle being a reasonable 24° This is due to the low center of gravity (10″ from the ground), achieved by mounting the batteries and the drivetrain components as close to the ground as possible, and installing the relatively lightweight computer equipment in the upper compartment of the base.

FIGURE 1: Mobile Base System. A view of the three-wheeled mobile system with the PUMA-260 arm and the sensate hand The base carries its own status display, shown in stowed position

The low number of drive components serves to reduce the size of the base overall, and reduce the power requirements. The base has a 24″ diameter and a 30″ height (without the arm). The weight of 350 lbs. is due in large part to batteries (150 lbs.), but is consistent with the weight of an electric wheelchair with its occupant. Battery power is sufficient for three to six hours of autonomy, depending on the duty cycle.

The ¼HP motors assure a 1.5 mph maximum speed and a 12° climbing angle, sufficient to be compatible with human walking speeds and typical wheelchair ramps

Robotic Arm

The arm we are using for this generation system is a Unimation PUMA-260 augmented with a force wrist and sensate hand. The arm will also acquire a "torso," or vertical and outward reach extender, to permit objects on the floor, on high shelves, and at the back of counters to be accessed. It was considered desirable to use a small arm, augmented in its reach, rather than a large fixed one, for reasons of safety and user acceptance. The manipulation of typical household objects rarely requires more than 5 pounds of force to be applied by the hand, robotic or human, so a larger and stronger robot arm was not mandated for this application.

Gripper and Force Sensor

The development of a smart sensate hand has been an area of research for several years [2,6], and the current design includes a set of 12 optical proximity sensors mounted on a one-motor parallel jaw gripper. Sensor readings are corrected in software for ambient lighting, and work is proceeding on the elimination of the effect of surface reflectivity. Algorithms are being established for automatic object centering and grasping and obstacle avoidance. The hand itself has a 10 lb. maximum grip, and is instrumented as to grip force and finger position

The force sensor measures all six force and torque components of the load applied at the hand The sensor is fitted into the wrist of the arm, and is optimized for the PUMA-260 and the hand being used It will allow such procedures as operating appliance pushbuttons, turning doorknobs, and obstacle and collision detection.

Current Status of Research

At this point, the mobile base and the arm are fully operational, with the lowest level of control implemented. The on-board computer has access to all the relevant system states, and is programmed to transmit these to the control workstation on command Omnidirectional motion has been implemented, as well as joint-interpolated and straight-line motion of the arm.

The software to accomplish the integration of the sensor signals, the commands from the host computer, and the outputs to the motor controllers themselves was written in DEC's MicroPowerPascal© by S. Michalowski, and is described in a companion paper in these Proceedings.

A first safety system has been installed, that being an instrumented 2-mph bumper. The bumper localizes the impact, and the controller can decide, for example, whether to push harder (to open a door), or to retreat (in the case of an unknown obstacle).

Future Developments

The design of the first base is being followed by the construction of four more units, all derivatives of the first one, but exhibiting newer technologies in terms of motor, drivetrain, and power amps. These units will serve not only as back-ups, but also as additional systems for path-planning, navigation, and sensor substation development Below is a discussion of some technology related projects currently in progress.

Ultrasonic Obstacle Avoidance System

An ultrasonic scanning system is being developed to establish a polar plot of the range from the base to the nearest obstacle. The system is expected to have a range of several inches to 50 feet.

Scanning Laser Absolute Ranging System

This system will employ fixed reflectors mounted at known locations in the mobile base's environment to extract absolute position information by triangulation.

Two-axis arm support

A "torso" is to be designed, as previously mentioned, to extend the manipulation range of the arm As yet. this feature has not been implemented.

Docking fixture

A "live" dock will be designed to provide the base with a fixed position reference, as well as a battery charger and a direct link to the stationary computer

Conclusion

This paper has concentrated on the design aspects of the system. Application, computer architecture, and software design are discussed in companion papers presented at this conference. The system under development promises to be a powerful test bed for research into the use of robotic technology as a manipulation aid for the severely disabled. The project has proven the feasibility of the technology, and now pushes on to establish its usefulness.

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REHAB BRIEF Bringing Research into Effective Focus

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ROBOTICS AND REHABILITATION

Space, deep-sea, and radio-active explorations called for the development of technology to allow humans to control inaccessible environments. Some of the solutions arrived at are now being transferred to allow sevei :ly disabled people to control their environments. Human-scale manipulators, used to increase independence and the quality of life for severely disabled people, have found a place in rehabilitation.

Richard A. Foulds, Ph.D., of the Tufts Rehabilitation Engineering program, introduces the World Rehabilitation Fund's (WRF) 37th Monograph in the International Exchange of Experts and Information Project, *Interactive Robotic Aids—One Option for Independent Living: An International Perspective,* with the following statement:

> In marked contrast to the science fiction androids popularized in the Star Wars films, these real life robots attempt to deal with the down-to-earth problems of employment, education, and daily living. Unlike fictional robots which are intended to replace human tasks, the rehabilitation robot serves as a direct extension of the disabled user in an attempt to increase the involvement and independence of that person.

The monograph, a state-of-the-art review, contains papers written by rehabilitation robotics research and development experts from the United States and abroad. This *Rehab BRIEF* will summarize these papers on uses of robotic aids and philosophical issues relating to their place in rehabilitation.

THE ARGUMENT FOR USING ROBOTIC MANIPULATORS

When manual skills are affected by disability, rehabilitation often centers on substituting or compensating for the losses of physical and sensory abilities in the hands. Craig W. Heckathorne, of Northwestern University, observes, "manipulation aids can be divided into two categories: those that are task specific and those that more generally assist in manipulation."

Remote manipulators and robotic devices may be task specific, but they also hold the promise of serving as general manipulation instruments. They can provide action at a distance. They can be used in unstructured environments, or they can carry out preprogrammed tasks within highly structured environments. They can be used to manipulate larger and heavier objects than an individual could handle with orthotic or body-actuated manipulation aids. And they can accommodate characteristics of the environment, supplementing the commands of the user.

EXAMPLES OF ROBOTIC USES

The ensuing overview will highlight several projects and give examples of tasks that were completed by individuals using robotic devices. Readers are encouraged to read the original report for more examples, more technical descriptions of the equipment, and more complete discussions of the configuration, price, and accomplishments of specific devices.

From France: Spartacus

The Spartacus project, a 5-year robotics project intended to stimulate the development of industrial robotics in France, conducted a feasibility study to develop and test a telemanipulator, controllable by people with high-level spinal cord lesions.

To optimize performance, a fixed work station with an arm derived from nuclear manipulators was used to explore the limits of control feasibility and to avoid failure due to mechanical limitations.

The Spartacus project studied manipulation of the mechanical arm by a variety of methods, depending on the physical abilities of the users. Switches or joysticks operated by chin or mouth, breath-operated switches, eye-movement controls, various versions of head-movement transducers, and hum, melody, and voice control were all used. Often the arm was controlled with the combination of methods that best served an individual.

These configurations allowed participants to complete the following tasks:

- pour liquids or "play with water";
- obtain objects from shelves;
- open cupboard doors;
- eat;
- light a lamp;
- draw or paint;
- drink—using a special mode that combines tilting and lifting a cup or glass, simultaneously controlled by a single signal (This task was considered a "landmark" since it showed that a certain level of

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confidence and dexterity in controlling the system had been obtained.);
- turn pages of a journal or a book;
- use a standard dial telephone;
- use an electric range to heat water and prepare a pot of coffee;
- play games;
- shave with an electric shaver; and
- play with "Rubik's Cube."

From the United Kingdom

At the Cambridge University Engineering Department, the potential of robotics to assist the developmental education of disabled children is being investigated. The project provides a facility in which disabled children can manipulate the environment. This includes tasks such as examining the sizes, colors, relationships, and shapes of objects. In one substantial clinical trial, three learning tasks were investigated. Two were basic developmental tasks that are not achievable by children with severe physical disability—yet are considered central to their education. These were a routine to stack blocks in a pile and then break the pile apart and a routine to sort blocks into boxes depending on their shapes and colors.

The third task was the Tower of Hanoi puzzle, consisting of a tower of discs with decreasing diameters which must be moved to a second location. The rules are that only one intermediate location can be used and at no time can any disc be placed on a smaller disc. The robot enforces the rules but gives the user control over moving the discs.

The color and shape sorting task offers a good example of how the robot works. It picks up each block in turn and presents it to the user to identify either its color or shape. Once the user indicates that he or she has seen the block, the robot tries to sort it. This may be done on a scanning basis, wherein the robot goes to each bin, in turn, and waits for a yes or no response from the user, or by direct selection where the user can indicate the correct sorting bin.

The robot ensures that the block is eventually sorted correctly; if the user gives a wrong command, the robot's response is to appear to try to put the block in the bin, but to refuse and give a negative sound before continuing with the program.

From Canada

The Neil Squire Foundation set out to create a manipulator that could perform tasks done by personal assistants and was approximately human size. The result was a robot called M.O.M. (a Machine for Obedient Manipulation). M.O.M. is designed as a work station manipulator (as opposed to being mounted on the wheelchair) for technical reasons. It is hoped that a "second generation" M.O.M. will incorporate artificial intelligence, giving the user better control and allowing the arm to be mounted on a wheelchair. Presently, M.O.M. can:
- pick up a manual from a bookshelf and place it in front of an individual;
- turn pages;
- pick up, serve, and replace a drink;
- serve up a mouthstick;
- load a diskette in a computer;
- pick up an electric shaver and shave a person:
- brush hair; and
- brush teeth.

The manipulator is lightweight and easily removed from and replaced in its stand. Therefore, it can readily be moved to a new work area—such as a bookshelf or bedside.

The Neil Squire Foundation is testing M.O.M. with disabled people ranging in age from 19 to 80.

From the Netherlands

Dr. A.P. Zeelenberg and his son who is disabled by muscular dystrophy report on the use of a wheelchair-mounted robot (the Cobra Manipulator). Remaining slight finger function allows the son to control the robot by using very responsive switches grouped closely together. More expensive pneumatic (sip-puff) or voice command devices are not needed. The manipulator and a specially designed interface mounted on the wheelchair allow the user to eat, turn pages, pick up books, and use remote control devices (for a television set, doors, and other appliances).

The user is able to open interior doors in the house and roll a small table on castors through the rooms. These tasks require good coordination between the right hand driving the wheelchair and the left hand operating the manipulator.

Recreation and work activities are also possible using this simple manipulator configuration. Playing chess, sandpapering wooden components for ship models, drilling holes in electronic printed circuit boards, and soldering components into circuit boards are among the tasks completed by the younger Zeelenberg.

From the United States

An Independent Vocational Work Station

Boeing Computer Services sponsored a project to experiment with a speech-controlled work station for quadriplegic programmers and analysts. The work station has a microcomputer system that supports and is driven by two voice-recognition products and a voice-communication product.

This hardware configuration allows single-voice commands to produce the equivalent of multiple keystrokes. The use of graphics, multiple programming languages, and access to different networks also are permitted.

The robotic aid at the station allows the user to:
- display reading material on the reader-board;
- handle filing in a file cabinet;
- handle floppy diskettes;
- adjust a printer according to the operator's commands; and
- perform miscellaneous support activities.

In this application, the location of the robotic aids becomes more than a functional consideration. Safety

Reviewer Comment

Ability to exert control over one's environment is of paramount importance to self-esteem and good mental health. To illustrate: when children master their first bicycles you hear the triumphant scream, "Look what I can do!" Also, in tracing the etiology of emotional illnesses and relapses, one nearly always finds loss of control over circumstances as a *causal* factor.

A major thrust of rehabilitation is to restore as much control as possible to those in whom it has been diminished by disability. Robotics (and other environmental-control approaches) have just begun to scratch the surface of potential applications. The research expense is often justified in terms of the practical value of promoting vocational productivity. However, there appears to be a more fundamental value—stabilizing and elevating mental health. This can make attainment of "practical" goals in all realms of living more probable.

Herbert C. Rigoni, Ph.D., C.I.R.S.

of the operators becomes critical. Maneuverability of the operator is limited. The operator's attention is frequently on the computer monitor of the reader-board. The robot is expected to carry out assigned tasks without attendance and without posing a hazard to the operator.

The robot's placement determines the design of the sort station. The robot must access the disk drives, printer, reader-board, file cabinet, bookshelves, in/out tray, waste basket, diskette storage, and user's lap and back pack. A robot with two arms was needed to perform all these tasks. A vertical file and shelves were designed for easy access by the robot. Manuals and books are stored in special vertical bookshelves. Modifications of the hardware were also required.

This work station and special programming of the equipment allow a quadriplegic computer operator to function independently in a business programming environment at Boeing Computer Services.

Small Robot Arm in the Workplace

The Rehabilitation Engineering Center in Wichita, Kansas, helped develop a work station that allows disabled people to solder tinning of the electrical leads of small components prior to inserting them into circuit boards. The operation requires picking up the part, dipping it in a liquid flux, then dipping the lead in molten solder, holding for three seconds, inspecting the lead for uniform solder coating, placing the part aside for cooling, and then placing the part in an alcohol bath.

Disabled workers at Center Activities in Wichita, with precisely set up work stations, are performing these tasks on a subcontract with the Boeing Company.

The following observations made by the research staff are of interest:

1. The robotic arm not only performs fine motor tasks but acts as a "pacer," forcing the worker to be ready for the next cycle of operations. Staff have found pacing to be difficult for many to grasp without some external indicator.
2. Use of a small console with push buttons to control the arm and enter programmed positions suited this project better than entry of programming data.
3. The human element of judgement was necessary in this task. A robot could not have done the work alone.
4. When production rates are required, a programmed repeatable cycle works better than manual manipulation of the robotic arm.

Robot Arm Work Station

The Johns Hopkins University Applied Physics Laboratory is responsible for a robot arm/work table system that enables high-level quadriplegics to execute manipulative tasks with little or no attendant assistance. This research program has now reached a stage where a manufacturing prototype has been fabricated and is in the final stages of evaluation.

The latest model incorporates a low-cost computer with adequate flexibility to permit programming a number of useful manipulation tasks on structured work stations. The robot arm is a 6-degrees-of-freedom, computer-controlled anthropomorphic limb.

Small vertical chin motion provides proportional control over selecting individual joint motions or prestored motion sequences, while a single pulse—activated by slight rocking fore and aft—causes an event to start or stop.

The work station places components in fixed locations on the work table so that the robot arm can use manual, step-by-step motion or prestored computer-controlled motion to complete tasks.

THE PROBLEMS OF GETTING MANIPULATORS TO USERS

The papers in the monograph offer differing opinions on the level of technology that should be applied to solve rehabilitation problems. There is no general agreement on the type of manipulator that best meets users' needs. One author argues for a powerful device, custom designed to meet the optimal needs of each user; another argues for the use of low-cost technology that will satisfy economic demands, but necessarily will be limiting. One author advocates preprogrammed robot motions to minimize the demands placed on users, another just as strongly advocates maximizing user control.

Reacting to the papers summarizing clinical evaluations, John H. Leslie, Jr., of the Rehabilitation Engineering Center, The Cerebral Palsy Research Foundation of Kansas, Inc., states that a device (robotic or otherwise) must satisfy two tests to have practical use in a service delivery environment. Use of the device must result in a cost reduction of the overall system funding base, and the device must improve the quality of life for the disabled person. He also cites the cost to the consumer, reliability of the device, product liability, and potential consumers other than the disabled market (such as elderly people) as important issues.

Leifer, Michalowski, and Van der Loos, of the Rehabilitation R&D Center, Palo Atlo Veterans

Administration Medical Center, and the Department of Mechanical Engineering, Stanford University, maintain that the use of robots is cost-effective because they can replace human labor which averages about $15 per hour while robot costs average $5 per hour and are decreasing. Prototypes are now being readied for production and marketing.

It appears that robotic manipulators can enhance the lives of some users and may have vocational applications. What will it take to make them available to disabled consumers?

Newman et al. reviewed the literature on technological development and its application to the problems of disabled people (see sources). They summarized government reports, private industry findings, service providers' r ommendations, and consumers' requests and dema. ..ted seven general problem areas in bringing technology to disabled consumers: (1) limited market, (2) lack of financial incentive in the development and distribution of technological products for disabled people, (3) inadequate technology transfer, (4) lack of coordination among the relevant disciplines, (5) no mechanism for dissemination of information, (6) no evaluation of or standards for products, and (7) lack of training related to rehabilitation technology.

The fact that this monograph on robotic aids has been produced just 4 years after such problems were summarized indicates that the problems relating to technology transfer, training, coordination, and dissemination are being addressed. The three remaining problem areas, relating to the market, incentives, and evaluation, comprise major obstacles to getting robotic manipulators to disabled consumers who could benefit from them.

Rehabilitation researchers, developers, practitioners, and users who are interested in robotics should look closely at these and start developing solutions if they are convinced of the value of robotic applications.

The Market. Recognizing the limited market and limited buying power of most disabled people, manufacturers often fail to see potential for profit. When they do produce products and recognize a profit, they have a captive market and little competition so there is little incentive to improve a product in response to consumer needs, or to price it competitively. In 1978, La Rocca and Turem* pointed out that many of the approximately 400,000 American wheelchair users are dissatisfied with their wheelchairs. Despite the multimillion dollar revenues, manufacturers have not significantly changed the design of the wheelchair since the 1940's.

Financial Disincentives. Robotic manipulators won't offer manufactures the financial rewards that wheelchairs do The expense of such product design and development is enc mous compared to that ' ased on needs of an aver- population and a much larger number of potentia' buyers.

Newman et al. identify additional financial disincentives.

> Evaluation for safety, durability, and reliability presents problems in that potential users must be identified and the evaluation may be conducted in a hospital or clinic, thus adding to the costs of development. Product liability insurance is also high. In addition, most manufacturers are not willing to solve the marketing problems encountered with disability products. These include the inability to exploit the usual advertising sources and the requirement that some products be prescribed by a physician. Manufacturers trying to be competitive find that there is no existing marketing system and that it is difficult to collect accurate information on the market. Another problem to be faced is that the manufacturer is often expected to provide modification, maintenance, and repair of products. This includes the training of sales and service personnel, and represents an unrealistic investment in light of the limited market for many of the products. Clearly, costs on the one hand, and market size on the other, minimize the profit potential for private manufacturers.

Evaluation and Standardization. Product evaluation, although expensive, is necessary. Objective determination of durabiity, reliability, safety, and appropriateness can only be made using consumers and professionals in time-consuming tests. In addition, from the papers presented, it appears to be nearly impossible to mass-produce or mass-market manipulators. Devices develo d on an individual problem/solution basis cannot be standardized.

Leslie and the c her authors are convinced that this technology can provide what all disabled people need—the chance to be productive human beings. Perhaps if government, industry, and rehabilitation work together to accomplish the costly research, design, development, production, and dissemination of robotic devices, this can come about.

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*LaRocca, J., and Turem, J.S. 1978 *The Application of Te hnological Development to Physically Disabled People.* Washington, D.C.: The Urban Institute

SOURCES

World Rehabilitation Fund, Inc., 1986 *Interactive Robotic Aids—One Option for Independent Living: An International Perspective* Monograph No. 37 New York. (To obtain a copy of this monograph, send $4.00 to WRF IEEIR, c/o Diane Woods, 400 E. 34th St., New York, NY 10016.)

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