APPLICATIONS OF SPACE TELEOPERATOR TECHNOLOGY TO THE PROBLEMS OF THE HANDICAPPED

Performed for:

Office of Technology Utilization
National Aeronautics and Space Administration

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Essex Corporation

Stanley Deutsch, Ph.D.
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ALL PROSTHETIC AND ORTHOTIC DEVICES REQUIRE THE PATIENT TO ACCEPT SOME INCONVENIENCES AND DISCOMFORT. IN RETURN, THE DEVICE MUST SIGNIFICANTLY IMPROVE HIS FUNCTIONAL FREEDOM.

PROSTHETICS AND ORTHOTICS

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TELEOPERATOR TECHNOLOGY APPLICATIONS

I Introduction

This report is concerned with identifying feasible and practical applications of space teleoperator technology for the problems of the handicapped. The scope of the study was limited to:

- Space teleoperator technology applications or areas where research and development, being conducted by or for NASA for space teleoperator systems, is directly applicable to -
- Problems of the handicapped, specifically those who have limitations or deficiencies in their manipulative, locomotive, or sensory capabilities.

A teleoperator system is defined by NASA as a "remotely controlled, cybernetic, man-machine system designed to extend and augment man's sensory, manipulative, and locomotive capabilities." The important attributes of the teleoperator system which serve to differentiate it from other advanced space systems are that it is remotely controlled by man, and that it exists for the purpose of extending man's physical capabilities beyond his physical presence. A teleoperator system usually incorporates remote sensors (visual and tactile), remote manipulators, remote control, and a mobility unit.

Based on a consideration of teleoperator systems, the scope of the study was limited to an investigation of these handicapped persons limited in sensory, manipulative, and locomotive capabilities. If the technology being developed for teleoperators has any direct application, it must be in these functional areas.

As the progress of technology development proceeds at differing rates and along differing lines in different fields of specialization, the number of technology transfer studies of this kind will increase. Such studies sometimes reduce to identifying an equipment item developed for one use, and then finding a place to apply the item for a different use. One problem with this approach is that since the item was developed specifically for the original use, its application for the second use must be something less than optimal. A second problem with this specific technology item application approach is that it fails to consider the total problem involved in the second use of the item and attempts to resolve only one part of that problem. This may result in only a partial or inadequate solution.

The approach taken in this study to circumvent the problem of seeking to apply an equipment item developed for one specific use to a different purpose was to deal with technology concepts rather than with actual designed equipment. Thus, the study did not investigate the applicability of space manipulators as such for the handicapped, but rather attempted to identify applications of manipulator technology, including conceptual approaches for manipulator configurations, actuators, end effectors, and control systems. In considering applications at the conceptual level rather than at the design level, full use may be made of the innovative approaches developed for space applications when investigating their potential benefit for the handicapped without being limited by the constraints imposed by a specific design approach.

This study attempted to resolve the second difficulty prevalent in technology transfer investigations, i.e., that of focusing on limited (but applicable) aspects of the problem by using the systems approach. This approach demands that the technology application be viewed as part of a total system with all of its characteristic inputs and outputs. Second, the systems approach provides a structure for identifying and describing not only the operations and elements of the system but also the interactions, dependencies, and relationships (both temporal and spatial) among operations and elements.

Finally, the systems approach places prime importance on the careful and comprehensive identification, analysis, and integration of functional requirements and constraints.

The significant problems to be encountered in attempting to identify applications of space teleoperator system technology to the handicapped result from differences in the two areas (space operations and rehabilitation), and from wide disparities between the two in resource availability (especially dollars). Space teleoperator systems are being designed to retrieve and service satellites on orbit, to transfer and handle cargo, and support on-orbit experiments. The common link between these teleoperator missions and the rehabilitation problem is that both require some sort of augmentation to the capabilities (natural or degraded) of man. In space the augmentation is provided through remote sensing and control. For the handicapped, the augmentation is provided to restore lost capability. The handicapped individual may be located distally from his worksite (as in the teleoperator operation), or he may be proximally located. In either situation it is expected that techniques and technologies being investigated for teleoperator systems, especially in the area of control systems and controllers, have application to particular problems of the handicapped.

A constraint imposed on the development of systems for the handicapped is that such systems should enable the handicapped person to perform an activity in a manner as close as possible to the way that activity is performed by a normal person. This constraint results from two separate although related factors. First, the handicapped person generally prefers to live his life in a manner which does not call attention to him as being different. Secondly, the objects and artifacts which he must handle, manipulate, and use in his everyday activities are designed for use by the normal person, having normal manipulative, locomotive, and sensory capabilities. This is not to suggest that consideration should not be given to modifying or redesigning objects to facilitate their use by a handicapped person. Rather, it focuses attention on the fact that for a handicapped person to function effectively in the modern world, he will need the capability, to some degree, to interact with elements of his immediate environment which were not designed to interface with his specific aid or device.

The scope of this study was not to develop concepts for systems for the handicapped. Rather, the scope was limited to identifying areas of space teleoperator technology which are analytically determined to have application to the problems of the handicapped, and to develop concepts for rehabilitation systems based on these applications.

The next section of this report describes the teleoperator technology efforts currently being pursued within NASA. Section III describes the needs of the handicapped and develops, based on these needs, the objectives of the rehabilitation system. Attention is then focused on requirements identified for the system and for the handicapped person interacting with the system. Finally, the section describes problems for the handicapped in terms of limited or deficient capability to satisfy requirements without the augmentation provided by a rehabilitation system.

Section IV describes the state of technology in the fields of prosthetics, orthotics, and sensory aids. Capabilities restored by different device or system concepts are identified. Limitations of existing devices are also established as problem areas, either where the device fails to be fully effective, or where its use causes additional problems for performance of intended or desired activities. These limitations might affect the safety of the handicapped individual using the device or his comfort or convenience.

The fifth and final section of this report describes feasible and practical applications of teleoperator technology for the problems of the handicapped. Design criteria are presented with each application and a development plan is established to bring the application to the point of use.

II Space Teleoperator Technology

Overview

Remotely controlled manipulators, called Teleoperators, are being developed by the National Aeronautics and Space Administration to perform operations in space under the control of man who may be located at some distance from the work area. This permits NASA to combine the advantages and unique capabilities of man and machine as an adjunct to man's operations in space. The Teleoperator system combines the decision making and adaptive abilities of the man with the strength, endurance, durability, and expendable nature of the machine. The purpose of remote manipulators is not to replace man but rather to enhance and extend his capabilities into areas where he is not ready to enter physically but where his intelligence is required. For example, the teleoperator would augment and assist the man in situations where his physical presence presents hazards to his safety, where his actual presence is not required to satisfy mission objectives or where his involvement enhances the effectiveness of what would be essentially an unmanned system.

The teleoperator system includes both men and machines in a symbiotic relationship. Man processes the information sensed in the remote environment, decides on a course of action and provides the control to the remote teleoperator. The teleoperator itself is at the actual worksite. It senses the environment and accomplishes the required work. In this way, man and teleoperator work as a team, each contributing unique and significant capabilities and each depending on the other to achieve the common goal.

The use of teleoperators is not new to NASA. The Atomic Energy Commission has used them extensively to handle radioactive materials since the 1940's.

NASA used an early form of the teleoperator in the 1965 Surveyor exploration of the moon when a remotely controlled scoop on an unmanned vehicle scooped up a portion of the lunar surface to permit examination of lunar soil structure. However, with the advancements in NASA developed technology, teleoperators now in planning will be required to perform much more complex tasks including elements of on-board intelligence in order to reduce dependence on man for direct control.

A newly formed team at NASA, chaired by Dr. Stanley Deutsch, has identified feasible missions for the teleoperator and the technology development requirements. The feasible missions generally include three types:

Operations in low and synchronous earth orbit
Exploration of the moon or Mars
Exploration of deep space and the outer planets

Teleoperators under consideration for earth orbital operations are usually associated with the space shuttle and also are of three classes. The first class is the shuttle attached manipulator which is a large boom mounted to the exterior of the shuttle, controlled by a man located within the shuttle. This boom performs such activities as transfer of cargo to and from the shuttle, maintenance and servicing of satellites and assembly of modules in space. A second earth orbital teleoperator, which can also be used in conjunction with the shuttle, is the free flying system. This device is a small, unmanned vehicle with manipulator arms, sensors, and propulsion systems attached. The vehicle, controlled by the shuttle crew, can fly from the shuttle to satellites and spacecraft in the vicinity to perform such missions as maintenance and repair and satellite retrieval. The third class of earth orbital teleoperators represents an extension of the free flyer in that it too can be launched from and recovered by the shuttle. This system can be either manned or unmanned, includes manipulators, sensors and expanded propulsion capability, and can achieve geosynchronous orbit for satellite support operations as part of the space tug system.

In lunar or Mars exploration missions, two types of teleoperators have been discussed. The first class of lunar or Martian teleoperator includes systems which are stationary on the surface and which sample and sense the immediate environment. The second category includes the unmanned rover which drives about the surface collecting samples, mapping the surface and performing experiments. In each of these classes, man is included in the system as the controller/supervisor and he is located remotely from the actual site, either on earth or in earth orbit.

Teleoperator development efforts are proceeding at Marshall Space Flight Center, Huntsville, Alabama, on the shuttle free flying teleoperator. Work is underway at the Manned Spacecraft Center, Houston, Texas, to develop the shuttle attached manipulators and booms. Much of the research and technology required for planetary and deep space missions is being developed at the Jet Propulsion Laboratory, Pasadena, California.

Advanced teleoperator technology problems are being resolved at the Ames Research Center, Moffet Field, California.

The significant areas where teleoperator research and technology development is required include sensors, manipulators, actuators, control systems, and mobility, each of which are concerned with the man/machine interface. Sensors under development include video systems, touch sensors, force sensors and environment sensors. Manipulators include mechanical arm-like devices, grapplers, surface samplers and end effectors or tools for performing required mission operations. Actuators include hand and finger-like devices to perform tasks. Control system technology includes use of computer aided devices for manual control of manipulators, free fliers, sensors and support systems. Control technology for planetary teleoperators also includes artificial intelligence, which involves development of techniques of machine learning and adaptive control for providing some level of semi-autonomous behavior for systems located too far away to be controlled directly. These approaches provide the teleoperator with a limited amount of on-board intelligent behavior. Mobility System technology comprises integration of subsystems and development of navigation, guidance, and propulsion or locomotion systems. The man/machine interface area includes all aspects of the effort to integrate the human operator with the system hardware and software. On the machine site this involves worksite technology, manipulator/effector technology, and controllers and displays. On the man site the technology area includes sensory feedback, determination and maintenance of skills and skill levels, and measurement of operator workloads.

Teleoperator Technology Requirements

The specific technology requirements in each of the six teleoperator technology areas listed above are described in the following sections.

1. Sensor Technology

The overall objective of the sensor system is to acquire and process information concerning the remote environment, the worksite, or the teleoperator itself. The most important sensor for the teleoperator as for the man is the visual system. This system includes television cameras, picture processing, television displays, lighting, markings and aids at the worksite and at the display, and the operator himself. Specific technology efforts associated with visual system development include determination of design criteria for cameras, communications, processing displays, illumination, and markings and aids.

The technology development activities currently being implemented by NASA for the teleoperator visual system are being conducted primarily by Marshall Space Flight Center (MSFC), for the range of earth orbital teleoperator systems and missions, by the Johnson Space Center (JSC), for the shuttle attached manipulator system, by the Jet Propulsion Laboratory (JPL), for planetary teleoperator systems, and by the Ames Research Center, for advanced technology. The visual system work being accomplished and planned at MSFC involves the conduct of man-systems simulation investigations to initially define and describe the basic human operator performance capability, and then to develop design concepts and criteria for each subsystem of the visual system for each teleoperator mission. Advanced system concepts will investigate the use of computer generated graphics, flat screen displays, alternate techniques for presenting stereoscopic or three-dimensional information, and integrated display techniques. Efforts at JSC and JPL are more specifically concerned with visual requirements for shuttle attached teleoperator missions and planetary rover operations respectively.

The technologies being developed for non-visual teleoperator sensor systems include navigation sensors, ranging and proximity sensors for obstacle avoidance, environment sensors, analysis sensors, spatial orientation sensors, and sensors for acquiring feedback concerning manipulator operations, including force feedback, kinesthetic feedback or arm-effector position and orientation, tactile or contact feedback, and grip integrity feedback. These sensor technologies involve adaptation and integration of existing and advanced technology development efforts for radar systems, lazers, force/torque measuring systems, navigation and guidance systems, and accelerometers and rate measuring systems.

3. Actuator Technology

Actuators and drives for space manipulator systems include electrical motors or hydraulic drives. Specific technology efforts in this area will probably be limited to adapting technologies developed for other systems.

End effector technology work involves investigation of simple prehension devices, articulated graspers, and general or special purpose tools. NASA teleoperator technology development efforts are proceeding at MSFC to develop concepts and criteria for satellite capture graspers, an articulated three-fingered mechanical hand for high precision and dexterous activities, mechanically activated triggered hands, and a set of replaceable plug-in hand tools to serve as end effectors.

Worksite interface technology efforts are concerned with developing design concepts and criteria for the elements of the worksite which are physically contacted, held, manipulated, or otherwise used, by the manipulator/effector system. These include handholds, attach points, latches and locks, switches and control devices, fasteners and connectors, and module rails and alignment aids.

4. Control Systems

The efforts being accomplished for development of teleoperator control system technology are concerned with control of manipulators, mobility systems, and sensor systems. Manipulator control concepts under investigation range from direct manual control through computer aided control and supervisory control to adaptive control. In the manual mode, all control inputs are from the human operator via a controller. Advanced controller concepts are being developed by MSFC, MSC, and Ames Research Center. Controller design concepts are of two general types: individual manipulator joint control and integrated control. In joint control, the operator controls each degree of freedom of the arm individually to position the terminal device at the desired location and orientation. Examples of this class include pushbutton and switch control and stick controllers. The integrated control class includes concepts which require the operator to attend only to the position of the end effector with the motion of the arm following the control of the tip. Examples of this class include miniature replicas, analog controllers, and master-slave or exoskeleton controller configurations.

In computer assisted control some portion of the control task is performed by the computer. One promising technique of computer assisted control incorporates an advanced version of integrated control described above. The operator controls the position, orientation, and rate of change of the end effector, while the computer controls the manipulator degrees of freedom to position and orient the effector as commanded. Several controller concepts for this approach have been developed for, and are being evaluated, by MSFC.

Supervisory control involves having the human operator select a control sequence and activate it. The sequence is then performed in a pre-programmed fashion by the computer. This mode of control was employed in the NASA Surveyor System which performed remote sampling of the lunar surface in 1965. It was also used on the Russian Lunokhods I and II which were unmanned remotely controlled lunar roving vehicles placed on the moon in November 1970 and January 1973 respectively.

Adaptive control is similar to supervisory with the exception that the computer or logic system learns to perform required operations in the remote environment rather than carrying programs for control of these operations. Such control becomes a requirement for teleoperator systems operating at the great distances of Mars and deep space, where the time delay in telecommunications becomes excessive. In the case of a vehicle on the surface of Mars, communication time delays of up to 40 minutes can be expected.

While the emphasis for manipulator control is on the use of hand controllers or computer control to some degree, other techniques are being investigated for control of visual system components, such as camera angle, zoom, and transmission mode. Concepts involving the use of sight switches, head aimed TV, and photo sensitive switches are being investigated. In the latter concept, an operator would direct a beam of light (by head motion) to the appropriate cell of a matrix of light sensitive switches to affect the desired control switching.

5. Mobility Systems

The two basic requirements in the mobility system technology area include development of concepts for the actual teleoperator vehicle and integration of vehicle structures and support systems with sensors and manipulators. Work is proceeding at MSFC on the mobility system for the shuttle free flying teleoperator. Work has been done and is proceeding both at MSFC and JPL on lunar and planetary roving teleoperators. These systems will incorporate wheel or track locomotive systems and an array of special sensors and manipulators.

6. Man-Machine Interface

Since the teleoperator system always includes man to some degree, primarily in the control input and information processing elements of the control system, the man-machine interface technology for these systems takes on added significance. The primary areas of interest include: development of control and display concepts and criteria; specification of operator skills, skill levels, and workloads; and development of man-system simulation and evaluation technology.

Efforts in the control and display development are closely associated to developments in the teleoperator control system and sensor system technology areas. These efforts are basically concerned with the integration of these elements and the derivation of design concepts for data formats and rates, controller handling qualities and response characteristics, display aids, and workspace arrangement and layout. At a more basic level, the man-machine interface efforts are concerned with establishing system performance requirements, allocating system functions to man or machine, specifying the role of man in the system, and developing position descriptions for each operator in the system.

One of the more important technologies being advanced by teleoperator systems development involves man-systems evaluation. At present, full scale simulation programs are underway to investigate human operator capabilities and requirements in teleoperator systems at MSFC, JSC, and JPL. At Marshall, four separate teleoperator technology laboratories have been established, concerned with: visual system studies; computer based dynamic investigations; mobility system studies; and manipulator system studies. At JSC a model of the shuttle attached manipulator is being used to investigate control capabilities of the man. At JPL a number of studies are underway to investigate the requirements of man and computer in the control of a planetary roving teleoperator system.

This description of current teleoperator technology efforts is admittedly broad and general. The intention in this section was to provide some orientation to teleoperator technology efforts and requirements as a base for the technology application to be discussed in the final section.

III The Handicapped - Needs, Requirements and Problems

The scope of this study is limited to a consideration of the handicapped who suffer deficiencies in one or more of the following functional capabilities: manipulator, locomotion, or sensation. This would include: those who are limb deficient (amputees and persons with congenital limb deficiencies); those who have lost the use of one or more limbs through spinal injury, stroke, or disease; those who have abnormal limb function (palsy, arthritis); and those who have lost the use of one of their primary senses (vision, hearing, touch, or kinesthesis).

The Handicapped

The handicapped persons of concern in this report include essentially those with paralysis, absence of a major extremity, visual impairment, and hearing impairment. The incidence of these handicaps was reported by the Department of Health, Education and Welfare in 1968. The statistics, in terms of rate per 1,000 persons in the general population, are presented below:

Type	Ratio per 1,000 Population
Paralysis	8.1
Absence of major extremity	1.4
Visual impairments	28.8
Hearing impairments	45.7
Other impairments of limbs, back, trunk	94.8

The HEW report, in addition to citing the incidence of major handicaps, also indicates that there has been a marked increase in the prevalence of defects over the period 1957-1965. The only handicap which has not increased in incidence over this period is the absence of extremities (1.7 in 1957).

The proportion of males and females who suffer some limitation of activity is comparable. However, a much greater proportion of males are completely unable to carry on major activities as compared with females (34.4 vs. 23.8% respectively). The proportion of paralyzed individuals who are limited in their activities increases with age, with 50.7% of paralyzed individuals being limited in the under 45 age range, 61.5% for the 45-65 age category, and almost 75% for the over 65 group. This latter statistic means that 3 out of 4 over 65 paralyzed persons are limited in performing major activities. Of these, slightly more than half are completely unable to perform major activities.

2. Absence of Extremities

The HEW study reports that 257,000 persons suffered from the loss of a major extremity (arm, hand, leg or foot). Of these, 86% were males and only 14% were females. The rates per 1,000 population for males and females were 2.4 and .4 respectively. A total of 69.3% of persons deficient in one or more limbs was less than 65 years of age, and 83.3% were classified as white. In terms of income, 36.6% of the limb deficient persons earned less than $3,000 per year (25.8% for persons under 65 years of age, and 60.8% for those over 65). Limitation of activity was reported for 61.1% of the limb deficient individuals (50.7% for those under 45 years of age and 65.6% for those 45 and older). The etiology of limb deficiencies was injury in 70.8% of the cases in the 1965 HEW study.

Other studies indicate that peripheral vascular disease is now the most common cause of lower-extremity amputation. A Swedish study by J. Hansson covering the Western world shows that amputations due to peripheral vascular disease increased from 2% of the total in 1926 to 57% in 1955. H. W. Glattly listed vascular disease as the primary cause of amputation in 54.75 of males and 69.9% of females in a 1964 study of 12,000 new amputees in the United

States. The Committee on Prosthetics Research and Development of the National Academy of Sciences shows that 68% of the current amputee population of 311,000 in the U. S. are lower-extremity amputees and 70-90% of those (48-61% of the total) are secondary to peripheral vascular disease. McCollough, et al, who cite the three previous reports, also note in their own study of 625 lower-extremity amputations that 86% were secondary to peripheral vascular disease and nearly 70% were over 50 years of age.

The New York University Post-Graduate School Text on Lower-Extremity Prosthetics notes that lower-extremity amputations exceed upper-extremity amputations by a ratio of 85 to 15, and that the leading cause of all amputations is disease (50%) rather than trauma (33%).

3. Non-paralytic Orthopedic Impairments

The HEW study defines other defects to limbs, back, or trunk as excluding deformities and disc conditions, and including: limitations of motion; stiffness (complete or partial); flail joint; instability of joint; ill-defined, symptomatic but chronic difficulty, weakness, trouble, pain, swelling, limping, involving muscles, joints, limbs, back, or trunk, of unknown cause or due to healed injuries three or more months past or to past or now inactive diseases. The report states that 17.7 million persons suffered such disorders in 1965. Of these, 36.6% reported problems with the back or spine, 16.5% had upper extremity problems, and 37.3% had lower extremity problems.

The etiology of these problems was injury in 69% of the cases, and congenital or birth defects in 6.4%. For upper extremity impairments, 83.6% were caused by injury, while 4.5% were due to congenital or birth defects. For the lower extremities, injury was cited as the cause in 71.8% while congenital or birth defects resulted in 11.1%. For back and spine problems, 56.9% were due to injury while 3.7% resulted from congenital or birth defects.

A total of 73% of all defects were due to injury for males while 64.4% were attributed to injury for females. The proportion of impairments due to congenital or birth defects was identical for both males and females. There is no relationship between incidence of these impairments and annual income of the disabled person.

In terms of the degree to which impairments limit the ability to perform activities, the following statistics were noted:

For all impairments:

Limitation of activity - 21.7%
Unable to do major activity - 2.9%
Limitation in amount or kind - 13.0%

Back or spine:

Limitation of activity - 27.3%
Unable to do major activity - 2.5%
Limitation in amount or kind - 17.6%

Upper extremity:

Limitation of activity - 13.7%
Unable to do major activity - 1.7%
Limitation in amount or kind - 8.8%

Lower extremity:

Limitation of activity - 20.0%
Unable to do major activity - 3.6%
Limitation in amount or kind - 10.6%

Other and multiple impairments:

Limitation of activity - 33.4%
Unable to do major activity - 5.6%
Limitation in amount or kind - 19.9%

4. Visual Impairments

The HEW Report classifies 5.4 million persons as being visually impaired in 1965. Of these, 56% were females, and 46% were 65 years of age or older. Of the total number of visual impairments, 1.2 million (22%) were classified as severe (inability to read ordinary newspaper print with glasses, and impairment indicating no useful vision in either eye). Of the severely impaired, 63% are females and 69% are 65 or older. In terms of income, 60.6% of the severely impaired have a family income of less than $3,000 per year.

The impact of severe visual impairments on the capability to perform everyday activities is such that 53.6% of individuals severely impaired are limited in their activities, with 27.6% of these being unable to carry on major activities while 21.3% are limited in the amount or kind of major activities. The impact of impairments is greater for males than for females, with 38% of males and 22% of females being unable to perform major activities. Persons who are severely impaired and who are over 65 years of age are unable to perform major activities in 31% of the cases.

5. Hearing Impairments

As reported by the HEW study, in 1965 there were 8.5 million persons suffering hearing impairments in the United States. Of these, 56% were males and 58% were less than 65 years old. A total of 11% of the general population less than 65 years of age were classified as having hearing problems while 48% of the 65 or older population was so classified. Of this latter group, 32% were 75 or older. The actual etiology of hearing impairments is established in only 28% of the cases and, of these, 20.5% are due to infection with 7.6% due to injury. A total of 36.6% of the persons with hearing defects had a family income of less than $3,000 per year. For $4,000 or less, the figure was 46%.

Hearing impairments do not have a major impact on the capability to perform activities, with only 5.4% suffering limitations to activities and 1.7% being unable to perform major activities.

Summary

The data from the HEW study indicates that 2.75% of the general population are limited in their capability to perform normal activities due to paralysis, deficiency in limbs, and non-paralytic orthopedic impairments. To these can be added .6% of the population who are functionally limited due to sensory impairments, and we have a total of 3.35% of the population handicapped to the extent that they are limited in their ability to perform activities.

The proportion of persons affected with each type of handicap who are limited in their everyday activities is summarized below:

Type of Handicap	Proportion of those Limited in Activities
Paralysis	60.9%
Absence of major extremities	61.1%
Non-paralytic orthopedic impairments	22.9%
Affecting back or spine	27.3%
Affecting upper extremities	13.7%
Affecting lower extremities	20.0%
Other and multiple disabilities	33.4%
Severe visual impairment	53.6%
Hearing impairment	5.4%

As indicated by these data, persons suffering paralysis, absence of major extremities, and severe visual impairments are the most handicapped in terms of the proportion of persons who are limited in performing activities. For the handicaps associated with paralysis and absence of extremities, 6% of 10 persons so afflicted are limited in their capabilities. Over half of the persons suffering severe visual impairments are limited in terms of their capabilities to perform normal activities. Almost one person in four who have non-paralytic orthopedic impairments are functionally limited, while only one in twenty persons having hearing impairments are limited in their normal capabilities.

An important benefit to be derived in applying the systems approach is that design concepts are based on the set of integrated system requirements. Relying on requirements not only reduces the time required for conceptual design but also reduces the number of, and cost of, concepts which when fabricated are found not to be effective.

The careful identification of system requirements also facilitates the identification of problems for the handicapped. Such problems are of two types: those problems associated with the disability itself, in terms of reduced performance effectiveness or safety; and those problems associated with the effectiveness, or lack of effectiveness, of the system for the handicapped.

Needs and System Objectives

The primary need of the handicapped person is for independence. The Britannica World Language Dictionary defines the word "handicap" as any disadvantage or hindrance making success in an undertaking more difficult. To the degree that a person is hindered in performing a task, he is dependent on someone else to assist him. If means were provided to enable a quadriplegic, who has lost all use of his four limbs, to function independently of outside help, that person could no longer validly be designated as being handicapped or disabled. Such restoration of function is the objective of rehabilitation and the essential activity in rehabilitation is enabling independence in daily living.

It might be argued that causing a handicapped person to rely or depend on a mechanical device to perform his required functions is really not making him independent. Actually, man depends more and more on mechanical aids in his everyday life. He depends on transportation systems to take him where his legs cannot. He depends on the telephone to carry his voice to great distances. He depends on typewriters, ovens, elevators, oil well machinery, etc., without ever feeling dependent on these machines. Dependency is an inter-personal relationship which connotes reliance, and, to some degree, subjugation. Case histories of disabled individuals are repleat with the psychological problems attendant on dependency on another person for even the most basic of human functions.

Given the need for independence, the first objective of a system for the handicapped should be that the system enables the person to be independent, to be sufficiently competent to perform required or desired activities without the assistance of another person, i.e., to cease being handicapped in the dependency connotations of the term.

The second important need on the part of the handicapped is for a full capability of performing his required or desired activities effectively, safely, and with some degree of comfort. While no devices will return him to the full levels of dexterity, mobility, or sensory discrimination possessed by the normal individual, devices are being developed which can enable him to perform his daily activities with some degree of effectiveness and efficiency, safely, and comfortably. Therefore, the second objective of a system for the handicapped is to enable the disabled person to perform his required and desired activities with effectiveness, with accuracy, with minimal time and effort, with safety, and with comfort.

The third need of the handicapped is for normalcy. Any device, other than those absolutely required and which are more or less commonly encountered (such as a wheel chair), which calls attention to the user will be viewed with disfavor by that user if he doesn't outright reject it. The handicapped person desires to live in the normal world in a normal way. This attitude is based, not only on a desire for conformity, but also on expediency. The artifact environment surrounding us today is specifically tailored to the use of the human hand, and arms, legs, vision, hearing and locomotion. For a handicapped person to cope in such an environment must require that he interface with these artifacts in a manner resembling the mode used by his normal neighbor. In satisfying this need for normalcy, the system must achieve compromises with the first two needs, independence and performance capability. Obviously, not all objects encountered in the everyday world will or should require complete adaptation on the part of the handicapped system. Attention should be focused on the engineering design of objects encountered in everyday life to facilitate their use by the handicapped, the aged, the encumbered, as well as the "normal". Thus, public transportation systems should incorporate facilities and design principals to make their services more accessible and acceptable to the blind, the wheel chair bound, the individual on crutches, the arthritic, and the amputee.

While the design of public facilities, such as telephone booths, street curbs, flights of stairs, etc., must take into consideration the capabilities and limitations of the handicapped, it is obvious from past experience that such consideration may not rank high in the planning of such facilities. Rather than requiring the handicapped individual to wait patiently for a renewal in the planning of public accommodations, which would view their rights as equal with those of the "normal", systems must be developed (and are being developed) which enable the disabled person to cope with the world as it presently exists. Therefore, the third objective of a system for the handicapped is that it enables independent, effective, safe, and comfortable performance of activities in a manner approximating the normal. The essence of this objective is that a device be designed such that it does not call attention to the user while enabling him to interact with everyday objects and equipment items.

The fourth and final important need identified for the handicapped is for accessibility of objects in the environment. This need is usually reflected in a need for mobility on the part of the disabled, or a need for aided reach and prehension, or a need for shape coding to enable the blind to recognize objects. The patient restricted to a bed is severely limited in terms of the accessibility of objects. If he is limb deficient, paralyzed, or blind, the limitation is compounded. The need for accessibility implies that not only must a person be able to reach the object, but that once obtained, the object is configured or designed to facilitate its handling, operation, and use by the handicapped person. This need represents an alternative approach to the third objective since it requires, in some cases, special design features for objects. The fourth objective of a system for the handicapped is, therefore, that the system enhance and facilitate access to and use of required objects and artifacts.

The objectives of a system for the handicapped are as follows:

- The system should ensure a high degree of independence on the part of the handicapped person.
- The system should enable the performance of required and desired activities in a manner which is effective, safe, and comfortable.
- The system should emphasize the performance of activities in a manner which approximates the "normal".
- The system should enhance the accessibility and use of objects used in everyday activities.

System Requirements

The one idea common to the four objectives of a system for the handicapped listed above is the need to enable the handicapped person to perform activities. The four objectives may be summed by one system goal which is to enable and facilitate the performance of required and desired activities with effectiveness, safety, and comfort, in a manner which is independent of outside assistance and which approximates the normal, and which assures accessibility and usability of objects and items needed to perform the activities. Precisely what activities should the system enable? Obviously, the ultimate goal is to enable the handicapped person to perform any activity which he would be capable of performing if he was not handicapped. With the present state of technology this goal is still beyond our reach. A more practical approach is to ensure that the handicapped can at least perform those activities identified as being important for daily living.

The activities to be enabled by the system constitute the functional requirements of the system. These functions describe what the system must do. As such, they provide the framework for establishing the capabilities which the system must possess. The level of capability which must be incorporated into the system is derived from performance requirements, which define the accuracy, time, and energy requirements associated with each system function.

Functional requirements or system activities were developed based on an identification of what normal adult persons do in their daily lives. The initial classification of functions resulted in the following list:

- Eat and drink
- Food preparation
- Self care, including hygiene, waste elimination, grooming, and sleeping
- Dressing and undressing
- Translocation and transportation
- Work and recreation
- Shopping
- Housekeeping and personal equipment care

Obviously, a large number of tasks can be identified for each of these functions, some of which are dependent on the particular objects and systems used to perform each function while others are more or less independent of the means employed to complete the function. The tasks developed for each function will also differ in terms of their importance or criticality to the performer. In recognition of the advantages of taking a functional approach to describing the handicapped and of the importance of establishing priorities of activities, R. P. Mcwilliam of the West Henden Hospital in London reported an investigation of everyday tasks for use in prosthesis design and development

(Bulletin of Prosthetics Research, Spring 1970). McWilliam stated that prosthetics design should begin with a statement of all required functions and properties to be provided. A major portion of this statement would be a list of the purposes for which the prosthetics was to be used. According to this investigator, tasks should be specified in sufficient detail to enable an analysis of the essential functions, which could then be described in engineering terms as design data. The analysis should extract not how the normal person does the tasks but rather the necessary conditions for their performance.

In the McWilliam study a small sample of able-bodied doctors, engineers and their families were surveyed to identify the activities usually pursued in everyday life. No consideration was given to job related or recreational activities due to the expected variability in responses. The result of the survey was essentially a functional specification for powered upper limb prosthesis. Little or no consideration was given to locomotion or sensory disabilities. A listing of 625 tasks were compiled, each of which was then rated by the respondent as being essential, useful, or trivial. A total of 23% of the tasks were viewed as being essential, with 50% being useful and 27% rated as trivial.

Based on the task list and priority assignments reported by McWilliam, a classification of functions and tasks was developed. This list of functions and tasks included all of the activities cited by McWilliam as being either essential or most useful. To these were added tasks associated with general work and recreational activities as well as locomotive tasks. The final list numbered 205 tasks which are presented in Table 1.

For each task included in Table 1, performance requirements were identified.

TABLE 1

Everyday Living Tasks Rated by Engen (1970)
As Being Essential or Most Important

FUNCTION/TASK

EAT-DRINK:

Essential Tasks

Load spoon from jar, bowl, plate
Unload into plate, mouth
Impale with fork
Use fork as spoon
Use knife to cut, push, spread
Stir with spoon
Wipe mouth, fingers
Lift-tilt cup, tumbler, wine glass, jug, bottle, mug
Pour from jug

Important Tasks

Push with fork
Lift with fork
Peel fruit
Hold food with fingers
Serve soup
Open tab cans

FOOD PREPARATION:

Essential Tasks

Unscrew jar, bottle
Undo tin, packet
Hold kettle
Pour from kettle
Turn on cooker
Light gas cooker
Spooning
Undo milk bottle

Important Tasks

Lift dishes
Lift out cutlery, plates, cups, glasses, jars
Lift from hooks
Hold Saucepan
Lift lid
Stir-turn

Shake
Pull off lids - tops
Screw lids, corks
Pick up dishes, pans, food, small pieces
Undo butter packet, plastic film
Open oven door
Close

SELF CARE:

Essential Tasks

Wash:
- Turn taps
- Wash with towel
- Dip towel in water
- Squeeze

Teeth:
- Unscrew tube
- Squeeze-apply
- Brush teeth

Hair:
- Brush
- Comb

Lavoratory:
- Raise-lower seat
- Unroll -pull off paper
- Wipe
- Flush
- Arrange clothes
- Position body

Handkerchief:
- Get handkerchief
- Apply to nose
- Wipe
- Get tissue from box

Shave:
- Apply lather
- Move razor over face

Makeup:
- Undo lipstick
- Apply makeup
- Undo powder container
- Undo cream container

Bed:
- Get in-out
- Push/pull bedclothing
- Push/pull pillows
- Turn while sleeping

Important Tasks

Wash:
- Lift-replace towel
- Lift-replace wash rag
- Apply ointment - lotion
- Rub any part of body

Teeth:
- Clean dentures

Handkerchief:
- Fold
- Clean nose

Bathing:
- Hold side of tub
- Get into tub

Grooming:
- Cut-trim nails
- File-clean nails

Shave:
- Handle electric razor

DRESSING:

Essential Tasks

Hold-insert head or limb
- shoes
- socks
- stockings
- garter
- girdle
- bra
- pants
- trousers
- jersey
- shirt
- coat
- pajamas
- nightdress
- dress
- slip
- vest

Do-undo buttons, zipper,hooks
Tuck in - adjust
Lift-replace garments
Hang up skirt, coat, trousers
Put on watch
Put on boots

Important Tasks

Do-undo tie, snaps, pins, laces, buckles, braces, cufflinks, scarf, belt
Put on gloves

TRANSPORTATION:

Essential Tasks

Public:
- Get money from pocket
- Hand over money/ticket
- Put in slot
- Pick up from counter
- Hold rail-strap
- Ticket from purse
- Open train door

Private:
- Get in car
- Operate windows
- Operate car

Locomotion:
- Move about room
- Move on sidewalk
- Cross streets
- Climb stairs
- Carry luggage

WORK/RECREATION:

Phone:
- Lift-handle
- Dial

Read:
- Get book
- Get magazine
- Hold steady
- Turn pages
- Place on knee - table
- Read
- Turn on light
- Adjust light

Newspaper:
- Fold - unfold
- Handle - turn

Letters:
- Open
- Pull out
- Unfold

Write:
- Pick up paper
- Write
- Fold paper
- Place in envelope
- Seal
- Stamp
- Put in box

Radio - TV:
- Turn knobs
- Operate toggles

Handling:
- Office equipment
- Packages
- Tools

Doors:
- Handle keys
- Open doors
- Operate bolt
- Ring bell
- Use knocker

Recreation:
- Sports
- Card games
- Piece games
- Puzzles
- Painting
- Drawing
- Tooling
- Handicraft
- Ceramics
- Electronics
- Records

MISCELLANEOUS:

<u>Essential Tasks</u>

Plug in-out
Open-shut drawers, cupboards
Carry shopping bag

<u>Important Tasks</u>

Wipe spectacles
Put on-off spectacles
Wind watch
Two handled cupboards
Pushbuttons
Wind clocks
Set hands - alarm
Shut off alarm

These factors included requirements under three categories: manipulation, mobility, and sensation. The performance requirements were developed to identify the motion, types of forces, precision, and sensory feedback requirements usually attendant on the performance of each task. The specific requirements identified for each task in this analysis consisted of the following:

Manipulative Requirements:

Hand requirements

- Prehension or grasp - one hand or two
- Hand use other than prehension
- Requirements for precise placement of the hand or hands
- Requirements for the application of force
- Requirements for high dexterity in handling or manipulating objects associated with the task
- Requirements for different hand configuration during performance of the task, as dictated by the objects encountered and the motions involved
- Requirements for applying twist force
- Requirements for applying push-pull force
- Requirements for wrist rotation or flexion

Arm requirements

- Requirements for elbow flexion or extension
- Requirements for shoulder rotation or extension
- Requirements for gross arm motions
- Requirements for fine arm motions

Mobility Requirements:

- Requirements for trunk mobility short of whole body mobility
- Requirements for whole body mobility
- Requirements for translocation

Sensory Requirements:

- Requirements for visual feedback
- Requirements for kinesthetic feedback

The level of each requirement for each task was determined on a three point scale, such that a rating of:

0 indicated no requirement
1 indicated a potential requirement, depending on the objects used and the circumstance of use
2 indicated a definite requirements

The results of the performance requirements analysis for each of the 205 tasks are presented in Appendix A. In this appendix the designator of "level" immediately under the function title indicated the priority of the list of tasks, with an A level including those tasks cited by McWilliam (1970) or judged by the present authors as being essential while a B rating comprises the tasks judged to be important.

A summary of the requirements listed in Appendix A is presented in Table 2. Inspection of this table reveals some interesting requirements. While it is not surprising that a large proportion of the tasks require prehension (94%) since most of the tasks were from the McWilliam list which emphasized manipulative tasks, what was significant was the number of tasks which normally require two hand operation (80 tasks or 39% of the total). Precision placement of the hand is required for almost two-thirds of the tasks and is more important for one hand than two hand activities. Forces are required in 91% of the tasks with more importance being attributed to linear forces (push/pull) than to rotational forces (twist). One fifth of the tasks require both a linear and a rotational force.

Reasonably good hand dexterity is required for almost half of the tasks as is the capability of varying hand configuration during the task.

In terms of joint actuations the wrist and the elbow are involved almost equally and the frequency with which either is required for the tasks exceeds the frequency of shoulder motion. A little more than half of the tasks require motion of all three joints during task performance. Very few of the tasks require single joint activities (wrist alone, elbow, or shoulder).

About one-third of the tasks require gross arm motion while almost two-thirds demand fine motion control. About one-fifth of the tasks require trunk mobility while one-tenth require whole body mobility. Only 7 percent of the

TABLE 2
Summary of Performance Requirements

Task Requirement	Overall		One Hand		Two Hands	
	Number of tasks	%	Number of tasks	%	Number of tasks	%
Manipulation:						
Prehension	192	94%	117	61%	75	39%
Use of hand(s)	192	94%	112	53%	80	47%
No use of hand(s)	13	6%				
Precise placement	128	62%	80	63%	48	37%
Force application	186	91%	108	58%	78	42%
Twist	49	24%	22	45%	27	55%
Push/pull	143	70%	72	50%	71	50%
Both	40	20%	16	40%	24	60%
High Dexterity	92	45%	48	52%	44	48%
Precise placement and Dexterity	86	42%	46	53%	40	47%
Variable configuration	91	44%	40	44%	51	56%
Wrist motion	178	87%	99	56%	79	44%
Elbow motion	174	85%	105	60%	64	40%
Shoulder motion	140	68%	81	58%	59	42%
Wrist and elbow	159	78%	91	57%	68	43%
Wrist and shoulder	127	62%	68	54%	59	46%
Elbow and shoulder	127	62%	77	61%	50	39%
Wrist, elbow, shoulder	115	56%	66	57%	49	43%
Wrist alone	7	3.5%	7	100%	0	0%
Elbow alone	3	1.5%	3	100%	0	0%
Shoulder alone	1	.5%	1	100%	0	0%
Gross motion	70	34%	39	56%	31	44%
Fine motion	128	62%	80	62%	48	38%
Neither gross nor fine	7	3%	7	100%	0	0%
Mobility:						
Trunk mobility	37	18%				
Whole body	21	10%				
Translation	14	7%				
Sensory:						
Visual feedback	120	59%				
Tactile feedback	197	96%				

tasks require translation <u>during</u> the task. This does not consider requirements to translate or translocate immediately prior to or after task performance.

A good number of the tasks can be performed without visual feedback (41%). This follows from the fact that many tasks involve manipulation of objects already acquired and the subsequent use of such objects with respect to parts of the body. For such tasks no visual feedback is required. Kinesthetic feedback is required for 96% of the tasks. This includes proprioceptive, vestibular, and tactile sensations. Both visual and kinesthetic feedback are required for 57% of the tasks.

What all of this means is that in the normal performance of important everyday activities:

- Two hands are frequently required
- Prehension is required for almost all tasks
- The ability to accurately position the hand at a specific point in space with a specific orientation is essential
- The capability of applying forces, notably linear forces, is important for the great majority of tasks
- Dexterity and the capability of varying hand geometry are important for almost half of the tasks
- Motion of each joint is important for the majority of tasks
- Coordinated motion of two or more joints is required for from half to 78% of the tasks
- Single joint rotation is infrequently required
- The capability of fine arm control is twice as important as that for gross arm control
- Fine arm control is required for almost two-thirds of the tasks
- Either fine or gross arm control is essential for almost all tasks (97%)
- Trunk mobility is needed for almost one-fifth of the tasks, and is required more frequently than whole body motion
- Translation during task performance is fairly infrequent, however, these requirements are for the actual conduct of the task alone
- Kinesthetic feedback is required for almost all tasks (96%) and is more important, at least for these tasks, than is visual feedback
- Visual feedback is required for 59% of the tasks

A more accurate assessment of the relative importance of different requirements for one and two hand tasks can be made by computing the percentage of the one hand tasks and of the two hand tasks which incorporate the requirements. These data are presented in Table 3. As indicated in this table, precision placement, elbow motion, and fine arm control are more frequently required in one hand tasks as compared with two hand activities. On the other side, twist forces, linear forces, both twist and linear forces, high dexterity, dexterity and precision placement, variable configuration, and wrist motion are required more frequently for two hand tasks than for one hand tasks. These differences indicate a general trend for precise and fine hand placement and arm control for one handed tasks, and for two handed tasks to require more strength, dexterity, and actual manipulation and handling of objects.

The performance requirements discussed above indicate the capabilities required to perform specific tasks. An analysis was also performed of the safety hazards associated with each task. The list of potential hazards investigated in this analysis included the following:

- Electrical hazards - shock, electrical burns
- Mechanical hazards - contact with moving parts
- Structural hazards - impalement by pointed structures
- Eye hazards - conditions endangering the eye
- Laceration hazards - sharp edges
- Temperature hazards - burns
- Impact hazards - body or body part impact
- Slip-fall hazards - slips, trips, and falls
- Noxious fume hazards - gases
- Hazards to health - unhygenic conditions

The identification of potential hazards for each task is presented in Appendix B. The summary of the hazards for each functional category is presented in Table 4.

TABLE 3
Relative Importance of Requirements
For One and Two Handed Tasks

Requirement	% of one hand tasks	% of two hand tasks
Prehension	100%	94%
Precision Placement	71%	60%
Force Application	96%	98%
Twist	20%	34%
Push/Pull	64%	89%
Both	14%	30%
High Dexterity	43%	55%
Dexterity and Precision	41%	50%
Variable Configuration	36%	64%
Wrist motion	88%	99%
Elbow Motion	94%	86%
Shoulder Motion	72%	74%
Wrist and Elbow	81%	85%
Wrist and Shoulder	61%	74%
Elbow and Shoulder	69%	63%
Wrist, Elbow, Shoulder	59%	61%
Gross Motion	35%	39%
Fine Motion	71%	60%

TABLE 4
Summary of Hazards Identified for Each Function

Function	Number of tasks	Tasks with at least one hazard	Number of hazards	Hazard/Task	% of hazardous tasks
Eat/drink	26	22	28	1.3	85%
Food preparation	32	28	36	1.3	88%
Self care	41	26	31	1.2	63%
Dressing	36	14	14	1.0	39%
Transportation	15	11	21	1.9	73%
Work/recreation	43	19	38	2.0	44%
Miscellaneous	12	9	11	1.2	75%
	205	129	179	1.4	63%

As indicated in Table 4, almost two-thirds of all tasks (63%) have at least one hazard associated with them. Overall, there are 1.4 hazards per task. The most hazardous function, in terms of percentage of hazard tasks, include eating and drinking, food preparation, transportation, miscellaneous tasks, and self care. The most hazardous functions in terms of number of hazards per task include work and recreation and transportation.

A set of general performance requirements was developed for each functional category which included:

- frequency of performance
- duration
- translation requirements
  - before/after performance
  - during performance
    - trip distance
    - trip frequency
- operational site requirements
  - single site
  - multiple sites
  - special purpose site
  - general purpose site
  - indoors
  - outdoors

Environmental requirements
- solitary
- social
- performed in a group of strangers
- performed in a crowd

Equipment requirements
- personal
- general public use
- special purpose
- general purpose

Body position requirements
- sitting
- standing
- reclining
- varied
- any

The incidence of general performance requirements for each functional category are presented in Table 5. An assessment of these requirements indicates:

- All functions require translation immediately before or after their performance.

- Seven of the 12 functions require translation during function performance. These functions account for 61% of all tasks. This is contracted to the 7% of tasks which require translation during the performance of a task.

- Five functions are normally performed at a single site, five others are performed at multiple work sites, and two may require either a single or a multiple site. The functions requiring only a single site comprise tasks making up 43% of the total while those requiring a multiple site alone include 45% of the total tasks. In terms of type of site the tasks are evenly distributed in terms of whether a single site or multiple sites are required.

- Five of the functions are usually performed in a solitary manner alone, while a total of 10 functions may be performed alone or in a group. These ten functions account for 91% of the tasks. Thus, the great majority of tasks may be performed by a person in isolation from others. A total of seven functions (accounting for 57% of the tasks) may be performed in a group of friends or strangers or in a crowd. Four functions may involve performance in a group of strangers or in a crowd (25% of the tasks).

- Ten functions (accounting for 91% of tasks) involve the use of personally owned objects or equipment. For 11 functions the items used are special purpose rather than general purpose (99.5% of tasks).

- Eight of the 12 functions require either a sitting or standing position (63% of tasks). Ten involve a sitting position and 9 involve standing. Only one requires reclining.

TABLE 5
General Performance Requirements

	Eat-Drink	Food Prep.	Sleep	Bathe-Groom	Pers. Hygiene	Dress	Pub. Trans.	Priv. Trans.	Shop	Read/Write	Work	Rec-rea-tion
equency (per day)	2-4	2-4	1	1-2	1-3	2-3	Any	Any	Any	Any	Any	Any
ration (hrs.)	1/2-1	1/2-2	6-8	<1	<1	<1	Any	Any	Any	Any	Any	Any
anslation												
before/after	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
during		✓				✓	✓	✓	✓		✓	✓
trip dist. (ft.)		<10				<10	Any	Any	Any		Any	Any
trip freq.		high				mod.	Any	Any	Any		Any	Any
erative Site												
single	✓		✓	✓	✓					✓	✓	✓
multiple		✓				✓	✓	✓	✓		✓	✓
special	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓
general									✓	✓		
indoors	✓	✓	✓	✓	✓	✓				✓	✓	✓
outdoors							✓	✓	✓		✓	✓
vironment												
solitary	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓
social	✓	✓					✓	✓	✓		✓	✓
group							✓		✓		✓	✓
crowd							✓		✓		✓	✓
uipment												
personal	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓
general use							✓		✓		✓	✓
special	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
gen. purpose									✓		✓	✓
dy Position												
sit	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
stand		✓		✓	✓	✓	✓	✓	✓		✓	✓
recline			✓									
varied				✓	✓	✓	✓	✓	✓		✓	✓
mber of Tasks	26	32	4	18	19	36	8	7	1	20	23	11
of total (205)	13	16	2	9	9	17	9	3	.5	10	11	5

Based on the analysis of specific task performance requirements, general function performance requirements, and hazards, associated with tasks, the following conclusions can be formulated concerning requirements associated with essential and important everyday tasks:

- Prehension is the single most important (most frequent) requirement encountered for the set of tasks (required for 94% of tasks).

- Tasks requiring one hand performance are more frequent than those requiring two hands (61% vs. 39%).

- Precise placement of the hand is required for 62% of the tasks and is more important for one hand tasks than for two hand tasks (71% vs. 60%).

- Coordinated control of two arm joints is required for 62% to 78% of the tasks. This finding, coupled with the requirements for precision placement of the hand(s), indicates a general requirement for precise, fine control of the hand and arm for the everyday tasks investigated. This conclusion was borne out by the judgment that fine arm control is needed for twice as many tasks as gross arm control (62% and 34% of tasks respectively).

- Applications of force are required in 91% of the tasks and are generally more frequent for two hand tasks than for one hand operations. While only one quarter of the tasks require rotational force, 70% require both rotational and linear force.

- High finger and hand dexterity is needed for less than half of the tasks (45%) and is generally more important for two handed as opposed to one handed tasks (55% to 43%).

- A combination of high dexterity with precision placement of the hand is required for 42% of the tasks and is likewise more important for tasks requiring two hands as opposed to one (50% to 41%).

- The ability to alter hand configuration, geometry, or orientation during performance of an activity is required for 44% of the tasks and is decidedly more important for two handed tasks as compared with one hand activities (64% to 36%).

- All tasks require the rotation of at least one joint. Few require the activation of only one joint (6%). Most require wrist motion (87%), elbow motion (85%), and wrist motion in combination with either elbow motion (78%), shoulder motion (67%), or both elbow and shoulder motion (56%).

- For one hand tasks the most frequently required joint was the elbow (94%), while for two hand tasks the wrist was required in 99% of the tasks.

- Almost one-fifth of the tasks (18%) require trunk mobility while 10% require whole body mobility.

- While only 7% of the tasks require translocation during performance of the task, functions which require translocation during performance of the function account for 61% of the tasks.

- Tasks are evenly distributed in terms of the number of worksites involved, single site or multiple site.

- While 91% of the tasks can be performed in a solitary manner, 57% may involve performance in a group and 25% may entail performance in a crowd.

- Most tasks involve the use of personally owned items (91%). Almost all items used in the tasks are of the special purpose variety.

- A total of 86% of the tasks are associated with functions which can be performed in a sitting position. A standing position may be involved in functions accounting for 79% of the tasks.

- A total of 63% of the tasks have at least one safety hazard associated with their performance. A total of 1.4 hazards per task were identified.

- The more hazardous functions were:

  Eat, drink, accounting for 13% of the tasks
  Food preparation, 16% of the tasks
  Self care, 20% of the tasks
  Transportation, 12%
  Miscellaneous tasks, 6%

  These functions account for two-thirds (67%) of the tasks.

- The most hazardous functions in terms of number of hazards per task were transportation (12% of tasks) and work/recreation (20% of tasks). These functions account for about one-third of the tasks.

Problems for the Handicapped

In the preceding, an attempt was made to determine the requirements placed on a system for the handicapped. These requirements relate to the needs of the handicapped, the functions to be performed, the performance factors involved in successfully completing the functions, and the safety hazards inherent in the accomplishment of each task. The synthesis of these requirements generally indicates that in his daily life a person is required to perform a wide variety of diverse activities with precision, force control, fine arm control, dexterity, hand and arm articulation, maneuverability, and sensory feedback.

The probability of injury in performing these activities must therefore increase as the capability of accomplishing them decreases. Thus, in identifying the requirements for the handicapped, we have already begun to establish the problems for the handicapped, the first class of which includes safety problems. As indicated in Table 4, 63% of the everyday tasks can be considered to be hazardous. Thus, with his reduced capability, the handicapped individual in performing everyday activities, runs the risk of injury on two of every three of the activities he performs, a risk which is greater than for the normal person.

As indicated in Table 5, seven of the 12 everyday functions are normally performed indoors, while two others may be performed either indoors or outdoors. These nine functions which are usually, or which could be, performed indoors account for 92% of the tasks. A total of five functions, involving 28% of the tasks, may be performed outdoors. The safety of a handicapped person is probably successively degraded as he moves from a familiar indoor environment (the home) to an unfamiliar indoor environment (an office building) to an outdoor environment. The functions which are performed outdoors and which contain tasks rated high in degree of hazard involve those concerned with transportation, both public and private. On the performance side, it is this set of functions which must be accomplished if the handicapped person is to live a normal and productive life. The limitations imposed on a handicapped person by an inability or a fear to move about the outside world, to make use of public transportation facilities, or to drive his own automobile, severely hampers his capacity for gainful employment and degrades whatever independence he has attained in self care activities.

The performance problems of the handicapped can be analyzed by relating disabilities with the resultant expected loss of capability to perform everyday tasks. A summary of this analysis is presented in Table 6, where the percentage of tasks unaffected and the percentage lost or affected by each disability are presented. It should be pointed out that the purpose of this table is to relate disabilities to the total functional capability of the handicapped person suffering each disability. It implies nothing concerning the relative importance or value of tasks lost or affected to the handicapped person. Thus, loss of the ability to climb steps applies to only 7% of the tasks. We cannot therefore conclude that this ability is of little importance since for some handicapped people it may involve a major problem.

In an attempt to gain insight into the problems of the handicapped, Essex personnel interviewed patients at Rancho Los Amigos Hospital in Downey, California, and at VA Hospitals in the Bronx and Castle Point, New York. For these interviews, a special data sheet was constructed with the objective of identifying the degree of independence with which the patient could perform selected everyday activities. A secondary objective of the sheet was to identify safety, performance, and comfort problems associated with the activities. The data sheet is presented in Table 7. Characteristics of the 20 patients interviewed are presented in Table 8. As indicated in this table, 19 of the 20 patients were quadriplegics and one was a hemiplegic. A total of 10 of the patients were students. The mean age of the patients was 30 years of age. Only three of the patients lived at home. The average duration of disability was 4 years. A total of 5 of the patients' disabilities were due to disease, while 15 were due to accidents (6 auto accidents, 4 diving, 3 falls, 1 farm machinery, and 1 gun shot). Sixteen of the patients used wheel chairs and

TABLE 6

Effects of Disability on Capability to Perform Everyday Tasks

Disability	Tasks Lost or Affected	Tasks Remaining Intact
Below Elbow Amputation--1 Arm Prehension but no Variable Configuration	46%	54%
Below Elbow Amputation--1 Arm Prehension and Variable Configuration	30%	70%
Complete Loss of Arms or One Arm Function	47%	53%
Bilateral Loss of Arms or Arm Functions	94%	6%
Bilateral Loss of Arms or Arm Functions and Loss of Mobility	100%	0%
Bilateral Loss of Arms or Arm Functions With Restored 1 Arm Gross Motion and Prehension in 1 Hand	87%	13%
Bilateral Loss of Arms or Arm Functions With Restored 2 Arm Gross Motion and Prehension in 2 Hands	75%	25%
Loss of Both Legs	61%	39%
Inability to Perform in Crowds	75%	25%
Inability to Use Facilities Designed for General Use	25%	75%
Inability to Climb Steps	7%	93%
Problems with Wrist and Elbow Coordination--1 Arm with No Function in Other Arm	81%	19%

Disability	Tasks Lost or Affected	Tasks Remaining Intact
Problems with Wrist and Shoulder Coordination--1 Arm with No Function in Other Arm	61%	39%
Problems with Elbow and Shoulder Coordination--1 Arm with No Function in Other Arm	69%	31%
Inability to Apply Twist Force	24%	76%
Inability to Apply Linear Force	70%	30%
Loss of Kinesthetic and Tactile Sensation	96%	4%
Loss of Visual Sensation	59%	41%

TABLE 7
Patient Interview Sheets

PROSTHETIC - ORTHOTIC DEVICE
USER SURVEY

Location ____________
Date ____________
Interviewer ____________

Disability

Type: ____________

Cause: ____________

Duration-Onset: ____________

Extent: ____________

Finger Dexterity Remaining: ____________

Unassisted Arm/Leg Motion: ____________

Prosthetic - Orthotic Device:

Device in use: ____________

Control system: ____________

Effector System: ____________

Manipulative-mobility system: ____________

Feedback system: ____________

Duration of use: ____________

Previously used Devices: ____________

When used: ____________

Amount of training provided: ____________

User

Sex: ______ Age: ______ Occupation: ____________

Live at Home: ____________ Clinic: ____________ Other: ____________

Education: ____________

User Comments on Device (give after completing the questionnaire):

____

____

____

____

Table 7
Continued

TASK	PERFORMANCE CODE: 0 - Unassisted, 1 - 2nd Person, 2 - Need Device	SAFETY PROBLEMS: 0 - None, 1 - Moderate, 2 - Major	PERFORMANCE PROBLEMS	COMFORT: 0 - OK, 1 - Tolerable, 2 - Uncomfortable	PROBLEMS WITH DEVICE USE
Handle doors					
Handle keys					
Handle telephone					
Dial telephone					
Turn radio-TV on					
Handle kitchen appliances					
Handle broom-mop					
Sewing-mending					
Ironing					
Clothes washing					
Writing					
Page turning					
Reading					
Handling of Office Equipment					
Handling of Packages					
Handling of Tools					
Handling of Files					
Exercise					
Sports					
Group games					
Solitary games					
Move about room					
Move on Sidewalk					
Cross streets					
Use public transportation					

Table 7
Continued

PERFORMANCE CODE 0 - Unassisted 1 - 2nd Person 2 - Need Device

SAFETY PROBLEMS

PERFORMANCE PROBLEMS 0 - None 1 - Moderate 2 - Major

COMFORT 0 - OK 1 - Tolerable 2 - Uncomfortable

TASK	PERFORMANCE CODE	SAFETY PROBLEMS	PERFORMANCE PROBLEMS	COMFORT	PROBLEMS WITH DEVICE USE
Food Prep.					
Cooking					
Open containers					
Handling utensils					
Handling glasses					
Eating					
Drinking					
Handle clothes					
Use buttons					
Don shoes					
Don pants					
Don shirt-dress					
Wash face					
Wash hands					
Bathe-shower					
Brush teeth					
Shave face-body					
Apply lotions					
Comb-brush hair					
Apply makeup					
Waste elimination					
Arrange clothing					
Prepare for sleep					
Sleep					
Self first aid					
Self medication					

Table 7
Continued

PERFORMANCE CODE 0 - Unassisted 1 - 2nd Person 2 - Need Device

SAFETY PROBLEMS

PERFORMANCE PROBLEMS 0 - None 1 - Moderate 2 - Major

COMFORT 0 - OK 1 - Tolerable 2 - Uncomfortable

TASK	PERFORMANCE CODE	SAFETY PROBLEMS	PERFORMANCE PROBLEMS	COMFORT	PROBLEMS WITH DEVICE USE
Use public bus					
Use train or subway					
Use public airplane					
Operate a car					
Handle-read newspaper					
Other Tasks - LIST					

TABLE 8

Description of Patients

Place	Sex	Age	Occupation	Lives at home	Lives at clinic	Disability	Cause	Duration	Device
1. Bronx	M	51	soldier		✓	Quad	nerve root degen.	2 years	chair - ball bearing feeder
2. Rancho	F	16	student		✓	Quad	muscle atrophy	recent	h/s - chair - JS
3. Bronx	F	47	nurse asst.		✓	Quad C5-6	accident - auto	1 year	stick chair - h/s
4. Castle Pt.	M	24	student	✓		Quad C5-6	diving	1 1/2 yrs.	stick chair - h/s
5. Castle Pt.	M	30	farmer		✓	Quad & Amp.	farm machinery	6 years	chair - artificial arm
6. Castle Pt.	F	48	housewife		✓	Quad C4-5	auto	1 year	h/s - right arm
7. Castle Pt.	M	49	lineman		✓	Quad C3-4	auto	4 1/2 yrs.	chair - puff and suck
8. Bronx	M	37	embalmer		✓	Quad C5-6	fall	11 1/2 yrs.	chair - teeth; pull on/off - chin
9. Castle Pt.	M	50	machinist		✓	Quad C5-6	diving	13 years	chair - h/s; tendon transplants
10. Rancho	F	39	housewife	✓		Quad	polio	20 years	chair - RAM - tongue switch
11. Rancho	F	15	student		✓	Quad C3-4	gunshot	1 1/2 yrs.	elec. w/c
12. Rancho	M	18	student		✓	Quad C4-5	auto	7 months	arm support - h/s
13. Rancho	F	18	student	✓		Quad C4-5	diving	3 1/2 years	rachet & opponens - h/s
14. Rancho	M	18	student		✓	Quad C6	diving	4 months	h/s
15. Rancho	M	15	student		✓	Quad C4-5	fall	1 year	h/s - rad. arm support
16. Rancho	M	19	student		✓	Quad C5-6	fall	1 1/2 years	w/c - h/s
17 Rancho	F	16	student		✓	Quad C5-6	auto	4 months	h/s - w/c
18. Rancho	M	26	attorney		✓	Quad C3-4	auto	1 year	h/s - w/c
19. Bronx	M	52	clerk		✓	Hemi	disease	1 year	leg brace - w/c
20. Rancho	M	14	student		✓	Quad	polio	1 1/2 years	w/c - h/s - JS

* h/s - hand splint
JS - joystick
w/c - wheel chair
RAM - Rancho arm

TABLE 9

Summary of Patient Responses

Tasks	Perform	Need Assistance 2nd person	Perform Unassisted No diff.	Perform Unassisted diff.	Perform Using Device No diff.	Perform Using Device diff.
Food Preparation						
food preparation	4	2	1	0	1	0
cook	6	3	1	0	1	1
open containers	15	11	2	2	0	0
Eat/Drink						
eat	20	3	2	1	8	6
drink	20	12	5	0	3	0
handle utensils	17	2	3	0	4	8
handle glasses	18	8	3	2	1	4
Dress						
handle clothing	17	14	2	0	0	1
use buttons	17	13	0	1	1	2
don shoes	20	20	0	0	0	0
pants	20	20	0	0	0	0
shirt/dress	20	17	2	0	0	1
Self Care - Hygiene						
wash face	20	8	4	2	5	1
hands	20	11	4	2	3	0
bathe - shower	20	20	0	0	0	0
brush teeth	20	7	4	1	8	0
shave	13	10	2	0	1	0
apply lotions	17	8	6	1	2	0
comb-brush hair	20	9	2	0	5	4
apply makeup	11	6	1	0	2	2
waste elimination	20	19	1	0	0	0
arrange clothing	13	11	1	0	1	0
prepare for sleep	20	20	0	0	0	0
first aid	17	11	3	0	3	0
self medication	20	7	6	0	5	2
Work - Recreation						
handle doors	20	4	2	2	4	8
keys	17	11	1	1	2	2
phone	19	3	4	1	8	3
dial phone	19	2	3	2	8	4
radio-TV on/off	19	7	1	1	6	4
handle appliances	2	1	0	0	0	1
handle broom	1	1	0	0	0	0
sew	1	1	0	0	0	0
iron	1	1	0	0	0	0
wash clothes	1	1	0	0	0	0
write	19	2	2	0	10	5
turn pages	19	1	5	2	6	5

Transportation	Perform	Need Assistance of 2nd person	Perform Unassisted No Diff.	Perform Unassisted Diff.	Perform Using Device No Diff.	Perform Using Device Diff.
handle files	3	1	0	0	1	1
handle newspaper	14	1	6	0	2	5
exercise	12	3	3	0	4	2
group games	1	0	0	0	1	0
solitary games	2	0	0	0	2	0
move about room	20	0	0	0	17	3
move on sidewalk	20	0	0	0	16	4
cross streets	18	1	0	0	8	9
use public transp.	12	12	0	0	0	0
use bus	14	13	0	0	1	0
use train	14	14	0	0	0	0
use airplane	15	15	0	0	0	0
drive car	1	0	1	0	0	0

12 used hand splints. One used the rancho electric arm and one had had tendon transplants for myoelectric control.

The responses of the patients for each task on the data sheet are summarized in Table 9. The data sheet tasks were reduced to the 50 tasks listed in Table 9 after some items on the original list were deleted as being ambiguous (e.g., reading, sleeping, using tools, etc.). In Table 9, the responses are presented in terms of the number who actually do or can do a task and the method whereby they perform the task. The methods are:

- need assistance of a second person
- perform unassisted with little or no difficulty
- perform unassisted with difficulty
- rely on device to perform - no difficulty
- rely on device to perform - with difficulty

The compilation of responses over all tasks for each function (food preparation, etc.) is presented in Table 10:

TABLE 10
Summary of Responses Over Tasks - Each Function

Function	No. of tasks	No. who perform	% who perform	% need 2nd person	% unassisted no diff.	% unassisted diff.	% use device no diff.	% use device diff.
Food Prep.	3	25	42%	64%	16%	8%	8%	4%
Eat/Drink	4	75	94%	33%	17%	4%	21%	24%
Dress	5	94	94%	89%	4%	1%	1%	4%
Self Care	13	231	89%	64%	15%	3%	15%	4%
Work/Recreation	17	170	50%	24%	16%	5%	32%	24%
Transportation	8	114	71%	48%	1%	0%	37%	9%
Overall	50	709	71%	52%	12%	3%	21%	12%

As indicated in Table 10, in a little more than half of the attempts to perform a task, a patient needs assistance of a second person. 12% of the cases the patient can perform a task without any aid and without difficulty while in 3% of the attempts a patient can perform a task without assistance but with difficulty. In 21% of the cases a patient can use his device to perform a task without difficulty while in 12% he can use the device to accomplish a task with difficulty. Thus, a patient can perform a task with his device (either with or without difficulty) and the patient can perform activities independently of assistance in 48% of the cases. These patients therefore possess only a little less than half of the capability they require to be completely independent.

An examination of the results by function lends to some interesting findings. For instance, the functions for which patients are more dependent on a second person include food preparation, dressing, and self care, while they are more independent for eating/drinking, work and recreation, and transportation. Functions which are performed by most patients include eating/drinking, dressing, self care, and transportation. Functions where devices are most effective include eating/drinking, work and recreation, and transportation.

A further analysis of the work/recreation and transportation functions was performed. The results of this analysis are presented in Table 11. As indicated by this table, the most frequently performed classes of tasks for work/recreation are environment control, reading/writing/filing, and exercise. Very few patients engage in housekeeping activities, or in games. For all classes of tasks except housekeeping, use of a device is effective in performing the tasks (with or without difficulty) in 50% of the cases. Thus, devices are more or less effective for these types of activities in about half of the task situations.

TABLE 11
Results for Subclasses of Work/
Recreation and Transportation

Function/Subclass	No. of Tasks	No. who perform	% who perform	% need 2nd person	% unassisted no diff.	% unassisted diff.	% using device no diff.	% using device diff.
Work/Recreation								
Control of Envir.	5	94	94%	29%	12%	7%	30%	22%
Read/Write/File	4	55	69%	9%	24%	4%	34%	29%
Housekeeping	5	6	6%	83%	0	0	0	17%
Exercise	1	12	60%	25%	25%	0	33%	17%
Games	2	3	8%	0	0	0	100%	0
Transportation								
Public	4	55	69%	98%	0	0	2%	0
Private	4	59	74%	2%	0	0	69%	27%

The analysis of the transportation function into those tasks concerned with use of public transportation and private transportation (locomotion and personal automobile) reveals striking differences between these classes. While a second person is needed in 98% of the cases for public transport, this dependence is required for only 2% of the private transportation cases. Devices (essentially wheel chairs) are effective for private transportation in 69% of the cases without difficulty, and 96% of the cases either with or without difficulty.

A similar analysis of functional problems of the handicapped was reported by Engen (Orthotics and Prosthetics, June 1970), in an assessment of the effectiveness of powered orthotic devices. That investigator surveyed 58 patients using three types of CO_2 powered orthosis and indicated the general capability (or lack of it) before the application and after the application. All 58 of his patients were quads and 12 of the disabilities were due to disease while 46 had resulted from accidents. A questionnaire sent to each of the patients had been returned by 32 of them. The capabilities reported for these 32 patients are presented in Table 12.

TABLE 12
Responses of 32 Quad Patients (Engen 1970)

Activity	Number Capable	%	Activity	Number Capable	%
Feeding			Recreation		
finger foods	21	66%	cards	8	25%
soup	15	46%	checkers, chess	12	37%
cut meat	0	0	dominos	9	28%
put food on spoon	22	69%	turn pages	19	59%
drink from cup-glass	12	38%	write	22	69%
			handle phone	13	41%
Personal hygiene			type	20	63%
brush teeth	17	53%	draw or paint	10	31%
put paste on brush	3	9%			
wash face	6	19%			
comb hair	4	13%			
help in dressing	2	6%			
shave or makeup	13	41%			

The problems indentified for each functional category can be summarized as follows:

Food Preparation: Not many of the 20 patients interviewed in this study perform food preparation activities, which may result from the fact that 17 of them reside at the clinic or hospital rather than at home. There was also, as expected, a decided sex difference among patients for food preparation activities with a majority of females involved in preparing and cooking food. Only one patient (a male) was capable of preparing food and cooking food with no assistance. Two females were able to cook food using their devices. No patients were able to open containers using their devices.

The preparation of food is one function where patients rely heavily on assistance from a second person (64% of the cases). In only 24% of the cases was a patient capable of performing food preparation either unassisted or with a device, without difficulty. Added to this basic problem of performing food preparation activities is the finding that tasks related to this function are more hazardous than those related to any other function. Reference to Table 4 indicates that 88% of the 32 food preparation tasks were judged to be potentially hazardous.

The problems with food preparation tasks result largely from the fact that in performing these tasks a person is required to handle a wide variety of utensils, containers, and equipment items while moving about to alternate work sites. Modern kitchens are designed for a standing body position during food preparation, which makes these activities even more difficult for a wheel chair bound patient. To effectively and safely perform these tasks, a patient needs extended reach capability, which would not only make more items accessible but which would also possibly reduce the mobility requirements associated with the normal performance of the tasks.

Eating/Drinking: Almost all patients surveyed that they participate in these activities (94%). Independent functioning is fairly good in that patients can eat and drink either without assistance or with a device in two-thirds of the cases. In these cases, patients have no difficulty in 38% while they do report problems in 28% of the attempts.

The finding of capability for independent eating and drinking in two-thirds of the cases in this study compares well with the finding, reported by Engen (1970), that 69% of his patients were able to eat with a spoon and that 66% could eat using their fingers. Engen further reported that only 38% of his sample were able to drink from a cup or glass. In the present study, 40% of the 20 patients were capable of drinking in an independent mode while 60% were capable of handling a glass.

In the present study, of those who were capable of independent eating and drinking, twice as many relied on their devices (45%) than were able to perform the tasks unassisted (21%). This would indicate that a good deal more emphasis has been given to devices which enable the patient to eat and drink than to those which enable the patient to prepare food.

Reference to Table 4 indicates that eating and drinking constitutes the second most hazardous function (next to food preparation), with 85% of the tasks being potentially hazardous. The safety of a patient is compromised when he must perform hazardous tasks where 28% of the cases require him to perform with difficulty (4% unassisted and 24% with device).

Dressing: The tasks where patients are most dependent on a second person are those associated with dressing. In only 10% of the cases is a patient capable of independent action, and these are evenly distributed into unassisted performance (5%) and use of devices (5%). In only 5% of the cases is a patient capable of independent dressing without difficulty. No patients were able to put on shoes and pants without help from a second person. A large majority of patients needed help in putting on shirts or dresses.

Dressing tasks as a group comprise the least hazardous of functions (table 4) and yet 39% of the dressing tasks are judged to be potentially hazardous. Therefore, performance problems with dressing outweigh safety problems. The primary performance problems include the trunk mobility and coordinated body and limb motion required to dress. The findings here are generally in agreement with those reported by Engen (1970) where only 6% of patients were able to help in dressing.

Self Care: Performance of self care and personal hygiene activities require a second person in 64% of the cases. Where independent action is possible, 30% of the cases involve performance with little or no difficulty. Three self care tasks require almost total dependence on a second person.

These are bathing, waste elimination, and preparation for sleep, including getting into bed. All of these tasks require whole body mobility and translation from one location to another. Such tasks constitute the most difficult activities for a quadraplegic patient, since they essentially involve getting in and out of the wheel chair. The remaining tasks in the self care activity generally require dependence on a second person in about one half of the cases (washing face and hands, brushing teeth, shaving, applying lotions, combing hair, and applying makeup). Engen (1970) reported that 53% of his 32 patients were able to brush their teeth, 41% were able to shave or apply makeup, 19% were able to wash their face, and 13% were capable of combing their hair.

In terms of safety, 63% of the 41 self care tasks investigated in this study were judged to be potentially dangerous. Thus, in performing almost two of three self care tasks, a patient exposes himself to the danger of injury.

Work/Recreation: Only 50% of the 20 patients interviewed in this study participated in work or recreation activities. A breakout of these activities indicated that a majority of patients perform environment control tasks (94%) which include opening doors, use of telephone, control of radio and TV, and control of appliances. A little more than half perform reading, writing, or filing. Few patients perform exercise, housekeeping, or engage in games.

Of patients who engage in environment control type of activities, they can perform independently in 71% of the cases (52% using devices). Engen (1970) reported that 41% of his patients could handle and dial the telephone. In the present study, 87% of the patients were capable of independently using the phone although 30% of these reported difficulty.

For reading, writing, and filing in 91% of the cases, patients can perform independently. Of these, 63% can perform using devices. Engen reported that while 59% of his sample could independently turn pages, 69% could write using a ballpoint pen or pencil.

The major discrepancy between the current study identified only 8% of the sample who perform games. For Engen's sample, 25% played cards, 37% played chess or checkers, and 28% played dominos. One possible explanation for the differences might be that the great majority of patients interviewed in the present study were still living in the clinic or hospital while most of Engen's sample were living at home. It is conceivable that, living at home, a patient would have more time and inclination to engage in games.

The Engen study sampled the avocational or recreational preferences of 46 of the 58 patients in the sample. The responses reported by Engen are summarized in Table 13:

TABLE 13
Recreational Preferences of
Handicapped Persons (Engen 1970)

N = 46 patients	Activity	Number	%
	Cards	37	80%
	Checkers	25	54%
	Dominos	25	54%
	Chess	12	26%
	Painting	11	24%
	Drawing	7	15%
	Table games	5	11%
	Ceramics	2	4%
	Tooling	1	2%
	Checkers and/or Chess	31	67%

An examination of Tables 12 and 13 reveals the proportion of Engen's patients who were interested in playing games and those capable of such performance. In Table 13 it is stated that 67% of the patients prefer to play chess or checkers. In Table 12 we see that 37% of the patients were capable of playing these games. Again, 80% of the sample were interested in playing cards while only 25% were capable of card playing. Finally, 54% of the patients preferred to play dominos while 28% were able.

These findings point up a problem with the handicapped, the loss of ability to participate in games. Such participation should be viewed not merely as a means of passing time but also as an opportunity for recreation in the same way as such activities are performed by "normal" people.

Transportation: A surprisingly high percentage of the sample of handicapped patients surveyed engage in transportation activities (71% overall, 69% public, and 74% private). As indicated in Table 11 there is a clear differentiation of dependency for public and private modes with patients dependent on others for 98% of public transportation activities and only 2% of private transportation tasks. The primary difficulties with private transportation were the inability to drive and the capability of maneuvering a wheel chair up and down curbs when crossing streets.

The mobility needs for the physically impaired were eloquently described by H. A. Schweickert, Jr. of the Paralyzed Veterans of America (1969) who stated that mass transportation is an utter impossiblity for the severely handicapped, and that the needs of the disabled have apparently never entered the minds of the inventor, designer, or manufacturer. Schweickert goes on to categorize the problems for transportation facing the handicapped as problems of height, space, and velocity. Street curbs and flights of steps make many areas inaccessible to the wheel chair patient. Dimensionally, the common doorway is the greatest single obstacle, being too narrow, or revolving. Since the chair occupies about nine square feet of floor space, narrow hallways and small rooms also constitute difficulties for the disabled. Velocity in the horizontal plane is dangerous for the unstable and the wheel chair patient, while in the vertical plane, velocity is more of a hazard for the unstable disabled person. Applying these conditions to the transportation media, according to Schweickert, reveals that none of them can adequately accomodate the unstable, or accomodate the wheel chair bound person at all. He goes on to report that only one state (Maryland) has enacted legislation to require that public transportation accomodations be made accessible and usable by the physically handicapped.

One other significant point made by Schweickert was that, humane considerations aside, enabling the disabled to perform gainful employment provides economic benefits to the nation. Unemployed, they represent an expensive responsibility. One study cited by Schweickert indicated that for every $1,000 spent by Federal and State agencies for vocational rehabilitation of disabled persons, there will be an expected increase of more than $35,000 in the lifetime earnings of each rehabilitated person. The handicapped must therefore be employed, and the essential capability required for employment is the ability to move from place of residence to place of employment.

As stated in the first portion of this section, the primary needs of handicapped persons are for: independence; effective, safe, and comfortable performance capability; normalcy of activities; and enhanced accessibility of objects. The problems of the handicapped can be summarized in light of these four basic needs. These problems can further be classified by virtue of the different environments in which activities are performed. The environments which impose significantly different requirements and constraints on the person, and which consequently have different problems associated with them, are three:

- a familiar, interior environment - the home or clinic.
- a less familiar interior environment - the office, shop, or factory.
- an exterior environment between place of residence and place of employment.

The familiar interior environment is characterized by functions usually performed alone, or in the company of family or friends. The need for normalcy of operations would not be as important in this environment as it would in others. The needs for independent action, safe, effective, and comfortable performance capability, and accessibility of objects are important in this environment, due to the fact that handicapped persons spend much of their time in the home or clinic, and due to the potential hazards associated with tasks performed in this environment.

While handicapped persons need better systems to enable their independent, safe, effective, and comfortable performance of activities in the home, this environment is not as constrained as others in terms of the degree to which objects and items encountered or handled can be designed specifically for the individual. Most of the items used in the home environment are privately owned and can be modified for the handicapped person without much impact on others.

In the office, the shop, or the factory, a handicapped individual will require more normalcy of operations than needed in the home. He will also probably require more mobility, and will interact with more objects not specifically designed for use by him and him alone. The need for independence takes on added significance in the working environment as compared with the home environment, since in the former, considerations of economics are added to the psychological needs of the disabled for independence. A handicapped person will have a greater likelihood of obtaining employment to the degree that he is capable of independent performance, which will not necessitate requiring a second employee to spend some portion of his time in assisting or aiding the disabled worker.

In dealing with a wide range of objects designed for "normal" performance in the work environment, the need for normalcy of operation in this environment also transcends the psychological need of not appearing different. A working handicapped person will need to operate, use, manipulate, and handle many objects which are not designed specifically for him. In interacting with these objects, the need for enhanced accessibility also takes on added significance since the work space will not generally be laid out for easy access by the handicapped individual.

The critical requirement underlying the ability of the handicapped to hold gainful employment is the capability of the person to transport himself or be transported to the place of employment. Thus, transportation takes on added significance beyond the need for mobility associated with the performance of many everyday tasks. The primary need here is for safe, effective, and comfortable performance capability since the disabled person must use facilities and vehicles which, by virtue of their design and arrangement, impose numerous, and in many cases insurmountable barriers to their use. The need for independence in transportation is associated with freedom and flexibility in selecting media, routes, and travel times. The need for normalcy is basically the psychological need of operating in a manner so as not to call attention to oneself. The need for enhanced accessibility is integral to the need for safe, effective, and comfortable performance, since barriers make many routes and facilities inaccessible.

The problems confronting the handicapped individual in the world today are therefore of considerable scope and complexity, and are in many instances overwhelming. The state-of-the-art in systems for the handicapped, to alleviate some of these problems, is described in the next chapter. The next chapter also discusses some of the more significant problems and shortcomings of systems and devices in satisfying requirements and resolving problems for the handicapped.

IV Prosthetics, Orthotics and Sensory Aids

It is the purpose of this section to review relevant background material pertaining to the area of the chapter title. Initially the authors will briefly discuss selected devices developed in the recent past to show the direction of post-World War II research, and they will then review selected existing devices in more detail, and make an effort to identify future goals.

Cooperative efforts amongst those researchers concerned with prosthetics, orthotics and sensory aids and those involved with teleoperators will inevitably lead to benefits which can only be anticipated at present. Even at this writing "teleoperators" have been developed by, and are in use at, a number of prosthetic centers under the designation of "Environmental Controls." One such system, employing breath control to operate a unit which was developed by the bioengineering research group at the Veterans Administration Prosthetics Center (VAPC), will be discussed in detail later, as will the Rancho Los Amigos robotized upper limb orthosis for the quadriplegic, also a true teleoperator device.

However, most of the progress that has been made from the earliest historical record of limb bracing to the present era of sophisticated electromechanical devices has been concentrated into the relatively few years of the immediate past. Historical evidence of the use of limb bracing dates back to the Egyptian Fifth Dynasty (2750-2625 B.C.). This was a simple stick splint which was undoubtedly initially used by earlier primitive civilizations. During the Middle Ages armorers fabricated quite respectable looking prosthetic devices.*

*An outline of the history of the early development of prostheses and orthoses will be found in "Orthopedic Appliance Atlas" (see bibliography).

To limit the area of prosthetic-orthotic discussion to the range encompassed by teleoperator applications, the authors will avoid going far afield into such subjects as cosmetic artificial eyes, or artificial hearts.

The Recent Past

The prostheses and orthoses available immediately after World War II had undergone little change since the turn of the century. The usual below-knee (BK) amputation prostheses were of the thigh corset, side-joints type, with open-ended, hand-carved wood sockets and single axis feet. The above-knee (AK) prostheses were fabricated of plug-fit wood sockets, single axis knees and single axis feet. The suspension employed for the AK limb was usually a waist-belt and occasionally a shoulder harness.

In the field of lower limb orthoses, the basic brace was the double-bar orthosis. For forearm, wrist, and ankle immobilization bracing a good deal of metal and leather were used, as in the Hessing brace.

Orthotic development lagged except for a limited number of new and, from our present vantage point, seemingly lasting orthoses, such as, for example, the VAPC PTB (Patellar-Tendon-Bearing) brace, developed by McIlmurray and Greenbaum from a concept presented by one of the authors (Rubin, 1972). This, in its application of prosthetic principles to orthoses, was the precursor of the treatment of fractures by cast-bracing methods. The Engen Wrist-driven orthosis is an example of an important upper limb development, but upper limb innovations were few until external power was employed and plastics were introduced into the field, primarily by Lehneis and Engen. In 1955 North American Aviation, Inc., attempted to develop an hydraulic upper limb orthosis (Sabre arm). The patient for whom it was fabricated was unable to adequately control the arm and this approach was scrapped. Nevertheless, hydraulic principles were found to have useful application for the lower limb prosthesis.

After the Second World War, a greater effort was directed at improving the lot of the amputee than that of the brace wearer. The concentration on prosthetics resulted in the construction of many experimental devices that were subsequently discarded but nevertheless survived long enough to form links in the evolutionary process leading to modern devices. The same evolutionary process dictates that some of these latter will eventually reach the scrap heap, but those presently-used devices that will be described later are the best now available. They will disappear only with further advances, many of which will be initiated by cooperation amongst disciplines.

An approach which has survived in diminishing degree is the concept of the cineplasty controlled prosthesis. The concept was originally proposed in 1898 by Vanghetti and, after a period of development in Italy, reached its present status through the efforts of Sauerbruch. The technique of Sauerbruch was developed in Germany during the First World War and was popularized in the United States by Henry H. Kessler. A skin lined tunnel was constructed through the belly of a muscle such as the biceps humeris. The cable activating the terminal device was attached in Y-fashion to the ends of a yoke passed through the tunnel. Contraction of the muscle yielded cable excursion and terminal device operation. Eventually a variety of other muscles were employed with different devices.

Examples are the triceps, forearm flexors and extensors, the pectorals, and even the quadriceps femoris, but these were not satisfactory for cineplasty. Occasionally one still sees a cineplasty user but they are rare and are usually patients with biceps cineplasties. Because of his concentration on this method and his extensive experience with it, Kessler had much more success with cineplasty than the average surgeon. In most instances problems with the skin of the tunnel and loss of range of excursion of the muscle resulted in discontinuance and transfer to other, more conventional prostheses. When good function has been achieved and no tunnel problems have developed, the patients remain very enthusiastic about their cineplasties. In a few instances the tunnel has been used to activate the switch control employed with some electromechanical prostheses since only a very small excursion range is required for such a function. But we have observed patient rejection of this as well.

The IBM - Alderson electric arm was the product of early post-World War II research in electromechanical devices. The motor was switch-controlled, but seemingly insurmountable problems related to control function developed. The prosthesis was controlled by means of switches activated by heel and toe motions. This was unphysiological and overcomplicated and the amputee had to concentrate to such a degree that he was unable to carry on a conversation and operate the prosthesis at the same time. The IBM arm never left the research laboratory.

Marquardt in Germany, in 1955, pioneered in the design and application of pneumatic orthoses for the upper limb amputee, employing the McKibben Bellows and compressed gas. The McKibben muscle is a hollow fabric cylinder which, by virtue of its helical weave, shortens significantly when inflated, thereby simulating muscle action. Valves are readily controlled by the patient. An improvement on this approach has been used at the VAPC for the bilateral shoulder disarticulation patient with quite positive patient response. The method used was that of Kiessling of the American Institute of Prosthetics Research (AIPR), wherein the compressed gas drives a helical piston rod rather than inflating a McKibben Bellows. Pneumatic locks stabilize the extremity. This is less bulky and more acceptable to the patient than the McKibben Bellows. At lower levels than shoulder disarticulation, a 1965 VAPC evaluation considered the AIPR prostheses (for adults) to be less efficient than conventional prostheses, requiring more energy and performing more slowly than the conventional artificial limb. In the case of child amputees, pneumatic prostheses designed for the use of children have been successfully employed by McLaurin in Canada and Simpson in Scotland.

Various centers throughout the world have been working on powered upper limb problems. The pneumatic and electrical prostheses discussed above are examples of two different approaches to the problem. In the case of the pneumatic limb some degree of initial success was achieved, but the useful application of electromechanical techniques to the problem of the upper limb amputee had to await further research developments.

Other prosthetic research items which may have application to the area of teleoperators were also developed in the post-World War II period. Northrop's Bowden Cable and housing were designed as a transmission system to operate the terminal device and elbow of upper extremity prostheses, under U. S. government contract. The Army Medical Biomechanical Research Laboratory (AMBRL) developed a wrist flexion unit which allows the terminal device to be positioned closer to the body (flexion of 0°, 22 1/2°, and 45°). Kegel in France, and Scalas in Italy have produced ball and socket joints.

A variety of hook and hand terminal devices have been fabricated, some multipurpose, and some for special tasks. Research in hydraulic and pneumatic knee mechanisms, initiated after World War II has lead to the development of the sophisticated Mauch hydraulic Swing-and-Stance (S-N-S) Knee. Basically, by oversimplifying, this may be compared to an hydraulic door closer. In normal gait deceleration occurs at both ends of swing (extension and flexion). During activation at the knee, a silicone fluid passes through a series of programmed holes in the side of a cylinder, being driven out by piston action.

As more and more holes are bypassed by the moving piston the resistance to outflow increases, thus accomplishing deceleration and the desired mimicking of normal swing. This is a basic characteristic of all fluid-controlled units. The distinctive feature of the Mauch S-N-S is a stance control system which allows for slow yielding of the "knee" if the patient should stumble. This is a complex pendulum-controlled system which has proven itself in practice. Mauch is in the final stages of producing a clinically useful hydraulic ankle.

There are numerous developments of interest to clinicians and prosthetists which have no relevance to a text concerned with teleoperators. This category includes such innovations as the suction socket, the quadrilateral AK socket, the PTB socket, and its variants, the Solid Ankle Cushion Heel (SACH) foot, modular limb prostheses as well as the principle of immediate post-operative fitting of amputees. These are mentioned in passing because they have been particularly significant landmarks in the development of modern prostheses.

The Present

Electromechanical Devices

Electromechanical devices have been used sporadically in the field of prosthetics, orthotics, and orthopedic aids for almost 25 years since the first practical electrically-powered wheelchair came into use. It was not until the Russians showed an electromechanical hand at the Brussels World's Fair (1958) that an expanding effort was made in this country to employ such systems for rehabilitation of orthopedically-disabled patients. The VA, along with other institutions in this country, has been among the most active in research and development in this area. First generation families of electromechanical hands, hooks, elbows, as well as devices to enable the totally paralyzed to control electrical appliances in the hospital and at home, non-manual wheelchair controls, and most recently manipulators, have been developed and are being refined for clinical use.

Far from satisfying all the needs of the orthopedically-disabled patient, the available devices have simply opened the door to vast opportunities for improving service by means of electromechanical technology. The bioengineering research and development efforts which are needed should be applied in close association with those clinicians already heavily engaged in care and treatment. It is only during the last five years that we have seen a significant increase in the use of electromechanical devices. The current wave of interest centers on the development of powered artificial hands, hooks, and elbows. The greatest need, however, particularly in relation to the degree of disability, is found among patients with partial quadriplegia in which both lower limbs are completely paralyzed but a small amount of function still remains in the upper limbs.

The problems attendant on providing electromechanical aids for the quadriplegic are rooted in the extremely small quantity of control information available to the quadriplegic patient. Almost all other types of orthopedically-disabled patients have two or more functioning limbs, either arms or legs. The quadriplegic on the other hand, with two functionless legs and either non-functioning or extremely weak arms, can only provide a limited amount of control information through his respiratory mechanism - exhaling or inhaling - or by head motions which are limited to approximately 15 or 20 degrees forward, backward, and to either side. Until two years ago this problem was apparently the main drawback in furnishing electromechanical aids to those patients with the greatest need. Paradoxically a rather great variety of devices has been developed for other kinds of patients, people with less of a loss in function and control capabilities, such as amputees or hemiplegics.

Wheelchairs

Electromechanical orthopedic aids designed for the non-quadriplegic include a family of wheelchairs, examples of which are described below. Among the disabilities which may require wheelchair use are functional impairment of the lower extremities, such as:

1. Hemiplegia (or hemiparesis): paralysis (or weakness) of one side of the body
2. Paraplegia (or paraparesis): paralysis (or weakness) of the legs and lower part of the body
3. Quadriplegia (or quadriparesis): paralysis (or weakness) of all four limbs, usually including the trunk

The Motorette is an electronically controlled, battery-powered motor unit manufactured by the Motorette Corporation, Reseda, California. It is designed to be installed on or removed from any standard wheelchair easily and quickly. A single "joy stick" control box is snapped onto either of the wheelchair arms. Two 1/4 horsepower (.235 metric h.p.) motors turn individual pinion drive gears which bear on the wheelchair tire surfaces, propelling the chair at velocities up to 8.3 km/hr (5 mph).

The Mono Drive is a motorized wheelchair, manufactured by the Everest and Jennings Corporation, Los Angeles, California. Powered by a single 12-volt storage battery, the motor, with a speed reducer, drives, by means of a chain, the single powered wheel. It is controlled by a handle containing switches in series to alter both motor polarity and voltage. The handle is mounted (left or right) on a steering column which provides directional control. Axial twist of the handgrip mounted on the steering column provides two forward speeds and one reverse speed; turns are made by rotating the handle in the horizontal plane.

The Power-Aid Unit manufactured by California Medical Aids, Montrose, California, is designed to replace either the left or right caster of a conventional wheelchair to convert it from a conventional hand-propelled chair to a power-driven chair. The complete power unit consists of a 12 volt D.C. electric motor mounted directly above the drive wheel to which it transmits power by means of a chain drive. The battery is shielded by a plastic cover and is mounted on brackets resting on the horizontal bars beneath the seat. The wheelchair can be folded for storage after the battery and its mounting brackets are removed, a process in which the battery and its bracket are simply lifted off the lower horizontal bars of the wheelchair frame. The topmost portion of the vertical steering column is bent to form a horizontal tiller with a vertical handle for rotation of the tiller for steering. Squeezing the speed control lever supplies power to the drive wheel in proportion to the force exerted in squeezing.

All of these represent newer versions of the older and classic Everest and Jennings Power Glide.

Seat Lifts

Two seat lifts, both designed to assist patients in rising to a standing position or in lowering themselves to a sitting position, are typical of this class of powered orthopedic aids. The Cushion Lift manufactured by Ortho-Kinetics, Inc., of Waukesha, Wisconsin, is an electrically powered device which operates on ordinary house current (115 volts). As the cushion rises, it tilts forward at an angle that can be adjusted, in four attitudes, to provide the optimum standing angle. The Everest and Jennings Elevating Wheelchair Seat is a hydraulically operated elevating wheelchair seat mechanism. The seat can be installed in existing Everest and Jennings chairs and is readily removable so that the chair can be folded. It also facilitates transfer from wheelchair to bed.

The electrically operated Wolfe lift is designed for use at home or in an automobile when attached to a floor-board-dash support stanchion. This unit typifies a whole family of electrically operated patient lifts.

Crutches

The Hydro Crutch, although not now in production, is another example of the application of external power. The prototype consisted of a telescoping steel tube sealed at the ends acting as a piston inside a second tube, a two-piece molded plastic axillary support, a two-phase motor driven by two nickel-cadmium batteries, and a hydraulic lift system. The crutches are designed to lift and lower patients from and into chairs and to serve as crutches for ambulation. Combining these two functions in a single pair of crutches is a novel concept for crutch users who have considerable difficulty in rising from a chair and in sitting down, as for example, patients with arthritis, multiple sclerosis, or other generally debilitating diseases.

There are, of course, other similar devices of both North American and European design in each of the categories described above. They are not mentioned here because our purpose is to examine the kinds of external power applications made to date, rather than to list all of them.

Upper Limb Prosthetics

The human hand is at once a very powerful and extremely delicate tool. Grip or prehension grasp forces of 100 lbs. or more are possible, yet the hand is capable of positioning objects meaningfully in a microscopic field. The hand is also a sensory organ. In modern society neither survival nor personal fulfillment is as dependent on the hand as they were in more primitive cultures.

Today, loss of one hand reduces the motor and sensory capacities of an individual but need not seriously impair his ability to earn a livelihood and to derive adequate personal satisfaction from life. Prosthetic replacement of a hand restores some of the function lost and some, although a good deal less, sensation.

Among the conventional terminal devices in use today, are rubber-band-powered voluntary-opening* hands or hooks which provide from 1 to 4 lbs. of pinch. Spring-loaded terminal devices provide up to 7 or 8 lbs. and voluntary-closing devices may provide as much as 40 to 50 lbs., a figure approximating the forces applied between the normal finger tips. Although it is possible to approximate the forces of the normal hand, it has only been possible to provide a very small fraction of the vast number of ways in which the normal hand exerts these forces.

Conventional artificial hands and hooks provide two kinds of sensory feedback; proprioceptive feedback based on the relationship between the stump and the position of the fingers, and tactile feedback. Objects pushed, pulled, or hooked produce reaction forces which are transmitted through the socket to the stump where they are converted to tactile sensations - a far less sensitive feedback loop than the normal physiological pattern.

To operate a body-powered terminal device both below-elbow (BE) and above-elbow (AE) amputees use some of the force and motion remaining at the shoulder. A well-trained amputee grades the opening or closing range of the terminal device by "hold off" in the case of elastically loaded voluntary-opening devices, or by directly applied forces in voluntary closing devices.

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*Voluntary-opening terminal devices are those which are opened by muscular exertion against a closing force furnished by rubber bands or springs. Voluntary-closing devices are closed by muscle force, and are opened by springs or elastic bands.

Thus, conventional terminal devices replace lost hand function to the extent that they furnish forces approaching those of the normal hand and some small, but significant, degree of sensory feedback. A prevailing view is that the function of the remainder of the artificial arm is to position the terminal device and to act as a power and sensation transmission link between the terminal device and the man.

Conventional artificial hands are often heavy, and lack eye appeal. They provide either two or three-finger prehension and some models permit manual adjustment of finger position. In general all auxiliary functions other than opening and closing are operated manually. Except for one or two voluntary-closing devices, the prehension force is considered to be lower than desirable. In general, development of externally-powered hands and hooks has not been a systematic process. There are several designs which use external power sources but which do not incorporate related control systems. Other developments ignore currently accepted principles of upper-extremity prosthetic management, e.g., we do not ordinarily involve the sound limb to control a prosthesis, yet several externally-powered hands depend on this type of control.

Much has been written and said about two special features of externally-powered hands - feedback and proportional control. These terms are used in several different contexts. Unfortunately, they mean different things when used in relation to the patient and when referring to the function of a device.

The classical definition of feedback is "the return of a portion of an output to the input for controlling the output." Feedback, therefore, is a characteristic of hands in which information about the behavior of the fingers is fed back to the motor which then modifies or adjusts finger behavior. The information from the fingers may describe their behavior in terms of position, velocity, or the force they apply. The information may be in the form of electrical current or mechanical forces. The information is used to alter the output (speed or power) of the motor to control the fingers. For example, the USAMBRL hand, discussed below in detail, includes a classic feedback feature. By turning on a switch, the patient simply actuates the motor to close the fingers. The fingers close on and grasp an object with a specific force. If the initial force is inadequate and the object begins to slip when lifted, a device in the thumb senses the motion of the object and sends an electrical signal (information) to the motor causing it to close the fingers further or to increase the prehension force. This closed loop type of automatic control of prehension force is based on a feedback system completely contained within the hand and does not require effort on the part of the patient.

Often overlooked in considering the control of a prosthetic hand are more conventional kinds of feedback ordinarily required to control conventional mechanical hands. In a mechanical hand the output is the behavior of the fingers, and the input is the central nervous system (CNS) of a patient which controls the hand through a musculoskeletal link, the "motor", and a prosthetic link. This system also depends on feedback. Information about the position or the velocity of the fingers is "fed back" to the CNS to alter the output of the muscles which transfer power to the hand to modify or adjust finger behavior. In this system the information may be in the form of visual or auditory cues. Information may also be "fed back" in the form of tactile sensations received by skin receptors. Control systems for conventional mechanical devices also depend on feedback, but the CNS is one link in the feedback system which is essentially of the open-loop or non-automatic variety. Both a conventionally-harnessed APRL VC hand and the EMG controlled Soviet-

Canadian hand depend heavily on visual and auditory cues for the control of finger position, velocity, and force.

The principal difference, therefore, between automatic and non-automatic control systems lies in the fact that in one case the feedback path runs from the fingers of the hand to the motor which responds automatically; the second case involves the conscious effort of the man.

A great deal of discussion in this field centers about the concept of proportional control. Classically, proportional control refers to the correspondence of duration and magnitude between an input and an output, as for example, when the position, velocity and force applied by the fingers are proportional to the respective inputs, i.e., the position, velocity, and force of the cable in a conventional prosthesis. The duration and/or the magnitude of an input EMG signal may be proportional to the position, velocity and/or force applied by the fingers of the hand (output).

In these terms, which are admittedly unorthodox with respect to control engineering terminology, all conventional and externally powered hands feature proportional control. Some hands feature direct proportional control in which (1) the force of an output is related to force of the input or (2) position of the output corresponds to position of the input. This is considered superior to indirect proportional control in which, for example, the duration of the input signal determines the prehension force.

During the past five years a number of electrically powered hands and electrically powered elbows have been evaluated. As a class both terminal devices and elbows were found to be heavy and bulky and patients objected to exposed wires, control elements, and power sources. At this writing, a second generation electric hand and elbow for adults now in clinical use is the Veterans Administration Prosthetics Center (VAPC) system used in conjunction with the Northwestern University myoelectric control systems. The Veterans Administration Prosthetics Center system is typical of the attempts to overcome the problems noted earlier.

These elbows are essentially the same weight as the conventional elbow. This advantage simplifies the direct replacement of a conventional unit by the electric elbow. It fits both the standard forearm and the elbow turntable. The device is powered by a small permanent magnet electric motor and the limits of flexion and extension are controlled by two microswitches. Attempts to extend or flex the elbow past these limits shut down the power. The hand is constructed on a skeletal framework with a polyvinyl chloride inner shell and a cosmetic glove over the outside. A special feature of the VAPC hand is its safety break-away that permits the hand to open mechanically when subjected to a load greater than 40 pounds (177.92 Newtons), as for example, when a man grasps a handle on a moving vehicle. The small and efficient motor and the special drive gear arrangement are compatible with the VAPC elbow.

The control system consists essentially of one or more multiposition microswitches. The switches are easily inserted into the control attachment strap of the below-elbow or the front support strap of the above-elbow figure-of-eight harness. They may be attached in series in any section of the harness normally used to transmit forces and other information.

In a typical above-elbow harness the VAPC elbow control switch is located in the front support strap. The same motion formerly used to lock and unlock the conventional elbow provides full control of the position of the VAPC powered elbow. Cable excursion and force to operate the elbow are reduced, facilitating terminal device control for the above-elbow patient.

If a patient is fitted with a powered terminal device in addition to the powered elbow, a second identical switch is installed on the control attachment strap permitting the patient to operate the terminal device by the same motion he previously used to operate the terminal device but with far less force and excursion.

It is possible to locate two control switches in series. By means of rubber bands, which increase the force required for operation, one switch can be discriminated from the other by the patient on the basis of the different force requirements.

Hand with Northwestern University Myoelectric Control System

The hand used in the Northwestern University (NU) myoelectric control system is the VAPC hand with the end plate reduced in diameter to fit the NU wrist unit. The wires to the electric motor within the hand are of a smaller gauge. The myoelectric controller in the NU system is similar in principle to that of other myoelectric systems including these commercially available from Viennatone and Otto Bock which market an electric hand in this country.

The electrical activity of two stump muscles is detected and amplified on the skin over the muscles, as, for example, the wrist flexors and the wrist extensors in the below-elbow stump. If the electrical activity of the flexor group is sufficiently greater than that of the extensor group, the electric artificial hand closes. When the activity levels are reversed, the hand opens. The hand is inactive when the muscles are relaxed. Speed of opening and closing as well as grasp force is controlled by the intensity of the muscle contraction (proportional control).

The NU electronic system is completely packaged in a plastic oval wrist. Amputees with stumps at least 5 cm. (2 inches) above the styloid level of the wrist can be fitted, since all components (batteries, circuits, wires, switches) are packaged within the wrist. This is made possible through the use of small integrated electronic circuits and by the use of small batteries. Two wires connect distally to the electronic circuit in the wrist and pass proximally through the forearm shell to the electrodes over the muscles.

At a CPRD meeting (1969) the utility and application of each of the available devices were considered. Seven hands and one hook were fitted to a variety of patients, including seven previous wearers of prosthetic devices and one new amputee.

Two of those which are still in use will be described as reported by CPRD, one as an example of a terminal device for children and the other as an example of a terminal device for adults. The details of the evaluation will serve to illustrate the problems involved in fabricating electrical terminal devices for amputees, as distinct from those made for space or commercial use.

Ontario Crippled Childrens Centre (OCCC) Electric Hook

Size: This device is approximately six inches long. The mechanism is encased in a four-inch long container to which are attached two flat, stainless steel hook fingers lined with neoprene.

Weight: At 285 gr. the weight of this device is probably acceptable.

Mechanism: The electromechanical force of the OCCC hook is supplied by a small D.C. permanent magnet Globe motor. The first stage of speed reduction is achieved by an O-ring belt reducer with approximately 3 to 1 speed reduction. This drives a worm screw with a worm nut attached to the lever arm of the moving finger. One rotation of this worm screw results in approximately 1/8 inch fingertip opening. The unit also incorporates two micro switches and shaft displacement provisions to permit the unit to switch itself off when the desired prehension force is reached. (In the unit tested the actuating mechanism for these switches were not present.)

Maximum Opening: The OCCC Hook opens to 2 1/2 in., a figure below the desired 3 1/4 in., but as a child's device it is probably adequate.

Type of Prehension: This device provides essentially the same type of prehension as conventional two-finger split hooks.

Minimum Prehension Force: This unit produced three lbs. of pinch force, a figure which may be adequate for a child's hook.

Closure Rate: The hook closed at a rate of 2.9 in. per sec., just under the reference rate of 3.25 in. per sec.

Breakaway: None.

Angle of Approach: Although the precise angle of approach was difficult to measure, this device easily picked up a test object 1/4 inch thick, 1 1/2 inches diameter. It handled the test object with less difficulty than any of the hands tested.

Fingertips: The inner surfaces of the hooks are covered with neoprene pads, but they do not readily conform to the shape of objects between them.

Closure: The hook is capable of maintaining an initially applied prehension force.

Control: The hook may be controlled by gross body motions to actuate a micro switch incorporated on the socket. The switch is mounted so that a tension force maintains the switch in the off position. When the patient reduces the tension, the hook opens and then closes automatically. It applies a fixed prehension force of three lbs. The input information to output function ratio is nevertheless 1 to 1 since the opening and closure resulting from the one body motion input are essentially one function; the hook opens to close. Tension in the harness is input information which keeps the hook closed to maintain grasp on an object. Relaxing this tension is input information which causes the hook to open. The output of this device is fixed and controlled by micro switches.

Life: According to the developer, the device is capable of more than one year's use at 600 cycles per day.

Noise: The device generated 47 db., 47 db., and 60 db., when tested on the A, B and C scales respectively of the conventional acoustical test. The unit is relatively quiet at the lower frequencies.

Cosmesis: This device is not a hand, but as a hook it is cosmetically acceptable.

Special Features: The battery and battery charger are stored in the forearm of the AE prosthesis. This simplifies the wiring and harness but it does require the patient to lift its weight during elbow flexion.

Auxiliary Equipment: No auxiliary equipment is necessary since the unit is completely self-contained.

Adaptability: The OCCC Hook is compatible with conventional prosthetic components.

Patient Training/Retraining Requirement: Due to the reflex nature of this hook, i.e., opening first and then automatically closing, special training is necessary. The need to maintain tension on the control cable to prevent the hook from opening required a good deal of practice.

Research Institute of Montreal (RIM) Myoelectric Hand

Weight: The RIM hand weighs 500 gr. complete with the internally-mounted amplifiers. The battery pack brings the total weight of the device to 800 gr. making it one of the lightest systems tested.

Mechanism: The RIM hand consists of a skeletal framework, metal fingers, and a plastic covering. The palm section is a nylon shell. All four fingers articulate as a unit. It is powered by a small D.C. motor with an operating speed of 10,000 RPM which drives a two-stage gear train which in turn drives a lead screw. A small block mounted on the lead screw is connected to levers on the thumb and forefingers. The entire drive mechanism is mounted in the metacarpal area of the hand.

Maximum Opening: The maximum opening between the distal pads of the fingers and thumb is three inches, slightly smaller than the guideline of 3 1/4 inches.

Type of Prehension: The hand closes in palmar prehension (three-jaw chuck). The fourth and fifth digits are rigid and are capable of closing against objects in the palm in a modified cylindrical type of grasp.

Prehension Force: Measured on a 1/2 inch test block the maximum prehension force available in the RIM unit was five lbs.

Closure Rate: The RIM hand closed at a maximum rate of 3.4 inches per sec., a figure close to the empirically derived standard of 3 1/4 in. per sec.

Breakaway: None.

Angle of Approach: This unit had a nominal 40° angle of approach. It could not pick up a 1/4 inch, 1 1/2 inch diameter disc.

Fingertips: The fingertips of the RIM hand are made of hard nylon covered with rubber, and did not conform to objects grasped.

Closure: This hand is capable of maintaining a desired prehension force.

Control: The RIM hand is controlled by myoelectric signals from the flexors and extensors of the wrist. The ratio of input information to output function was 1 to 1. Finger position and force applied are proportional to the duration of the input signal.

Life: According to the developer the RIM hand is capable of producing 600 cycles per battery charge. During extensive use at RIM, the device gave one year's service. During the two-months wear period of this program, no significant problems in this respect occurred.

Noise: The RIM hand generated 45 db., 47 db., and 67 db. on the A, B and C scales respectively.

Cosmesis: The hand is shaped in a cosmetically acceptable manner and it is covered with a reasonably acceptable cosmetic glove.

Special Features: The RIM hand has a motor driven thumb permitting it to close in palmar prehension about an object equidistant between the digits.

Auxiliary Equipment: A battery charger is needed. A device to measure the strength of myoelectric signals is also necessary.

Adaptability: This device is compatible with present fabrication techniques and components.

Patient Training/Restraining Requirement: As with the other myoelectrically controlled devices, a significant amount of special training is required.

The accompanying chart of the CPRD Evaluation of the terminal devices list all of those tested and the results of the evaluation.

At the present stage of development of powered hands, there is no evidence, as revealed in this report, that powered hands for the BE amputee provide improved function over available body-controlled terminal devices. However, the cosmetic and psychological advantages are significant, and these units are, hopefully, the precursors of more advanced designs. As a result of a thorough study of existing devices, the VAPC has proposed a series of suggestions relative to future developments:

TABLE 14

Chart of CPRD Evaluation of Terminal Devices

TERMINAL DEVICE SPECIFICATIONS WORK SHEET	EXISTING STD GUIDELINE OR SPECIFICATIONS ARPL/SIERRA 4C	AMBRL	AIPR	BOCK	INAIL	NORTHERN ELECTRIC	OCCC HOOK	RIM	VIENNATONE
SIZE	LENGTH: 6.50 WIDTH: 3.18 THICKNESS: 3.10	SAME AS STD EXCEPT WRIST SECTION	SAME AS STD	SKELETAL STRUCTURE LARGER THAN STD	SKELETAL STRUCTURE LARGER THAN STD	NOT APPLICABLE CHILD SIZE	NOT APPLICABLE CHILD SIZE	NOT AVAILABLE APPROX THE SAME AS STANDARD	SKELETAL STRUCTURE LARGER THAN STD
WEIGHT W/GLOVE & W/AUX EQUIP	397 GR	590 GR 900 GR	310 GR 950 GR	442 GR 880 GR	540 GR 840 GR	325 GR 1005 GR	285 GR 529 GR	500 GR 800 GR	440 GR 780 GR
MAX OPENING	3 1/4 IN	2 5/8 IN	2 3/4 IN	4 IN	4 IN	2 1/2 IN	2 1/2 IN	3 IN	3 1/2 IN
PREHENSION & FORCE	3 JAW CHUCK 15 LBS	3 JAW CHUCK 13 LBS	3 JAW CHUCK 16 LBS	3 JAW CHUCK 20 LBS	3 JAW CHUCK 26 LBS	2 FINGER PINCH 7 LBS	NOT APPLICABLE 3 LBS	3 JAW CHUCK 5 LBS	3 JAW CHUCK 10 LBS
CLOSURE RATE	3 1/4 °/SEC	1.25 °/SEC	3 °/SEC	2.8 °/SEC	3.2 °/SEC	3.9 °/SEC	2.9 °/SEC	3.5 °/SEC	2.8 °/SEC
BREAKAWAY	LESS THAN 50 LBS	NO	NO	NO	NO	NO	NO	NO	NO
APPROACH ANGLE	15±5°	15°	20°	30°	30°	16°	NOT APPLICABLE	40°	30°
FINGERTIP	HARD TIP RUBBER COVERED	HARD TIP THUMB SENSOR RUBBER COVERED	HARD TIP RUBBER COVERED	HARD TIP RUBBER COVERED	HARD TIP RUBBER COVERED	HARD TIP RUBBER COVERED	NEOPRENE LINED	HARD TIP RUBBER COVERED	HARD TIP RUBBER COVERED
NO LOAD AMPS & VOLTAGE		0 MA 13 V	NOT APPLICABLE	35 MA 12.5 V	30 MA 12 V	0 MA 13 V	0 MA 13 V	25 MA 14 V	25 MA 11.5 V
RUNNING AMPS & VOLTAGE		210 MA 12.8 V	NOT APPLICABLE	300 MA 12.4 V	125 MA 9.4 V	1.2 A 11.5 V	600 MA 10.75 V	200 MA 13 V	200 MA 11 V
STALL AMPS & VOLTAGE		1 A 12.2 V	NOT APPLICABLE	500 MA 11.5 V	300 MA 8.4 V	1.6 A 11 V	1.25 A 9 V	710 MA 12.2 V	470 MA 10.5 V
CONTROL MOTION INPUT:OUTPUT, TYPE OF OUTPUT	GROSS BODY 1:1 FORCE PROPORTIONALITY	GROSS BODY 1:1 FORCE PROP TO SLIP	GROSS BODY 1:1 PARTIALLY FORCE PROP	MYOELECTRIC 1:1 FORCE PROP TO DURATION	MYOELECTRIC 1:1 FORCE PROP TO DURATION	FINE BODY 1:1 FORCE PROP TO DURATION	GROSS BODY 1:1 NO FORCE CONTROL	MYOELECTRIC 1:1 PARTIALLY FORCE PROP	MYOELECTRIC 1:1 FORCE PROP TO DURATION
NOISE	LOCK CLICKS	50-66 dB	50-60 dB	ABOUT 35 dB	ABOUT 40 dB	50-60 dB	47-60 dB	45-67 dB	54-57 dB
SHAPE COSMESIS	ACCEPTABLE	YES	YES	YES	YES	YES	NOT APPLICABLE	YES	YES
SPECIAL FEATURES	2 POS THUMB, FUNCTION LOCK, VOLUNTARY CLOSING	2 POS THUMB, FUNCTION LOCK, VOL CLOSING, SLIPPAGE SENSOR IN THUMB	2 POS THUMB, FUNCTION LOCK, VOL CLOSING	FUNCTION LOCK, VOL CLOSING, 2 STAGE FORCE MULTIPLIER	FUNCTION LOCK, VOL CLOSING, MOTOR DRIVEN THUMB	3 POS THUMB CYLINDRICAL GRASP, FUNCTION LOCK, VOL CLOSING	FUNCTION LOCK, BATT & CHARGER STORED IN FOREARM	FUNCTION LOCK, VOL CLOSING, MOTOR DRIVEN THUMB	FUNCTION LOCK VOL CLOSING, MOTOR DRIVEN THUMB
BACK UP EQUIPMENT	NONE	BATTERY CHARGER	CO_2 TANK, FILLING DEVICE	BATTERY CHARGER MUSCLE TESTER	BATTERY CHARGER MUSCLE TESTER	BATTERY CHARGER	NONE	BATTERY CHARGER MUSCLE TESTER	BATTERY CHARGER MUSCLE TESTER
COMPATIBLE W/ STD PROSTHESIS	STANDARD	REQUIRES SPECIAL FOREARM	YES	YES	YES	YES	YES	YES	YES
PATIENT TRAINING RQD	MINIMALLY MORE	MINIMALLY MORE	MINIMALLY MORE	SIGNIFICANTLY MORE	SIGNIFICANTLY MORE	MINIMALLY MORE	MINIMALLY MORE	SIGNIFICANTLY MORE	SIGNIFICANTLY MORE

1. Externally powered hands should not require extensive changes in current techniques of fabricating conventional prostheses. Externally powered hands should be compatible with other conventionally used prosthetic components and not require the fabrication of new or modification of old components or their control systems. The control of externally powered hands should not require patients to undergo retraining programs of significantly greater duration than those for conventional hands.
2. A standard minimum opening range should be 3 1/4 in.
3. Specifications for externally powered hands should include the requirement that they be capable of maintaining desired prehension forces without fatiguing the user.
4. A sensible standard for daily hand life would require approximately 600 cycles per charge, or per day. As regards total life at least one year of replacement-free life of 600 cycles per day or approximately 1/4 million cycles should be required.
5. Control should not require the use of the sound side in the case of a unilateral, and the muscles most closely related to the normal performance of the function desired should be employed. At least one specification of the standard should require that a particular device be designed with a particular method of control.
6. A specification for fingertips should require that they be of a material and construction which tends to conform to the shape of objects in contact with them.

7. A standard should be established to the effect that powered hands should not weigh significantly more than conventional hands.
8. All hands should be capable of grasping objects 1/4 in. thick by 1 1/2 in. in diameter lying on a horizontal surface.
9. At minimum, externally powered hands should be capable of producing 0 to 15 lbs. of force measured between the fingers when they are 1/2 in. apart.
10. While great versatility is, of course, desirable, the minimum standard should require at least three-jawed palmar type of prehension.
11. It is recommended that all hands be required to breakaway at 45 lb., plus or minus 5 lb.
12. The minimum recommended standard for closure rate should be established at 3 1/4 in. per sec.
13. The maximum acceptable noise level should be established at 60 db.
14. Input to output ratios should not exceed 1:1.

Ontario Crippled Children's Centre (OCCC) Elbow

The Ontario Children's Elbow is described below, as an example of the elbow units tested.

Size: The Ontario Crippled Children's Centre elbow is slightly larger than the Hosmer child's size elbow. It is interchangeable with the Hosmer elbow and forearm. No limitations are placed on stump length which may be fitted with the unit.

Weight: The unit weighs 10.5 oz., approximately the same as the adult standard Hosmer E-400. The Nicad power package weighs 12.2 oz., well below the operating standards of 40 oz. for auxiliary equipment.

Range: The OCCC elbow unit provides 125 deg. of flexion/extension, ranging from 10 deg. to 135 deg.

Speed vs. Load: Without load, the elbow rotates through the full range of flexion in 2.1 sec. When the standard operating load was applied, flexion required 4.3 sec. or more than twice as long as the operating standard, 2.0 sec. The maximum lift to stall was 1.5 lb. Though well below the operating standard for adults, as a child's elbow it may be adequate in this respect.

Life: Models of this elbow have been used by children at OCCC. Although exact figures on the number of cycles per day or on total life are not available, these factors have not been a problem according to the developer.

Noise: The OCCC elbow is relatively quiet, being rated at 62 db. The use of a special low speed, high torque motor has helped reduce the noise level.

Applicability: No changes in conventional fabrication methods are required to install the elbow. The unit is interchangeable with the Hosmer standard child's elbow. A small Nicad battery charger is required. The unit does not affect terminal-device control and only minimal retraining is necessary.

Special Features: An overload clutch is featured which yields under load to prevent breakage.

Cosmesis: The unit is adequately covered with a cosmetic cover and appears similar to the standard Hosmer unit.

VAPC Electric Elbow

The VAPC Electric Elbow is described as an example of an adult unit.

Size: The VAPC elbow is essentially the same size as the conventional Hosmer E-400.

Weight: The elbow unit weighs 237.7 gms. or approximately 8 oz., two ounces less than the Hosmer E-400 elbow. The battery, belt and the operating switch weigh 13.2 oz., a figure significantly below the operating standard of 40 oz.

Range: The unit produces a flexion range from 10 deg. to 135 deg. meeting the operating standard. It is electrically blocked from exceeding these limits and does not waste power if activated in the end positions.

Speed vs. Load: Unloaded, the VAPC elbow rotates through its entire flexion/extension range in 1.8 sec. With the standard load of 1 lb. in the terminal device, it traversed the complete standard of 2.0 sec. The unit lifted a maximum load of 2.1 lb. placed 12 in. from the elbow center. This function is well below the operating standard of 8.3 lb. at 12 in. from the center of rotation. The unit resists external loads of approximately 30 lb. before yielding.

Life: The unit has been cycled for 25,000 cycles with no discernible wear. Although no standard has been established, 25,000 cycles are estimated as equivalent roughly to 4-6 months' use. The unit provides over 250 cycles per battery charge.

Noise: The unit was tested and rated at 73 db.

Applicability: It requires no changes in the present prosthesis and minimal retraining of patients. The only auxiliary equipment required is a conventional battery charger.

Special Features: The control switch is designed to employ a very small range of the same control motion and shoulder flexion as the conventional system.

Cosmesis: This unit does not have a cosmetic cover at present.

Potentially useful accessory components are under development. Examples of these are:

1. The Gilmatic Electric Elbow Lock which is solenoid operated and activated by bulging muscles against a switch fitted into the socket. This is a more efficient device than the conventional elbow lock.
2. The VAPC Humeral Rotator which is operated by batteries providing power to a miniature electric motor which rotates the elbow turntable.
3. Myo-Sonic Control System (AMBRL) Voice command is employed to select a desired function. As projected now, more command words will provide further control sources. When perfected, the very major problem of seeking an adequate number of control sources may be solved.

As Peizer points out: "adapting these machines to human beings with widely different capabilities, needs, desires and values is a clinical evaluation task. Out of these experiences will come vital information for redesign and improvement of these devices and quite possibly improved service to patients.

Of greater importance is the matter of redirecting design and development efforts away from the field of upper extremity prosthetics. More creative engineering talents should be applied to such other areas as lower extremity and spinal orthotics."

TABLE 15

Details of the Results of VAPC Evaluation of Powered Elbow Units

	STANDARD[1]	AMBRL	VAPC	BOSTON	OCCC[3]	GILMATIC	RANCHO[4]	AIPR PNEUMATIC[6]
A. DIMENSIONS								
1. Width at axis, inside saddle	2¼ in.[1]	2 5/8	2¼	2 5/8	2 5/32	2¼	2 5/16	3
2. Minimum distance-axis to stump end	2 in.[1]	5¼	2	1 7/8	2½	2 3/8	2 1/8	2¼
3. Total length in full extension	3 3/16 in.[1]	6 13/16	3 1/8	3 9/16	--	3 5/16	3 3/8	--
4. Can regular turn-table be used?	--	No	Yes	No	Yes	Yes	Yes	No
5. Can regular fore-arm be used?	--	No	Yes	No	Yes	Yes	No	No
B. WEIGHT								
1. Elbow unit only	12 oz.[1]	15.6	8.2	33.7[2]	10.5	13[5]	18.5	12.5
2. All additional equipment amputee must carry	40 oz.	12.3	13.2	60	12.2	12	27	28
C. RANGE OF MOTION (Flexion-extension)	10-135 deg[1]	0-125	12-138	17-135	0-135	10-135	0-135	8-134
D. SPEED (Flexion)								
1. No load	2 sec.	2.0	1.8	1.0	2.1	3.0	2.5	2.0
2. With 1 lb. at 12 in.	2 sec.	2.6	1.9	1.0	4.3	3.0	3.5	2.3
E. MAXIMUM LIFT	100 in. lb.	72	25	84	18	30	36	48
F. RESISTANCE TO LOAD-FLEXION-EXTENSION PLANE	600 in. lb.	192	360	--	--	50	--	--
G. NOISE LEVEL	<68 db	64	73	65	62	79	60	63
H. ESTIMATED COST	$601	$250	$150	$1000	$200-250	$150	$300[4]	$3357

Notes - 1. Data taken from Hosmer E-400 Elbow
2. Includes forearm
3. Child Size
4. Commercially available in 3 sizes
5. Includes built-in charger
6. All units except AIPR are powered electrically
7. Includes all auxiliary equipment

Lower Limb Prosthetics

In lower limb prosthetics there have been no significant applications of external power to date. Proposals have been advanced from time to time for control of knee motion by means of external power sources and for providing push off in stance phase by means of externally powered sources. None of these proposals has advanced beyond the experimental prototype stage. Among others, Hans Mauch of Dayton, Ohio, U.S.A., is currently engaged in basic studies on myoelectric and other means for controlling hydraulic or externally-powered limb components. The VA Prosthetics Center is considering the design of an electric swing-and-stance-phase knee control. As presently conceived, the knee is essentially an electric motor generator whose resistance to cranking would be used to control swing phase. The current generated thereby would be stored and perhaps used to control stance phase.

Quadriplegia

Trauma of the spinal cord is obviously a catastrophic event whose treatment requires procedures for saving life, maintaining vitality, and salvaging all functional residuals. Treatment invokes the full range of the medical and paramedical skills available, each of whose essential role is well defined. The defense against death and immobility is conducted by the neurosurgeon, internist, urologist, orthopedist, physiatrist, nurse, physical and occupational therapist, orthotist, psychologist, and social worker.

The ministrations of this extensive array of medical talent often produces a human being who still spends most of his life between the table and the toilet.

Many patients with high-level lesions live their lives in bed with their energies directed toward simply staying alive and maintaining reasonable hygiene. This is in contrast to the potentialities of some paraplegics with upper extremity function to whom the doors of education and vocation are being opened. Here, as nowhere else in the whole spectrum of orthopedic disability, is there a vital need for electromechanical hardware and, unfortunately, to date, the surface has just been scratched.

Our experience in this area, derived through an intensive crash program of bioengineering support of spinal cord injury facilities, reveal three areas of fundamental need: mobility, environmental control, and intellectual/emotional enrichment.

Mobility

A. Wheelchairs

The quadriplegic has lost a fundamental characteristic of the animal kingdom - the ability to displace his body. He has also lost the fundamental human capacity to manipulate objects about him. The first loss makes him completely dependent on mechanical means for transportation and the second eliminates the possibility of controlling any type of vehicle by arm or hand movements. The positive and negative pressures generated by breathing into or sucking on a tube have been utilized to control the movement of electrically-powered wheelchairs. Such a device, developed by the Veterans Administration, consists essentially of two plastic tubes positioned on a bracket in close proximity to the patient's mouth while he is seated in the wheelchair. Each tube controls switches that feed power to one of two motors driving the wheelchair. Blowing on both tubes produces forward motion of the chair; sucking on both tubes produces backward motion of the wheelchair, and blowing only on the left or right tube produces a left or right turn. This two-tube system is the simplest form of this type of control and requires the least amount of command information. It has a drawback, however, in that patients whose respiratory capacity may be below par are required to maintain a low pressure, low volume stream of air while driving the chair. Other models are now being introduced featuring four tubes which do not require maintenance of respiratory pressure and which provide proportional speed control. These devices, however, require more command information in that starting and stopping is not simply a matter of stopping breathing or sucking but require a command in the form of another puff or suck. Despite these advances which are providing mobility where there once was none for the severely disabled patient, these devices can be considered primitive steps which simply open the door to the general problem.

B. Vans

While wheelchairs furnish local mobility in the hospital, around the grounds, in the home, and in the proximate environment, they do not restore the long range mobility available through motor vehicles. This problem is being attacked through the use of vans which no longer distinguish between those who are and who are not capable of operating a standard automobile. The van requirements for such patients include a control system enabling the patient to operate the vehicle safely, and an access system enabling him to enter and exit the vehicle and to position himself stably in the driver's position.

The Scott van meets this need in providing a control column rather than a steering wheel. With minimal movement of the hand or shoulder, a patient can accelerate or maintain forward speed by a low force, low excursion movement of the column position on his hand. Backward movement drives the vehicle in reverse and a movement to the right or left turns the wheels accordingly. In short, the control column represents a joy stick controlling both the direction and the velocity of the vehicle. The patient enters the van from the rear by operating an outside control panel which automatically moves the tail gate lift to a horizontal position and then causes it to descend to the street level. The back doors of the van open in sequence. The patient drives his wheelchair down the curb break and onto the elevator where he actuates a redundant control panel lifting the elevator to the level of the van bed, enabling him to drive his wheelchair into a position previously occupied by the driver's seat. Here at the touch of a button he closes the rear doors and locks his wheelchair into position. He is now in a position to operate the vehicle whose starter button, lights, horn and dimmer are on the control column. The van also features redundant brakes, ignition and steering system.

The other type of van is for the less handicapped patient who has reasonable use of both arms but not of his legs, and who may for several reasons be unable to operate a conventional wheelchair which he might utilize with a conventional sedan modified with hand controls for driving. The normal procedure is to drive up to the automobile positioned at the curb, open the door, pull and slide himself into the seat, reach out and collapse the wheelchair, drag the wheelchair into the rear passenger compartment behind him, jiggle himself into the driver's position, and operate the car with hand controls. Patients unable to do this but yet with at least partial functioning arms may use an electric wheelchair and a simpler type of van than that described above. These vans feature an elevator mechanism and a non-automatic tie-down system for the wheelchair. The otherwise conventional car is operated by means of commercially available hand controls.

C. Unmet Needs

Between the wheelchairs and the vans a great deal of the lost mobility of these patients is being restored. There are, however, many highly important but unmet needs. Transporting the patient from his bed into a wheelchair and from the wheelchair back into the bed now requires the services of at least two other people. There are no devices at the present time which satisfactorily accomplish this for the patient, leaving him dependent on others.

Environmental Controls

A. Home Appliances

As a consequence of having lost his ability to manipulate objects, the quadriplegic patient does not have the use of a wide variety of common, everyday appliances such as TVs, tapes, radios, lights, fans, air conditioners, etc. To meet these needs the VAPC has developed a 12-channel controller into which almost any 110 volt household appliance can be plugged. The patient turns these appliances on or off, switches radio stations or TV channels, or dials a telephone by a pneumatic controller similar to that used for operating a wheelchair. Observing an illuminated display board, he selects the desired function by sucking into a tube. Sequential sucks shift the selector of the controller from radio to tape a to lights, etc. Having located the proper selection, he puffs on the tube and turns on the selected appliance. A second puff turns off the appliance. This device is receiving substantial approval from patients to whom it has been made available. Breath control is being employed to operate games for the quadriplegic, such as pin ball machines and television screen ping pong. The potential here is great.

B. Unmet Needs

There are, however, many other functions which are not now available. Although these patients can see, they are incapable of reading independently since they can not hold reading material or turn pages. A juke box type reading machine controlled by a pneumatic controller may meet the need if it were available. One can conceive of a system in which the patient would select the book he wanted from a magazine or rack, which the machine will deliver to a viewing stage in an open position. The patient could then select the TD mode and the channel connected by cable to a TV camera over the viewing stage. A page turning device operated by sucks on the tubes would complete the system. One can also envision reading material reduced to microfilm or microfiche and stored in a viewer which the patient could operate by a similar control system. Once medically stabilized, these patients have two fundamental requirements - mobility and manipulation. The problem of locomotion for these patients has had a great deal of recent attention as described above, in the form of powered wheelchairs controlled by movements of the chin, breathing pressure, and other more exotic systems. But manipulation, the capacity to control the movement of objects in space, to give them access to music, television, reading material, food, and recreational outlets, has not been attacked in any meaningful way. Here, obviously, is a fertile field for the application of remote manipulator technology. But before considering the problem well on the road to solution, the requirements should be examined.

Consider the two basic elements in a remote manipulator system: the man and the machine; and consider the terms of some recently minted jargon: that of smart bombs and stupid bombs. Most remote manipulators today were designed for control by normal humans through the use of highly dexterous end organs - the hands. The amount of information, therefore, that the human operator can provide the machine - the manipulator - is very great, and in this sense the machine is rather stupid and the operator rather smart, although perhaps not so strong. On the other hand, in dealing with the handicapped we have a situation in which the operator is "stupid" in a control sense: he does not have the use of highly dexterous command elements and is, therefore, capable of giving the manipulator very little information. The manipulator for the spinal cord patient, therefore, must be "smarter" than that designed for use by a normal individual. The tetraplegic patient can only command the manipulator by breathing in a code consisting of puffs and sucks, or by two-dimensional movements of his head, or perhaps by generating myoelectrical signals in the active muscles of his face and neck, or by movements of the tongue, or by movements of the eyeball.

Superficially at least, eyeball movement as a command origin suffers from the fact that the target can not be observed; tongue movements involve the maintenance of some actuator or transducer in or near the mouth; and myoelectric control depends on appropriate muscle sites, interfacing electrodes and appropriate motor points, and adjustment requirements due to skin resistance variations occasioned by sweating or skin temperature changes. However, both head movements and pneumatic control by blowing into tubes positioned close to the mouth have proved quite adequate for wheelchair control and for fairly rudimentary environmental controllers already designed.

However, a vast number of other highly important functions can not be performed by simple on-off systems but require a form of manipulator technology because their performance requires a three-dimensional displacement of an object in space, and; indeed, the three-dimensional orientation of both patient and object have to be considered. With a poverty of command information available, the required manipulator must indeed be very "smart."

We do not know how to build such a manipulator. The kind we are talking about is one that would enable a man to pick food out of a tray placed near him, bring it to his mouth and eat it, and to perform these functions with very little input information - puffs and sucks or small motions of the head. We need a manipulator to select a book or other reading material from a nearby receptacle and place it in a position to be read by such a patient while he is in bed or a wheelchair, to turn pages, and to replace the book. We need a manipulator to enable a man to shave himself and to wash his face and to comb his hair. We need a manipulator to enable a man to operate various games such as the commercially-available electric football, hockey, etc. games, as well as checkers, chess and cards.

Intellectual/Emotional Enrichment

Many of the above devices under development or simply being conceptualized could obviously increase the emotional content and intellectual input to patients whose social ambience has been extremely limited for many years. To fill this void we need better telephone dialers, games, and reading machines which these patients are capable of operating.

It is in this specific area of quadriplegia and similar disabilities that the skills of advanced technologists can best be applied. There are obviously major problems and, therefore, major needs which not only require but demand the efforts of bioengineering resources. In the area of mobility and environmental control we see some progress, yet much more needs to be done. In the area of enriching the intellectual and emotional lives of people with quadriplegia the problems are still formidable and the solutions require sophisticated approaches based on intensive research.

Some equipment can be effective in improving the recreational scope of these people. More is needed. Toilet needs are formidable: there is a major role to be considered here for functional electrical stimulation. Sex needs require major efforts in physiological research to provide function in these crucial problem areas.

Lower Limb Orthotics

Except for a relatively few instances, advances in modern orthoses awaited the development of external power and the identification and application of plastics suitable for use in brace design.

As a result of the plastics revolution, metal double bar braces are being replaced, wherever possible, by plastic orthoses. A polypropylene ankle-foot orthosis has been developed which can be modified to allow or eliminate ankle motion. Teufel, of Stuttgart, Germany, has marketed an ankle-foot orthosis of a plastic material (polyethylene) trademarked "ortholene." Whereas the polypropylene is thermoplastic, the "ortholene" is not only thermoplastic, but can also be cold-worked. Lehneis used a thermoplastic acrylic-nylon composite to fabricate the spiral brace, an ankle-foot orthosis, which employs resistance to plantarflexion and dorsiflexion as do most of the other plastic ankle-foot orthoses. Since rotation of the area encompassed by the brace is dependent on subtalar motion, the limitation of such motion by the brace does not allow tibial rotation in spite of the helical design.

The VAPC, as well as other centers, has been employing plastics for

TABLE 16

Prescription Procedures for AFO's

ETIOLOGY	PATHOLOGY	MODIFYING FACTORS	PRESCRIPTION
1. LOWER MOTOR NEURON DEFECT (PERONEAL N.)	FLACCID PES EQUINUS	STABLE*	VAPC SHOE CLASP
		UNSTABLE* — MILD	TEUFEL (POLYETHYLENE)
		UNSTABLE* — MOD.	POLYPROPYLENE
2. LOWER MOTOR NEURON DEFECT (SCIATIC N.)	FLACCID PES EQUINUS (WITH CALF MUSCLE CONTRACTURE**)	STABLE*	VAPC SHOE CLASP
		UNSTABLE* — MILD	TEUFEL
		UNSTABLE* — MOD.	POLYPROPYLENE
	FLACCID PES EQUINO-CALCANEUS (WITHOUT CALF MUSCLE CONTRACTURE)	STABILITY NOT A FACTOR SINCE CHOICE IS LIMITED TO STABLE ORTHOSES	IRM SPIRAL ORTHOSIS-IF BILATERAL INVOLVEMENT, THEN- TEUFEL OR POLYETHYLENE POLYPROPYLENE FABRICATED TO RESIST DORSIFLEXION AND PLANTAR FLEXION
3. UPPER MOTOR NEURON DEFECT	SPASTIC PES EQUINUS	MILD***	VAPC SHOE CLASP FES
		MOD.***	TEUFEL-IF NOT ADEQUATE, THEN- POLYPROPYLENE
		SEVERE***	POLYPROPYLENE-IF NOT ADEQUATE, THEN - EXTERNAL (SHOE ATTACHMENT) BRACE
4. ANY OF THE ABOVE	ANY OF THE ABOVE	EDEMA OF FOOT-ANKLE	VAPC SINGLE BAR ROTATION ORTHOSIS (FLACCID)
		IMPAIRED SENSATION****	VAPC SINGLE BAR; NO ROTATION (SPASTIC)
		VARUS OR VALGUS (REQUIRING T-STRAP)	DOUBLE BAR BRACE IF SUBJECT IS OVERWEIGHT OR VERY ACTIVE
5. PAINFUL DESTRUCTIVE DISEASE OF ANKLE	ARTHRITIS (POST-TRAUMATIC, INFECTIOUS, INFLAMMATORY, ETC.)	PAIN ON AP OR ML STRESS BUT NO PAIN ON WEIGHT-BEARING	POLYPROPYLENE ORTHOSIS MODIFIED TO RESTRICT DORSIFLEXION AND PLANTAR FLEXION
6. a) STRUCTURAL INADEQUACY DISTAL TO THE KNEE b) PAIN DISTAL TO KNEE, ON WEIGHT BEARING	a) NON-UNION OR DELAYED UNION OF TIBIA; CHARCOT'S DISEASE OF ANKLE/FOOT, ETC. b) DESTRUCTIVE DISEASE OF ANKLE, ETC.	TISSUE BENEATH THE CUFF AREA MUST BE CAPABLE OF TOLERATING THE PRESSURES OF PARTIAL UNWEIGHTING; FOR EXAMPLE, SENSATION MUST BE INTACT	VAPC PTB BRACE

* Stability is: a. evaluated during trial of a stock brace (VAPC shoe clasp, Teufel, Polypropylene) on the patient by the Clinic Team, or, b. can be assumed by the nature of the terrain the subject may walk upon (fields, golf courses, etc.).

** Many patients with sciatic nerve injuries develop calf contractures sufficient to stabilize the ankle at about 90°, in the weight bearing position. These patients need only a correction for the flaccid pes equinus.

*** During the clinic team evaluation of orthoses, the degree of spasticity is related to the "triggering" of spastic equinus (or equino-varus) by the stock braces tested directly on the patient as part of the evaluation procedure. For example, if the stock shoe clasp triggers the foot into spastic equinus, one must try the stock Teufel, or finally, the stock Polypropylene. If the foot deforms within the Polypropylene, external (shoe attachment) bracing is required. Very severe spasticity cannot be controlled by a brace.

**** Most such patients will tolerate a properly fitted shoe insert brace, or a shoe clasp. Those who develop areas of irritation should be changed to external bracing with individualized shoe modifications, if indicated.

long leg braces as well as knee and back orthoses. For example, "prenyl," a trademarked thermoplastic material, may be obtained in several thicknesses and has proven useful for the fabrication of thigh corsets. It does not become perspiration soaked as does leather.

Upper Limb Orthotics

Significant advances in the use of external power in orthoses for the paralyzed upper limb have been made in recent years. Systems such as those developed at Rancho Los Amigos Hospital, Texas Institute for Rehabiliation and Research, and the Institute for Rehabilitation Medicine in New York, among others, have been available for several years and are constantly being improved.

The Rancho Electric Arm with tongue-operated control provides quadriplegic patients with the ability to drive an electric wheelchair and to perform many useful activities through volitional control of their arms.

The McKibben muscle was probably the first widely used actuator in an external-power system. Technically, it belongs in the general category of pressure-actuated devices of which pistons and bellows are other examples. The "muscle" consists of a straight piece of hollow, braided sleeving, a gas-tight inner tube, and suitable end closures for external attachment and pressurization. In order to achieve the maximum amount of longitudinal contraction, the angle between the helically woven fibers of the braid and the axis of the tube is made as small as possible, consistent with bursting strength. When inflated, the sleeve tends to expand radially, with a consequent decrease in axial length. It can be shown that the maximum contractive pull for an ideal braided actuator is three times the pull of a piston-type actuator having a cross-sectional area equal to the maximum stable cross-sectional area, of the braided actuator. In practice, somewhat less tension is developed because of weave binding, internal friction, and elastic effects.

Perhaps the earliest electrical powered orthosis was the Electromechanical Hand of the Lionel Corporation in the early 1950's. This electrically operated mechanical hand could be used to perform many of the simple functions which require grasping and release, such as picking up pencils or pens for writing, using utensils for eating and drinking, shaving, and use of cosmetic equipment. Other normal everyday tasks such as typing and using a telephone could also be performed, but the user required reasonably good arm movement. The electromechanical "hand" consists of a lightweight glove-like frame encasing the hand, thumb, and the index and middle fingers. The part encasing the first two joints of the index and middle fingers is hinged to the rest of the structure to obtain motion simulating normal finger flexion. This part, as well as the casing for the thumb, is made of a thermoplastic material which can be formed to any required shape by application of a small amount of heat. A power unit contains a mechanism for opening and closing the index and middle fingers in relation to the thumb by means of flexible cables attached to the movable part of the casing. The motor, controlled by a sensitive pneumatic switch, can develop a maximum force of 4 - 5 pounds between the fingers (17.792-22.240 Newtons). The power unit weighs approximately 2 1/2 pounds (1.134 kg.).

This entire class of externally-powered hardware was conceived to handle problems due to paralyses in which the structural integrity of the limb may be relatively unimpaired. These designs, therefore, are aimed principally at providing motor power for existing joints. In many cases the patients are confined to wheelchairs, a situation which substantially reduces the problems of weight, adequate power supply, and the number of functions which can be supplied.

Lower Limb Orthotics

In the field of lower-limb orthotics, external power applications to date have been few. Liberson has attacked the problem on an experimental level by providing paraplegic patients with electrically driven hip joints which are mounted in long leg braces and controlled by means of switches placed in the heels of the shoe. The motor on one hip joint provides hip flexion; at the same time the motor on the other side provides hip extension or a form of pushoff to enable the patient to walk with a step-over-step gait. He also has devised a locking mechanism for a knee joint. It consists of a small electro-magnet which locks the knee joint of the brace at the time when the foot is on the floor, i.e., when the shoe switch is closed. Apart from these efforts, most of the work in this area has been devoted to muscle stimulators which are designed to eliminate the need for mechanical braces.

Muscle Stimulators

In a hemiplegic patient, an electric switch placed in the shoe of the involved leg briefly energizes a pulse stimulator which (via a direct message-activating effect on the peroneal nerve) activates the muscles which dorsiflex and evert the foot. Artificially induced dorsiflexion and eversion automatically occur each time the subject lifts his involved foot. In this way, foot drop and foot inversion may be partially corrected. These are experimental devices which are only in limited use today.

A portable electronic muscle stimulator, the Theratronic Muscle, designed primarily for patients with residual drop-foot conditions caused by hemiplegia or hemiparesis consists of a stimulator and battery pack fitted with belt loops. The pulsed signal range is adjustable between 20 and 80 volts. A pulse applicator, consisting of a small flexible electrode covered by an absorbent pad, is worn over the motor point of the paralyzed muscle.

The pad is saturated with electrolyte and replaced daily. A reference electrode is worn over the calf of the leg to complete the circuit. A heel switch, enclosed in rubberized cork, is turned off and on automatically during the normal walking cycle, thus governing the muscle-activating pulse. Throughout the walking cycle, the activating pulse to the paralyzed muscle is turned on when the heel is raised and stays on until the foot is set down again. When the patient stands, the switch is closed and the current stays off.

Muscle stimulators such as those of Moe and Post, as well as Liberson, are intended to eliminate braces and to apply small electrical charges to stimulate muscle in cases of upper motor neuron disorders. Their principal problem has been to provide stimulations below the threshold of pain.

Nerve Stimulators

Gracanin, of Ljubljana, Yugoslavia, has developed a method of nerve stimulation which may significantly reduce some of the problems encountered in muscle stimulation, and perhaps may have even wider application. Again this is a highly experimental, but developing area of application.

The spinal motor neuron has been termed "the final common pathway" because it is coupled not only with the cortical and subcortical structures of the brain but also with the spinal afferents, which are the nerve trunks designed to carry messages from the periphery to the central nervous system. Efferents function in the reverse direction. Efferent functional electrical stimulation of sufficient duration gives rise to little understood conditioning of motor reflex mechanisms, and changes their organization during walking. However, the relatively lower stimulation threshold of large diameter afferent fibers (as compared to small diameter fibers) and the specific excitability of receptors offers the possibility of selective afferent stimulation with electrical or mechanical stimuli.

Studies of the effects of such stimulation in hemiplegic patients have shown that it is possible to suppress involuntary activity, such as clonus in antagonistic muscles, by careful selection of the type of electrical stimulus.

Functional Electrical Stimulation (FES)

The following briefly summarizes the electrochemical basis for the biologic production of the voltage necessary to operate myoelectric devices, as well as the manner in which functional electrical stimulation introduces the stimulus into the neuromuscular pathway to elicit muscle contraction.

Functional electrical stimulation may make it possible to eliminate the use of braces for certain paralytics by utilizing the residual functional neuromuscular components. It may be applicable to spastic conditions and the problem of restoring a degree of coordinated function to otherwise uncontrolled muscles. Previous attempts at direct electrical stimulation of muscles were impeded by the relatively intense stimuli required for direct stimulation, causing pain and the frequent readjustment of gains.

The technique for stimulating nerves rather than muscles has been developed by Dimitrijevic and Gracanin of Ljubljana, Yugoslavia, to a level of clinical applicability. In the Yugoslav technique, stimulation of the peroneal nerve not only produces dorsiflexion and eversion of the foot, but also causes relaxation of the spastic muscles. Adequate stimulation is accomplished at relatively low intensity levels, reducing the possibility of pain.

A. Neurophysiologic Basis of Function.

Functional electrical stimulation of nerves depends upon and takes advantage of several phenomena of neuromuscular physiology. The inside of the nerve axon is electrically negative in relation to the fluid bathing its outer surface. This is primarily the result of a relative excess of positive ions (Na+) which predominate on the outer side of the axon membrane. Sodium ions which leak into the axon are pumped out again by a little understood mechanism conveniently referred to as a sodium pump. Normally, in the inactive state there is about a 60 to 90 millivolt difference between the two sides of the membrane. When the electrochemical stability of the membrane is disturbed to a degree which overwhelms the capacity of the sodium pump, a surplus of Na+ ions enters the axon, reducing the difference to under 50 millivolts. An electrical impuse, the action potential, is then propagated along the axon to the synapse. This is what happens under normal conditions, when a volitional impulse is initiated and, also, in the situation under consideration here, when the peripheral nerve is electrically stimulated.

The stimulus which reaches the synapse is not, of itself, powerful enough to stimulate the muscle. As in the case of the nerve, there is a difference in potential on both sides of the muscle fiber membrane. The nerve impulse, on reaching the synapse, releases acetylcholine. The acetylcholine disturbs the electrochemical stability of the muscle fiber, making it more permeable to ions. This results in an action potential which is propagated through a communications system which passes along and within the muscle fiber (the longitudinal and transverse sarcotubules, i.e., the L- and T-systems). The change in membrane permeability effected by the electrical impulse releases calcium which is necessary for the adenosine triphosphatase reaction in myosin, triggering the release of energy for contraction. The sliding filament theory of muscle contraction proposes that molecules of myosin and actin, arranged as alternating filaments, slide together in a microscopic muscle contraction. The energy for this reaction is obtained by the breakdown of adenosine triphosphate (ATP) to adenosine diphosphate (ADP) through the agency of the enzyme adenosine triphosphatase activated by the release of calcium. In an unknown manner the chemical energy is converted to mechanical energy with an efficiency of about 40 percent.

B. Muscle Spasm.

We can consider some reflexes, such as the patellar tendon and achilles reflexes as small units of spasm. When a rubber hammer taps the tendon it suddenly stretches the tendon. This, in turn, stretches specialized receptors in the muscle (the annulospiral fibers of the muscle spindle) which pass the message to the anterior horn cells of the spinal cord via the sensory afferents. From the anterior horn cells the impulse passes along the alpha motoneurone via the nerves supplying the appropriate muscles, as for example, the gastrocnemius and soleus, inducing a contraction and the familiar achilles reflex. If this contraction should be maintained and uncontrolled, a spastic state would exist. This is what occurs when brain injury releases the gamma motoneurones (the efferents to the muscle spindles) from central control so that they fire without inhibition. Receptors discharge when the tension of the intrafusal muscle fibers of the muscle spindle is increased by:

1. An externally applied stretch reflex (as the "jerk")
2. Activation of fusimotor fibers (gamma efferents)

Not only does FES stimulate the tibialis anterior and peroneal muscles supplied by the peroneal nerve but at the same time, by the neurological mechanisms described below, FES relaxes the spastic antagonistic plantarflexors and invertors supplied by the tibial nerve which is quite remote from the location of the cutaneous electrodes.

6. FES Inhibits the Spastic Antagonists.

The Hoffman Reflex, (H-Reflex) is a reaction to the stimulation of the sensory afferent fibers of a nerve when the stimulus is applied through a cutaneous electrode. The stimulus applied to the peroneal nerve produces not only a distally directed impulse to activate the tibialis anterior and peroneals, but also a proximally directed component which enters the spinal cord where the activities of the agonistic and antagonistic muscles are coordinated, reestablishing some control over the uninhibited firing of the gamma motoneurones of the spastic muscles. The significance of neural FES rests on the fact that the H-Reflex is elicited with stimuli of low intensity, an advantage over the technique of direct muscle stimulation in which high intensity stimuli are required. The largest nerve fibers have the lowest thresholds to electrical stimulation. These fibers come primarily from the annulospiral (afferent) endings in the muscle spindle. When the stimulus is of high intensity, the H-Reflex is blocked and only the direct muscle response is obtained. Muscle stimulating devices, such as the Theratron, used a relatively high intensity stimulus, blocking out the coordination function of the H-Reflex.

The Ortazur

The French have produced a "space suit" lower extremity orthosis for the paraplegic. This "ORTAZUR"* consists of a snugly fitted nylon half-suit, resembling fishermen's waders, or hip boots, depending on the level of involvement. When medial, lateral, and posterior tubes, which are incorporated into the suit, are gas inflated, the suit becomes rigid and the patient can be supported in the erect position.

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*Manufactured by Societe Aerazur, Issy-Les-Moulineaux, France.

When used for low-level involvement such as Thoracic 12 or lumbar 1, the boots are all that are required. When involvement is higher, as Thoracic 5 or 6, the wader type of pneumatic brace is used in the absence of adequate pelvic control musculature. At this writing the apparatus is under investigation in this country by the VAPC.

AIDS FOR THE BLIND

Among the several reading devices being developed for the blind is the Battelle Model D Optophone. A 200-hour training course is given to interpret the polyphonic output of this machine as it moves over the printed page. Twenty-five words per minute have been achieved by one user, a 71 year old man, on such material as proofing typing, reading magazines, books and the Bible.

The Cognodictor is a recognition machine with spelled-speech output. This type reader is still in the experimental stage. It is claimed that reading speeds up to 80 to 90 words per minute are possible with spelled-speech.

The Visotoner and Visotactor are similar reading machines but with different outputs. Each has a vertical column of narrow photocells which scan letters and electronic circuits that change the "blankness" seen into tonal patterns for the ear or touch sensation for the fingers. The Visotoner is used with an earphone. The Visotactor's output is presented on the backs of the four fingertips used to guide the machine, making it suitable for the blind-deaf. Ten words per minute have been achieved. Both machines can be used with the Colineator tracking device for extended periods of reading. Weight is ten ounces plus twelve ounces for the battery. The VA has 36 Visotoners and 14 Visotactors for evaluation.

The Digitactor is a hand held tactile-output device similar to the Visotactor. This experimental machine stimulates the underside of only one finger with a large number of vibrators.

The Stanford Research Institute's Opticon is also similar to the Visotactor.

AIDS FOR THE DEAF

Workers in the field of sensory aids for the deaf have not produced significant clinically applicable new developments which would be of interest to researchers in the area of teleoperators. One of the great problems is teaching deaf children to speak.

The lack of universality of application of sensory aids reduces the number of any one device needed, raises the unit cost, and discourages mass market oriented manufacturers.

CONCLUSION

To be effective the bioengineering technologist who sees a role for himself in the problems of the physically disabled should relate his efforts to the clinicians who are daily exposed to these problems. Association with a research-oriented physician does not bridge the gap between engineering and medicine. Even though such relationships may be beneficial in fundamental research, there is a real need for the more important bridge to the clinic and to the patient. The solutions to these problems of the severely handicapped will not come out of research laboratory work alone. They will be the results of applying bioengineering talents to clearly specified clinical needs.

V. Applications of Teleoperator Technology For Problems of the Handicapped

NASA has become increasingly involved over the past several years with identifying uses of space systems technology for medical applications. A good number of these applications have made use of, and are currently making use of, technology developed originally for remotely controlled space systems. A representative listing of the teleoperator technology applications currently under development for the fields of prosthetics, orthotics, and sensory aids was developed based on the authors' knowledge and experience of teleoperator technology efforts and based on a report published by the Research Triangle Institute on Biomedical Research and Aerospace Technology Applications (NASA-CR-127792, December 1971). This listing is presented below:

- Application of a mechanically actuated triggered hand, developed as a teleoperator end effector by NASA Marshall Space Flight Center in 1972, for amputees requiring control of the trigger of power tools. The application, developed by Rancho Los Amigos, involves adding the trigger mechanism to a Dorrance hook.
- Application of a set of replaceable hand tools as end effectors, being performed by Rancho for Marshall Space Flight Center.
- Application of Laser proximity sensors for the blind, being developed at Marshall Space Flight Center and at the Jet Propulsion Laboratory.
- Application of teleoperator sensor technology for tactile sensors for the blind, being developed by Stanford Research Institute for NASA Ames Research Center.
- Applications of remote control technology for patient control of his room environment from his bed, being developed by Marshall Space Flight Center, Huntsville, Hospital, and the University of Alabama at Huntsville.
- Applications of controls, control systems, and controllers for the handicapped, Marshall Space Flight Center, and NASA Technology utilization office - numerous applications.

- Potential application of an articulated, dexterous three fingered hand being developed for Marshall Space Flight Center by the University of Massachusetts.

- Application of a small motor for powering a prosthetic unit (Research Triangle).

- Application of remote control technology for a signalling (nurse call) system for multiple sclerosis patients (Research Triangle), based on development work by Southwest Research Institute for Marshall Space Flight Center and Langley Research Center. Control options include breath activated control, eye movement and blink, and head movement.

- Application of remote control technology for a device to pick up and transport single sheets of paper (Research Triangle) - Langley Research Center.

- Application of remote manipulator technology for precise remote micromanipulator control (Research Triangle).

- Applications of teleoperator control technology to reduction of friction in upper extremity prostheses control mechanisms (Research Triangle).

- Application of manipulator technology for development of an improved value for total contact lower extremity prosthesis (Research Triangle).

- Application of manipulator and control technology for establishing the interface between prosthetic and living material (bone) being developed by Marshall Space Flight Center and Rancho Los Amigos.

- Application of control system technology for measuring evoked cortical response by aural stimulation, to test non-responsive (deaf) children, Southwest Research and Marshall Space Flight Center.

- Application of teleoperator control system technology for proportional control systems for externally powered orthotic arm braces for Marshall Space Flight Center.

- Potential application of teleoperator control technology for coordinated control of prosthetic arms, MIT for Marshall Space Flight Center.

- Application of manipulator technology for orthotics, myoprosthesis, and therapeutic aid - the NASA Ames manipulator system.

- Potential application of mobility unit and remote control technology developed for unmanned lunar and planetary surface rovers, for prosthetics, orthotics, and patient service systems, by Marshall Space Flight Center and Jet Propulsion Laboratory.

- Application of remote sensor technology for conversion of photic to tactile stimulation for the blind, Marshall Space Flight Center.

As indicated in this list of applications, the one NASA organization which is deeply involved in developing applications of teleoperator technology specifically for the handicapped is the Marshall Space Flight Center. This is probably due, at least in part, to that center's position as the responsible organization for earth orbital teleoperator technology development.

As indicated by these representative efforts in applying teleoperator technology for the handicapped, it is obvious that each application area represented an attempt to resolve a particular problem. While such an approach may be valuable to resolve pressing problems, additional consideration needs to be given to the overall problems confronting the handicapped and to the integration of solutions proposed for those problems (i.e., the systems approach). The preceding chapters of this report considered at length the requirements of the handicapped, their problems, and the problems associated with the state-of-the-art in prosthetic, orthotic, and sensory aid systems. Based on a consideration of these requirements and problems in terms of potentially applicable teleoperator technology, the identified, practical and feasible areas of direct application were as follows:

- Manipulator technology
  - Anthropomorphic manipulators and end effectors which can serve directly as prosthetic and orthotic devices.
  - Manipulators to increase the reach of, and reduce requirements for mobility of, disabled persons.
  - Manipulator systems to enable participation in table games.
  - Manipulator systems to assist in dressing, food preparation, self care activities, and work related tasks.
  - Effector - object interface design.
- Mobility Unit Technology
  - Remotely controlled vehicles as mechanical servants
  - Aids for automobile driving by the severely handicapped.

- Remote Control Technology
  - Remote control of the immediate environment
  - Advanced controllers for the severely handicapped, including voice actuated control and special hand controllers.
- Manipulator System Evaluation Technology
  - Evaluation criteria and standardized evaluation tests.
- Sensor System Technology
  - Tactile and proximity sensors for the blind.

An analysis was conducted to determine the priority order of these eleven candidate applications. The assessment was based on such factors as:

- Potential number of handicapped individuals to be benefited
- Value of the benefit to the individual
- Technical feasibility

The priority ranking of the applications was as follows:

- Highest Priority
  1. Aids for automobile driving
  2. Manipulator systems to assist in general everyday activities
  3. Advanced control systems
- Middle Priority
  4. Remote control of the environment
  5. Manipulator to increase patient reach
  6. Manipulator to enable and assist in table games
  7. End effector - object interface design criteria
  8. Remotely controlled vehicle to serve as a mechanical servant
- Low Priority
  9. Tactile and proximity sensors
  10. Manipulator end effector as prosthetic or orthotic device
  11. Development of criteria and standard evaluation tests

The application of space teleoperator technology to develop aids for automobile driving was considered to be the highest priority item due to the need on the part of the handicapped for independence and transportation capability. The aids to be considered would include vehicle controls and displays, worksite layout, and assistive devices for entry and egress to and from the vehicle.

The second priority application is the development of systems to assist and enable general everyday activities. Thus, the first two applications involve the two critical needs of the handicapped; that of transportation capability, and ability to perform self-care activities. The essential characteristics of any or all of the remaining nine applications can essentially be included in these first two, or any of the eleven applications can be handled on an individual basis. The more efficient and economical approach, and hence the approach recommended, is to proceed with development of the two applications having the highest priority, to include aspects of the other applications as required, and to then determine what other development, if any, is required for any of the remaining applications.

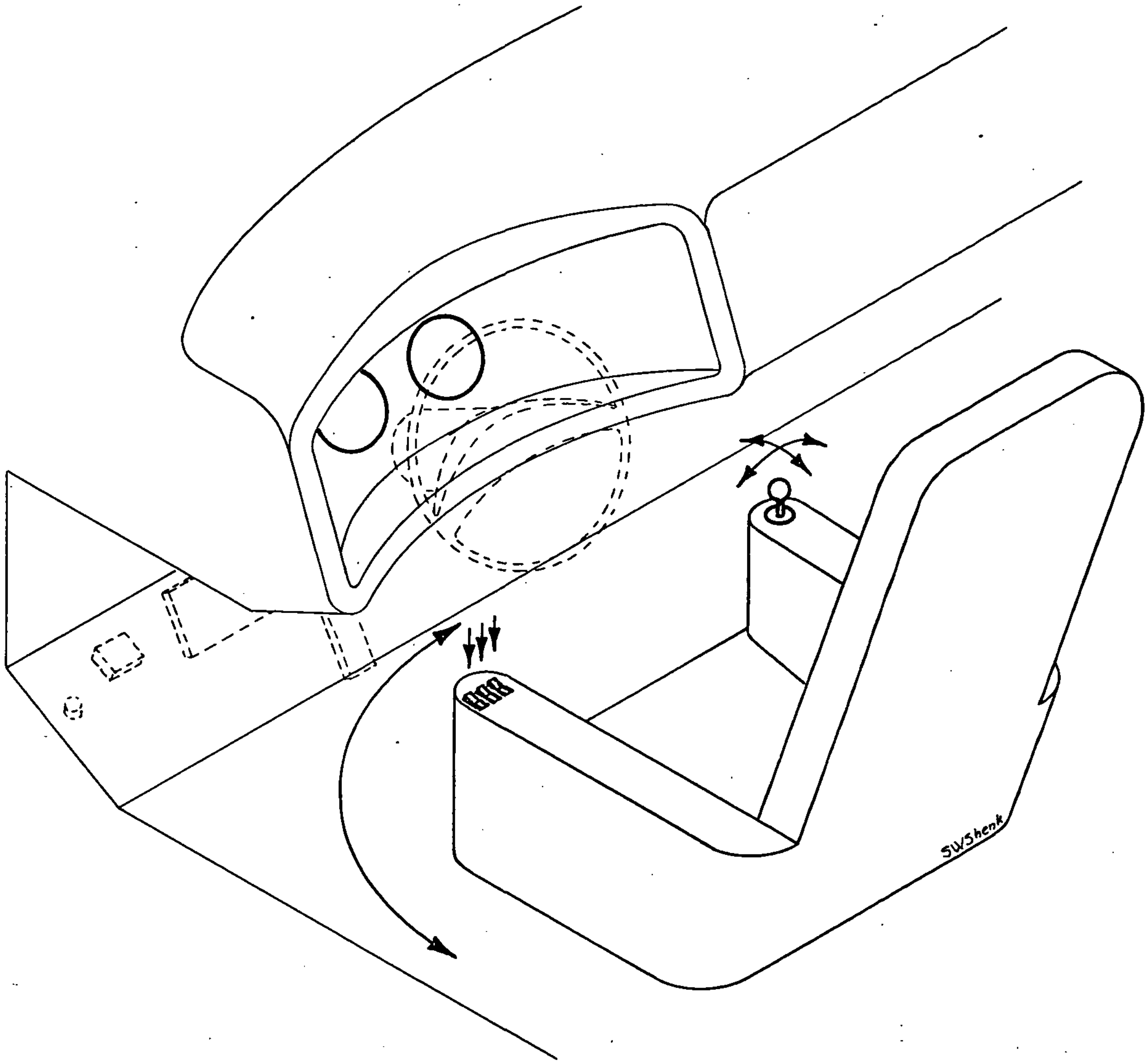
A description of each application is presented in the following pages. This description includes:

- Background information on the need for the application
- Statement of the Problem
- Requirements to be satisfied and problems to be resolved
- Technical approach to be implemented
- Application Development Plan
- Expected costs, if sufficient information exists for the projection
- Projected benefits

Development of Design Criteria for Automobile

Aids for Handicapped Drivers

1



" . . . teleoperator/worksite interface technology as an input to the development of design criteria for automobile controls and displays. . ."

Teleoperator Technology Application 1

Application Class: Mobility
Application: Development of design criteria for automobile Aids for handicapped drivers.
Application Type: Development

Background Information

One of the more important needs of the handicapped is for independence of action. The degree to which real independence and self sufficiency can be realized depends on whether or not the handicapped person can acquire and hold gainful employment. The employment opportunities available to the handicapped, and the effort entailed in maintaining an employed status, depend on the degree to which the individual can transport himself or be transported between his place of residence and his place of employment. One alternative is to rely on public transportation, with its architectural and physical barriers and hindrances for persons in wheel chairs or those deficient in manipulative skills. An added disadvantage of the sole use of public transportation includes the constraints that it places on the individual, in terms of scheduling his time, and in terms of requirements to maneuver from place of residence to place of transportation to place of employment. An alternate solution to the transportation problem is to enable an individual to drive his private automobile to and from his place of employment, as well as his place of worship, shopping, recreation, education, and social activities. The value to the individual of enabling him to operate his own automobile is obvious. The feasibility of providing a totally paralyzed individual with this capability is not so obvious. It can be concluded that there are some individuals where disabilities are such that, within the framework of existing technology, it is impossible to provide them with a capability to drive. The blind person is a case in point. Whether or not this impossibility applies equally to the quadriplegic, the stroke victim, the arthritic, or the spastic remains to be fully investigated. As more sophisticated and effective assistive systems are developed for the severely handicapped, such as powered orthotic devices which increase and enhance the person's hand and arm coordination, mobility, articulation, dexterity, force applicability capability, and precision placement, the feasibility of such a person driving his own car becomes greater. What is needed, in addition to the increasing attention being given by the medical engineering profession to improve orthotic systems, is a parallel effort to develop design criteria for controls and displays specificially tailored for use by the assisted handicapped individual. The application of teleoperator technology enters here in that the design on effective interface between the teleoperator manipulator and the work site represents a major technology area for spare teleoperators. This same problem of effectively interfacing the manipulative system (elements of a satellite or control console of an automobile) are encountered in the space applications and in the medical applications of teleoperator technology.

Statement of the Problem

The problem to be resolved in this application is to develop automobile assistive aid design criteria to enable the operation of private passenger vehicles by severely handicapped but aided individuals. It seems that a good deal of the effort expended to date in developing automotive controls and displays for the handicapped have been largely concerned with the amputee. Although this is in end of itself a commendable endeavor, it does point up the fact that the needs for the paralyzed, in terms of specially designed vehicles, have not received due consideration. The report on Rehabilitation Engineering published by the Committee on Prosthetics Research and Development, National Academy of Sciences (1971) bears out this conclusion by stating that, although the ratio of orthotic patients to amputees is about 10 to 1, the amount of research money presently allocated is about 1 to 1. The report cites the fact that the committee and others in the past several years have been directing more attention and allocations to the field of orthotics to improve this situation (Appendix D, Page 3).

The NAS report indicates that the civilian, noninstitutional population of amputees in 1967 was 311,000 while the number of orthotic patients was 3,370,000. Of the amputees, 32 per cent of the cases involved upper extremities while for orthotic patients 29 per cent of the cases had upper extremity defects. Of the population of orthotic patients, 18 per cent were due to paralysis and 82 per cent were due to deformities.

Objective of the Application

The objective of this application is to use teleoperator/worksite interface technology as in input to the development of design criteria for automobile Assistive Aids tailored for the severely handicapped and assisted driver.

Requirements to be Satisfied

The essential requirements to be satisfied is the need of the handicapped person for independence of action. In enhancing this person's mobility, his earning power must also be enhanced, thereby increasing his own independence and self sufficiency. This need then is not only a psychological need felt by the handicapped person, but it also affects his earning power, and consequently, the degree to which he is able to satisfy his own daily living requirements rather than relying on assistance from other persons and support from public funds.

Approach

The Essex Corporation of Alexandria, Virginia, recently completed an effort for the National Highway Traffic Safety Administration, Department of Transportation, to develop standards for motor vehicle controls and displays. These standards were based in part on the reach envelopes, visibility envelopes, and manipulative capabilities of "normal" drivers. The approach to be taken in this application will be to develop similar standards for the handicapped driver, and furthermore, to design, develop, fabricate and evaluate the effectiveness of the controls and displays conceptualized in this study for these drivers. The overall objective of the effort will be to provide control/display designs which enable and facilitate the numerous discrete and continuous motor tasks required in the safe handling of a passenger car under a wide range of weather conditions, traffic conditions, and emergency conditions.

In order to facilitate the determination of the feasibility of alternate design concepts under varying conditions while maintaining a high level of operator safety, it is recommended that concept development be based on automobile simulations rather than actual on-the-road tests. A test bed for such simulation exercises is available at the computation laboratory of Marshall Space Flight Center. This facility, designated the General Purpose, Moving Base, Vehicle Simulation System, is a computer driven simulation facility with a moving base capable of applying longitudinal and lateral high fidelity acceleration forces to the operator as well as a good representation of vehicle handling qualities and vibrations encountered over a wide range of conditions.

In the document "Aids to Independent Living", Lowman and Klinger (1969) of the Institute of Rehabilitation Medicine, New York University Medical Center assert that the disabled person must be provided the capability to drive, and that he must be able to drive with the same degree of safety as other drivers. The document describes many of the devices currently available to assist disabled individuals in operating a car. For individuals with little leg and foot motion but with some residual shoulder and elbow movement, wrist cuffs are available where the wrist is attached to the wheel, which is controlled through arm motions. A left hand lever is usually used in conjunction with the cuff which provides for manual control of acceleration, brake and dimmer switch.

The importance of being able to drive, even for quadriplegics, was recognized by the Rancho Los Amigos Hospital, which has a policy of attempting to train to drive any quadriplegic willing to try. Many of the trained drivers are even able to acquire licenses.

The Center for Safety Education, New York University, conducted an indepth study of the Physical and Mental Requirements for Driver's License in the states of the U. S. in 1959. Their recommendation at that time was that, to be licensed to drive, one arm should be normal with normal lower extremities and suitable operational devices, or one lower extremity should be normal, with normal arms.

Application Development Plan

- Specify manipulative capabilities of persons with different disabilities and degree of disability using different assistive devices (electric arm, powered hand orthoses, devices for active damping of tremor and involuntary motions, etc.)
- Develop design concepts for automobile seats, access/egress aids, and controls and displays whose performance requirements are compatible with the manipulative capabilities established above.
- Design, plan and conduct simulation exercises to support the development of design concepts.
- Develop analytic evaluation criteria to compare concepts.
- Perform tradeoffs of design approach for each Assistive Aid component and for the internal vehicle arrangement, and select an optional approach for each.

- Perform detailed engineering design of selected aid concepts, including control-display panels, seats, back rests, arm rests, head rests, special controllers, and access-egress aids.
- Fabricate and install in the simulation facility the worksites developed in this study.
- Perform full task evaluation of driver performance under different road, traffic, and emergency conditions and modify the design concepts as required.
- Develop final design criteria for controls and displays, seats, and access aids.
- Fabricate and install into test vehicles the systems developed and validated in this study.
- Perform on-the-road evaluation of the systems.
- Interpret and report findings.

It is expected that this effort would entail 40 man-months of effort or 18 calendar months and would cost $100,000 to $150,000. The unit price for an automobile equipped with assistive devices, should not exceed $10,000.

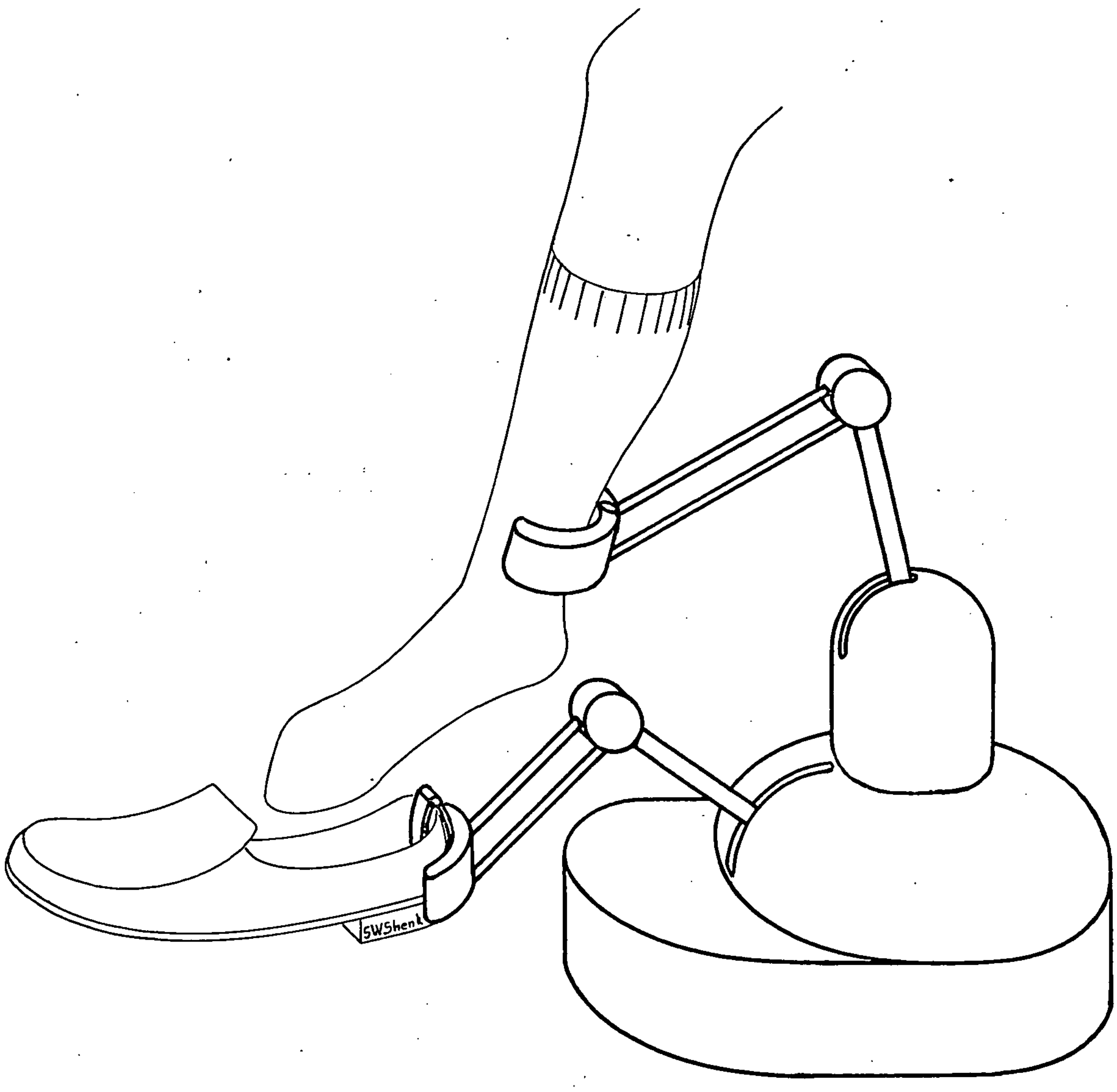
Projected Benefits

The benefit of this effort is to significantly enhance the mobility of the handicapped individual. As indicated in Section III of this report, 1.5 million persons were classified as paralyzed in 1965, of which 42 percent were under 45 years of age and 53 percent were males. Approximately half of these individuals are judged to be severely limited in their everyday activities. In addition to these paralyzed persons, there were 257,000 persons classified as limb deficient in 1965, and 17.7 million others who suffered non-paralytic orthopedic impairments. Of these, approximately one half million are unable to perform major activities, and 2.3 million are limited in their ability to perform major activities.

It is estimated that providing aids for automobile driving will benefit up to four million paralyzed, limb deficient, and impaired individuals.

Manipulator to Assist in General Everyday Activities

2



"Another example would be a manipulative system which would hold a shoe, grasp the user's foot, and insert the foot into shoe."

Teleoperator Technology Application 2

Application Class: Manipulator System
Application: Manipulator to Assist in General Everyday Activities
Application Type: Development

Background Information

The survey of paralyzed patients conducted in this study indicated that these persons, even using state-of-the-art assistive devices, are dependent on others for performance of everyday tasks in 89% of the cases for dressing, 64% for both food preparation and self care, and 48% for transportation. These then are the areas where the paralyzed person is most in need of additional aid in order to achieve a greater level of independence.

Statement of the Problem

The problem here is to investigate the applicability of teleoperator manipulator technology for problems associated with the performance of everyday activities by handicapped persons. While Application 1 will be concerned with developing general purpose manipulator design concepts which will enable and assist the handicapped to perform a wide range of activities, this Application is dedicated to development of manipulators which are more task specific and which are concerned primarily with those tasks which require the greatest degree of dependence on others.

A 1971 report published by the National Academy of Sciences Committee on Prosthetics Research and Development, entitled "Rehabilitation Engineering: A Plan for Continued Progress", states that "with regard to the total rehabilitation engineering effort directed toward the quadriplegic patient (and perhaps other types of patients with upper-extremity disabilities as well), it is noted that braces or assistive devices may be of two broad general types:

1. Those that are attached to, or worn by the patient.
2. Those that are not fitted to the patient but rather are attached to a wheelchair, table, desk, or other stable base.

"While even less is known about the role and value of the latter group of appliances (or manipulators), their potential appears worthy of assessment. Such assessment should be the responsibility of the major spinal-cord injury centers in the U.S.A., and immediate implementation of such programs is recommended" (Page 22).

<u>Objective of the Application</u>

The purpose of this application is to develop manipulators to enable and assist the handicapped in everyday activities, based on manipulator technology developed for teleoperator systems.

<u>Requirements to be Satisfied</u>

The requirements for the handicapped to be satisfied by this application include those concerned with dressing, food preparation, self care, and use of public or private means of transportation. The functional requirements to be considered include the following:

Dressing:

Retrieval or storage of clothing
Donning and doffing of stockings, shoes, pants, shirts, dresses, coats, hats, gloves, bras, girdles, robes, pajamas, etc.

Self Care:

Washing of face and hands
Bathing or showering
Waste elimination
Combing - brushing hair
brushing of teeth
Fingernail grooming
Application of makeup
Shaving of face or body

the shoe. A good deal of attention will be given to the showing of these manipulators for other tasks, thereby making them more economically feasible for the user.

The specific technologies to be used in developing these manipulator systems for everyday activities include manipulator configuration and reach envelope, end effector design and interface with the manipulator arm, and manipulator/effector control. This last technology area presents the major problems for the severely handicapped. Control techniques such as puff and suck, sight switch, head activated switch, foot activated switch, and hand or finger controllers will be investigated. Techniques of using supervisory control, being developed for space teleoperators, will also be investigated. In this control mode the user or operator of the system has only to initiate a pre-programmed sequence of events and the manipulator/effector system conducts the sequence without requiring individual commands for each individual activity.

Of the functions to be addressed by this application, the most difficult to support is dressing. A manipulator system designed to assist a disabled person to dress must be capable of not only handling clothing in the required way but also of handling the limbs of the disabled person. Failure of the system itself or failure to perform required activities in a specified manner could prove hazardous to the user. Obviously, some override control capability is needed, which could range from a simple deactivation of the system to a manually controlled backup mode of operation.

Application Development Plan

The steps to be taken in the development of this application are:

- Identification of tasks for which use of a manipulator, as separate from a prosthetic or orthotic device, is judged as a feasible means

- of assisting a handicapped person.
- Development of design requirements for the manipulator(s).
- Cost analysis for alternate design concepts.
- Design of and fabrication of a prototype system for selected operations.
- Evaluation of the performance capability of handicapped persons using the manipulator systems.

The development is expected to require three to six months for each application.

The cost of the manipulator systems will vary as a function of complexity, which will depend on operations to be performed.

Projected Benefits

The benefits to be obtained from this application is the development of systems to enable handicapped persons to perform operations which they can not currently perform. As with Application 1, it is expected that 4 million persons would be benefited by the development effort described above.

Advanced Control Techniques for Systems for the Handicapped

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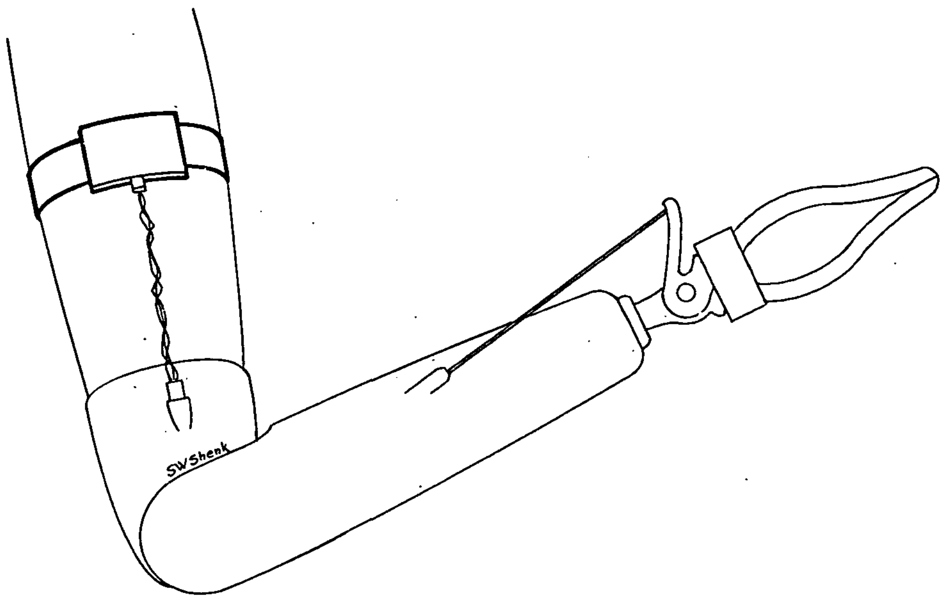


" . . . based on teleoperator technology, . . . the amplification of residual, minimal muscular capability to apply control inputs . . ."

Teleoperator Technology Application 3

Application Class: Remote Control
Application: Advanced Control Techniques for Systems for the Handicapped
Application Type: Research

Background Information

Throughout the descriptions of feasible teleoperator technology applications for the handicapped, the most significant recurring problem for all proposed systems and devices is the question of control. Control devices and techniques are being developed which will make use of any motion capability present in a severely handicapped individual. These include use of inputs provided by eye control (position or blink), head control, foot control, hand control, cheek control, tongue control, breath control, and muscle control. Each of these control techniques have inherent problems and difficulties, notably in terms of time and effort. However, when the option is to provide a disabled person with an inefficient method of controlling his own limbs and the world around him versus leaving him at the level of natural performance capability present with his particular handicap, the difficulties are of less significance. Even though this is true, and that any and all residual capabilities of the handicapped individual should be considered as potential means of controller activation, additional research and development is required to extend and perfect the state-of-the-art in controls for the severely handicapped.

Statement of the Problem

The problem to be discussed in this application is the requirement to perfect methods of control of systems for the handicapped to increase their independence of action, to enable efficient and safe performance of required and desired activities, to perform operations in a manner which approximates the normal, and to enhance the accessibility of objects in the environment. The basic problem is one of attempting to realize these objectives for individual handicapped persons on an on-going basis while simultaneously attempting to build on the control technology base for such systems. Thus, the sight switch was identified as a feasible method of controlling activation, braking, and steering of a wheelchair. The concept incorporated a technique for controlling these chair parameters by positioning the eyeball in different specified orientations. The evaluation of this control technique conducted by the VA prosthetics center established certain basic problems with the implementation and mechanization of the system. For one thing, the system relied on receipt of reflected infrared light from the eyeball to determine eye orientation, and was, therefore, subject to extraneous signals as the illumination environment changed. For another, the user was required to make inputs which, for him, were logically inconsistent (look right to turn left). The concept also requires the user to move his line of sight away from his path of motion to affect a change in state. A more basic problem with the particular system evaluated by the VA was the reliability of the control logic. Incidents were reported where the chair failed to stop when commanded, a situation which could prove disastrous for a person provided with no backup technique for overriding or supplementing the system. An evaluation of the sight switch as a controller for a hand splint which enabled the hand to operate a wheel chair was reported by personnel of the Hot Springs Rehabilitation Center in "Orthotics and Prosthetics", September, 1972. These investigators concluded that while the sight switch is an intriguing idea, in its present form it is not realistically applicable. The rationale for this conclusion included the system's complexity, cumbersome size, poor reliability, and poor man-machine relationships. The authors do recommend, however, that development of an improved system is indicated. This example has been cited to indicate that, in the urgency for assisting disabled persons, a "good" system concept may be reduced to a "poor" system mechanization. The problems with the sight switch are basically problems of implementation, of the particular design implemented, rather than inherent problems of the concept. Admittedly, the requirements for the user to look away from the location where his attention must be focused is a disadvantage inherent in the concept. Development of systems with improved reliability and effective man-machine relationships must take this basic limitation into account and either reduce the time to activate (thereby reducing the time when vision is averted from the focus of attention) or reduce the angular excursion for the area of interest in order to affect a control input. The inherent problem of looking away with the sight switch might be resolved by using coded eyeblinks rather than eye rotation to activate control commands.

An alternative control system being applied for the severely handicapped is the breath activated control or puff and suck. The user puffs and sucks (or sips) on a drinking straw-like protuberance and his coded breath inputs activate specified mechanisms or devices. One implementation of this concept for wheelchair control requires the patient to continually puff to maintain chair motion. If he stops puffing, the chair stops moving. However, the VAPC model, using four control tubes, focuses on this problem. The patient puffs on two to start the wheelchair and it continues to move until he puffs again to stop it. By puffing on one or the other of the two tubes he can turn the chair. The third tube is used to vary the speed and the fourth as an emergency stop. Another implementation (in the POSSUM Environment Control System) requires the user to puff when an indicator reaches a desired code, which causes the control logic to accept that code as the input. The basic problem with breath activated control other than the VAPC method is that many severely handicapped persons have some difficulty with normal breathing. For such persons, requiring forced, programmed, repetitive breath inputs to affect control can be a problem. The VAPC unit has functioned well for a patient who has a tracheotomy tube in situ.

The tongue activated controller developed at Rancho, as reported in the "Investigation of Externally Powered Orthotic Devices" (Rancho Los Amigos, 1968), when used in conjunction with a Rancho electric arm, has enabled patients to perform such activities as:

Typing on an electric typewriter, including paper insertion.

Handling and dialing of a telephone.

Self feeding and grooming, including application of lipstick, mascara, powder, etc.

Operation of light switches and electrical appliances.

Playing cards, chess.

Reading and page turning.

Brushing of teeth with electric toothbrush.

The tongue switch consists of seven bidirectional levers capable of operating 14 microswitches. Used with the Rancho Arm each lever controls one degree of freedom with the lever direction controlling direction of activation of the degree of freedom. Thus, when a patient desires to reach out and grab an object, he must actively and successively control each joint of the arm to move the hand to the object. The system has been reported to have good user acceptance. The basic problem is cost, with the control system and arm assembly costing nearly $3,000.

At this point in the development of control techniques for systems for the handicapped, two separate although related efforts are required. One would be concerned with establishing the range of capabilities and limitations of currently available or prototype controllers. The second would pursue advanced control methods through the application of teleoperator technology.

Objective of the Application

The objective of this application is to provide additional research on advanced controllers for the handicapped.

Requirements to be Satisfied

This application will be concerned with the entire scope of requirements for the handicapped described in Section II of this report.

Approach

The overall methodology to be used involves an application of the systems approach to identify specific requirements and constraints for control systems for a range of assistive systems used by a range of individuals with different disabilities. Based on the assessment and integration of requirements and constraints, concepts will be developed for methods of improving existing control systems and/or for development of advanced controllers.

Three concepts of advanced controllers, based on teleoperator technology, include the use of voice control, the amplification of residual, minimal muscular capability to apply control inputs, and computer aided control techniques. Techniques of voice control, wherein the control logic would recognize specific control words spoken by the user, and implement control inputs based on these words, have been discussed in the unpublished documentation of the NASA Teleoperator and Robot Task Team, 1970. This discussion specifies that machine capabilities for parsing and understanding English, based on verbal input from the human controller, is a feasible area for advanced technology development for teleoperators of the future. The task team recommended the launching of a research program in the areas of phonics, acoustics, grammar, and heuristics, to effect a speech recognizer and understander.

The benefits of control of systems for the handicapped by means of speech are numerous. The time and effort to affect control inputs is minimal. Control can be applied while the user attends to the area of interest. Speech control should require a minimum of training of the user, and should therefore be usable by a wider range of individuals having different levels of intellectual and cognitive capabilities. Based on these benefits, it is obvious that additonal effort to develop speech control techniques is indicated.

The second advanced method of control of systems for the handicapped would use amplified signal detected from residual and minimal voluntary muscle contractions. This basic approach is under study at the Rehabilitation Medicine Engineering Laboratory of the State University of New York at Buffalo as a method of exercising limbs of stroke victims. This laboratory is beginning a research program directed toward the development of a six degree of freedom upper extremity orthosis which is controlled by weak voluntary residual muscle forces. As described by the laboratory personnel, the rationale for this approach is based on their conclusion that in more than half of the cases of paralysis, some innovation and voluntary control over affected muscles remains. These contractions may appear at a trace level only, with no resulting limb motion because of larger gravity or spasticity forces. The Buffalo laboratory approach is to detect and amplify these weak signals to provide control inputs to move an arm brace.

An approach which is similar to the residual muscle force amplification and which is being evaluated for teleoperator control technology, is the use of the force stick controller. This technique involves use of a control stick which is rigidly mounted and which provided control signals based on the sensing of forces applied in a given direction. For disabled persons having some arm motion remaining, the use of a sensitive, minimum force rigid controller may be feasible.

Although having potential problems with complexity and cost, computer aided control techniques should be evaluated for use in systems for the handicapped. The techniques derived from teleoperator technology development would include computer aiding, supervisory control, and adaptive control. In computer aiding the computer or logic system would assume some portion of the control in conjunction with operator generated inputs. The computer activities could involve smoothing,selection of alternatives, and hand return after an object has been grasped. In supervisory control, the user would select a control sequence which would then be performed in a preprogrammed manner. In adaptive control the computer would "learn" from experience where manual control is provided and, on command, either perform the activities in an automatic manner or serve to smooth out and coordinate required motions.

Application Development Plan

The plan for the conduct of research recommended in this application consists of the following activities:

- Analytically evaluate the capabilities and limitations of existing control techniques for a range of devices for a variety of disabilities.
- Identify problem areas inherent in and specific to each control technique.
- Identify requirements for additional information to enable the analytic evaluation and identification of problems.
- Describe and plan a program of research to provide the required information.
- Develop concepts for modifications to existing control systems to overcome inherent problem areas.

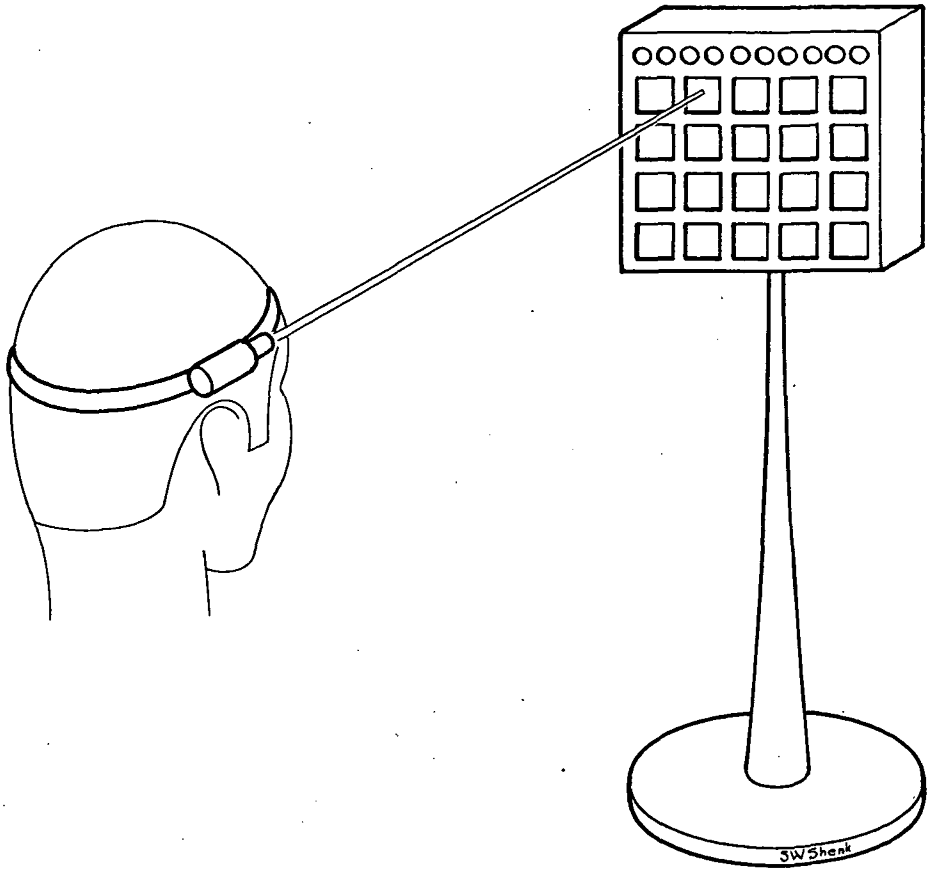
- Develop concepts and techniques for advanced control methods.
- Fabricate experimental modifications and advanced concepts.
- Plan and conduct evaluations of the system modifications and advanced control concepts.

Projected Benefits

The essential benefits to be realized in this application is the development of criteria and concepts for new or improved control systems for systems for the handicapped.

Remote Control of the Environment

4



"A method of random access control . . . activates a selected code by merely focusing the light on the selected cell . . ."

Teleoperator Technology Application 4

Application Class: Remote Control
Application: Remote Control of the Environment
Application Type: Development

Background Information

Three systems for providing a severely handicapped person with the capability of controlling the environment include: the Environmental Control System developed jointly by the NASA Office of Technology Utilization, the Huntsville Hospital, and the University of Alabama at Huntsville; the VA Prosthetics Center Environment Control System; and the Patient Operated Selector Mechanism (POSSUM) developed by the National Spinal Injury Center, Stoke Mandeville Hospital, England. Each of these three systems is currently at a different status in the development cycle, with the Huntsville system undergoing evaluation, the VAPC control system available to their patients, and the POSSUM commercially available on special order. The major requirement to be satisfied with each system is the control of a number of states of a number of appliances and environment control devices. The systems differ in the manner in which the requirement is satisfied. The VA approach is to offer a few control techniques for patient selection, including breath control, and chin control. The present control mode in the VA approach is basically on-off or discrete function control of the television (on-off and channel select, and volume), radio (on-off station select and volume control), head and foot of bed position (up-down), telephone dialing, and bed lamp (on-off). Two of the quadriplegics interviewed at Castle Point use the VAPC environmental control for telephoning, controlling radio, TV, lamps, bed, nurse call and alarm system.

The Huntsville system offers a wide range of control techniques and incorporates proportional control of some functions. The VAPC considers breath control superior to other techniques, such as sight switch, and a variety of touch controls.

There are twelve channels in the VAPC control system. The Huntsville system also provides for twelve channels and employs these as follows:

Electric blanket (on-off and temperature)
TV (on-off, channel, volume)
Radio (on-off, tuning, volume)
Bed head-foot position (pulse control)
Bed lamp (on-off or proportional)
Heater (proportional control)
Page turner (pulse control)
Air conditioning (Proportional control)
Window curtains (proportional control)
Fan (on-off)
Telephone answering and dialing - and dial display
Game

Currently control of the Huntsville system is by initiating a cycling routine through all codes and commanding a stop to the cycling when the desired code or number is reached. The VAPC system requires a patient command for each channel selection. The stop is automatic. The POSSUM system uses a matrix display where cells are coded by X-Y coordinates with the Y axes incorporating 14 devices or special functions and the X axes giving up to six possible states. A total of four TV functions are available (channel, volume, brightness, and contrast) and two radio functions are given (tuning and volume). The system also incorporates the capability to control tape recorder, telephone, typewriter, respirator, intercom, heater, light, and call buzzer.

Statement of the Problem

While the development of technology for remotely controlled environment control systems is well underway, and although NASA technology applications are currently being identified for these systems, there are still basic problems associated with remote environment control which are amenable to teleoperator technology solutions. These problems include the limitation of the system to a single room, the time and effort required to make a control input, the relatively low level of proportional or continuous control available, and the limitation of control to those functions requiring switching as opposed to adjustment (of lamps) or retrieval (of objects).

Objective of the Application

The objective of this application is to extend and enhance the capability of remotely controlling the environment through application of teleoperator remote control and manipulator technology.

Requirements to be Satisfied

The important everyday living tasks (Table 1 in Section III) which are constrained by or dependent on environmental control are as follows:

Self care tasks:

Control of lighting, intensity and direction
Waste elimination - Control of ventilation
Sleep preparation - adjust, push, pull covers and pillows

Dressing Tasks:

Room temperature and lighting
Position of clothing and clothing racks or storage areas

Transportation Tasks:

Retrieve objects in the room

Work/Recreation Tasks:

Telephone - lift, handle, dial
Reading - control of noise, light intensity and direction, page turning, book stand
Writing - accessibility of materials (paper, pens, etc.)
- control of typewriter
- adjustment of writing surface
Radio - control volume, tuning
TV - control volume, tuning, color, contrast, brightness, horizontal and vertical hold, antenna position
Doors - opening and closing, latching, and locking
Bells, etc.- activation
Recreation - games and hobbies
Record player - record selection, handling, reject, volume
Tape recorder - selection, record, playback, volume
Appliances - kitchen, bathroom, bedroom, etc.
- plug in-out
- switch on-off
- select states (speed, mode, etc.)
Closets, cupboards, drawers - open-close

Security Associated Tasks:

Direct link to the local police, fire department, rescue squad, doctor, etc.
Closed circuit television of other rooms in the residence
Emergency call capability for others within the residence

Approach

The approach to be taken in this application is to extend the control of the environment beyond the good start already taken in this direction. This extension will include the following characteristics:

- Development of a mobile environment control system for use from a wheelchair as well as at a fixed location.
- Development of remotely controlled mechanisms for physically moving, re-orienting or positioning objects in the environment (adjustable lamps, bed clothing, doors, drawers, closets, clothes racks, clothing)
- Development of random access control systems
- Development of control systems making more extensive use of proportional or continuous control
- Development of improved feedback systems informing the user of the existing state of the object or appliance being controlled, and of his control input.

The approach to be used is to apply the systems approach described in Sections I and II of this report to the development of environmental control systems. Based on a comprehensive analysis and integration of requirements, alternate control and activation concepts will be developed and analytically evaluated. A cost-benefit analysis will be performed which will indicate the estimated cost of including each candidate item for remote control vs. the expected benefits of such control. Based on this analysis, a basic set of items to be controlled will be established with indications of the cost to add other items. The selected system will be fabricated and evaluated using actual quadriplegic patients.

As indicated above, this development effort will seek to extend existing environment control systems in five specific ways. The approach for each extension is described below.

For a mobile environment control system, consideration will be given to locating the control console at one area in each room, requiring the user to maneuver his chair to the console, vs. use of radio frequency telecommunications to actively control the elements to be controlled without the encumbrance of hard wires. If the console is to be carried on the wheel chair it must be compact and must not interfere with other requirements, such as visibility and reach. The approach of providing a wheel chair patient with environment control is already being discussed by personnel engaged in developing the Huntsville system.

The relative advantages and disadvantages of the mobile system as opposed to the fixed system will be determined prior to a development of mobile design concepts. In addition, the rough order of magnitude costs of the two approaches will be established.

Consideration will be given to providing the environmental control system with a capability to manipulate or move, orient, or position objects in the environment. This may extend to the manipulator approach described in Application 5, or it may involve the mechanization of windows, lamp adjustments, doors, etc., such that they can be operated from a single remote location. During this analysis, an assessment will be made of the requirements and constraints associated with mechanizing each everyday task which is concerned with some aspect of the immediate environment. The assessment of requirements will involve not only a determination of the requirements associated with remote control of each individual task, but also of the interrelations among tasks and the effects of remoting one task on performance of others. The constraints will primarily include performance limitations on the part of the handicapped individual, and costs.

The problem in controlling the existing or prototype environment control systems is the time and effort required to complete a command. The VAPC and the Huntsville systems currently require the user to cycle through the series of available command codes until the desired code is achieved. The POSSUM uses a matrix of appliances and states wherein the user selects a code based on the X-Y coordinates of these parameters. The next generation of the Huntsville system will reportedly include a matrix control approach rather than the sequential cycling. It is suggested that the matrix solution is preferable over the sequential approach for a large number of channels in terms of time and effort. However, even with the matrix method, a user must still revert to the cycling procedure for such operations as selection of numbers for telephone dialing or selection of characters for typing. A method of random access control being investigated for teleoperator visual system control is the use of a light sensitive matrix coded surface with a head aimed light source which activates a selected code by merely focusing the light on the selected cell for a specified (relatively short) period of time. The light source could be continually on, as an aid to directing it to the proper cell, or it could be off until the beam is judged to be pointed to the cell at which time it is activated. This approach would greatly reduce the time and effort required to make successive and repetitive entries into a coded control system. An alternate approach would use any residual motion in the wrist and hand of the patient to manually depress or place a metal stylus on any one of a structured arrangement of cells. Where depression is required, the force required to activate must be minimal, of the order of ounces rather than pounds. Where a stylus is used, the simple contact of the pointer to the desired surface would be all that is required to activate the code.

The more extensive use of proportional or continuous control as opposed to discrete control offers the user a wider range of options in selecting the desired state of the environmental parameter. The continuous control capability could be provided either spatially or temporally. In the spatial approach, the user of the system would vary the dimension of a parameter through different control inputs. In the temporal scheme, the quantity of the dimension (e.g., temperature) would vary as a function of the duration of control application.

One essential characteristic of any environment control system is the feedback to the user concerning existing states of parameters to be controlled and the specific control input commanded by him to alter this state. The most useful feedback mode is the visual, where a good deal of information is presented simultaneously rather than sequentially as is the case for aural and tactile feedback. Any remote telephone dialing device must display to the dialer the number selected and entered as he dials. Control of room temperature depends on the user knowing what the present temperature is and what the commanded temperature is. In order to package an environment control system into a volume which is feasible for the mobile control unit, a good deal of integration of control and feedback must be accomplished. Even for the stationary systems, improved integration is required to ensure that as functions are added to the system that it does not require an entire wall for display of control and feedback information.

Application Development Plan

The activities to be accomplished in developing this application are:

- Analyze requirements, constraints, benefits, and costs of remotely controlling each everyday living activity which requires an interaction with the immediate environment.

- Prioritize the activities in terms of effectiveness and independence benefits on the one hand, and performance limitations and costs on the other.
- Develop concepts of mechanization, packaging, arrangement, instrumentation, control, and feedback for selected activities, based on individual activity requirements and the integration of requirements across activities.
- Develop analytic evaluation criteria based on requirements and needs for control of the environment as well as constraints and costs of development and mechanization.
- Trade off concepts on the criteria and select a few number of feasible solutions as the optimal compromises of requirements and constraints.
- Develop and fabricate prototypes of selected systems.
- Develop evaluation plans, requirements, schedules, measures, and experimental conditions.
- Conduct evaluations using actual handicapped persons.
- Report on evaluations and system design criteria.

Expected Cost

The cost of the Huntsville prototype Environment Control System is reportedly less than $300. The reported cost of the modularized Possum system ranges from $15 to $3,000 depending on the options selected. In order to be accessible to a maximum of persons needing such control, a stationary environment control system should be available for $300 to $500. The cost of a mobile system would be somewhat greater due to the additional complexity of an RF link and packaging constraints.

Expected Benefits

The benefits of an environment control system primarily involve the level of independence attendant to the use of such a system as well as the improved accessibility of objects in the environment.

Manipulators to Increase Patient Reach and Object Accessibility

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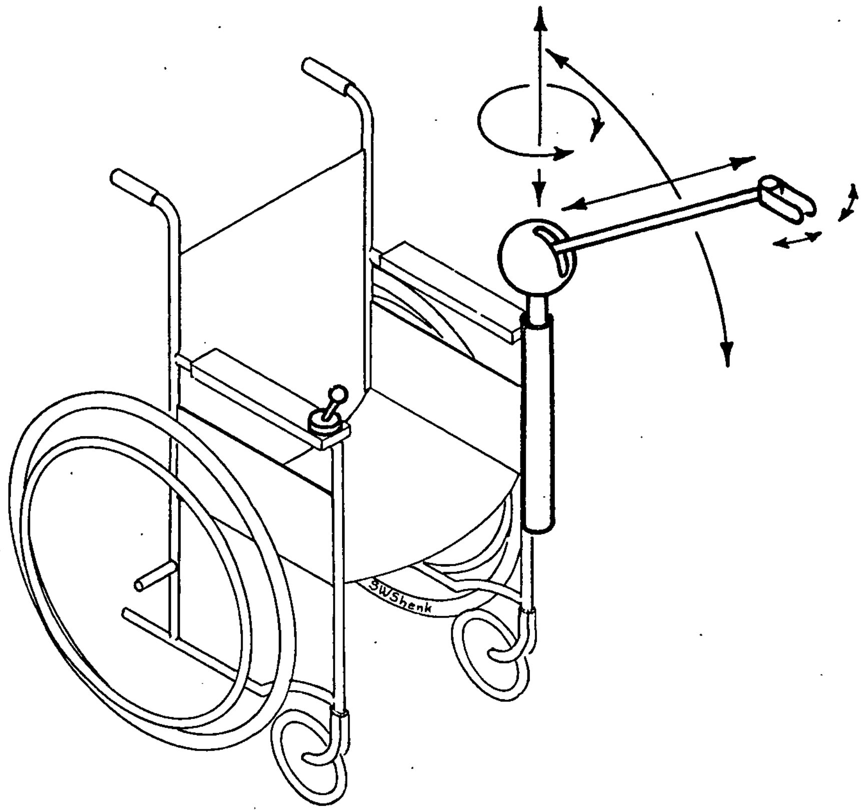


" . . . to provide the mobility limited person with a method of increasing and extending his reach capability . . ."

Teleoperator Technology Application 5

Application Class: Manipulator System
Application: Manipulators to Increase Patient Reach and Object Accessibility
Application Type: Development

Background Information

One of the primary needs of the handicapped is for enhanced or extended reach capability. Patients relegated to wheel chairs are limited in their reach capability by the mobility of the chair and the chair configuration as it affects arm extension. Add to these basic limitations due to the chair the additional constraints placed on amputees, quadriplegics, stroke victims, and other persons deficient in limbs or in limb function, and the reach capability of such persons becomes severely impaired. The capability for extended or enhanced reach serves not only the need for object accessibility, but also serves the primary need of the handicapped, the need for independence of action. As more objects in the environment become accessible (and consequently usable) by disabled persons, the requirement for assistance from other persons decreases, consequently reducing the dependence on these other people.

Statement of the Problem

The problem to be attacked in this application is the loss of reach capability prevalent in persons confined to wheelchairs or beds, which person may also be severely limited in terms of their reach ability due to paralysis, deformation or deficiency in one or both upper limbs. A total of 85% of the important, everyday tasks identified in Section III of this report require elbow flexion and extension, the basic constituents of arm reach. Almost all tasks (94%) require prehension or grasp of an object. To the degree that these objects are not located in close proximity to the handicapped person, he will be required to maneuver and/or reach to acquire them, or he will be dependent on someone else to retrieve them for him.

Objective of this Application

The objective of this development effort is to increase the reach capability of the disabled through application of space teleoperator manipulator technology. The result of the increased reach capability will be improved accessibility of objects in the immediate environment.

Requirements to be Satisfied

The requirements of the handicapped to be satisfied by this application include those which demand that a handicapped person acquire objects in his environment which are located beyond his reach.

Approach

The basic device to be implemented in extending the reach of disabled persons will consist of an extendable manipulator, a general purpose vise grip end effector, and a control system tailored to the capabilities of the user. The teleoperator technology to be used in developing this manipulator system will be derived from the development efforts being applied for the Extendable Stiff Arm Manipulator (ESAM) at the Marshall Space Flight Center. This manipulator system has two degrees of freedom at the base (tilt and azimuth), one degree of freedom at the midpoint which consists of a telescoping number, and three degrees of freedom at the wrist (pitch, roll and yaw). For the application described here these six degrees of freedom can be reduced to three by eliminating the motion capability at the wrist. Thus, the end effector will be simply mounted at the end of the manipulator and will not have motion capability other than opening and closing. This approach is taken in order to reduce to an absolute minimum the degree of freedom which must be controlled since a different control input will be required for the control of each degree of freedom. To offset the limitations imposed on the system due to the absence of motion at the wrist of the manipulator, a third degree of freedom will be added to the base of the manipulator which will allow the base itself to move up or down in the vertical plane.

The manipulator selected for this application will need to be lightweight and capable of precision placement of the end effector. It will need to extend and retract at a rate slow enough to enable precise placement of the tip while moving at a rate fast enough to ensure that reach activities are accomplished as quickly as possible. The optimal approach would require fixed rate rather than a variable rate since the capability for varying the rate implies an additional control requirement placed on the user.

The manipulator for this application will consist of a device developed by Spar Aerospace Products LTD of Toronto, Canada for the support of film retrieval activities for the Apollo Telescope Mount system of Skylab. This device, termed the Storable Tubular Extendible Member (STEM), is essentially a tape or element of thin metallic material which assumes a tubular shape of high strength when extended. It can be stored in a minimum of space when coiled in the flattened condition on a spool.

As described by the STEM system specifications published by Spar, the deployment mechanism for a one inch diameter tubular element ranges from two to five pounds. The power required to drive the one inch stem ranges from .08 to 8 watts depending on the rate selected. The packaging of the STEM will require a minimum volume of 3x4x7 inches (84 cubic inches). The critical bending movement of the one inch diameter STEM is about 20 foot pounds. The critical comprehensive tip load for a 10 foot STEM is about 10 pounds of force. The critical torque per element for the one inch STEM is about two inch pounds. The preliminary estimate for the STEM extension and retraction rate is 10 inches per second. This will require six seconds to move the tip of the device five feet.

The STEM manipulator will be mounted on the front of the wheelchair or on a bed table. In the wheelchair application, the base of the device will be at the lap board such that objects retrieved from the environment can be delivered to the board without additional control on the part of the user. Consideration will be given to providing the capability of moving the base to any position up and down to a maximum of 12 inches above the lab board.

The handicapped person, in using the manipulator, will activate the manipulator and point the tip toward the desired object by means of tilt and azimuth control of the base (and possibly moving the base up in a vertical direction). The end effector will then be extended toward the object and the group mechanism will be opened. When the effector encloses the extension motion is terminated and the grip closes over the object. The manipulator is then commanded to retract and the object is delivered to the lap board. The effector will be designed to enable grasp of a book from a shelf of books, grasp of clothing, writing materials (pen and paper), and small size objects of different shapes and configurations. The preliminary estimate of manipulator length required is 10 feet and the grip force required will be 5 pounds.

The major problem confronting the user of this manipulator system is control. The basic systems will require five different control inputs, including:

- Device activation and deactivation
- Control of base tilt
- Control of base azimuth
- Control of extension and retraction
- Control of grip opening and closing

To these may be added the control of base vertical position. There is no problem of control if the user has unlimited use of at least one arm or even only wrist and hand. The difficult problem for control is development of controllers for the quadriplegic patient having little or no unaided motion capability in either arm. One approach for providing control capability for these severely disabled persons is through the use of control techniques currently being developed for other prosthetic and orthotic devices, including sight switches, pneumatic pillows, puff and suck controllers, and tongue switches.

Application Development Plan

The development plan for this application will proceed through the following activities:

- Establish specifications for the prototype device - angles, rates, forces.
- Determine requirements for vertical displacement of the base
- Purchase a STEM mechanism from Spar
- Design and develop the end effector and effector - manipulator interface.
- Fabricate a prototype and effector and fit to the STEM
- Mount the assembly to a wheel chair
- Design the electrical interfaces and circuit design for powering each degree of freedom
- Design and fabricate prototype control systems
- Develop standard evaluation tests, measures, and procedures
- Conduct a full evaluation of the concept using the prototype system and actual quadraplegic, hemiplegic, and paraplegic patients

Expected Cost - Each Unit

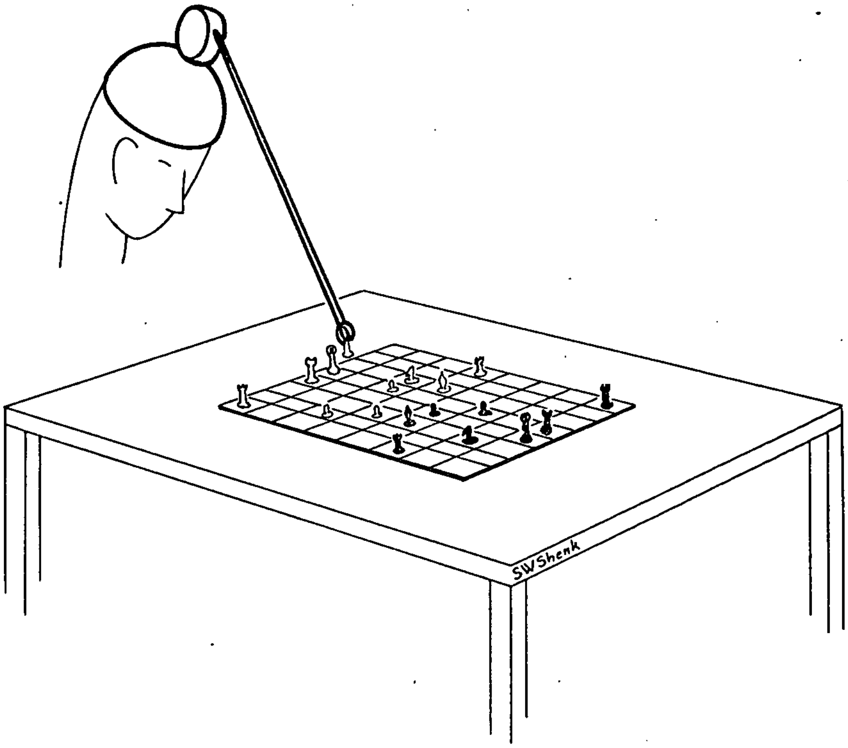
The target figure for cost of the total system to the patient will be $200, assuring procurement of the basic STEM systems in large lots.

Projected Benefits

The benefit of this application is basically to provide the mobility limited person with a method of increasing and extending his reach capability thereby increasing the accessibility of objects around him. Enhancement of the reach capability of the disabled person will have the dual benefits of reducing his dependence on others while increasing his own capabilities to perform required and desired activities. There is, however, an important psychological problem to be overcome: devices that tend to robotize the patient tend to be rejected.

Manipulators to Enable and Assist Participation in Table Games

6



"The second approach to manipulator positioning is to mount the base of the manipulator on a special hat worn by the user."

Teleoperator Technology Application 6

Application class: Manipulator System
Application: Manipulators to enable and assist participation in table games
Application Type: Development

Background Information

Section II of this report cited the desires of handicapped persons on the one hand to participate in table games, and the few number of such persons who are actually capable of such participation. The value of this capability does vary in importance for different individuals, however, it can be stated that a demand for the capability represents a general need over a large segment of the handicapped. These persons, especially during convalescence, have a good deal of time on their hands. Devices to aid them in taking part in table games would help them to pass this time. They would also provide the disabled persons with a form of recreation and relaxation, which closely parallels the recreational activities of "normal" individuals.

Statement of the Problem

The problem for this application is to enable and assist handicapped persons to play table games through the use of teleoperator manipulator technology. One approach would be to develop systems where the person would not need to contact actual three dimensional objects such as pieces. In this approach, the game would be played using only a visual display and a control input mechanism. It was concluded that following this approach would not be as satisfying for the handicapped person as would providing him the capability of acquiring, handling, and moving pieces of the same types as those used by "normal" individuals.

Objective of the Application

The objective here is to develop systems using space teleoperator technology to assist and enable handicapped individuals to participate in table games such as chess, checkers, dominoes, mosaics, puzzles, and board games. An investigation will be conducted to establish the additional complexity required for a system which would also enable card playing.

Requirements to be Satisfied

The principle requirements to be satisfied in this application involve those associated with the needs of the handicapped for recreation and relaxation, particularly by means of participation in games.

Approach

The approach to be taken to meet the objective of this effort is to develop a manipulator system based on teleoperator technology. As in Application 5, the STEM will be investigated as the manipulator mechanism. Use of the STEM is preferred to the use of a standard manipulator configuration in that the STEM is stored when not in use and therefore does not impinge on the space immediately around the user when the device is not in use. A one-quarter to one-half inch tubular member would be sufficient for this application, and the maximum reach required would probably not exceed three feet. The acceptable tip loading would be minimum since only table game pieces would be handled. The basic device would require two essential degrees of freedom, extension-retraction, and grip opening and closing.

The position of the end effector at the desired location in space in terms of X-Y coordinates in the horizontal plane can be accomplished in two ways. The first concept would have the manipulator mounted to a frame which is mounted over the board or table. Fore/aft and right/left motion of the base of the manipulator along the frame would position the end effector at the desired location. This approach has the advantage of requiring only one manipulator for two or more disabled players. It also implies a device which is integral to the board or table and which does not interfere with the capability to perform other activities. The basic disadvantage of this approach is that it requires two additional control activities on the part of the user: control of motion along each of the two axes of the horizontal plane. An additional disadvantage is that diagonal motion, required in chess and checkers, would require control of both of these axes simultaneously.

The second approach to manipulator positioning is to mount the base of the manipulator on a special hat worn by the user. This approach uses the capability of the user to move his head to position the tip of the manipulator and therefore reduces the control problem confronting the user. With this approach only the basic two degrees of freedom need to be controlled. The disadvantages of the approach include its departure from normalcy, the requirement to don, doff, and wear the hat, and the alignment and sighting problems which could result from viewing the workspace and moving manipulator via head position.

According to the Spar Description of STEM system capabilities and specification, a one-fourth to one-half inch in diameter STEM would require a storage housing weighing from .7 to 2 pounds. Power required would probably be less than one watt. The deployment mechanism housing would require a volume of about 20 cubic inches. The critical bending mount for this STEM would be about one foot pound and the critical compromise tip loading would be about 10 pounds of force. Critical torque per element is of the order of 13 to 1.0 inch pounds.

Application Development Plan

The activities to be performed in developing this application include the following:

- Development of specific system requirements and specifications
- Development of the manipulator positioning concept
- Development of the control system concept
- Identification of the requirements for use of the system for card playing
- Procurement of a STEM unit from Spar Aerospace LTD
- Development and fabrication of the end effector
- Instrumentation of the manipulator-effector, interface with the controller
- Fabrication of the system prototype
- Selection of evaluation criteria, procedures, measures, and tests
- Conduct of evaluation
- Report of system performance capability

Expected Cost

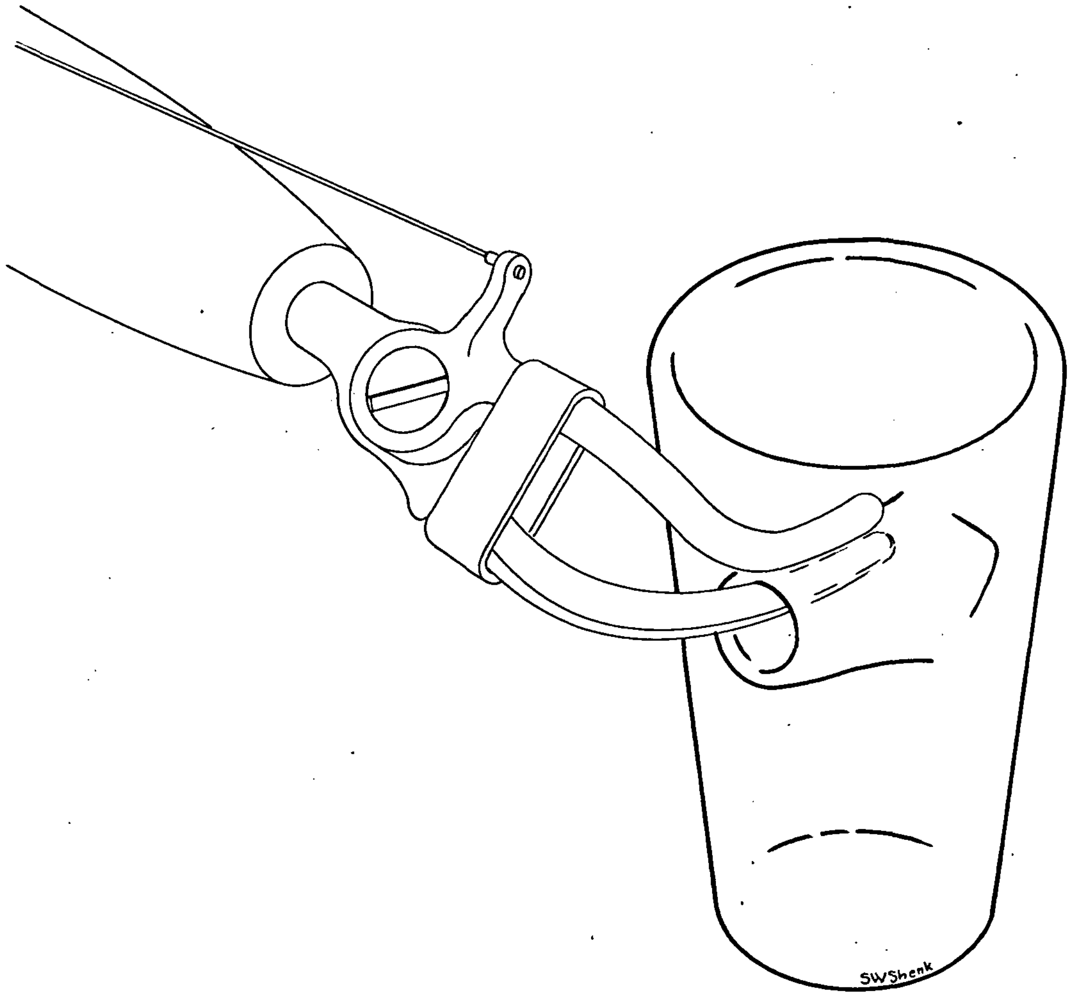
The target price per unit is $200.

Projected Benefits of the Application

The benefit to be realized from this application is the fact that it will enable handicapped persons, who do not presently possess the ability, of participating in solitary or group recreational activities involving the acquisition, handling, and movement of small pieces.

End Effector - Object Interface Design Criteria

7



"Specific items for each function class would include. . . .

- Hand holds for glasses, cups, pitchers, etc."

Teleoperator Technology Application 7

Application Class: Manipulator System
Application: End Effector - Object Interface Design Criteria
Application Type: Development

Background Information

One of the needs of the handicapped as identified in Section III of this report is for normalcy of operations or the capability of performing everyday activities in a manner closely approximating the normal. This need is based on two requirements, one psychological and the other physical. The psychological basis of the need for normalcy is the general aversion encountered in many persons to being considered different, to standing out as being abnormal. The physical basis for the need is the fact that in the performance of everyday activities a person must continually interact with, handle, or otherwise manipulate objects which are designed specifically for the normal human hand.

In the development of space teleoperator technology, it was apparent at an early stage that the most effective approach to the use of manipulator systems is to design the worksite for the end effector. Thus, design concepts are being developed for attach points or hand holds, fasteners, connectors, module extraction mechanisms, etc., which are based on a consideration of the manipulator and effector capabilities and limitations.

Statement of the Problem

Reference to Table 5 indicates that 90.5% of all everyday tasks can be performed using personally owned equipment. Some of these items are for long duration use while others are used only temporarily, and then discarded or used up (bottles, food containers, tooth paste tubes, etc.). Consideration must continually be given to improvement of the manipulative capability of the disabled such that they will be able to perform activities in the normal manner using objects as they are designed for normal use. However, to assist the handicapped in effectively performing required or desired activities at this time, some consideration should also be given to modifying the design of objects to enhance the use mode of those objects by handicapped individuals.

In reviewing documentation describing design of devices for the handicapped, it is obvious that the common approach is to modify existing equipment to facilitate its use by the handicapped. This approach usually results in a design which is cumbersome and difficult for both the handicapped and the normal. It is admittedly a low cost approach but better design concepts, in terms of time, effort, and accuracy to operate, might be feasible at little added cost. There should be no reason why telephones, typewriters, page turners, switches and knobs, etc., cannot be designed and fabricated for the handicapped at a cost comparable to conventional design. The market for such devices would include not only the paralyzed or partially paralyzed, but also those with reduced dexterity and manipulative capability, including the aged, the arthritic, the stroke victim, the palsied, the upper limb deficient, and those suffering chronic illnesses which impair their finger and hand strength and articulation. Devices for persons with manipulative defects should be as available as large print editions of publication for those with visual defects. The market is there. What is needed is engineering imagination and innovative design.

Objective of the Application

The intent of this application is to develop design criteria and prototype designs for objects and items in the environment to be handled and manipulated by handicapped persons.

Requirements to be Satisfied

This application is concerned with the design of objects for use by the handicapped, which could include 94% of the activities encountered in normal living which require prehension or grasp of objects. Specific items for each function class would include the following:

Food Preparation:

- Shelves and storage area layout
- Handles for pots and pans
- Adjustable automated container
- Twist off openers
- Hand holds for plates, cups, and glasses
- Can openers designed for use by the handicapped

Eating/Drinking:

- Specially designed knives, forks, and spoons
- Integrated knife and fork for holding meat while cutting
- Hand holds for glasses, cups, pitchers, etc.
- Specially designed napkins

Self Care:

- Devices for assisting a disabled person into and out of a tub or shower
- Specially designed:
    - razors and related shaving materials
    - combs and brushes
    - tooth paste container and brush
    - towels and wash rags
    - makeup materials
- Devices to enable a person to interface with toilet facilities
- Devices to assist a person in and out of bed

Work/Recreation:
- Specially designed:
    - doors, locks, latches
    - book holders, page turners
    - writing materials
    - games and recreational materials
    - telephones
    - switches and activation devices for electrical appliances, lamps, motors, etc.
    - lamp adjustment mechanisms

Dressing:

- Special clothing - designed for ease of donning and doffing

Layout and design of closets, storage areas, drawers, hampers, etc.

Public Transportation:

- Design of entranceways, ramps, corridors, doorways, cabin interior, straps and hand holds

Private Transportation:

- Design of doors, curbs, steps, room layout
- Design of personal automobile controls and displays

Approach

The approach to be employed in this application will be to develop design criteria for the items listed above to facilitate their handling and use by:

- Quadriplegics
- Wheel chair bound paraplegics and hemiplegics
- Palsied
- Stroke victims suffering paralysis
- Person having degraded manipulative capability due to injury, arthritis, or limb deficiencies (including amputees)

The methodology will consist of an analysis of the specific use requirements associated with each selected object or item, and a development of design concepts based on a consideration of the capabilities and limitations of the various types of disabled persons listed above. In defining these capabilities and limitations it will be assumed that the persons are using a wide variety of assistive devices such as hand splints, dorrance hooks, Rancho electric arms, powered and manually controlled wheelchairs, etc. A set of evaluation criteria will be developed based on the requirements for each task identified in Section III of this report. The evaluation criteria will also consider the degree to which each design approach is usable over other disabilities as well as by "normal" persons. For this analysis, a differentiation will be made between personal equipment items (tooth brush) and those objects which are usually shared with others (bath tub).

Each of the design concepts for each selected item will be evaluated using the evaluation criteria, and one approach will be selected as optimal. For a subset of these specially designed items, prototypes will be fabricated and evaluated in actual use.

Application Development Plan

The activities to be pursued in this application include:

- Comprehensive analysis of use requirements for objects
- Structured description of capabilities and limitations of persons with different disabilities using different devices.
- Development of design concepts for items based on the capabilities and limitations
- Development of evaluation criteria based on use requirements, on the requirements for tasks described in Section II of this report, and on the degree to which a design can be used by other disabled or normal persons.
- Selection of the optimal approach for each object
- Fabrication of prototype designs for selected objects
- Evaluation of the effectiveness of selected prototype design concepts
- Preparation of design criteria for each selected design approach.

Expected Costs

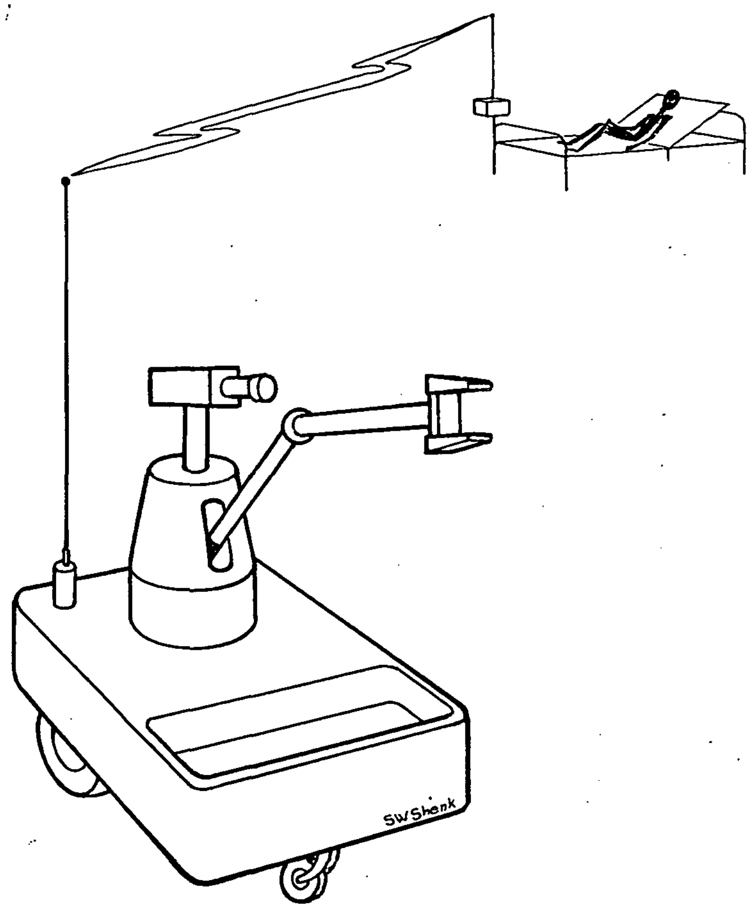
The cost of each specially designed object will vary as a function of its complexity. Cost will be one of the factors included in the evaluation criteria and a good deal of emphasis will be placed on development of low cost objects for the handicapped.

Projected Benefits

This application will result in design criteria for objects the use of which will enhance the performance capability of the handicapped.

Remotely Controlled Vehicle to Serve as a Mechanical Servant

8



" . . . a remotely controlled vehicle equipped with a manipulative capability, and possibly an adaptive or supervisory control capability, would greatly extend the reach of a handicapped person. . ."

Teleoperator Technology Application 8

Application class: Mobility System
Application: Remotely controlled vehicle to serve as a mechanical servant
Application Type: Development

Background Information

One of the most significant efforts in space teleoperator technology development is the program devoted to the free flying teleoperator system. This free flyer will operate at some distance from the parent vehicle under control of an operator located in that vehicle. The use of an unmanned remotely controlled free flying system serves to extend the reach of the man in the parent craft without the stabilization problems usually encountered with long manipulator arms. This objective of extending man's reach also applies to the situation of the handicapped, as described in the plan for Application 5, use of a remotely controlled vehicle equipped with a manipulative capability, and possibly an adaptive or supervisory control capability, would greatly extend the reach of a handicapped person, even beyond the limits which are feasible for telescoping manipulator systems.

Statement of the Problem

One problem with such a system could be its cost, since it could represent a highly sophisticated and complex retrieval device. This problem might be overcome by using the systems within an institutional setting where the device actually serves many patients at one time, with the cost borne by the institution. The benefit to the institution would be a reduced workload on nurses and aide personnel, especially for routine time consuming activities such as retrieving desired objects. The benefit to the patient would be a reduced dependence on these personnel. A remotely controlled device could conceivably be designed at low cost for individual handicapped persons if the control logic and mobility systems are kept simple. The device could use wheels for translation, or it could travel on a track with all objects located within reach of its manipulative system. One problem here is that if the system must operate at locations where the activity can not be adequately viewed by the user, a visual feedback system, such as closed circuit television, will be required. Another problem is control. The user will need to control direction and rate of translation while controlling the manipulative system as well. This may require control of as many as six different parameters (two degrees of freedom for the mobility unit and four for the manipulator). Careful consideration will need to be given to the techniques for inputting control commands since the motion capability of a high level quadraplegic is severely limited.

Another difficult problem for such a remotely controlled vehicle is the power source. Use of pneumatic and gasoline engines is not feasible in an indoor environment. Use of an electric motor offers the best alternative, however, the size of the motor, as limited by the available power, will limit the dimensions and capabilities of the vehicle.

The concept of a mechanical servant becomes more feasible if, in addition to simple retrieval activities, the system is also designed to assist in daily living activities. This approach would require that the system be provided with a manipulative system as described in Application 2, handling objects designed as in Application 7. Thus the system would retrieve objects for the user and would also assist him in dressing, food preparation, self care, and transportation activities.

Objectives of the Application

The primary objective of this application is to develop a mobile system to enhance and extend the retrieval capability of a handicapped person. A secondary objective is to develop these systems with a capability to assist in the use or operation of an object once it is retrieved.

Requirements to be Satisfied

The system described in this application would aid a handicapped individual in the performance of virtually all everyday activities described in Section III of this report. It would extend the reach of the disabled to increase the accessibility of objects in the immediate environment. It would also contribute to the performance of selected operations which currently require dependence in a second person.

Approach

The two driving requirements for this application include (1) the need to develop an effective and efficient mobility system to extend the reach of a handicapped individual while also assisting in the performance of specific activities, and (2) to achieve this in a manner that the ultimate system is economical, both in terms of initial dollar price and in terms of life cycle costs. The basic system will incorporate three principle subsystems: mobility, manipulation, and control.

The mobility system can be a free moving system or a slaved system. A free moving system is one which can move to any location in one horizontal plane. A slaved system is one which is confined to a rail or track. The effectiveness of either approach to acquire any object in the environment will depend on the manipulative system. A free moving system will not require extended reach since by its nature it will maneuver to a location proximal to the item to be acquired. A slaved system, on the other hand, will require more manipulative capability (specifically reach) to offset limitation in vehicle maneuverability to any location. The control system for the free moving system would, therefore, be more complex for control of mobility and probably less complex than the slaved approach for control of the manipulator. The slaved approach, on the other hand, would require less complexity in the mobility control system since the vehicle would be limited to traversing the course established by the track. The manipulative system control for these slaved vehicles would probably be more complex due to the extended reach requirement to access objects not in the immediate vicinity of the track.

The remotely controlled vehicle would be of most benefit to those who would find it most difficult to provide control to the system--the totally or almost totally paralyzed bed-ridden or wheel chair-ridden person. For this reason considerable attention must be given to the control system and the controllers by which the user inputs commands. The feasibility of hand and/or finger control should be established as well as alternate control methods, such as muscle control, tongue switch, mouth implanted switch, puff and suck, sight switch, pneumatic pillow, hand-controlled switch, etc.

Application Development Plan

The activities to be pursued in this application are as follows:

- Determine the feasibility, utility, and benefits of a mobile mechanical servant for the severely handicapped and establish the performance and economic constraints on such a system.

- Develop, analyze and integrate system functional, performance, information and support requirements, and user requirements related to different disabilities.

- Identify requirements and constraints for the system to support the performance of activities in addition to its basic retrieval capability.

- Develop concepts for the system and for the major subsystems of mobility, manipulator, and control.

• Develop analytic evaluation criteria to establish the relative effectiveness, efficiency, and economy of alternate approaches, in terms of system operability, feasibility, safety, reliability, maintainability, transportability, and costs including research and development costs, production costs, and life cycle costs.

• Compare alternate design approaches on the evaluation criteria and select the best compromise from the competing approaches.

• Develop and fabricate a prototype system for evaluation.

• Plan, conduct, and interpret data from evaluation tests using actual handicapped individuals.

• Document design criteria, concept detailed design and evaluation results.

Expected Cost Per Unit

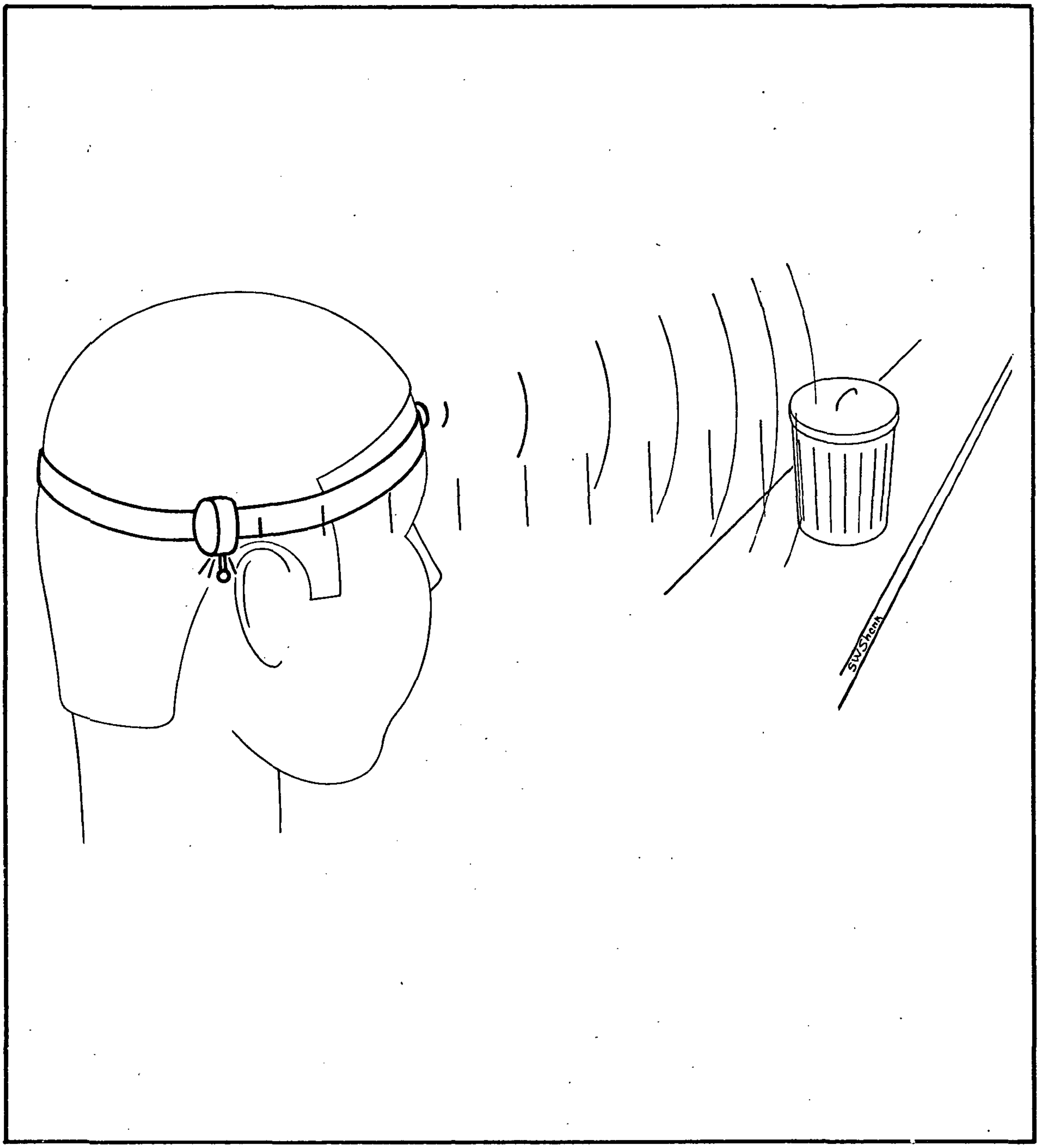
The cost of the system to the user will vary as a function of the complexity of the selected system concept. A manipulator arm on a track comprises a simpler, and less expensive approach than a self-contained, remotely controlled, mobile rover equipped with manipulators and possibly special sensors. As a production item it is estimated that the cost of a free moving rover would be on the order of $500.

Expected Benefits

The major benefits of this system would include its enhancement of user independence, its contribution to the performance effectiveness of the user, and the increased accessibility of objects in the environment.

Tactile and Proximity Sensors for Providing Feedback to Individuals Deficient in Tactile or Visual Capability

9



"Teleoperator technology development in the area of tactile sensing has been concerned with tactile sensors to represent the contours, texture, size and shape of objects encountered in the environment. . ."

Teleoperator Technology Application 9

Application Class: Sensory Aids
Application: Tactile and Proximity Sensors for Providing Feedback to Individuals Deficient in Tactile or Visual Capability
Application Type: Research

Background Information

The analysis of everyday living activities reported in Section II of this report indicated that, for these activities, tactile and kinesthetic feedback was more important than visual. This was due to the fact that many of the tasks identified were concerned with manipulations of body parts or of objects in contact with the body. Such operations are probably degraded to a greater degree by a loss of information on arm and hand positions with respect to the body than by a loss of visual feedback.

Tactile and kinesthetic feedback is required for two basic types of disabilities, for different reasons. The paralyzed individual, whose disability results from spinal cord injury, is usually deficient in pressure sensing and sensing of limb joint position and orientation. While equipped with vision, this disabled person requires tactile and kinesthetic information to supplement his visual feedback, making activities more effective, efficient, and safe. The blind individual must rely on other sense mobilities for any interaction with the immediate environment. One of the primary channels of information for these individuals is the tactile or pressure sense.

Teleoperator technology development in the area of tactile sensing has been concerned with tactile sensors to represent the contours, texture, size and shape of objects encountered in the environment, primarily as applicable to remotely controlled unmanned planetary rovers. Technology developments for teleoperators are also under way for obstacle avoidance or proximity sensors, primarily with respect to the shuttle free flying teleoperator and the planetary rovers. In a description of requirements for a human factors research and development program for space teleoperator systems, Malone (1971) identified requirements for the development of early warning and pre-contact sensing systems and for display of proximity to the teleoperator operator.

Statement of the Problem

The problem to be investigated in this application is the degree to which the concept of proximity sensing is useful and beneficial for the blind and for those deficient in tactile feedback.

Objective

To plan and conduct research into the degree to which proximity sensing can assist and aid the blind and the tactile sense deficient persons.

Requirements to be Satisfied

The requirements to be addressed in this application include those tasks cited in Section III of this report which require tactile feedback.

Approach

The everyday living tasks and performance and safety requirements associated with each task will be analyzed to determine the benefits of providing proximity information to: a blind person; and to a paralyzed individual who has lost tactual sensation. Concepts for providing the feedback will then be developed and evaluated in a program of research.

Application Plan

The activities to be accomplished include the following:

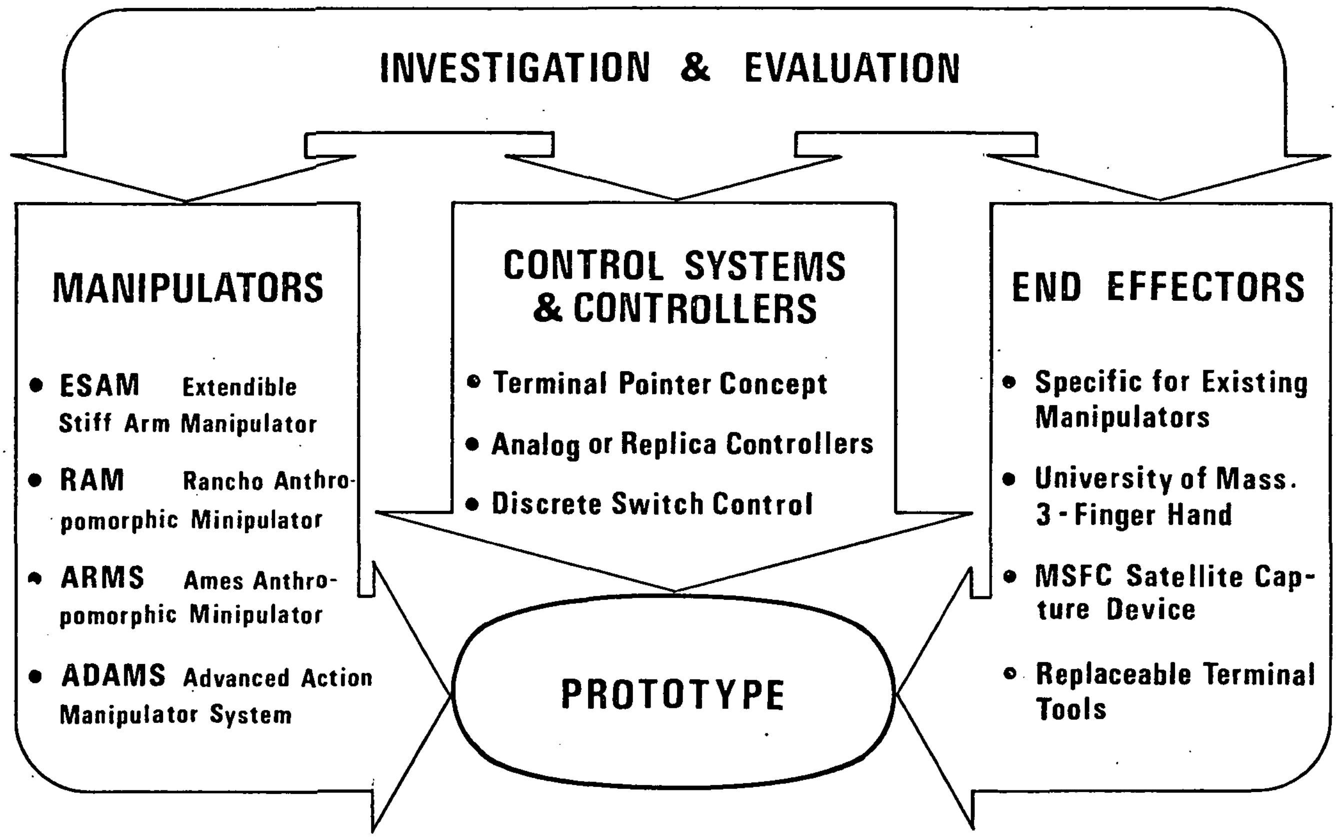
- Identify tasks requiring proximity sensing
- Determine required levels or gradients of this sensing
- Develop concepts for providing proximity feedback to the blind and to the tactually deficient.
- Evaluate concepts analytically and, through a feasibility analysis, select a few of the more promising concepts
- Fabricate prototypes of the selected concepts and evaluate in a simulation setting

Projected Benefits

The primary benefit to be derived from this application is requirements, concepts, and criteria for proximity sensors for the blind and for individuals deficient in tactual sensation.

Manipulator End Effector as a Prosthetic or Orthotic Device

10



" . . . to evaluate the capabilities of the alternate manipulator system configurations, currently being developed for space teleoperators, for satisfying the performance requirements associated with everyday activities performed by the handicapped."

Teleoperator Technology Application 10

Application Class: Manipulator System
Application: Manipulator/end effector as a prosthetic or orthotic device
Application type: Research

Background Information

The application of space manipulator technology for prosthetics or orthotics is well established within NASA, particularly at Marshall Space Flight Center and Ames Research Center. MSFC has been cooperating with Rancho Los Amigos Hospital to develop a triggered hand and end effector tool kit assemblies for amputees, and to design and fabricate a dual arm anthropomorphic manipulator system. Marshall is also contracting with the University of Massachusetts for a three fingered articulated hand, to MIT for advanced control systems for manipulators, and to the University of Tennessee for manipulator system feedback information processing and integration. The Ames Research Center has developed an advanced manipulator and exoskeletal master controller based on earlier developed hard space suit technology.

Statement of the Problem

In the development of remote manipulators for space operations, NASA has been pursuing an objective very similar to that being attacked by medical systems engineers concerned with the development of improved prosthetic and orthotic devices. This objective is essentially for a highly versatile, high precision, general purpose, dexterous, articulated anthropomorphic extension of the arm and hand of the human operator or disabled patient. Although the objectives are comparable, the degree to which a manipulator system, developed for satellite servicing or experiment control in space, is based on design principles which are directly applicable to the everyday activity requirements and problems of the handicapped, remains to be demonstrated.

This application will seek to identify the degree to which manipulative systems being developed for space operations meet requirements and satisfy problems such as those described for the handicapped in Chapter III of this report.

Objectives of the Application

The objective of this application is to determine the degree to which manipulator, end effector, and manipulator control systems being developed for space teleoperator systems have direct application for prosthetics and orthotics.

Requirements to be Satisfied

The requirements to be satisfied by this application include those identified for the handicapped in Section III of this report. These requirements fall into the general functional areas of eating/drinking, food preparation, dressing, self care and personal hygiene, work and recreation, and transportation.

Approach

The basic approach to this application will be to evaluate the capabilities of the alternate manipulator system configurations, currently being developed for space teleoperators, for satisfying the performance requirements associated with everyday activities performed by the handicapped. The manipulator systems to be evaluated include:

Manipulators

- The entendable stiff arm manipulator (ESAM) developed by MSFC.
- The Rancho Anthropomorphic manipulator (RAM) developed for MSFC.
- The Ames Anthropomorphic Remote Manipulator (ARMS) developed by ARC.
- The Advanced Action Manipulator System (ADAMS) developed by General Electric for MSFC.

End Effectors

- End effectors specifically tailored for each of the manipulator systems listed above.
- The University of Massachusetts three fingered hand.
- The MSFC satellite capture device.
- Replaceable terminal tools developed by Rancho for MSFC.

Control Systems and Controllers

- Terminal pointer controller concepts developed for MSFC by MIT and URS/Matrix.
- Analog or replica controllers.
- Push button or discrete switch control.

It is suggested that this application effort be conducted at MSFC primarily because the systems listed above are currently undergoing analysis and additional development at that center.

Application Development Plan

The development plan for this program would proceed as follows:

- Analytically prioritize and integrate requirements for handicapped systems.

- Analytically determine the degree to which existing manipulator/effector configurations being developed for teleoperator systems at MSFC meet requirements for handicapped systems.

- Support the above analysis with empirical investigations of manipulator applicability.

- Identify required design modifications in manipulator systems to enhance their operability as prosthetic or orthotic devices.

- Develop simplified techniques and hardware to enable unassisted donning and doffing of prosthetic and orthotic devices.

- Develop manipulator controllers and control systems consistent with manipulator design criteria and handicapped person requirements.

- Fabricate an improved prototype manipulator for use as a prosthetic or orthotic device.

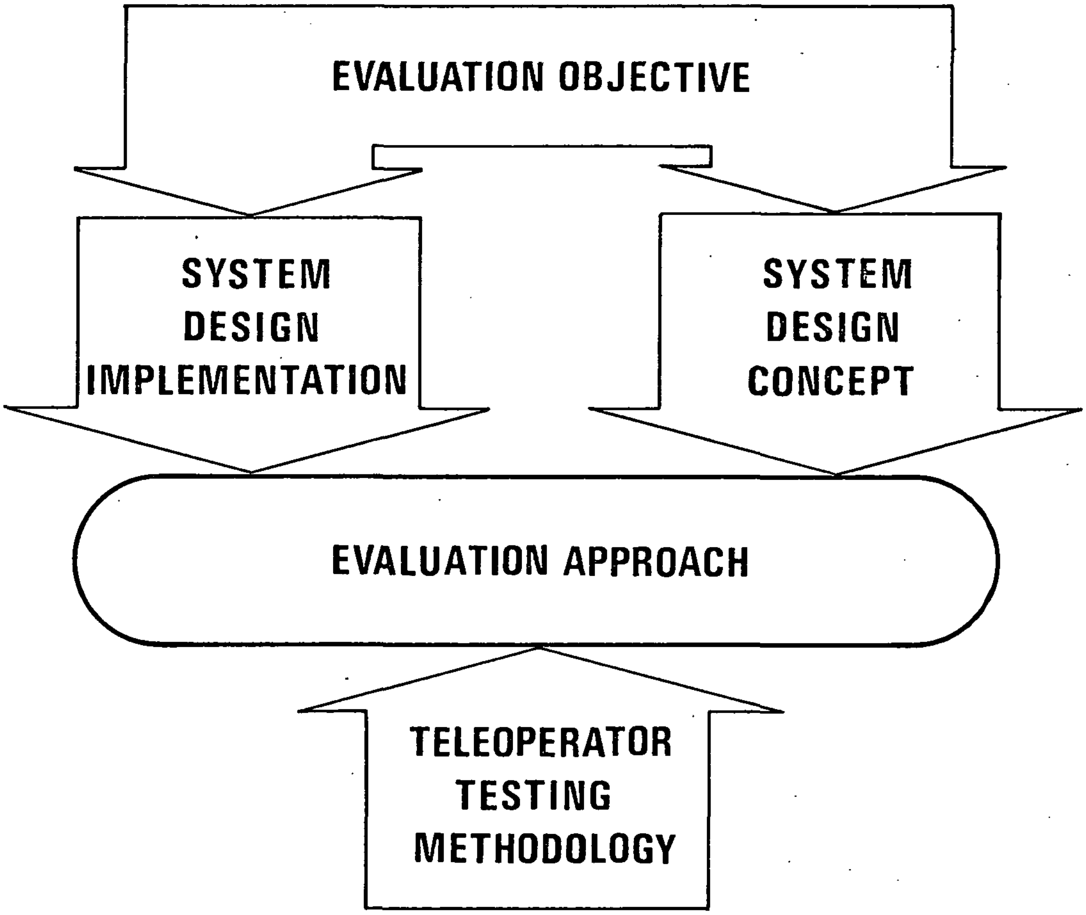
- Evaluate the prototype system and report findings.

The expected duration of this effort would be 1.5 years at a man level of 3 man years. The output would be a prosthetic/orthotic device making maximal use of teleoperator technology while being based on requirements and problems of the handicapped. One primary system driver during design and development will be system cost to the handicapped individual.

Projected Benefits

The primary benefits to be derived from this application include: (1) the development of aids for the handicapped based on a comprehensive assessment and integration of requirements for such aid, and (2) the maximal use of teleoperator technology to develop aids for the disabled.

11



" . . . to develop standard tests and test methods for the evaluation of prosthetics, orthotics, and sensory aids."

Teleoperator Technology Application 11

Application Class: Evaluation
Application: Development of Criteria and Standard Evaluation Tests
Application Type: Development

Background Information

The National Academy of Sciences Committee on Prosthetics Research and Development (CPRD) report on Rehabilitation Engineering (1971) states that it has been long recognized that evaluation is a difficult, arduous, expensive task. Due to the great number of interdependent variables that enter into the success of prosthetic and orthotic items, it is seldom practicable to employ the scientific method of evaluation. The alternative is to fit relatively large numbers of patients under ordinary clinical conditions, keep accurate, comprehensive records of progress, and make general comparisons with past practices whenever possible.

The CPRD document also reports that the Subcommittee on Evaluation of the Committee on Prosthetics Research and Development has been charged with the responsibility of improving evaluation techniques and lines of communication. The evaluation program was judged to be effective in its present form and it was recommended that it be continued. However, every effort should be made to recognize necessary changes as research programs and education programs develop.

Statement of the Problem

The overall objectives of an evaluation program are usually of two types: evaluation of the degree to which the system meets design specifications; and degree to which the device is effective in assisting the user.

There is a very real difference between these objectives. The first applies to the evaluation of a particular system design implementation, while the second involves an assessment of the feasibility of the system design concept. The initial problem to be resolved in planning an evaluation is therefore to clearly specify the purpose of the evaluation. Such a differentiation would reduce the incidence of situations where a concept is rejected because of a faulty design implementation, as seems to be the case for the sight switch control concept.

The importance of specifying the objective of an evaluation is evident when one identifies what is done differently to achieve each of the two types of objectives. If a system design implementation is being evaluated, attention will be given to the degree to which the implementation meets design and performance specifications, such as reliability (mean time to fail, failure rates, etc.), operability (time, effort, and accuracy), maintainability (component accessibility, mean time to repair, availability of test points, etc.), and physical characteristics (power, volume, weight, etc.). The evaluation is therefore centered on this particular system operating under carefully specified conditions. If a system concept is being evaluated, one must perform the assessment in a manner which enables him to separate limitations of the concept from limitations of this representation of the concept. This type of an evaluation essentially becomes part of the development process since improvements in the mechanization of the concept are made as problems are identified. At the point when no additional improvements are possible, what remains is the best representation of the concept within the limitations of the existing state-of-the-art.

The evaluation of teleoperator systems currently being conducted within NASA is essentially of the concept evaluation variety. A range of designed implementations of alternate manipulator concepts are presently being evaluated at Marshall Space Flight Center with the goal being to establish the basic configuration, orientation, articulation, and control capabilities and limitations inherent in each concept.

The second basic problem usually encountered in prosthetic and orthotic system evaluations (primarily of system implementations) is the degree of objectivity inherent in the data obtained. While it is granted that evaluation is difficult and that a good number of interacting variables are involved, this should not be taken as a license for replacing carefully controlled evaluations with informal appraisals, or for accepting qualitative subjective opinions over quantitative, objective measures. The evaluation of a system for the handicap, including the device, the user, and the man-machine relationship, cannot be inherently more complex than the evaluation of a sophisticated man-machine space system, and yet for the development of the latter system, engineers have not retreated from the objective of objectively measuring system performance.

The essential attributes of an evaluation is that it enables the acquisition of data to predict performance capability of the system over a wide range of conditions of use. In order to maximize this prediction attribute, consideration must be given to two important characteristics of the data obtained from the evaluation. These are data reliability and data validity. Data reliability measures the degree to which measurements of performance reflect actual performance capabilities. Reliability depends on the degree of experimental control and varies as a function of experimental error inherent in the data due to the operation of spurious or uncontrolled conditions. Data validity measures the degree to which the evaluation measures what it is intended to measure. Validity of a test depends on the fidelity of the test conditions or the degree to which these conditions represent the real world conditions for which performance capability is being predicted.

In order to maximize the degree of reliability and validity of data obtained from an evaluation, the evaluation itself must be carefully controlled and must sample conditions which are representative of the real world where the system will operate. This would indicate a need for a well conceived and controlled series of standardized, representative tests producing objective measurements of both the system outputs and the conditions operating on the system at the time of evaluation.

Objectives of the application

The objective of this application is to develop standard tests and test methods for the evaluation of prosthetics, orthotics, and sensory aids.

Requirements to be Satisfied

All requirements cited in Section III.

Approach

This application will seek to apply the tests and testing methodology developed for the evaluation of teleoperator systems and concepts to the evaluation of systems for the handicapped. In the manipulator area the set of tests being used to evaluate the performance capability of existing representations of alternate system concepts include the following:

- Evaluation of tip positioning accuracy

- Evaluation of tip orientation accuracy.
- Evaluation of the capability for making minimum positional changes.
- Evaluation of force-torque application capabilities.
- Evaluation of available dexterity.
- Evaluation of the component parts of specific activities - such as antenna deployment, module removal and replacement, and fastener connection.

The approach in these evaluations is to specify the experimental conditions so as to maximize the degree to which data can be generalized to other situations, to control and standardize the tests so as to maximize data reliability, and to select the essential attributes of a wide variety of potential tasks, and to incorporate the range of expected conditions so as to maximize data validity.

This application will seek to establish a set of well controlled, representative, objective, high fidelity, standardized tests for evaluation of systems for the handicapped. A description of tests will be presented for each class of systems and will include specifications for experimental methods, procedures and measures, data validation techniques, data analysis, procedures, and data acquisition and recording techniques.

Application Development Plan

- Identify evaluation requirements and constraints (time and cost)
- Classify systems for the handicapped
- Develop a set of candidate activities to be used in the evaluation of each class of systems
- Develop tests and experimental designs for evaluation of each class of systems for each activity
- Identify the benefits of evaluating each activity vs. the cost of the individual test and the test sequence.

- Reduce the number of tests to a manageable number, maintaining test options associated with different evaluations within any one class

- Develop the details of test: Hardware, data acquisition and recording, software, methods, controls, experimental design and experimental conditions, subject selection and training, and data analysis and interpretation

- Fabricate prototype tests

- Conduct an evaluation of the standardized tests and validate the tests by comparing performance estimates developed from the tests with actual performance capabilities of handicapped individuals using the tested systems

Expected Benefits

Improved evaluation of Prosthetic, Orthotic, and Sensory Aid systems.

APPENDIX A

Performance Requirements
Identified for Each Task

Function Eat/Drink Level A Page 1 TASKS	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Lift - Tilt cup	(1)-2	2	2	2	0	0	0	0	2	2	2	0	2	0	0	0	0	2
tumbler	(1)-2	0	0	2	0	0	0	0	2	2	2	0	2	0	0	0	0	2
wine glass	(1)-2	0	2	2	2	0	0	0	2	2	2	0	2	0	0	0	0	2
jug	(2)-1	0	0	2	0	0	0	0	2	2	2	0	2	0	0	0	0	2
bottle	(1)-2	0	0	2	0	0	0	0	2	2	2	0	2	0	0	0	0	2
mug	(1)-2	0	2	2	0	0	0	0	2	2	2	0	2	0	0	0	0	2
Pour from jug	(2)-2	0	0	2	0	0	0	0	2	2	2	0	2	0	0	0	2	2

Function Eat/Drink Level B Page 1	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
TASKS	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Push with fork	(1)-2	0	2	2	0	0	0	2	2	2	0	2	0	0	0	0	2	2
Lift with fork	(1)-2	0	2	2	0	0	0	2	2	2	0	2	0	0	0	0	2	2
Peel fruit	(2)-2	0	2	2	2	2	2	2	2	2	0	0	2	0	0	0	2	2
Hold food with fingers	(1)-2	0	2	2	2	2	0	0	2	0	0	2	0	0	0	0	0	2
Serve soup	(1)-2	0	2	2	0	0	0	2	2	2	2	0	2	0	0	0	2	2
Open tab cans	(2)-1	2	2	2	0	0	0	2	2	2	0	2	0	0	0	0	0	2

Function Level A Work/Rec. Page 1 TASKS	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Phone Lift handle	(1)-2	0	2	2	0	0	0	2	2	2	0	0	2	0	0	0	0	2
Dial	0	2	2	2	0	0	2	0	2	0	0	0	2	0	0	0	0	2
Read Get book	(1)-2	0	2	2	0	2	0	2	2	2	2	0	2	0	0	1	2	2
Get magazine	(1)-2	0	2	2	0	2	0	2	2	2	2	0	2	0	0	1	2	2
Hold steady	(1)-2	0	2	2	0	0	0	0	0	0	0	0	2	0	0	0	2	2
Turn pages	(1)-2	2	2	2	2	2	0	2	2	2	0	0	2	0	0	0	0	2
Place on knee, table	0	2	2	0	0	0	0	0	2	2	0	0	2	0	0	0	0	2
Read	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Turn on light	(1)-2	0	2	2	2	2	0	2	2	2	2	0	2	0	0	0	2	2
Adjust light	(1)-2	2	2	2	2	2	2	2	2	2	2	0	2	0	0	0	2	2
Newspaper Fold - unfold	(2)-2	0	2	2	0	2	0	2	2	2	2	0	2	0	0	0	2	2
Handle - turn	(2)-2	0	2	2	0	2	0	2	2	2	2	0	2	0	0	0	2	2
Letters Open	(2)-2	2	2	2	2	2	0	2	2	2	0	0	2	0	0	0	2	2
Pull out	(2)-2	0	2	2	2	0	0	2	2	2	0	0	2	0	0	0	2	2
Unfold	(2)-2	0	2	2	2	2	0	2	2	2	0	0	2	0	0	0	2	2

Function Work/Rec.
Level A Page 2

TASKS	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Write Pick up paper	(1)-2	0	2	2	2	0	0	0	2	2	0	0	2	0	0	0	0	2
Write	(1)-2	0	2	2	2	0	0	0	2	2	0	0	2	0	0	0	2	2
Fold Paper	(1)-2	0	2	2	2	0	0	2	2	2	0	0	2	0	0	0	2	2
Place in envelope	(2)-2	0	2	2	2	0	0	2	2	2	0	0	2	0	0	0	2	2
Seal	(1)-2	0	2	2	2	0	0	2	2	2	0	0	2	0	0	0	0	2
Stamp	(1)-2	0	2	2	2	0	0	2	2	2	0	0	2	0	0	0	2	2
Put in box	(1)-2	0	2	2	2	0	0	2	2	2	2	0	2	0	2	2	2	2
Radio-TV Turn knobs	(1)-2	0	2	2	2	0	2	0	2	0	0	0	2	0	0	0	2	2
Operate toggles	(1)-2	2	2	2	2	0	0	2	2	0	0	0	2	0	0	0	2	2
Handling Office Equipment	(1)-1	0	2	2	2	2	2	2	2	2	2	0	2	0	0	0	2	2
Packages	(2)-2	0	2	2	2	2	0	2	2	2	2	0	2	0	0	0	2	2
Tools	(2)-1	0	2	2	2	2	2	2	2	2	2	0	2	0	0	0	2	2
Doors Handle keys	(1)-2	0	2	2	2	0	2	2	2	2	0	0	2	0	0	0	2	2
Open doors	(1)-2	0	2	2	2	2	2	2	2	2	2	0	2	2	0	0	2	2

Function Work/Rec. Level A Page 3	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
TASKS	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Doors Operate bolt	(1)-2	2	2	2	2	0	0	2	2	2	0	0	2	0	0	0	2	2
Ring bell	(1)-2	2	2	2	0	0	0	2	0	2	0	0	2	0	0	0	0	2
Use knocker	(1)-2	2	2	2	0	0	0	2	0	2	0	2	0	0	0	0	0	2
Rec. Sports	0	0	0	0	0	0	0	0	2	2	2	2	0	2	2	2	0	0
Card games	(2)-2	2	2	0	2	2	0	2	2	2	0	0	2	0	0	0	0	0
Piece games	(1)-2	2	2	2	2	2	0	2	2	2	0	0	2	0	0	0	2	2
Puzzles	(1)-2	2	2	2	2	2	0	2	2	2	0	0	2	0	0	0	2	2
Painting	(1)-2	0	2	0	2	0	0	0	2	2	2	0	2	0	0	0	2	2
Drawing	(1)-2	0	2	2	2	0	0	2	2	2	0	0	2	0	0	0	2	2
Tooling	(2)-2	0	2	2	2	2	2	2	2	2	2	0	2	0	0	0	2	2
Handicraft	(2)-2	0	2	2	2	2	2	2	2	2	2	0	2	0	0	0	2	2
Ceramics	(2)-2	2	2	2	2	2	2	2	2	2	2	0	2	0	0	0	2	2
Electronics	(2)-2	0	2	2	2	2	2	2	2	2	2	0	2	0	0	0	2	2
Records	(2)-2	0	2	0	2	0	0	0	2	2	2	0	2	0	0	0	2	2

Function Transport
Level A Page 1

TASKS	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Public																		
Get money from pocket	(1)-2	0	2	2	2	2	0	2	2	2	2	0	2	0	0	0	0	2
Hand over money/ ticket	(1)-2	0	2	0	2	0	0	0	2	2	2	0	2	0	0	0	2	2
Put in slot	(1)-2	0	2	2	2	0	0	2	2	2	2	0	2	0	0	0	2	2
Pick up from counter	(1)-2	0	2	0	2	2	0	0	2	2	2	0	2	0	0	0	2	2
Hold rail/strap	(1)-2	0	0	2	0	0	0	2	2	2	2	2	0	0	0	0	0	2
Ticket from purse	(1)-2	0	2	0	2	2	0	0	2	2	2	0	2	0	0	0	0	2
Open train door	(1)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	0	0	2	2
Private																		
Get in car	(1)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	2	2	0	2
Operate windows	(1)-2	0	0	2	2	0	2	2	2	2	2	0	2	0	0	0	0	2
Operate car	(2)-2	2	2	2	2	2	2	2	2	2	2	0	2	0	0	0	2	2
Locomotion																		
Move about room	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2
Move on sidewalk	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2
Cross streets	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2
Climb stairs	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2
Carry luggage	(1)-2	0	0	2	0	0	0	2	0	0	0	2	0	0	2	2	0	2

Function Dressing Level A Page 1	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
TASKS	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Hold-insert head or limb																		
Shoes	(1)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	0	0	0	2
Socks	(2)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	0	0	0	2
Stockings	(2)-2	0	0	2	0	2	0	2	2	2	2	2	0	2	2	0	0	2
Garter	(2)-2	0	0	2	2	0	0	2	2	2	2	2	0	2	0	0	0	2
Girdle	(2)-2	0	0	2	0	2	0	2	2	2	2	2	0	2	2	0	0	2
Bra	(2)-2	0	0	2	2	2	0	2	2	2	2	2	0	2	0	0	0	2
Pants	(2)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	2	0	0	2
Trousers	(2)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	2	0	0	2
Jersey	(2)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	0	0	0	2
Shirt	(2)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	0	0	0	2
Coat	(2)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	0	0	0	2
Pajamas	(2)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	2	0	0	2
Nightdress	(2)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	0	0	0	2

Function Dressing Level A Page 2 TASKS	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Hold-insert head or limb																		
Dress	(2)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	0	0	0	2
Slip	(2)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	0	0	0	2
Vest	(2)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	0	0	0	2
Do-undo buttons	(1)-2	0	2	2	2	2	0	2	2	2	0	0	2	0	0	0	0	2
zipper	(1)-2	0	2	2	2	2	0	2	2	2	0	0	2	0	0	0	0	2
hooks	(1)-2	0	2	2	2	2	0	2	2	2	0	0	2	0	0	0	0	2
Tuck in - adjust	(2)-2	2	2	2	0	2	0	2	2	2	2	2	0	2	0	0	0	2
Lift-replace garments	(2)-2	2	0	2	0	0	0	2	2	2	2	2	0	0	0	0	0	2
Hang up skirt	(2)-2	0	0	2	0	2	0	2	2	2	2	0	2	0	0	0	2	2
coat	(2)-2	0	0	2	0	2	0	2	2	2	2	0	2	0	0	0	2	2
trousers	(2)-2	0	0	2	0	2	0	2	2	2	2	0	2	0	0	0	2	2
Put on watch	(2)-2	2	2	2	2	2	0	2	2	2	0	0	2	0	0	0	2	2
Put on boots	(2)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	0	0	0	2

Function Dressing Level B Page 1 TASKS	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Do-undo tie	(2)-2	2	2	2	2	2	2	2	2	2	0	0	2	0	0	0	0	2
snaps	(2)-2	0	2	2	2	2	0	2	2	2	0	0	2	0	0	0	2	2
pins	(2)-2	0	2	2	2	2	0	2	2	2	0	0	2	0	0	0	2	2
laces	(2)-2	0	2	2	2	2	0	2	2	2	0	0	2	0	0	0	2	2
buckles	(2)-2	0	2	2	2	2	0	2	2	2	0	0	2	0	0	0	2	2
braces	(2)-2	0	2	2	2	2	0	2	2	2	0	0	2	0	0	0	2	2
cufflinks	(1)-2	2	2	2	2	2	2	2	2	2	0	0	2	0	0	0	2	2
scarf	(2)-2	0	2	2	2	2	0	2	2	2	0	0	2	0	0	0	0	2
belt	(2)-2	0	2	2	2	2	0	2	2	2	2	0	2	0	0	0	0	2
Put on gloves	(1)-2	2	2	2	2	2	0	2	2	2	2	0	2	0	0	0	0	2

Function Self care Level A Page 1	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
TASKS	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
<u>Wash</u> Turn taps	(1)-2	0	0	2	0	0	2	1	2	0	1	2	0	0	0	0	0	2
Wash with towel	(1)-2	1	2	2	0	1	0	2	1	2	2	2	0	2	2	0	2	2
Dip towel in water	(1)-2	0	0	0	0	0	0	0	1	2	1	2	0	0	0	0	1	2
Squeeze	(1)-2	0	0	0	0	0	0	0	1	2	1	2	0	0	0	0	1	2
<u>Teeth</u> Unscrew tube	(2)-2	0	2	2	2	2	2	2	2	0	2	2	0	0	0	0	2	2
Squeeze - apply	(2)-2	0	2	2	2	0	0	2	0	1	2	2	0	0	0	0	2	0
Brush teeth	(1)-2	0	2	2	0	0	0	2	2	2	2	0	2	0	0	0	0	2
<u>Hair</u> Brush	(1)-2	0	2	2	0	0	0	2	2	2	2	2	0	0	0	0	0	2
Comb	(1)-2	0	2	2	0	0	0	2	2	2	2	0	2	0	0	0	2	0
<u>Lavatory</u> Raise - lower seat	0	2	0	2	0	0	0	2	1	2	2	2	0	0	0	0	0	2
Unroll - pull off paper	(1)-2	0	0	2	0	0	0	2	2	2	2	2	0	0	0	0	2	0
Wipe	(1)-2	0	2	2	2	2	0	2	2	2	2	0	2	2	0	0	0	2
Flush	(1)-1	1	0	2	0	0	1	2	1	2	2	2	0	0	0	0	2	2
Arrange clothes	(2)-2	0	2	2	0	2	1	2	2	2	2	0	2	0	0	0	2	2
Position body	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2

Function Self care Level A Page 2 TASKS	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Handkerchief Get handkerchief	(1)-2	0	2	2	0	0	0	2	2	2	2	0	2	0	0	0	0	2
Apply to nose	(1)-2	0	2	0	2	2	0	0	2	2	2	0	2	0	0	0	0	2
Wipe	(1)-2	0	2	2	2	0	2	2	2	2	2	0	2	0	0	0	0	2
Get tissue from box	(1)-2	0	2	2	0	0	0	2	2	2	2	2	0	0	0	0	2	2
Shave Apply lather	(1)-1	2	0	2	0	2	0	0	2	2	2	0	2	0	0	0	2	2
Move razor over face	(1)-2	0	2	2	2	2	0	2	2	2	2	0	2	0	0	0	2	2
Make-up Undo lipstick	(2)-2	0	2	2	2	2	2	2	2	2	2	0	2	0	0	0	2	2
Apply make-up	(1)-2	0	2	2	2	2	2	2	2	2	2	0	2	0	0	0	2	2
Undo powder container	(2)-2	0	0	2	0	2	2	2	2	0	2	2	0	0	0	0	2	2
Undo cream container	(2)-2	0	0	2	0	2	2	2	2	0	2	2	0	0	0	0	2	2
Bed Get in - out	(2)-1	1	0	2	0	2	0	2	2	2	2	2	0	2	2	2	2	2
Push/pull bedclothing	(1)-2	1	0	2	0	2	0	2	2	2	2	2	0	0	0	0	0	2
Push/pull pillows	0	2	0	2	0	2	0	2	2	2	2	2	0	0	0	0	0	2
Turn while sleeping	0	0	0	2	0	0	0	2	0	1	2	2	0	2	2	0	0	0

Function: Self care, Level: B, Page: 1	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
TASKS	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Wash Lift-replace towel	(1)-2	0	0	2	0	0	0	2	0	2	2	2	0	0	0	0	0	2
Lift-replace wash rag	(1)-2	0	0	2	0	0	0	2	0	2	2	2	0	0	0	0	0	2
Apply ointment, lotion	(2)-2	2	2	2	2	2	0	2	2	2	2	0	2	1	1	0	2	2
Rub any part of body	(2)-2	0	2	2	0	2	0	2	2	2	2	2	2	1	1	0	0	2
Teeth Clean dentures	(1)-2	0	2	2	2	2	1	2	2	2	2	0	2	0	0	0	2	2
Handkerchief Fold	(1)-2	0	2	0	2	0	2	1	2	2	2	0	2	0	0	0	0	2
Clean nose	(1)-2	0	2	2	2	2	2	2	2	2	2	0	2	0	0	0	0	2
Bathing Hold side of tub	(2)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	0	0	0	2
Get into tub	(2)-2	0	0	2	0	0	0	2	2	2	2	2	0	2	2	2	2	2
Grooming Cut - trim nails	(1)-2	2	2	2	2	2	1	2	2	1	2	0	2	0	0	0	2	2
File-clean nails	(1)-2	2	2	2	2	2	1	2	2	1	2	0	2	0	0	0	2	2
Shave Handle elec. razor	(1)-2	0	2	2	2	2	2	2	2	2	2	0	2	0	0	0	2	2

Function Food Prep. Level A Page 1	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
TASKS	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Unscrew jar	(2)-2	0	0	2	1	2	2	2	2	0	2	2	0	0	0	0	0	2
bottle	(2)-2	0	0	2	2	2	2	2	2	0	2	2	0	0	0	0	0	2
Undo tin	(2)-2	0	2	2	2	2	1	2	2	0	2	0	2	0	0	0	0	2
packet	(2)-2	0	2	2	2	2	1	2	2	0	2	0	2	0	0	0	0	2
Hold kettle	(1)-2	1	0	2	0	0	0	0	0	0	2	2	0	0	0	0	0	2
Pour from kettle	(1)-2	0	0	2	0	0	0	0	2	2	2	0	2	0	0	0	2	2
Turn on cooker	(1)-2	0	2	2	0	0	2	1	2	0	1	0	2	0	0	0	2	2
Light gas cooker	(1)-2	0	2	2	0	2	2	1	2	2	1	0	2	0	0	0	2	2
Spooning	(1)-2	0	0	2	0	0	0	2	2	2	2	2	0	0	0	0	2	2
Undo milk bottle	(2)-2	0	2	2	2	2	2	1	2	2	2	0	2	0	0	0	2	2

Function Food Prep. Level B Page 1	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
TASKS	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Lift dishes	(1)-2	0	0	2	0	0	0	0	0	2	2	2	0	0	0	0	2	2
Lift out cutlery	(1)-2	0	0	2	1	2	0	0	2	2	2	2	0	0	0	0	2	2
plates	(1)-2	0	0	2	0	2	0	0	0	2	2	2	0	0	0	0	2	2
cups	(1)-2	0	0	2	0	2	0	0	0	2	2	2	0	0	0	0	2	2
glasses	(1)-2	0	0	2	0	2	0	0	0	2	2	2	0	0	0	0	2	2
jars	(1)-2	0	0	2	0	2	0	0	0	2	2	2	0	0	0	0	2	2
Lift from hooks	(1)-2	0	2	2	2	2	0	0	2	2	2	0	2	0	0	0	2	2
Hold sauce pan	(1)-2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Lift lid	(1)-2	0	2	2	2	0	0	2	2	2	0	2	0	0	0	0	2	2
Stir - turn	(1)-2	0	2	2	0	0	0	2	2	2	2	0	2	0	0	0	2	2
Shake	(1)-2	0	0	2	0	0	0	2	2	2	0	2	0	0	0	0	0	2
Pull off lids - tops	(1)-2	0	2	2	0	0	0	2	2	2	2	0	2	0	0	0	2	2
Screw lids	(2)-2	0	0	2	0	0	2	0	2	0	2	2	0	0	0	0	2	2
corks	(2)-2	0	2	2	2	0	2	0	2	0	2	0	2	0	0	0	2	2

Function Food Prep.
Level B Page 2

TASKS	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Pick up dishes	(1)-2	0	0	2	0	2	0	0	2	2	2	2	0	0	0	0	2	2
pans	(1)-2	0	0	2	0	2	0	0	2	2	2	2	0	0	0	0	2	2
food	(1)-2	0	0	2	0	2	0	0	2	2	2	0	2	0	0	0	2	2
small pieces	(1)-2	0	2	2	2	2	0	0	2	2	2	0	2	0	0	0	2	2
Undo butter packet	(2)-2	0	2	2	2	2	1	2	2	2	2	0	2	0	0	0	2	2
plastic film	(2)-2	0	2	2	2	2	1	2	2	2	2	0	2	0	0	0	2	2
Open oven door	(1)-2	0	2	2	0	0	0	2	2	2	2	0	2	1	0	0	2	2
Close	(1)-1	2	0	2	0	0	0	2	0	2	2	2	0	1	0	0	2	2

Function Misc. Level A Page 1	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
TASKS	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Plug in-out	(1)-2	0	2	2	2	0	0	2	0	2	2	0	2	0	0	0	2	2
Open-Shut drawers	(1)-2	0	0	2	0	0	0	2	0	2	2	2	0	0	0	0	0	2
Open-Shut cupboards	(1)-2	0	0	2	0	0	0	2	2	2	2	2	0	0	0	0	0	2
Carry Shopping Bag	(1)-2	0	0	2	0	0	0	0	0	0	0	2	0	0	2	2	0	0

Function Misc. Level B Page 1	HAND REQUIREMENTS									ARM REQUIREMENTS				MOBILITY			SENSORY	
TASKS	One-Two Hand Grasp	Hand Used No Grasp	Precision Placement	Apply Force	High Dexterity	Variable Config.	Twist	Push/Pull	Wrist Rotation Flexion	Elbow-Flex-Extend	Shoulder Rotate-Raise-Lower	Gross Motion	Fine Motion	Trunk Mobility	Whole Body Mobility	Trans-Location	Visual Feedback	Tactile
Wipe spectacles	(2)-2	0	2	2	2	2	2	2	2	0	2	0	2	0	0	0	2	2
Put on-off spectacles	(1)-2	0	2	2	2	2	0	2	2	2	2	0	2	0	0	0	0	2
Wind watch	(2)-2	0	2	2	2	0	2	0	2	0	0	0	2	0	0	0	2	2
2 handled cupboards	(2)-2	0	0	2	0	0	0	2	2	2	2	2	0	0	0	0	0	2
Pushbuttons	0	2	2	2	2	0	0	2	0	2	0	0	2	0	0	0	0	2
Wind clocks	(1)-2	0	2	2	2	2	2	0	2	0	0	0	2	0	0	0	2	2
Set hands-alarm	(1)-2	0	2	2	2	2	2	0	2	0	0	0	2	0	0	0	2	2
Shut off alarm	(1)-2	0	2	2	2	2	0	2	2	2	2	0	2	0	0	0	2	2

APPENDIX B

Safety Hazards Identified For Each Task

Function Eat/Drink

Level A Page 1

TASKS	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
	HAZARDS									
Load spoon from jar					X					
Bowl					X					
Plate					X					
Unload into plate										
Mouth			X							
Impale with fork			X							
Use fork as spoon			X							
Use fork as spoon					X					
Use knife to cut					X					
Push					X					
Spread						X				
Stir with spoon										
Wipe with spoon										
Wipe mouth										
Fingers										

Function Eat/Drink

Level A Page 2

TASKS	HAZARDS									
	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Lift - Tilt cup					X	X				
tumbler					X	X				
Wine glass					X	X				
Jug					X	X				
Bottle					X	X				
Mug					X	X				
Pour from jug						X				

Function Eat/Drink

Level B Page 1

TASKS	HAZARDS									
	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Push with fork			X							
Lift with fork			X							
Peel fruit					X					
Hold food with fingers										
Serve soup						X				
Open tab cans					X					

Function *Food Prep.*

Level A Page 1

TASKS	HAZARDS									
	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Unscrew Jar					X					
Bottle					X					
Undo tin					X					
Packet					X					
Hold Kettle						X				
Pour from kettle						X				
Turn on cooker	X		X			X				
Light gas cooker			X			X			X	
Spooning						X				
Undo milk bottle					X					

Function Food Prep.

Level B Page 1

TASKS	HAZARDS									
	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Lift dishes					X	X				
Lift out cutlery					X					
Plates					X					
Cups					X					
Glasses					X					
Jars					X					
Lift from hooks			X							
Hold saucepan						X				
Lift lid						X				
Stir - turn						X				
Shake										
Pull off lids						X				
Screw lids					X					
Corks					X					

Function Food Prep.

Level B Page 2

TASKS	HAZARDS									
	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Pick up dishes					X	X				
Pans						X				
Food						X				
Small Pieces										
Undo butter packet										
Plastic Film										
Open oven door						X		X		
Close						X		X		

Function Self Care

Level A Page 1

TASKS	HAZARDS									
	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Wash										
Turn taps						X				
Wash with towell						X		X		
Dip towel in water						X				
Teeth										
Unscrew tube										
Squeeze - apply										
Brush teeth										
Hair										
Brush										
Comb										
Lavoratory										
Raise - lower seat							X			
Unroll - pull off paper										
Wipe										X
Flush										
Arrange clothes								X		
Position body							X	X		

Function Self Care Level A Page 2	HAZARDS									
TASKS	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Handkerchief Get handkerchief								X		
Apply to nose										
Wipe										
Get tissue from box										
Shave Apply lather						X				
Move razor over face					X					
Makeup Undo lipstick										
Apply makeup				X						
Undo powder container					X					
Undo cream container					X					
Bed Get in - get out							X	X		
Push - pull bedclothing								X		
Push - Pull Pillows								X		
Turn while sleeping								X		

Function Self Care Level B Page 1	HAZARDS									
TASKS	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Wash Lift-replace towel			X					X		
Lift-replace wash rag			X					X		
Appoint ointment-lotion				X						
Rub any part of body								X		
Teeth Clean dentures										
Handkerchief Fold										
Clean nose										
Bathing Hold side of tub								X		
Get into tub								X		
Grooming Cut-trim nails					X					
File-clean nails					X					
Shave Handle elect. razor	X									

Function Dressing

Level A Page 1

TASKS	HAZARDS									
	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Hold-insert head/limb										
Shoes								X		
Socks								X		
Stockings								X		
Garter								X		
Girdle								X		
Bra								X		
Pants								X		
Trousers								X		
Jersey										
Shirt										
Coat										
Pajamas								X		
Nightdress										

Function Dressing

Level A Page 2

TASKS	HAZARDS									
	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Hold-insert head/limb								X		
Dress										
Slip										
Vest										
Do-undo buttons										
Zipper										
Hooks										
Tuck in - adjust								X		
Lift-replace garments										
Hang up skirt					X					
Coat					X					
Trousers					X					
Put on watch										
Put on boots										

Function Dressing Level B Page 1	HAZARDS									
TASKS	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Do-undo tie										
Snaps										
Pins					X					
Laces										
Buckles										
Braces										
Cuff links										
Scarf										
Belt										
Put on gloves										

Function Transportation
Level A Page 1

TASKS	HAZARDS									
	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Public Get money from pocket										
Hand over money/ ticket			X							
Put in slot			X							
Pick up from counter										
Hold rail - strap								X		
Ticket from purse										
Open train door		X	X				X	X		
Private Get in car										
Operate windows			X				X			
Operate car										
Locomotion Move about room							X	X		
Move on sidewalk							X	X		
Cross streets							X	X		
Climb stairs								X		
Carry luggage								X		

Function Work/Recreation

Level A Page 1

TASKS	HAZARDS									
	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Phone Lift - handle								X		
Dial										
Read Get book										
Get magazine										
Hold steady										
Turn pages										
Place on knee/table										
Read										
Turn on light	X									
Adjust light	X									
Newspaper Fold - unfold										
Handle - turn										
Letters Open										
Pull out - unfold										

Function Work/Recreation

Level A Page 2

TASKS	HAZARDS									
	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Doors Ring bell	X									
Use knocker										
Recreation Sports				X			X	X		
Card games										
Piece games										
Puzzles										
Painting										
Drawing										
Tooling		X			X					
Handicraft					X					
Ceramics				X		X				
Electronics	X					X				
Records					X					

Function Work/Recreation Level A Page 3	HAZARDS									
TASKS	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Write Pick up paper					X					
Write			X							
Fold paper					X					
Place in envelope					X					
Seal										
Stamp										
Put in box			X							
Radio-TV Turn knobs	X									
Operate toggles										
Handling Office equipment	X	X	X							
Packages	X	X	X				X	X		
Tools	X	X	X				X	X		
Doors Handle keys										
Open doors			X				X	X		
Operate bolt			X							

Function Misc.

Level A Page 1

TASKS	HAZARDS									
	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Plug in - out	X									
Open - shut drawers			X							
Cupboards			X							
Carry shopping bag								X		

Function Misc.

Level B Page 1

TASKS	HAZARDS									
	Electrical	Mechanical	Structural	Eye	Laceration	Temperature	Impact	Slip, Trip, Fall	Fumes	Health
Wipe spectacles					X					
Put on - off Spectacles				X	X					
Wind watch										
Two handled cupboards			X				X			
Pushbuttons	X									
Wind clocks		X								
Set hands - alarm										
Shut off alarm										

APPENDIX C

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