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A PRELIMINARY EVALUATION OF REMOTE MEDICAL MANIPULATORS[a]

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ABSTRACT

This paper traces the development of teleoperators and associated control technology leading to the development of remote manipulators for medical application. The implications of various design approaches are elaborated in a general review of the UCLA Biotechnology Laboratory's preliminary evaluation of medical manipulators. The manipulators were made available through the auspices of the Veterans Administration, and included some early models which have since been improved. Conclusions from our preliminary evaluation, and suggestions for further development, are discussed.

INTRODUCTION

The medical manipulator is a design concept for providing functional rehabilitation to high-spinal-cord-injured or other severely disabled individuals through manipulative function and consequent en-

[a] This work was conducted under Veterans Administration Contract Number V101 (134) P-474, "Effectiveness for Veteran Quadriplegics of Medical Manipulators and Design Specifications for Improved Control."

vironmental control. The purpose of this study is to develop and implement an evaluation protocol for use in providing the comparative data that will be needed to form prescriptive decisions for medical manipulator systems.

The use of advanced teleoperators (remote manipulators) to aid the severely disabled represents a significant new area for rehabilitative engineering. The application of the rapidly developing teleoperator technology (along with a lack of objective and generally accepted standards for functional rehabilitation of the severely neuromuscularly handicapped patient) precludes evaluation on an absolute basis (Bruett, 1969; Taylor, 1974). Our protocol delineates what we believe is the first comparative evaluation technique, standardized across manipulators and patient populations, to provide a suitable basis for eventual prescriptive judgments.

The patient/manipulator system is considered to be composed of three interactive subsystems:

a. The manipulator/effector subsystem, which is made up of the manipulator hardware and its mounting;
b. The control subsystem, which is composed of the components that transduce the operator's physical control output, the architecture of the control logic (including any aiding or processing), and the components outputting the driving signals; and
c. The patient/operator subsystem, composed of the patient/operator characteristics that impact on manipulator use; e.g., etiology, residual control function, time post trauma or pathology onset, occupation, family situation, age, etc.

BACKGROUND

This section contains a review of research in teleoperators, arranged according to the subsystem breakdown just defined.

Manipulators

Some of the earliest work on manipulators was done by R.C. Goertz and his collaborators at the Argonne National Laboratories. Goertz designed a bilateral master/slave control manipulator for work with radioactive materials (Goertz and Thompson, 1954; Goertz, et al., 1966).

A similar master/slave control approach was used by Mosher and Wendel (1960) in the General Electric (G. E.) "Handi Man." This unit, like Goertz's, incorporated force feedback to the operator (Mosher, 1960). The concept was expanded from imitation of human manipulation to its augmentation in a combination pedipulator/manipulator exoskeleton by the G. E. group (Mosher, 1967).

The concept of basically anthropomorphic design for a general purpose manipulator has become fairly well established (Johnsen and Corliss, 1967; Corliss and Johnsen, 1968; Vertut, 1974). The primary benefit of such a system design is the ease of master/slave control, in which the manipulator assumes a configural analog of the operator's arm. That is, anthropomorphic designs benefit from their kinematic similarity to human motion, and the resultant control compatibility. The multiple articulations required for what can be called "reach around" capability are inherent in anthropomorphic designs.

Reswick and his co-workers extended the concept of exoskeletal bracing and externally powered manipulation to the area of rehabilitative engineering. With a computer-controlled powered orthosis system, the Case Institute of Technology team moved the paralyzed patient's arm to perform the desired manipulation (Reswick and Mergler, 1962; Corell and Wijnschenk, 1964).

The construction and fitting of an orthosis to provide all movement for the upper arm of a severely disabled person is a difficult task. Adding to this difficulty are safety considerations. Many of the paralyzing pathologies or traumas result in insensibility of the affected limbs, and it may be dangerous to use a patient's arm in the manipulator because no warning sensory feedback is available, and the arm could therefore be injured inadvertently by the manipulator or the environment. Such considerations are among those that have led designers to develop stand-alone (also called remote) manipulators. Despite the reduced adaptability of the operator for master/slave control, some manipulators designed as remote units continue to use anthropomorphic design. For example, the Rancho Los Amigos Remote Manipulator, using a design configuration similar to the Case Institute powered orthosis, is a seven-degrees-of-freedom (7 DOF) manipulator having the kinematic range limitation of the human arm (Fig. 1). (Note that DOF is used here to describe reciprocal movement through a plane or about a rotation point; e.g., flexion/extension, or pronation/supination.) The Rancho Los Amigos manipulator is controlled through a bank of 7 bidirectional "bang bang" tongue switches (Fig. 2.). General Teleoperators has adapted a similarly configured manipulator for wheelchair mounting (Fig. 3); this provides a mobile mount with the possibility of control by telemetry (Fig. 4).

An approach to limiting the control burden of an anthropomorphic

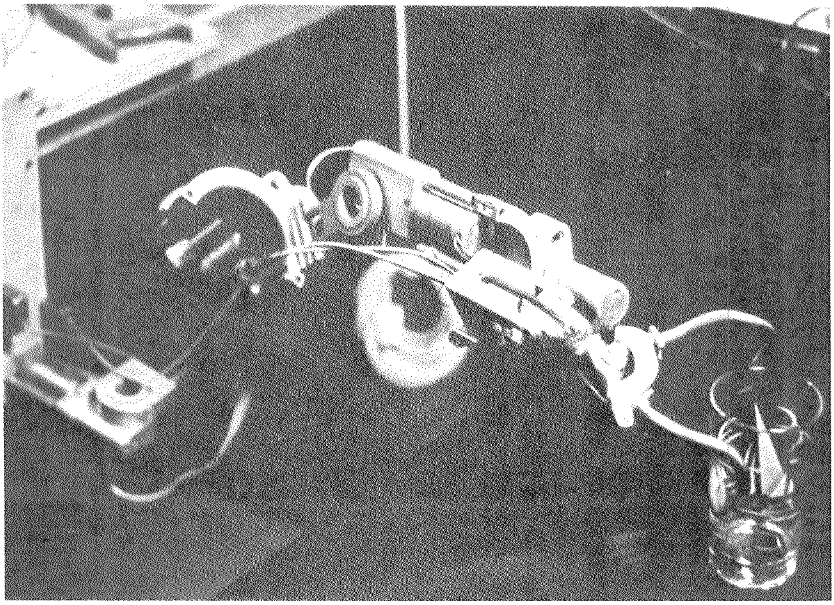

FIGURE 1. — Rancho Los Amigos Remote Manipulator.

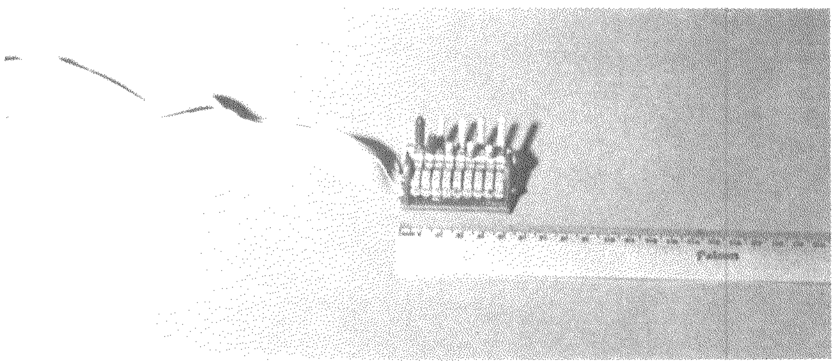

FIGURE 2. — Rancho Los Amigos Remote Manipulator bidirectional "bang bang" tongue switches.

design is to incorporate the manipulator into a structured work environment. The Johns Hopkins manipulator-and-worktable design combines a 5-DOF anthropomorphically designed manipulator, moving on a track, with a structured work environment. The Hopkins group uses the stability of the work area to allow preprogramed computer control of certain fixed trajectories and repetitive actions (Seamone, et al., 1978) (Fig. 5).

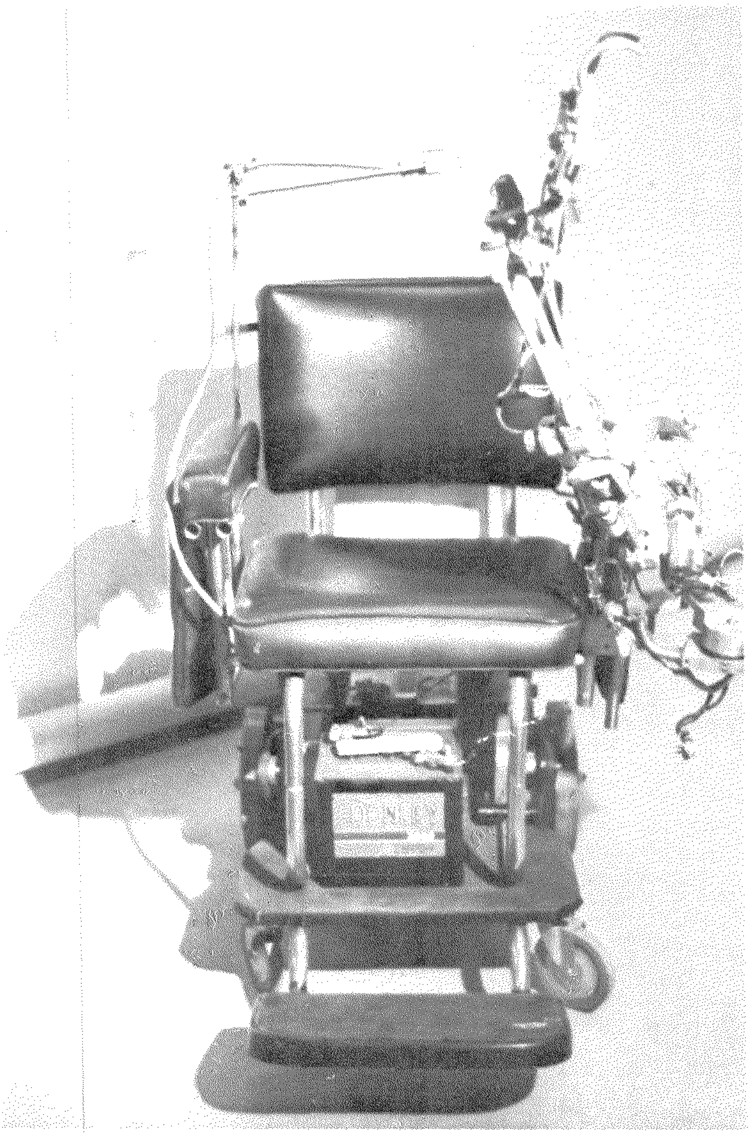

FIGURE 3. — General Teleoperators Manipulator mounted on a wheelchair.

Another structured environment and manipulator system has been developed by the Heidelberg group, headed by Roesler. This 6-DOF semi-anthropomorphic manipulator system is designed to work interactively with a special-purpose work environment. The manipulator itself is designed to have configural similarity to human

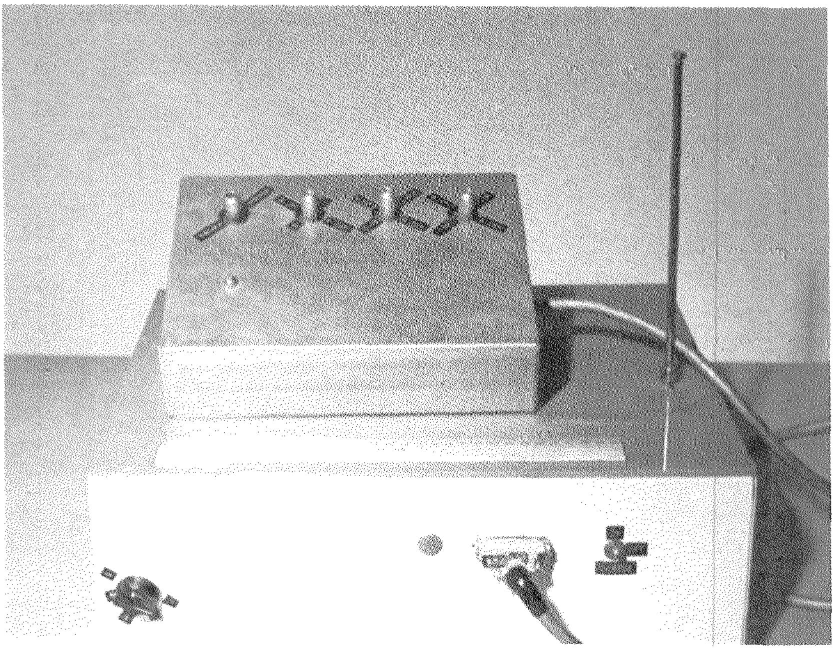

FIGURE 4. — Telemetry control system for possible use with wheelchair mounted General Teleoperators Manipulator.

kinematics, but its range in the selected DOF's is larger than the corresponding human range. Its control philosophy and control aiding differ from the Hopkins manipulator, and will be discussed later in this paper (Schmalenbach, et al., 1978).

As the design of medical manipulators has moved to a stand-alone manipulator having no direct physical contact with the subject, some developers have explored the possibility of adapting commercially available manipulators to a rehabilitation application. The benefits of using such commercial manipulators are expected to be a reduction of cost, an availability of maintenance and a broad user base to support development. The Spartacus Project in France makes use of a 7-DOF manipulator, the CEA-LaCalhene MA-23, which is used by the French Atomic Energy Commission (Guittet, et al., 1978). Leifer et al. (1978) report the adaptation to clinical use of the commercially available 7-DOF Unimation Model 250 Electric Arm. The manipulator has been developed as a "smart robotic arm" designed for computer control.

Finally, anthropomorphic articulated arms have been developed at the Jet Propulsion Laboratories: The NASA/Ames arm is an 8-DOF

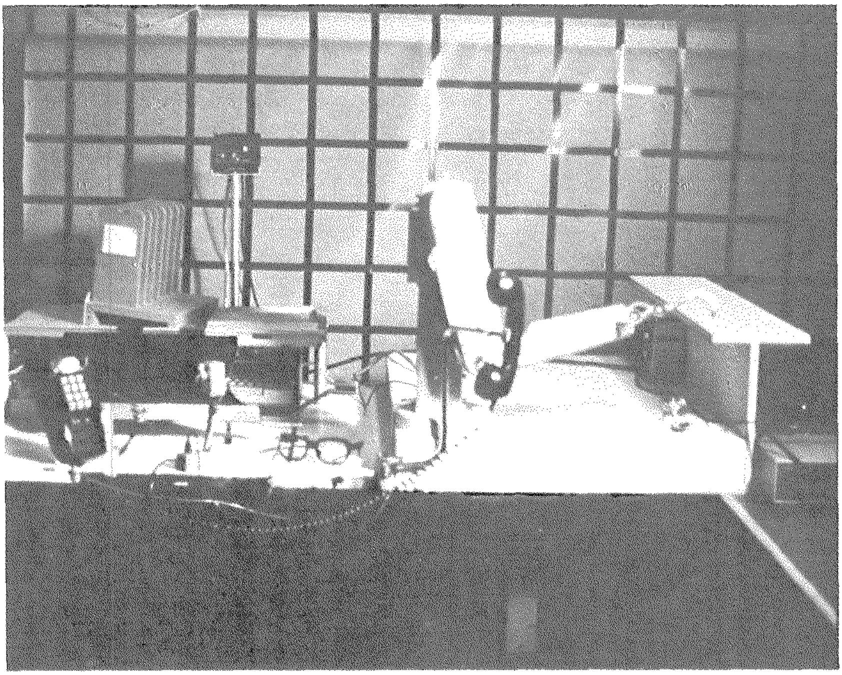

FIGURE 5. — The Johns Hopkins Manipulator and Worktable.

arm originally designed for master/slave control, and the 7-DOF NASA/CURV arm, using a multilinkage design, has basically anthropomorphic kinematics (Ulrich, 1971). These arms are not used clinically, but are used in the development of control dynamics and in interactive sensor control technology (Bejczy, 1978).

The limitations inherent in the output capability of the disabled operator break the tight loop required for master/slave control. This, along with feasible computer control, abnegates anthropomorphic design constraints through transition from configural to symbolic control. As Roth (1973) states, there is no a priori reason to construct a manipulative device which is kinematically identical to the human limb. It should also be noted that the "anthropomorphic" designs discussed above are extremely reduced kinematic replications of human arm/hand manipulative ability — the most complex of the manipulators have 8 DOF, as compared with the human range of 42 DOF.

Mason has developed a wheelchair-mounted extensible manipulator which has been adapted by several developers to varied control and environment configurations. The benefits of such an extensible manipulator (Fig. 6) as reviewed by Mason and Peizer (1978) include:

a. A smaller size with less blocking of the visual field, so that more visual feedback is available for the operator;
b. A close matching between range of motion and effective work area; and
c. A position control, uniquely described by three position equations, requiring only three drive elements to position end-point within work area—the prehension control is independent of the positioning.

Several of the adaptations of Mason's design are under evaluation in our laboratory.

General Teleoperators has provided three telescoping manipulators. One has been interfaced with the Denver Research Institute

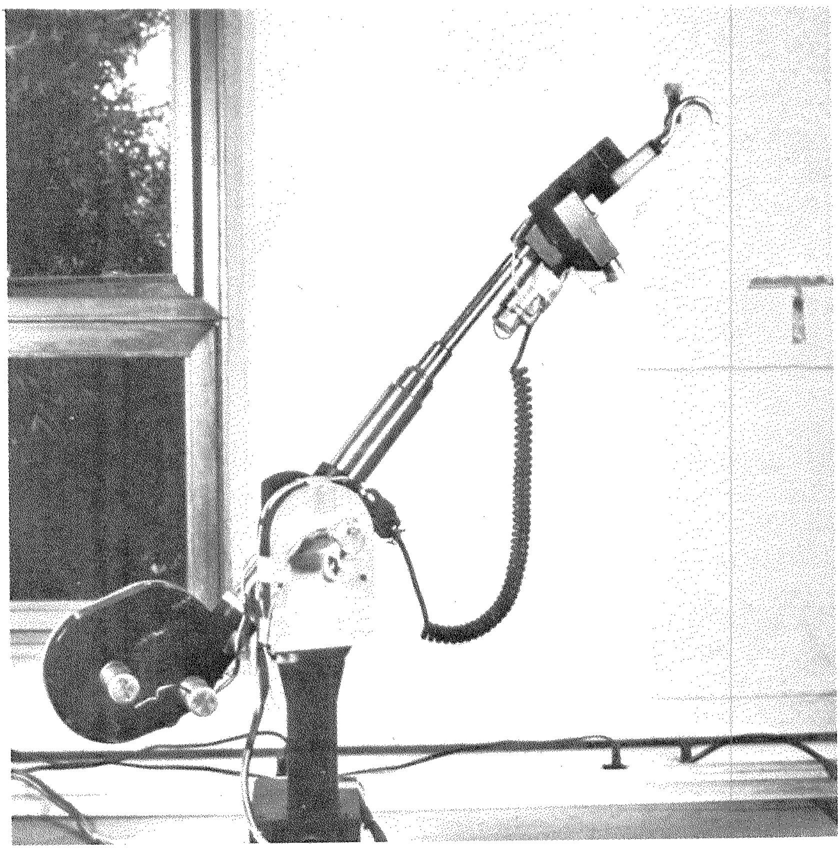

FIGURE 6. — VAPC wheelchair-mounted extensible manipulator.

Ocular Control Unit (Fig. 7). Another is controlled by voice command, through a microprocessor voice-control system developed at the University of California, Santa Barbara, by Robert Roemer's group (Fig. 8). The third General Teleoperators Telescoping man-

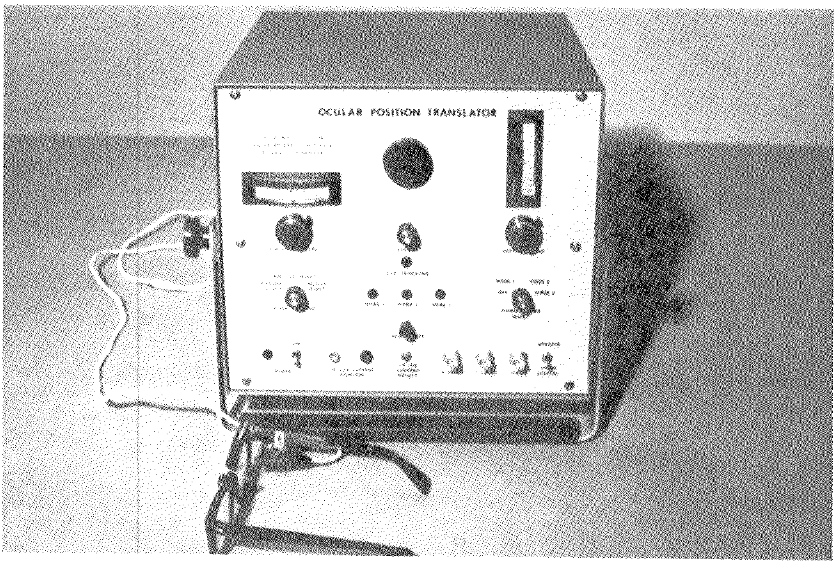

FIGURE 7.—Ocular control unit, developed by Denver Research Institute, interfaced with General Teleoperators telescoping manipulator.

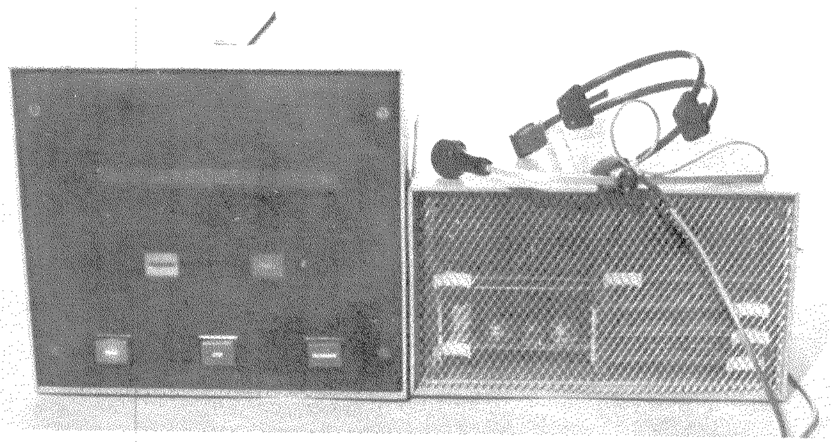

FIGURE 8. — Microprocessor voice-controlled system, developed by UC-Santa Barbara, interfaced with General Teleoperators telescoping manipulator.

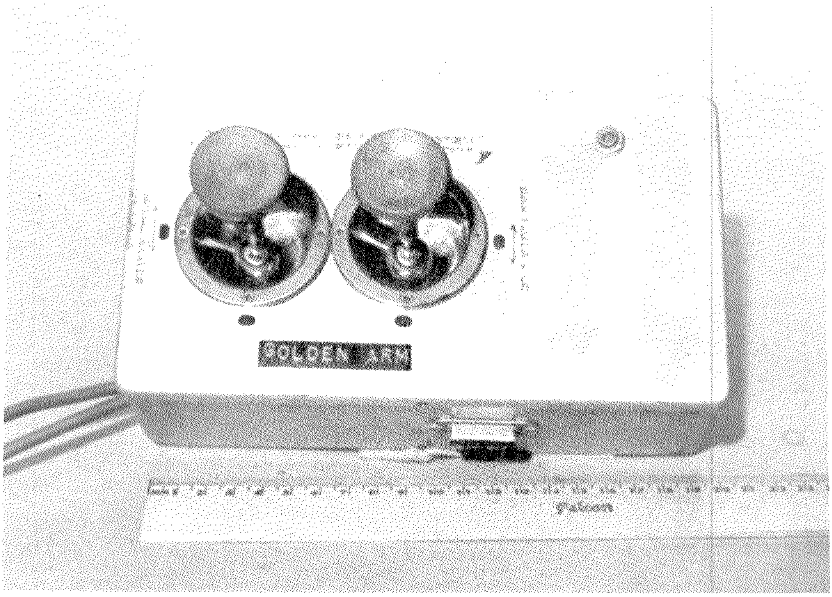

FIGURE 9. — General Teleoperators telescoping manipulator has proportional control of a joystick.

ipulator is controlled by a proportional joystick (Fig. 9). NASA/JPL provides an additional approach in which, using the advantages of the telescoping design, they have mounted the manipulator on a wheelchair with voice activation for the control system (Fig. 10).

Still another variation on the extensible manipulator, with a folding rather than telescoping action, is reported by H.J. Taylor (1978).

Other special purpose manipulators used in industry have varied configurations for specific task applications. These manipulator systems are not sufficiently versatile to serve the needs of the disabled operator.

Control

The need to maintain personal control over the manipulator, in the face of severe constraints in the output capability (and possibly also the sensory capability) of the disabled operator, is the technological challenge in control design.

Direct coordinated joint control of more than 3 DOF has proved to be an extremely taxing task even for able-bodied operators (Freedy, et al., 1972). Sequential control of individual joints, to which the operator usually resorts, trades off speed to reduce control load and results in drastically increased task completion time. The mental load-

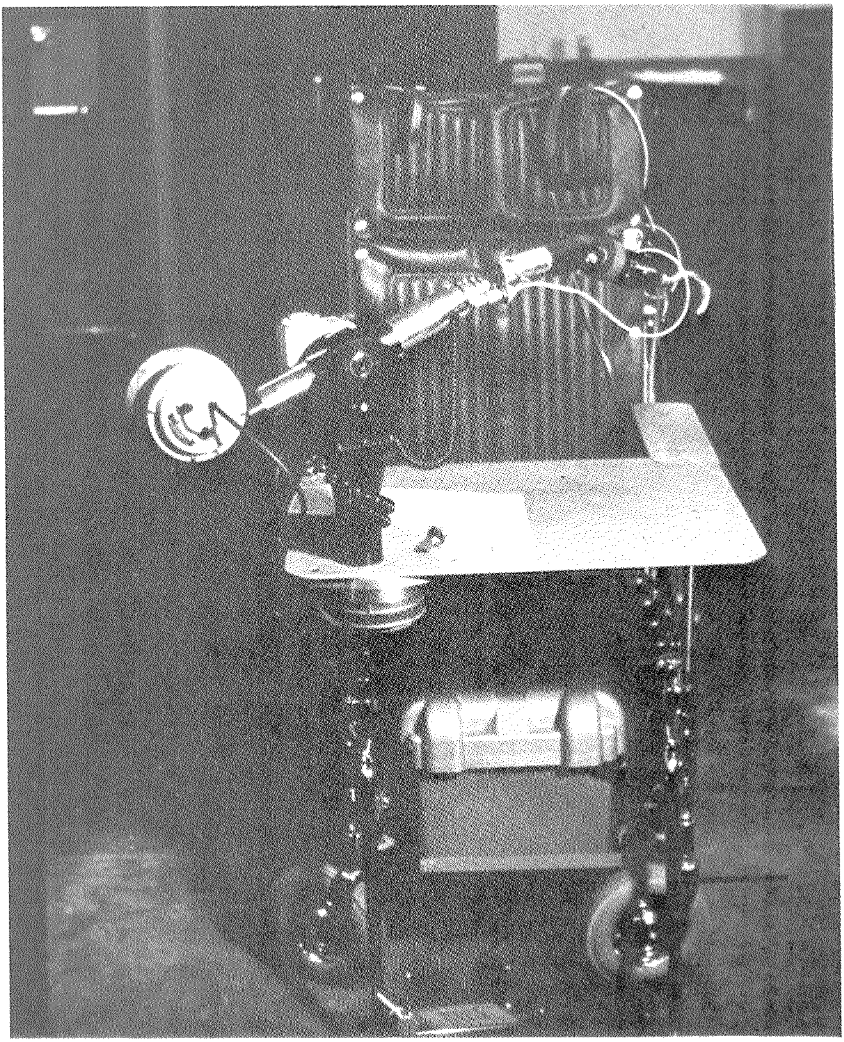

FIGURE 10. — NASA/JPL voice activation control system interfaced with wheelchair-mounted General Teleoperators telescoping manipulator.

ing in control contributes significantly to formation of the operator's opinion toward, and acceptance of, the manipulator (Corker, et al., 1978).

The gap between operator control capability and required manipulator dexterity is bridged by computer aiding. The operator stands in some supervisory or higher-order control position, with direct control of the manipulator under the aegis of the computer. The basic structure of such hierarchical control systems is set forth by Ferrell and Sheridan (1967). The operator is in the supervisory role of setting goals and strategies; the manipulator is controlled by a computer system capable of creating realizable subgoals from the operator commands, carrying out the subgoals to effect the movement, and monitoring the state of the manipulator. The level of goal specification should be a dynamic man/computer interaction (Rouse, 1975; Freedy, et al., 1972).

There has been a significant amount of research directed toward aiding the human operator of a complex system such as a medical manipulator. The extent and nature of man-in-the-loop involvement in manipulator control is dependent on the particular design philosophy of the manipulator, its platform, and its environment. The range extends from preprogramed control, with essentially open-loop manipulation, to continuous operator control with some type of coordinate transformation as aiding.

The extent of preprogramed automatic control is a variable, dependent on system design. The Johns Hopkins manipulator system, with a fixed work area, has full manipulation sequences preprogramed. For example; at program selection the manipulator will prepare a typewriter for operation, load the paper, and move to a "ready" position. Other preprogramed activities include a feeding function and a reading materials preparation. The man enters the loop at particular points in these programs to provide personal selection or timing. Less complete open-loop control is provided by the Spartacus Group manipulator, which is provided with certain "reflex" operations controlled by peripheral sensors. For example; when appropriately positioned the manipulator can be directed to a preprogramed "reach and hold" sequence (Guittet and Parent, 1978), or it can reduce arm pressure in a "soft touch" mode (Kwee, 1978).

Winograd (1972) developed a control system, SHRDLU[b], which accepts natural language command inputs. Using a structured deductive system and a model of a manipulative world, SHRDLU will plan and perform the movements to carry out a requested manipulation goal in a simulated environment. SHRDLU's world is a completely internal computer simulation. In real-world application of control

[b] "Unlike most of the acronyms used to name programs, 'SHRDLU' was picked by Winograd because it is meaning*less*. One row of the keyboard of a standard linotype typesetting machine consists of these letters, and typesetters often "correct" a mistake by inserting them in a faulty line so that the proofreaders will easily spot that a mistake has been made. Bad proofreading may result in this deliberate gibberish being printed in the final text—a fact made much of in MAD magazine. Being an ex-devotee of MAD, Winograd picked this nonsense word as the name for his program. (Winograd, personal communication.)" (Boden, 1977, p. 501, Note 5.)

aiding, information flow from the operator and feedback from the manipulator become integral system components. For a discussion of the implications of manipulator interaction with the real world, see Ernst (1962).

The importance of adequate sensory feedback to perform manipulation has long been recognized. At high levels of control aiding, the possibility of providing sensory feedback for use by the computer controller has been explored. Farnum, et al. (1978), have designed a system wherein the manipulator function is controlled by the operator commands (which specify subgoals of manipulation) and by sensor feedback, (which provides information from the environment). These information inputs operate interactively through a hierarchical grammar. Catros (1978) has modelled an arm whose machine performance requirements can be relaxed by providing multiple sensor information channels at the endpoint. Bejczy (1978) has implemented automatic grasping through sensor feedback control, as have the Spartacus Group (Kwee, 1978). The MIT group (Whitney, 1974; Hardin et al., 1972) also provided sensory feedback to the computer control to optimize path selection. A significant advancement in the area of supervisory control is represented by Shaket and Freedy's work (1977, 1978) in which the level of operator/control system interaction is variable. The subgoal development takes place through procedural nets, which allow anomaly at any level of subtask execution to be referred to the operator.

Still another approach to aiding keeps the operator directly in the control loop while providing coordinate transformation for end-point control. Whitney (1969) describes the purpose of this "resolved-motion rate control" as a coordinated control to command the rates of the arm's hand along axes which are convenient, task-related, and visible. This is accomplished by simultaneous movement of several arm joints in appropriate time relations. This type of control has been widely adopted and modified. Marić and Gavrilović (1971) use end-point control linked in logically synergic manipulation patterns. Luh et al. (1976) provide trajectory determination with a microprocessor. Roth et al. (1974) solve the 32 possible configurations (given a 6-DOF manipulator) for each end point position, controlling each joint independently, and optimizing for shortest path and smallest manipulator area.

In the area of aiding for medical manipulators, the Heidelberg group has adopted end-point control in their structured work environment. Their choice of continuous operator control, rather than preprogramed control, was made on the basis of presumed patient/operator preference for direct control (Schmalenbach, et al., 1978).

The Spartacus group also provides an end-point coordinate transform control (Guittet and Parent, 1978). Mason and Peizer (1978) provide end-point control in conjunction with their wheelchair-mounted telescoping design.

Methods which put the operator in even more direct control of the manipulator generally use sequential control of individual degrees of freedom. The proportional position-velocity joystick has been used to control both the articulated and extensible designs. Digital switching has been used in the General Teleoperator manipulator and wheelchair, and with the Rancho Los Amigos manipulator. A hybrid (switch and proportional) control was used in early versions of the Johns Hopkins manipulator.

Other direct-transduction units currently in use are the Santa Barbara voice control system, the Jet Propulsion Laboratories' device using a voice control system, and the Denver Research Institute's Ocular Control. (The Ocular Control transduces head movement relative to eye position into an analog following signal; its use in manipulator control will soon be evaluated by our laboratory.)

The Patient/Operator Subsystem

There are certain similarities among the disabled operators of the manipulator systems described. These similarities, including drastic reduction of control output capability, corresponding increased need for machine-aided function, and limited feedback channels, allow general design criteria to be established for medical manipulators. There are also profound differences among the patients who would benefit from aiding provided through a remote manipulator. These differences (in etiology, need, occupation, family situation, income, etc.) must be taken into account in the design of a particular system for a particular operator. At the operator/machine interface level, these manipulators must be designed on a custom basis to make maximum use of the control input-output ability of the operator. The environment should be altered as much as possible to work around the manipulator and the operator's needs, to produce optimal rehabilitative benefit.

This preliminary evaluation is directed toward clarification of the general principles applicable to manipulator design, and toward characterization of those situations which call for individual consideration in prescription of manipulator systems.

METHOD

In consideration of the complexity of manipulator systems, the nature of the population for which they were designed, and the multiplicity of factors beyond the experimenter's control in dealing with extremely disabled individuals, the evaluation is conducted in a "semi-case study" style. A wide base of etiologically varied individuals was chosen to provide information about the parameters of the types for which the manipulator systems could be of service (Groth, et al., 1963).

The evaluation was divided into three stages. Continuation of the evaluation of a manipulator or control system through these stages was contingent upon meeting performance and safety criteria at the previous stage. This favored subject safety as the extent of subject participation in, and interface with, the manipulator system increased at each stage of the evaluation process.

The stages of the evaluation are:

1. System description and bench tests;
2. Pre-clinical performance tests; and
3. Long-term clinical evaluation.

System Description and Bench Tests

At this stage of the evaluation, it is useful to consider the manipulator in terms of subsystems for which criteria of performance have been explored. In later stages, this type of breakdown is not operative and total system function is considered.

In the prehension subsystem assessment, criteria established by Peizer (1967) concerning grip force, grip surface, weight, power requirement, and availability are adapted to our application.

Other relevant research on manipulator configuration and control subsystem design is reviewed above.

The problem posed in this study is to combine previously established evaluation criteria[c] into an entire system analysis and, when necessary, to establish new performance criteria.

The procedure adopted to provide evaluative assessment at this level of system function is an extensive bench test, in which the first area of concentration is the verification of designer's claims about manipulator specifications. The next area of interest is a description

[c] Book and Field (1977) document 19 mechanical and electrical characteristics which have a significant effect on manipulator performance. McGovern (1977) confirmed the validity of Fitts' "Index of Difficulty" in task analysis of remote manipulators (Fitts, 1954). Roth (1974) suggests kinematic analysis of design. Similarly, Kobrinskii, et al. (1974), suggest volumetric criteria of manipulator quality. Bejczy (1978) outlines a performance evaluation of computer aided manipulators, stressing three criteria: effectiveness, quality, and cost (monetary, physical and cognitive). Paeslack and Roesler (1974) stress consideration of the patient's needs and abilities to structure a work area contiguous with manipulator function and to guide prescriptive judgments of patient rehabilitation potential.

of the physical components of the system and their dynamic characteristics. Finally, performance limens are established in established areas of concern; e.g., excursion/recursion time for all degrees of freedom, range of motion, forces and velocities produced, power requirements, control dynamics, etc. These tests serve to familiarize the research staff with each machine's operation, and allow for a rigorous safety check before presenting the manipulator to the subject at the next stage of the evaluation.

Pre-Clinical Performance Tests

At this stage the subject uses the manipulator system in the clinical setting under the supervision of the research staff. The subject is shown the function and control of the manipulator and instructed as to the particulars of its use.

The first series of performance tests are exploratory; they familiarize the subject with the machine and afford the experimenter an indication of the range of the subject's control abilities.

After this introductory phase, a test, practice, retest paradigm is followed for an objective cross-subject, cross-manipulator, measure of learning. Daily activity data are collected and are used to indicate trends of learning.

The objective test is to pick up blocks of various forms (cylindrical, square, rectangular, triangular, oval, and hemispheric) and transfer those blocks from the worktable to the lap board. On the lap board is a form with areas cut out corresponding in shape with the shape of the blocks. When a block is placed in the appropriate hole, 1.27 cm of the block extends above the hole, and there is a 1.57 cm tolerance between the block and the hole. The trajectory distance for block movement was 76 cm. A Fitts Index of Difficulty (Id) measure was used for standardization (Fitts, 1954; McGovern, 1974). Task difficulty is expressed as:

$$\mathrm{Id} = \log_2 \frac{2 \text{ x length of trajectory}}{\text{final tolerance}}$$

In this case,

$$\mathrm{Id} = \log_2 \frac{2 \text{ x } 76}{1.57} = 7 \text{ bits}$$

which, by Fitts' Performance Ranking, indicates a task of moderate difficulty. The test provides an exacting measure of control and manipulator performance.

As practice between tests, the subject performs activities in which the manipulator is used to serve realistic functional goals. Tasks are varied according to the patient's individual goals; for example, bringing a reading stand and reading material into a functional position on the lap board where it can be reached with a mouthstick. (Incidentally, it is felt that this type of cooperation between high-technology and low-technology functional aids should be encouraged at all times. The subject should be urged to learn to use all possible rehabilitative aids, and should seek to optimize their interaction.)

After these practice sessions, the subjects are again tested on the objective performance test. The shape of the learning curve provides information concerning the relative difficulty of control and system functions.

Long Term Clinical Evaluation

At this stage of the evaluation, the subject is provided with the manipulator system continuously for a period of months, and asked to use it at his own discretion. This use is monitored through an unobtrusive integrated circuit system which can record frequency data of the manipulator control activation (Fig. 11). This information reflects the subject's opinion concerning the usefulness of the manipulator in his daily routine. The long-term aspect of monitoring surmounts the problem of novelty effect produced by the increased attention paid the subject in the previous stage. On a long-term basis, the clinical staff is asked to unobtrusively monitor the subject's use of the manipulator, and problems with its use are investigated periodically with a Critical Incident Technique interview (Flanagan, 1954).

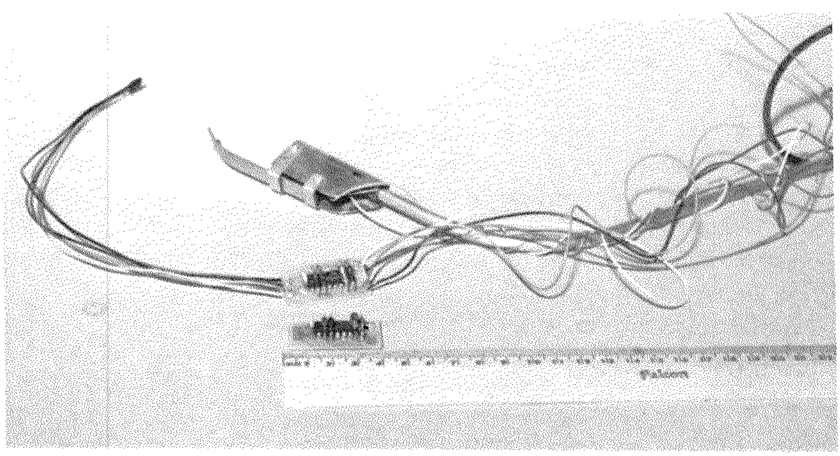

FIGURE 11.—Integrated circuit system developed to record frequency data of manipulator control activation.

The same interview is conducted with the subject after an extended time, and his subjective opinions about the manipulator and its various subsystems are assessed using a questionnaire. These data can later be compiled and subjected to a statistical treatment, such as Anderson's (1972), and areas of significance in the formation of opinion about manipulators can be distilled.

RESULTS

The engineering details of the descriptive and bench-test phase of our evaluation have previously been reported (Corker, et al., 1978). They will be described here, therefore, only as they impact on operator/machine performance measures, which shall be our primary emphasis.

The sequence of our protocol requires successful completion of one stage before the unit is tested at the next stage. Of the six manipulators made available to us through the Veterans Administration, only two (the Rancho Los Amigos Manipulator and the Johns Hopkins System) have met criteria of safety and reliability which permit their use by volunteer subjects in the Veterans Administration Hospital system. Those manipulators which have not been advanced to the performance-testing phase are being modified to meet our safety and reliability requirements.

Performance Testing of the Rancho Los Amigos (Golden Arm) Manipulator

Two chronic care males in mid-fifties and one semi-independent female in late forties participated as subjects in this phase of our evaluation. The subjects were selected to provide an etiological range of disabilities (Table I).

The Rancho Arm supplied has no high-level aiding. Control for subjects E. B. and M. B. was a velocity-proportional joystick which sequentially drives each joint motor. Subject J. J. used a tongue-actuated bank of digital switches. Figure 12 represents the training curves for these subjects over several weeks of practice. The slope of the curve indicates rate of skill acquisition. M. B. and E. B. have a higher rate of acquisition, suggesting that even the minimal aiding represented by proportional control has impact.

The asymptote of the curve represents the final level of proficiency. All three subjects reach an asymptote of two minutes to complete the task. This performance level is similar to the proficiency reported by Marić and Gavrilović (1975) in a similar manipulation task. The asymptote may reflect an absolute limit of proficiency due to difficulty of direct manual control.

Other data were analyzed along with the total performance time.

Table 1

Subject	Sex	Age	Diagnosis	Time Post Onset	Residual Function
J.J.	M	54	C4-C5 Quadriplegic Complete spinal transection	4 yr	Head and neck movement
E.B.	M	52	Guillain Barré	4 yr	Flexion both hands Internal/external rotation of right wrist Internal rotation of left wrist Right biceps full range of motion (ROM) Left biceps limited ROM Limited arm movement possible with balanced forearm orthoses (BFO's)
M.B.	F	47	Multiple Sclerosis	16 yr	Limited flexion/extension of both hands Limited unassisted arm function

Number of control moves was considered as a dimensionless metric which would remain stable over various manipulator types and tasks. These data were recorded over the training and practice section of the evaluation. The number of control commands to complete a motion correlated highly (Pearson product moment $r = .91$) with the total task time. This finding indicates that the most efficient task completion strategy is likely to be one which minimizes the number of control moves to complete a motion. This information should be taken into account when training strategies of use of the manipulator, and in the arrangement of the operator's environment.

Another consideration in observing the subject's use of the Golden Arm was an attempt to discover what type of movement schema the subject developed to complete the assigned task. Specifically, we were interested in discovering what type of coordinate reference system the subject used to direct the machine. A tabulation of all movements

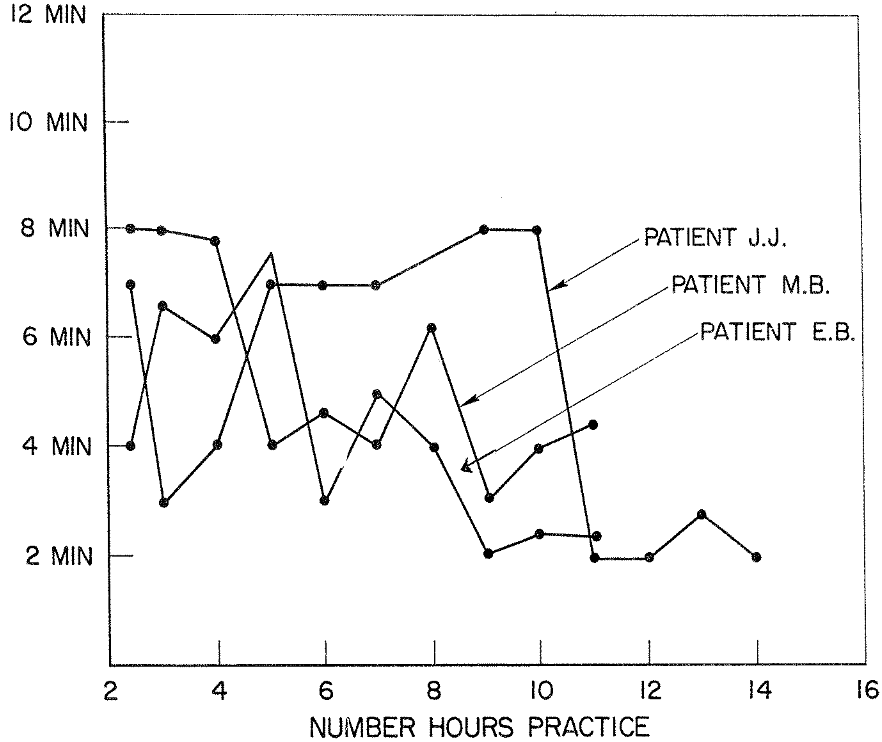

FIGURE 12. — Training curves of three subjects over several weeks of practice.

was kept, differentiating between rotational and horizontal movements. The environment was arranged in this task to allow the manipulanda to be accessible through an equal number of rotational moves. This was done to avoid interaction artifacts directing the subject's choice of movement. There are three degrees of freedom for each movement type. A Chi Square test was run to determine if there was a significant variation from equal use of both movement types. The results ($Chi^2 = 28.59$, $p < .01$ for E. B., and $Chi^2 = 140.1$, $p < .01$ for J. J.) indicate that there are significantly more horizontal and vertical moves attempted than rotational moves. The coordinates used by the operators are a subset of those available. Design toward or aiding in this subject may improve performance.

At 3 months of the 6-month long-term monitoring of subject J.J., the indication is that the manipulator is used about 10 percent of the time it is available for him.

The Johns Hopkins Manipulator System

The Johns Hopkins System is currently being tested against the same criteria as established for the Ranch Los Amigos Manipulator.

Subjects are using a hybrid control whereby the particular DOF to be moved is selected by switch stopping of a cursor moving across a display of the DOF's of the manipulator. Proportional velocity control of the selected DOF is then effected by chin movements.

Santa Barbara Voice Operated Controller

This voice controller has not been interfaced with a manipulator which we deem clinically safe or reliable. Data have been compiled on the recognition characteristics of the controller. Cross control performance testing with a manipulator is forthcoming.

The Santa Barbara system approaches the problem of acquiring control information from the disabled operator by accepting spoken commands. Speech control is a natural command mode which entails limited equipment encumberment for its user.

The input to the system is limited both in vocabulary and in command sequencing. The patient speaks into a microphone, and the system, composed of twin Z80 microcomputers, divides the input into a vector matrix for pattern recognition. The controller pattern-recognition system looks for consistency in pronunciation. The machine is also provided with a display to indicate either the word being processed or a diagnostic error message. System parameters are listed in Table 2.

The system must be trained to each individual operator's voice pattern, and can hold only one pattern at a time. This feature, and the fact that the system has no mechanical override to control the manipulator function (with the exception of a mechanical stop) represents a safety hazard during operation by a severely disabled subject, because while it protects against inadvertent operation by the voice of a bystander, etc., it would similarly prevent a nurse from intervening by voice to rescue the subject from a potentially hazardous situation.

Once trained to the basic vocabulary, the controller accepts input strings of the form "noun, verb." The basic vocabulary provides a method of addressing the machine parts and thus performing actions. Command sequences must be separated either by a spoken or mechanical "off" command, or by a 15 sec lag between commands, which also initializes the recognizer. This means the system does not allow complex command strings as input for control of complex motion.

It is believed that clinical usefulness could be enhanced if command sequences could be linked to perform smooth complex movements.

The subjects for the following recognition test were equal numbers of male and female students and personnel of the UCLA Biotechnology Laboratory. The choice of able-bodied subjects in these recogni-

TABLE 2. — *Voice Controller System Characteristics*

Attack Time: 50 ms
Release Time: 200 ms
Lag Time to Manipulator Response: 50 ms

Matrix Components:
5 frequency bandpass filters, 3 Hz-14 kHz
1 energy-sensitive vowel/consonant window
Training Criteria: 6 matrix inputs, identical/word

Diagnostics in Recognition: 1=vowel, 2=fricative, and 3=stop

Diagnostics and Error Messages Post Training:

"N"	= noise
"s < 3"	= input too short
"NONE QUALIFIED"	= input dissimilar in structure to vocabulary
"BDPHN"	= bad phoneme
"NO CONFIDENCE"	= two or more similar structures in memory
"NONE CLOSE"	= matrix structure not contained in memory

10-Word Vocabulary: arm, wrist, grip, right, left, in, out, raise, lower, off

tion tasks is appropriate because this control system would be contraindicated for patients with speech involvement in their injuries. (It should be noted that it is not unusual for a quadriplegic subject to have breathing or vocal impairment. Voice involvement from phrenic nerve damage is secondary to loss of diaphragm control and the subsequent impairment of breath control; this is usually seen in the C-4 level quadriplegic subject.)

Three tests were conducted on the response of the voice-operated controller. One measured initial recognition rate, another measured training time to reach a 95 percent recognition criterion, and the third tested coarticulation effects on the system.

1. *Initial Recognition Test*

The controller was trained, and the training time to the machine's criteria was recorded. The subjects (n = 10) were then prompted to repeat the trained vocabulary sequence, reiterating each word as often as necessary for machine acceptance. The entire vocabulary was repeated until the machine had accepted each of the 10 words 10 times.

The results (Table 3) indicate that the system has an overall initial recognition rate of 68.9 percent. The machine also has the capability of being retrained on specific words (see below, 2). The data indicate that a large part of the recognition problem is represented by a few similarly formed words; i.e., wrist, right, and raise. The vocabulary as selected allows easy identification between command word and manipulator function; however, we feel this goal could be attained with a selection of words phonetically dissimilar.

TABLE 3.—Initial Recognition Data: Voice-Operated Manipulator

Number of Subjects:	10
Number of Trials:	10
Number of Words:	10

WORD	*Average % recognition over all subjects*
wrist	54.8
out	68.1
arm	85.5
raise	38.2
lower	59.1
left	95.8
right	81.6
in	53.7
grip	80.8
off	71.0

Average recognition rate overall: 68.9%

2. *Training Time to 95 Percent Recognition Rate*

Each of the subjects (n = 10) trained the controller, and then, using the retrain option, reached a 95 percent recognition rate over 20 trials each. The mean time to reach criteria was 5.9 min.

A signal detection paradigm is currently being used to further characterize the parameters of recognition.

3. *Coarticulation Effect Test*

As indicated above, the command sequence to the manipulator is "noun, verb, off." There are three noun groups associated with specific portions of the manipulator. They are "arm," "wrist," and "grip." The purpose of this test was to assess the effect of the noun associated with verb types in the spoken command. Subjects (n=4, 2 male and 2 female) trained the manipulator to a 90 percent recognition rate using the retraining option, and a repeated measures factorial AxBxCxS design was used, in which —

A = order of presentation of word groups;
B = order of presentation of noun types;
C = order of presentation of particular dyadic verb types (e.g., "raise, lower"); and
S = subject.

The order of presentation of the noun, verb sequence was randomly varied over all noun groups and dyadic verb types, and presented to the subjects as prompts. Every subject saw each possible order of word groups, noun types, and dyadic verb types.

An analysis of variance yielded no significance for any of the main effects or interactions. The lack of significance is in part explained by large intrasubject variance as a result of particular word recognition difficulties noted in the previous experiment.

This command modality may be limited in usefulness because of noise effects. Tests were conducted at an ambient noise level of 40-50 dB SPL. Higher ambient noise levels yielded erratic performance. Associated with these noise effects was the noise of the manipulator motors themselves, which appear to have frequency components in the area of some of the commands (specifically, "off").

General Teleoperators Telemetrically Controlled Wheelchair and Manipulator System

This system provides a mobile manipulator platform which can be telemetrically controlled when the user is not seated in the wheelchair onto which the manipulator is mounted. The unit, as provided by the designer, has not functioned reliably; therefore performance data are not available. In the bench test performed it was noted that the wheelchair blocked visual feedback in 50 percent of the total performance envelope of the manipulator.

DISCUSSION AND CONCLUSIONS

Manipulators provide the severely disabled individual with rehabilitation potential beyond that previously expected.

The manipulator can be considered functional to the extent that the operator comes to depend upon it in his daily routine. To that same extent, the manipulator must be safe and reliable. Based upon previous research and our results to date, the following conclusions can be drawn:

1. There is a strong need for increased reliability and safety across all manipulators tested. These are the primary concerns of all our subjects who have worked with the systems.
2. In systems tested to date, control aiding is essential if the manipulator is to be used. For multi-linkage general-purpose manipulators, resolved motion end-point control should be used. In a stationary environment, fixed trajectory motion should be preprogramed.
3. Operator unburdening through display aiding as well as control aiding should be explored. Previous research indicates performance in lag systems can be improved through quickened (or predictor) displays. Some integration of information should occur before operator decisions. This need is made more pressing with the advent of telemetrically controlled mobile manipulators, which may function outside the operator's immediate visual field.
4. Manipulators should be developed under more stringent safety criteria, specifying that the user never accidently be placed in a position where it is possible to be injured by the manipulator. Automatic speed control (a governor) should be used in the operator's immediate physical surround, to provide a zone of safety. Non-manual command transducers such as voice control should be able to be overridden by more primitive mechanical controls in case of malfunction.
5. The manipulator should not be viewed in isolation. It should be considered a tool in an arsenal of tools to aid the severely disabled. It should be integrated into a total rehabilitation program which may draw upon aids of all levels of technology, from mouthstick to computer-aided environmental controls.

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