STUDIES TOWARD A PRACTICAL COMPUTER-AIDED ARM PROSTHESIS SYSTEM

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INTRODUCTION

This paper summarizes a research and development program of the Biotechnology Laboratory, UCLA, that centers around the application of computer-based control techniques to the practical problem of externally energized arm prosthesis control. The impetus for this work is derived from the state of technology in microcomputer development which offers miniature implementable digital circuits. These capabilities provide a means for realizing advanced control schemes which involve on-line computation. Of particular interest is the use of this type of computer for auxiliary information processing to aid in the control task and reduce the control and information processing load of the patient. The objective of the work is the development of specifications and a prototype system which can be used by an amputee and which will aid him in the performance of a set of daily tasks.

In attempting to approach an advanced control system, the proposed work combines techniques developed in this laboratory with those of other research groups into an integrated package. The effort involves the establishment of the various interfaces between the subsystems and the fitting of each subsystem into operational use within the context of an externally energized arm package.

The following sections provide a brief description of each of the areas of work and summarize the progress to date.

EXPERIMENTAL ARM PROSTHESIS

Mechanical Construction

In the past year there has been a continuing effort to develop an

experimental arm prosthesis from available components. The approach involves the selection of available individual joints, actuators, and the development of mechanical interfaces between the components. The objectives are: 1. To test the feasibility of integrating individually developed modular components into a single arm and 2. to provide a means for testing and integrating the control concepts which were developed in the Biotechnology Laboratory.

A first attempt resulted in a three-degree-of-freedom arm which utilized the AMBRDL hand, the AMBRDL wrist rotator, and the Northwestern University elbow unit. The arm was worn by an amputee and was used in experimental work, reported elsewhere by Lyman et al. (1). The arm was tested sufficiently to determine that it had clinical potential, but a major problem was found in the reliability of the components. In an attempt to solve these problems and increase the number of degrees of freedom of the arm, a new version has been assembled from a new set of components. The components, which were provided by the Veterans Administration, were the VA/NU hand, Northwestern wrist rotator, and VAPC elbow. In addition, a humeral rotator was designed and constructed from a modified VAPC elbow motor. As a variation to the use of the Northwestern wrist rotator (which proved to have inertial overshoot problems), the VAPC elbow unit was modified to serve all rotation purposes of the new arm. Simple modifications of the external shell of the elbow motor make it suitable to serve either as wrist or humeral rotator. This approach has created several advantages, including reduction in the number of different motors required, simplification of maintenance and repair, and reduction in cost of the arm if large production quantities become feasible.

At present two VAPC elbow units have been modified to serve as wrist and humeral rotators. The external gear assembly of the original VAPC motor shell was cut out and glued with epoxy into a specially constructed cylindrical shell. The motor core is then slipped easily into the new shell, and limit switches are installed on the shell cover. The modified shell can be made of any external radius to fit cosmetically either the wrist size or the humeral size. In addition, the shell can be constructed of lightweight plastic (PVC) or aluminum.

In order to provide position/velocity feedback directly from the motor assembly, the modification process included the implementation of resistive carbon material glued around the top part of the shell, and a roller installed on the motor shaft that travels back and forth on the carbon material to provide resistance variations as an indication of position/velocity.

The above modification process provides a completely self-contained, instrumented arm joint. Preliminary testing and evaluation demonstrated the superiority of the modified units to other components speci-

fically in the aspects of torque, precision, and control characteristics along with excellent cosmetic appearance.

Further work is planned to increase the reliability of the feedback potentiometers by using solid carbon cut to size, and evaluation of several other configurations for mounting the carbon resistance chips on the shell.

Additional recommendations concerning the design will be given at a later date when the system has been evaluated on some amputees under various environmental conditions.

All wiring is contained in the interior of the arm, and the components are not visible or exposed except for 2 in. at the elbow unit. Figure 1 provides an overview of the assembled arm.

Pressure sensors are installed on the fingertips of the VA/NU hand. The hand, in turn, is connected to the self-contained rotator modified from the VAPC elbow unit as described above. The VAPC elbow unit is then attached to the wrist by a skeleton frame covered by cosmetic rubber foam. A position feedback potentiometer has been attached on the shaft of the elbow motor and anchored to the skeleton frame. Finally, another self-contained rotator, to serve as a humeral rotator, is attached to the elbow.

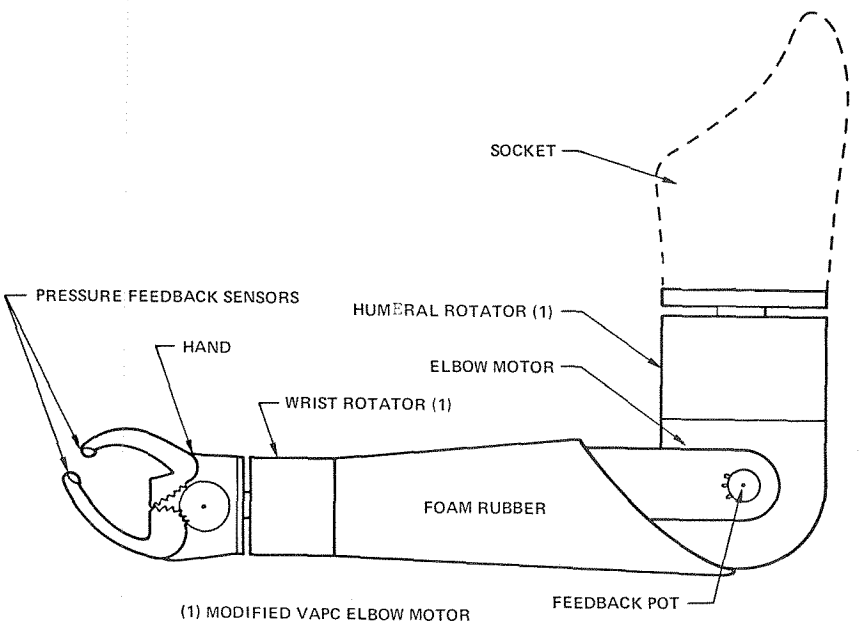

FIGURE 1.—Diagram of the artificial arm.

A digital to pulse width modulation (PWM) servo amplifier has been constructed and operates according to design specifications.

The digital to pulse modulation servo amplifier is believed to be the first practical prosthetic proportional controller which can be interfaced directly to a computer. Parts cost and size are relatively low because of availability of current technology.

Sensory Feedback

A fingertip pressure sensing system was implemented on the exper mental arm prosthesis in order to provide the operator/amputee with some sensation proportional to the pressure exerted by the fingers on various objects.

The purpose of this device is to decrease the amount of visual supervision required of the operator on the functions of his arm, and thereby reduce the attention and concentration required to perform standard operations.

The project has proceeded on three parallel routes:

1. Implementation of a pressure transducer, connecting pressure to some variable electrical quantity to control the electronic network.
2. Implementation of information transformation system electronics in a design suitable to be mounted on the prosthesis.
3. Determination of method of stimulation. Several methods of stimulation were considered, including:
   a. Skin stimulation by electrodes with choice of metal electrodes, conductive rubber, etc., in several configurations. Evaluation was made to determine the tradeoffs and advantages of several types of electrodes with special emphasis on resolution of sensation, amputee comfort, feasibility of implementation without interference with EMG signals, etc., and
   b. Examination of possibilities of implanted stimulators activated either directly through the skin via vitreous carbon contacts or by induction. The experience of Dr. Frank Clippinger (2) and his group at Duke University is being monitored closely.

Work in progress is concentrated on the refinement of a pressure sensitive transducer, constructed in this laboratory from foam rubber doped with conductive materials and yielding variations in resistance-capacitance proportional to the exerted pressure. Evaluation of the electrical-mechanical characteristics of such devices as control elements for an electronic system simulating a physiological sensor has shown good potential. Figure 2 shows the characteristics of one configuration.

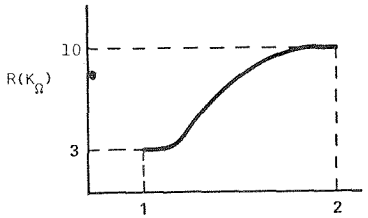

FIGURE 2.—Resistance deformation characteristics of the pressure sensor.

An electronic information transformation system, simulating a muscular sensing organ was designed and constructed.

Direct variations in resistance of the pressure transducer cause the information transformation network to increase the frequency of stimulation in the range of 10 to 120 pulses per second (p.p.s.). The pulses are 50 μsec. in duration and amplified by a step-up transformer to 250 v. in amplitude for skin stimulation. Capabilities exist for amplitude adjustment to a comfortable level for the subject.

Several electrode configurations were considered to interface the stimulating signal with the amputee. The purpose of the various types of electrodes is to eliminate pain/pinch effect felt by the subjects.

The following electrode configurations (as shown in Fig. 3) were designed, constructed, and tested:

1. Two round stainless-steel electrodes 2 cm. apart, mounted on flexible plastic base.
2. Concentric conductive sponge electrodes of several diameter sizes, installed in Plexiglas housing.
3. Two parallel cylinders mounted in Plexiglas housing.
4. Concentric metal electrodes installed in Plexiglas housing.

Evaluation of Various Electrodes

The rationale for testing various types of electrodes was to define the interaction of electrode size and material with the various parameters of stimulation, such as: resolution, pinch/pain, reliability of stimulation under various environmental situations, subject comfort, etc.

In the course of testing and evaluation, the following points became apparent:

1. Stimulation with conductive sponge electrodes resulted in reduced pinch/pain effect experienced by the subject.

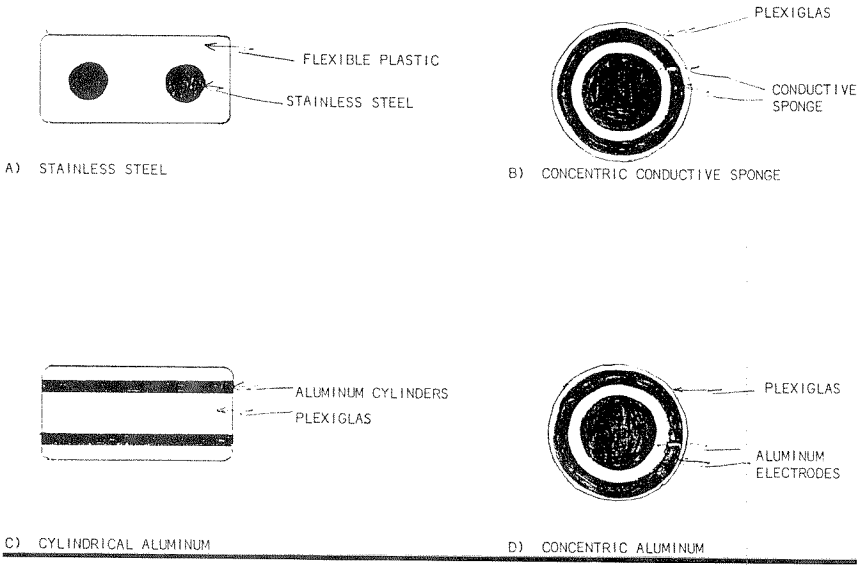

FIGURE 3.—Skin Stimulation Electrodes.

2. Larger diameter sizes of the central electrode also contributed to reduction of the pinch/pain sensation.
3. Stimulation with large electrode diameter caused localized stimulation in the skin area under the electrodes.

Close analysis of the various electrodes showed that the differences in the sensation felt by the subjects depend on several parameters, including:

1. Electrode diameter.
2. Contact area with the skin.
3. Amount of resistance introduced by the electrode material.

Since the skin could be taken as a medium into which an electric field is introduced, the electrical properties of the skin, along with the field strength, will eventually determine the sensation and comfort attained by any one electrode configuration.

The value of the electric field and the skin resistivity at its sensation threshold will determine the current density. It is the amount of current density that brings about the pinch effect, and increasing current density results in increased discomfort.

Another parameter to consider is the skin surface area which is in contact with the electrodes. As the surface area increases, the current density for a given fixed current will decrease. This will hold for the other electrode styles as well.

Still another factor to consider in the conductive sponge electrodes is the inherent resistance of the material itself. This added resistance contributes to limiting the current available, and therefore reduces pinch sensation.

The added comfort demonstrated by the conductive sponge electrodes is a direct result of the ability of the sponge to adjust itself to the skin surface curvature under slight pressure and therefore to increase the contact area.

It is clear from mathematical considerations that the added comfort provided by certain electrodes due to their geometry and material could be equivalently achieved by providing the stimulator network with proper regulation of voltage/current output for any electrical geometry. Fine adjustment of the powered output is necessary to achieve comfort for the individual to be stimulated, relatively independent of the electrodes used. Coarse output adjustment could compensate for simple electrical configurations.

The conclusion from this study is that electrode material and geometry should be considered for purposes of simplicity, cost, ease of the attachment and removal, shape of skin, etc. The comfort of stimulation and reduction of pain/pinch can be most easily achieved by power output adjustment.

Electronic Support System

The defined function of this system is to transform pressure information into physiologically meaningful coded signals. At present, the output of this system is dependent on the interface with the amputee. From our model and from experience evolved from this field in recent years (Reswick and Nickel (3)), it is well known that both skin and nerve fibers can be stimulated effectively by pulses of variable frequencies in the range between 10-100 p.p.s. Thus a reasonable requirement is that the system design contain a basic portion transforming the analog pressure information into pulses over the range of 10-100 p.p.s. The chosen interface with the amputee will determine the intermediate buffer network suitable for skin or nerve stimulation.

The system constructed at the Biotechnology Laboratory consists of the following components: pulse generator, frequency controller, and pulse width controller. The system is simple, and could be easily miniaturized for implementation in the socket or the forearm portions of the prosthesis; a power supply could be included.

A transformer was introduced at the output of the pulse generator to increase the strength of the pulses from 15 v. to 200 v., with a potentiometer output for adjusting the pulse characteristics for individual comfort.

COMPUTER-AIDED CONTROL

Background

An important aspect of the research and development on an adaptive aiding system is directed toward the specification of a software structure that can be implemented in a microcomputer, and used as an aiding device on arm prostheses. Computer aiding can be used in the following ways:

1. As an auxiliary control information source to supplement and aid the operator in the decision and control process, and
2. As an information transformation system which maps available patient control data into unique command signals in a manner compatible with operator capabilities.

The first type involves a parallel computer aiding where the computer generates control commands autonomously and can free the operator of part of the control burden.

The second type of computer function exists mainly in the direct control loop and provides computational transformation. Examples of this type of transformation have been used with end point and residual motion control (Whitney, 1970) and EMG pattern control (Wirta and Taylor (4) and Lawrence (2)).

Parallel Aiding

Parallel-type aiding has been realized by Freedy et al. (5) and has been the current focus of the Biotechnology Laboratory work. To date, a prosthesis-oriented adaptive aiding system has been developed and implemented on the Biotechnology Laboratory minicomputer. A recent, detailed description of the system has been provided by Lyman, Freedy, and Prior (1). The implemented system involves complete trajectory control and learning capabilities sufficient to acquire part of the control skill from the operator and take over that portion of the control.

The adaptive aiding system is based on an automaton that observes how the patient controls the arm and "learns" to take over a portion of the control responsibility. As the automaton takes over part of the control, the patient's control burden is reduced and performance improves. The system is implemented with a computer in parallel with the patient in the man/prosthesis control loop. The computer aids by making and displaying control decisions, and by supplying autonomous control inputs to the prosthesis control system. Adaptive aiding comes from a trainable "machine learning" algorithm programed on the computer. Prosthesis position and terminal device sensors allow the program to observe patient performance, and its results, and to optimize control decisions accordingly. The computer learns complicated control

strategies, can be pretrained for future tasks, and forgets unused actions.

The theoretical basis of the system is the maximum likelihood decision principle. It has been reviewed in several publications (Freedy et al. (5); Freedy, Hull, and Lyman (6)).

Advantages of adaptive computer aiding include:

1. The patient's information-handling load is reduced, enabling him to improve performance;
2. The patient concentrates on his most effective roles as initiator and supervisor;
3. The system provides an artificial means for removing part of the control function from the external visual control loop to an internal reflex loop;
4. The computer extracts task information from normal, ongoing, control actions;
5. The system concepts can be applied to various rehabilitative systems, at several levels of complexity; and
6. The system can be implemented with currently available minicomputers or microcomputers, and is therefore practical for current systems.

During the first year of the study, adaptive aiding for the generation of complete trajectory control of a prosthesis was implemented. Design modifications and improvements were introduced to the original actuator control system (Freedy et al. (5)). The basic principles of conditional probability and maximum likelihood remain, but the decision space and the input information have changed, and a new level of adaptability has been introduced.

SERIAL AIDING

EMG-Pattern Control Technique

The concept of EMG pattern control has recently become popular as a means for efficient and compatible control (Wirta and Taylor (4); Lawrence (2)). The philosophy behind the approach is the mapping of n electrode signal sources into m classes of patterns. Each pattern is used as a unique control signal to the arm. In this control scheme, signals from n control muscle sites are transformed into m prosthesis joint control signals. This is in contrast to the conventional control approach where control sites are uniquely linked to arm joints. The early success of the approach provided an impetus for testing the EMG-pattern control system as the control logic for operation with the computer-aided adaptive control system. The objective of this phase of work is to expand the application of EMG-pattern to end-point control; that is, to transform

signal from n signal sources into motion along m real world coordinates.

This was first done by Wirta's group at Moss Rehabilitation Center. In capsulated form, Wirta et al. (4), did pattern recognition work on the EMG signal generated by the anterior deltoid, posterior deltoid, middle deltoid, manubrial pectoralis major, upper middle trapezius, lower middle trapezius, lower trapezius, rhomboideus major, teres major, and infraspinatus correlated with arm motion. Data were gathered from a large number of normal subjects, the patterns found, and then used to control a prosthesis for an amputee, getting good control for humeral rotation, elbow flexion-extension, and forearm rotation. The amputee does not have to resort to articulated body English nor heavy concentration. Movements of the phantom limb correspond to movements of the prosthesis.

At UCLA, a slightly different approach to the same idea has been undertaken. Recognizing differences in EMG signals among individuals, different requirements of amputees due to level of amputation, etc., a system is being developed to measure ("learn" may be more apropos) a particular individual's EMG patterns and to create a personalized system. Rather than the subject being required to fit his EMG pattern to some standard, which does to some extent happen, the effort is being made at UCLA to fit the system to the amputee's peculiarities.

During a "learning" session (by which it is meant the system learns the amputee's EMG pattern, and not vice versa), nine EMG electrodes are attached to the amputee in the shoulder girdle region over muscles related to the amputated limb. In addition, an arm goniometer is fitted to the amputee's sound arm. Information from both sources is then fed into the laboratory minicomputer. The amputee is then instructed to move his phantom limb and sound limb in a parallel fashion; e.g., he extends both his phantom elbow and his sound elbow. While this is going on, the system watches the experiment and attempts to correlate the observed EMG pattern to observed arm movements. This phase of the learning session continues for 20 to 30 minutes, and is then stopped. The learned patterns are summarized in six probability matrices, which can then be transferred to the microcomputer that would ultimately be contained in the prosthesis.

Current experiments at UCLA with this system have been performed on a normal, nonamputated subject. The system has learned to move an arm prosthesis in the same manner as the subject moves his real arm after learning the EMG pattern for this subject. Experiments are scheduled for tests on an amputated subject in the near future. The system utilizes the Biotechnology Laboratory Interdata Minicomputer, an EMG amplifier, and analog to digital conversion equipment.

IMPLEMENTABLE MICROCOMPUTER

The principal objective of the work on an implementable microcomputer is to bring current development of computer-aiding control concepts and laboratory tested algorithms closer to clinical availability. This goal is approached through the application of the current state of technology in microcomputer developments which offer economically feasible miniature circuits of size and weight compatible for rehabilitation engineering applications. This state of technology has brought about the reasonable expectation of achieving a highly functional self-contained, self-supporting, externally energized computer-aided prostheses system for the mid to high above-elbow and shoulder-disarticulation amputee.

In the past, practical computer-aided prostheses have been physically impossible to construct. Several design limitations existed which precluded reduction of the computer and its power supply to a size and weight which would afford the amputee reasonable mobility. In addition, software programs previously developed for prosthesis control have been, at best, severely limited. This situation has recently been changed due to advances in microcomputer technology, as well as greatly improved control programs developed by our laboratory and elsewhere. The development of a practical, self-contained, computer-aided prosthesis is technologically feasible in the 1974 to 1977 period. Evaluation of the potential of this technology has led the Biotechnology Laboratory to perform a feasibility study for the utilization of microcomputers in prosthesis control (Lyman, Freedy, and Prior (1)).

This feasibility study, which was based on state of technology evaluation as of July 1973, has been completed. The objectives of the study were as follows:

1. To review the state of microcomputer technology and define available subsystems;
2. To recommend a specific microcomputer system suitable for controlling a prosthesis; and
3. To establish a preliminary design of a microcomputer-aided arm prosthesis.

Details regarding the results of the microcomputer study are given by Lyman, Freedy, and Prior (1). In the main, it was concluded that an electronic package for a four-degree-of-freedom above-elbow prosthesis, featuring pattern recognition of 10 EMG electrode sites as well as stored reflexes and autonomously generated subtask capabilities, could be placed in a 0.6-in. × 2.5-in. dia. package. The recommended microprocessor is the Teledyne series TDY-52 programable digital computer.

Included in the package would be a 51 instruction Control Processing Unit (CPU), 8,192 × 16 bits of Read Only Memory (ROM), 12,288 × 16 bits of Random Access Memory (RAM), 24-10 bit Analog to Digital (A/D) channels, and three servo amplifiers. Standby power drain is estimated at 192 mw, whereas all electronics would dissipate in the worst case about 5½ watts when the arm is in motion.

Using standard VA-powered components for the elbow and hand, plus VA elbows modified into a humeral rotator and a wrist rotator, sufficient energy from self-contained Ni-Cad batteries is expected to allow operation of the prosthesis throughout a normal day's activities. Programing of the Teledyne model TDY-52 computer can be accomplished from any standard teletype, remote terminal, or computer using an IBM 360 architecture. A comprehensive software support package is available from Teledyne.

Cost for the first prototype electronics package is estimated at approximately $7,900, whereas the 100 quantity price in 1975 should be less than $2,800. Electronic packages with fewer features (less memory, simpler CPU's, fewer A/D channels, etc.) are also available, with the cheapest costing about $500 in quantities of 100. The optimum performance versus cost tradeoff has not yet been established, although complete electronics packages useful to above-elbow and shoulder-disarticulation amputees are expected to add less than $1,000 to the cost of a powered prosthesis which does not contain a computer. The simplified package would also consume less power, thereby allowing the use of smaller batteries for the same wearing time.

TOWARD CLINICAL APPLICATION

In attempting to move the system to clinical applications, efforts are directed in three parallel paths:

1. Fitting the experimental arm prosthesis to a proper amputee subject.
2. Developing advanced EMG control schemes and their evaluation.
3. Integrating all hardware and software to form a practical arm prosthesis.

An amputee subject with high above-elbow stump was selected, and the socket-harness assembly is being prepared for him in cooperation with the UCLA Rehabilitation Center and the Sawtelle Veterans Administration Amputee Clinic. The subject is a machinist with good mechanical aptitude who is wearing the standard cable-controlled prosthesis. He is aware of problems associated with his prosthesis, and has made some changes in his terminal device to allow him to do several functions he could not do previously.

A series of experiments are planned which include;

1. EMG mapping to yield the best signal-emitting muscles;

2. Construction of a shoulder socket in which the EMG electrodes will be mounted permanently over the best EMG sites;
3. Learning and discrimination sessions to train the EMG adaptive-aiding system and the subject to perform a basic repertoire of motions that could be extended during use;
4. Evaluation of several control schemes such as the EMG pattern and aided control.

The culmination of the experimental sessions will be an evaluation study of the system hardware-software and the establishment of specifications that will include requirements for a microcomputer for integrating into a practical self-contained arm prosthesis.

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