A MULTI-LEVEL APPROACH TO ORTHOTIC/PROSTHETIC CONTROL SYSTEM DESIGN

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Summary

A multi-level approach to the design of control systems for complex orthotic/prosthetic (O/P) systems is described. All O/P systems are described as a Man-Machine System in which a computer provides a data acquisition, control, and decision-making function. The multi-level approach further divides the problem into more manageable sub-problems in which the overall control function is decomposed into a hierarchy of control functions which distributes the load and responsibility for satisfying the control objective. The levels of the hierarchy may be identified successively with direct, optimizing, adaptive and self-organizing control. This hierarchy is an ordering with respect to time scale, complexity of computation, degree of uncertainty, etc., which relates to important design considerations for the overall system.

Two upper-extremity system designs which have been simulated are discussed in the context of the hierarchy:

1) A system with plus, minus, zero velocity control of each individual axis.
2) A proportional velocity control system in which ΔX-ΔY-ΔZ input commands are given by the subject, to control the end-point of the arm. The computer generates the proper $\Delta\theta$ commands to move the arm ΔX-ΔY-ΔZ and maintains the hand in a level attitude.

Times to perform simple tasks under manual control are compared. Both systems provide important design data relating to the usefulness of a computer in the control of a multi-degree of freedom orthotic arm.

Introduction

In the past, much of the research, development and clinical application of orthotics and prosthetic systems has centered on the hardware devices which perform the functions required by the handicapped person. Designers have shown awareness of control and feedback, but their attention has been primarily directed toward the powering and fitting of devices to improve the function of the handicapped. Present state of the art is such that the hardware assistive device itself can be built; but there are serious problems involved in designing effective control systems for the patient and machine.

Control problems become especially acute for severely handicapped patients who require multi-degree of freedom assistive devices. The major emphasis of this paper is on the development of a multi-level control hierarchy for the design of O/P control systems. In the context of this hierarchy, two designs for the control of multi-axis orthotic arms are then discussed.

Cybernetic Orthotic/Prosthetic System

In an O/P system, the human being and his assistive device comprise a man-machine system. When the orthotic or prosthetic system uses external power and is operated by means of external feedback control, the result is a cybernetic system or man-machine system in the true sense of the term [1]. The control task of the man can be simplified by having an information processor share part of the control and decision-making task. Figure 1 is a block diagram of such a *Man-Machine-Computer* or *Cybernetic Orthotic/Prosthetic System.*

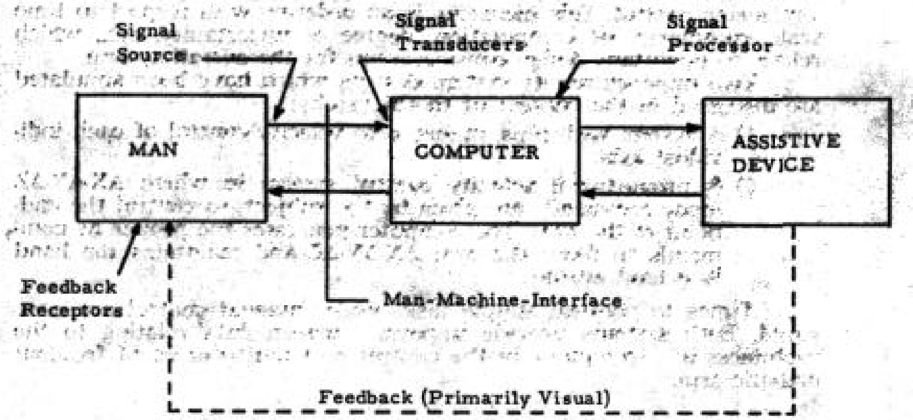

Fig. 1. Man-machine orthotic/prosthetic systems

The assistive device includes the power sources and supporting structure. The assistive device receives commands from the computer and, in turn, the computer can interrogate its state. The output of the assistive device is its specific physical function.

The man's function is to communicate his commands to the computer based upon his conscious desires and feedback from the assistive device. The man is the most adaptive portion of the system. In fact there is a significant learning/training problem involved in his function in the control loop.

The computer provides a data acquisition, control, and decision-making function. As an example, it may produce output commands to an orthotic arm based on the arm's present position and the man's input signals such that the arm appears to operate in an X-Y-Z cartesian coordinate system as observed by the man.

Multi-Level Approach to the Design of Cybernetic Orthotic/Prosthetic Control Systems

With this brief introduction into orthotic/prosthetic systems, the emphasis will now broaden to include not only the O/P systems, but also the engineering design of such O/P systems. There are two important aspects associated with this approach:

1. The approach should accurately describe the important features of the O/P system itself.
2. The description should be in a form which clearly shows where, how and why important design factors and decisions enter in.

Ideally, this approach gives better insight into why the engineering designs are made rather than a description of what was done. In order to accomplish this task, a two-step process will be followed:

1. *A Multi-Level Approach Applied to Control System Design* will be presented.
2. The theory will be applied to *Engineering Design of Multi-Axis Orthotic Control Systems.*

A. Multi-Level Approach Applied To Control System Design [2]

The general design problem for system scontrol is schematized in Figure 2. Associated with the process are a set of disturbance

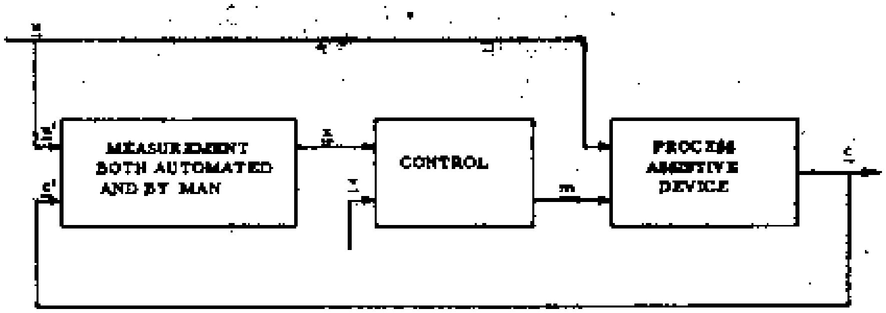

Fig. 2. General design problem for systems control applied to O/P system

inputs $u(t)$, a set of manipulated inputs $m(t)$ and a set of output variables $c(t)$. The disturbances are the independent variables of the system. They represent the effects of environmental variations and of variations in other systems to which the process is coupled. The manipulated variables are determined by the controller, they are thus dependent upon the control function and upon the observations $x(t)$ made on the system. They are also dependent upon a set of specifications, design assumptions, and hypotheses pertinent to the control, which will be denoted by the vector v. The information vector $x(t)$ represents the measurements of some of the disturbance inputs (designated by the vector u' and of some of the output variables (designated by the vector c').

$u(t)$ = Disturbance inputs.

$u'(t)$ = Measurement of some of the disturbance inputs.

$m(t)$ = Manipulated variables.

$c(t)$ = Output variables.

The control application assumes:

1. A deterministic relationship in terms of the inputs

$$c(t)=g[m(\tau),\ u(\tau)] \tag{1}$$

2. A performance functional

$$p=p[c(\tau),\ m(\tau),\ u(\tau)] \tag{2}$$

3. A set of inequality constraints

$$h[c(\tau),\ m(\tau)]\geq 0 \tag{3}$$

The control algorithm defines a transformation

$$m(t)=m[t,\ c'(\tau),\ u'(\tau)] \tag{4}$$

Ideally, Equation 4 is to be determined so that Equation 2 is maximized subject to Equation 1 and Equation 3. However, there are several practical difficulties:

1. The system equations are rarely known exactly or completely.
2. The $u(t)$ over the future interval of interest is seldom known a priori.
3. Mathematical techniques for optimization are not sufficiently developed to handle the system complexities met within process applications.
4. Even where the above difficulties could be resolved, the resulting computational problem makes implementation for on-line control impractical.

In order to implement automatic control of the process, it is necessary to make a number of simplifying assumptions. These assumptions can be associated with elements of the design vector v and may include decisions related to: The structure of a simple model to represent the process; the element of the vectors u' and c'; a simplifying approximation to the performance measure; etc.

1. Multi-Level Approach to the Control Problem

The systems control problem may be embedded in the determination of the design vector v. However, the great complexity of many processes precludes any overall control approach such as implied by Figure 2. The major reasons are:

1. Computers are not large enough to handle the total control problem.
2. The analytical techniques for analysis and design of such large scale systems are lacking.
3. There are many practical considerations based on reliability and efficient use of components.

The multilevel approach may be applied to reduce the difficulties cited above. There are two aspects of the approach in relationship to the control application.

1. The overall control function of Figure 2 may be divided into a number of simpler functions forming a hierarchy of control activity and responsibility.
2. The process may be divided into a number of simpler subsystems, each of which controlled according to a local or sub-optimal criterion.

Both aspects have the same primary objective; reducing the total computational effort required for achieving a given level of system performance. In essence, the same thing is done in each case. The overall complex problem is broken down into component parts, each of which is handled as a sub-problem. The final requirement is a coordination of the sub-problem solutions to achieve a "best" (in some appropriate sense) performance of the overall system.

2. Decomposition into Control Sub-Systems and Application to O/P Systems

The system of Figure 2 is expanded into the four-layer control configuration of Figure 3. The layers are identified successively with direct, optimizing, adaptive, and self-organizing control functions.

These somewhat arbitrary labels have been chosen to focus attention of the different functions to be performed. At the same time, Figure 3 associates one of the four layers with a part of the Cybernetic Man-Machine Computer O/P System.

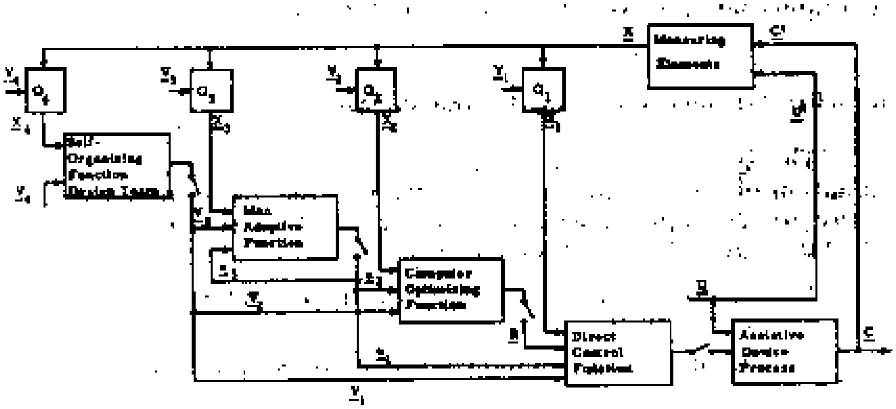

Fig 3. Four layer hierarchy for O/P control system design

The basic control activities associated with each layer and examples in terms of O/P systems follow:

Direct Control

First Layer — The primary function of the direct controller is to translate the decision of the higher level controllers into direct actions on the process. Specifically, the manipulated inputs m(t) are varied so as to force a subject of the process outputs $c_1(t)$ to follow as closely as possible the set of desired values r(t) generated by the optimum controller. In an O/P system, this layer is most often represented by motor control circuitry with perhaps a position or torque feedback control loop.

Optimizing Control

Second Layer — The objective of the optimizing controller is the determination of optimal operating conditions for the process besed on an appropriate performance criterion and mathematical model for the process. The desired conditions are defined by the vector $r(t)$; the vector is evaluated in terms of the feedback information set $x_2(t)$ and input parameter set $a_2(t)$. In many O/P systems, the optimizing control is represented by the electronics which convert the man's EMG input signals $a_2(t)$ over to command signal $r(t)$ for the controlled variables of the assistive device.

Adaptive Control

Third Layer — The first and second layers of control are developed from mathematical models which are generally only approximations of the real system. The purpose of the adaptive function is to compensate for model-induced errors by adjusting the parameter values associated with the control algorithms. Thus, parameter sets a_1 and a_2 are updated periodically based on observations of system behavior (contained in the information set x_3) and suitable criteria of performance.

The patient in an O/P system generates parameter sets a_1, a_2, a_3 based upon his conscious desires, (criteria of performance) and primarily visual feedback from the assistive device (information set x_3). Parameter set a_3 shows the learning of the man in the control loop in which the man with new control sites must calibrate himself to the system based on trying, experimenting, and experience with the actual O/P system.

Self-Organizing Control

Fourth Layer — The self-organizing system determines the design vectors v_{1-4}. These define the structures of the lower level controllers through assumptions and hypotheses concerning the system and its environment. In particular, the design vectors represent decisions which are made relative to the control of the overall system such as to improve the total system response. The decisions are based on accumulated experience and increased understanding of the system, but subject to the specifications, predictions and constraints embodied in the input vector v_4. In O/P control systems design, this layer, rather than being automated, is most often represented by the many different people from different disciplines who must share their knowledge and skills in order to evaluate and improve O/P designs. Information set x_4 represents the O/P performance evaluation variables which are chosen by the evaluation team itself.

B. Application of Hierarchy to Engineering Design of Multi-Axis Orthotic System

In order to study this Man-Machine Computer System, a Cybernetic Orthotic/Prosthetic Simulator (COPS) was designed and implemented [3]. COPS is a programmable real-time O/P system allowing the designer the ability to quickly and efficiently implement, test, and modify different designs. Figure 4 shows a block diagram of COPS with its major sub-system components. Control and decision making functions are programmed on a DDP-116 computer which supplies three basic functions:

1. It forms a central element in the real-time control loop.
2. It performs on-line data acquisition, analysis, and documentation.
2. It provides automatic error checkout of all sub-systems.

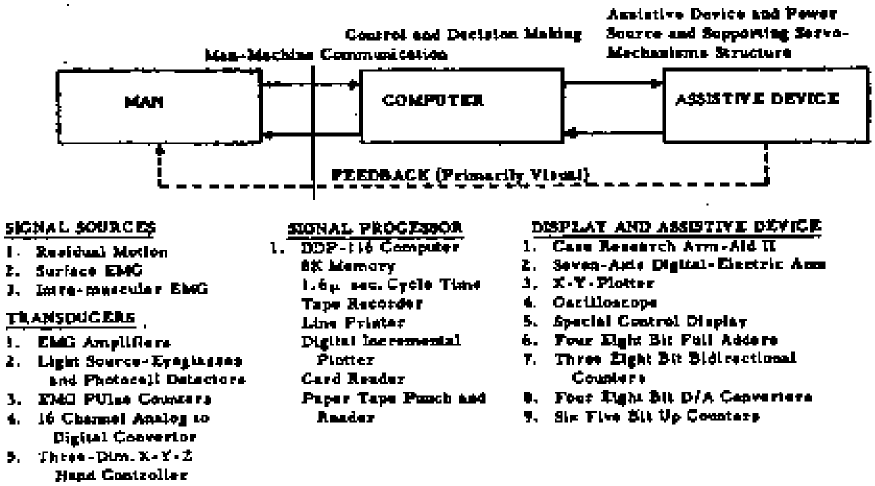

Fig. 4. Cybernetic orthotic/prosthetic simulator (COPS)

COPS is a direct hardware implementation of the four layer hierarchy. The objective was to provide such a general and flexible system that the structure of COPS would not materially constrain the system designer. An approach such as this lends itself to many research studies and avoids duplication of hardware which would occur if many special systems were constructed. Two different designs for the control of a multi-axis orthotic arm are now discussed in terms of the four layer hierarchy.

Direct Control Functions

In COPS, the main direct control functions for the Case Research Arm-Aid (CRAA) [4] and the Seven Axis Electric Orthotic Arm [3], [5] are digital incremental position loops as shown in Figure 5. The function of the incremental loops is to follow as closely as possible the desired thetas generated by the optimizing controller also insure stability of each axis. To further clarify the direct control functions, the electric orthotic arm shown in Figure 6 as an example. This arm has seven degrees of freedom with:

1. Shoulder Rotation
2. Shoulder Flexion/Extension
3. Humeral Rotation
4. Elbow Flexion/Extension

5. Wrist Rotation
6. Wrist Flexion/Extension
7. Prehension

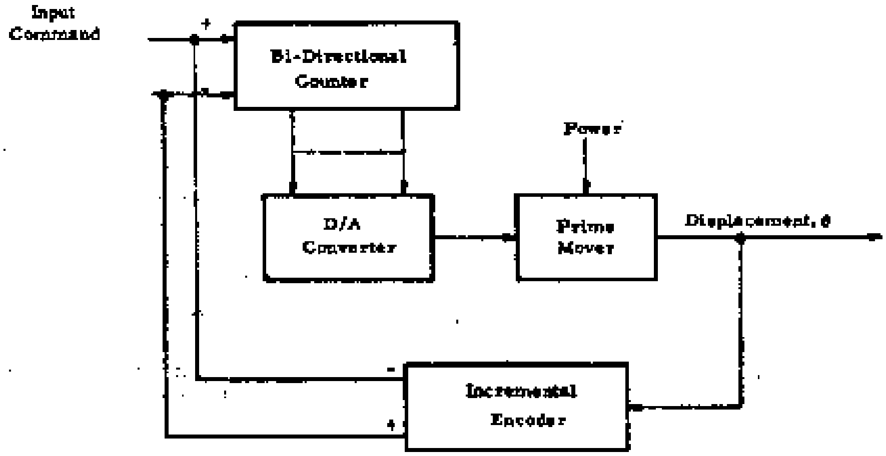

Fig. 5. Incremental digital control loop

Each axis is driven by a DC motor-gearhead system with an integral incremental encoder. Each incremental control loop forms a control sub-system. This is a decomposition of the total assistive device into subprocesses. Other direct control functions of the electric arm are:

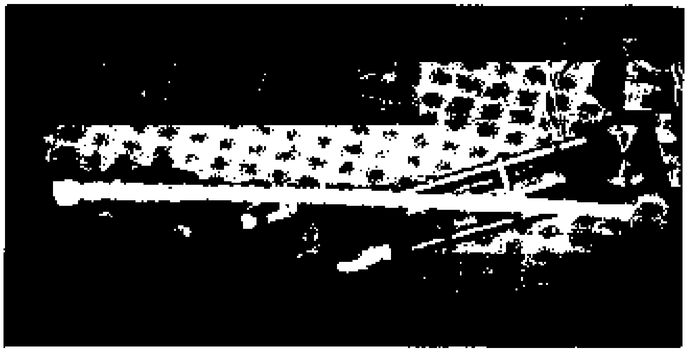

Fig. 6. Time exposure of seven axis electric orthotic arm under X-Y-Z control

1. DC motor stall protection.
2. Limit protection
   a) Electrical b) Mechanical c) Computer Supervised.
3. Safety release velcro straps.
4. Overload slip clutches.
5. Local torque feedback on prehension.

These additional functions protect both the patient and the arm from injury or damage. In this case, the final result of the direct control layer is a safe, reliable orthotic arm in which simultaneous path control of all axes is possible under real-time computer control.

Computer-Optimizing Control Function

The function of the optimizing control layer or computer is to coordinate the direct control functions of the orthotic arm. In terms of Figure 3, the computer generates desired theta positions $r_1(t)$ to the direct control loops of the arm based on the man's inputs $a_2(t)$ the control state of the arm $c_1(t)$ and an appropriate performance criterion. Due to the severe man-machine communication problems involved, the information rates required in parameter set a_2 should be at a minimum. At the same time, the organization of the optimizing control determined by design vector v_2 should be such that the man is able to conceptualize his task and thus maximize his information rate capabilities in a_2.

a) *Individual Axis Control Design*

Assuming prehension under separate voluntary control, one of the simplest optimizing control functions which can be proposed is one in which six control sites individually control the velocity of the six degrees of freedom of the arm for electro-myographic control.

In terms of Figure 3, a_2 and r_1 are now given in Equation 5 and Equation 6, respectively:

$$a_2 = [\dot\theta_1, \dot\theta_2, \dot\theta_3, \dot\theta_4, \dot\theta_5, \dot\theta_6]^T \qquad r_1 = [\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6]^T$$

The above optimizing control function represents a kind of "most simple" case. Any better optimizing control function must improve total system performance and/or reduce the number of input channels required. The "individual axis control" system has been implemented on COPS and also incorporates computer-supervised axis limits. The second optimizing control function design, which follows is an attempt to improve on the first design.

b) *X-Y-Z Coordinate Conversion Control Design*

The optimizing control layer establishes both a functional dynamic relationship between the man's inputs and the assistive device outputs. The dynamic relationship determines whether the operator has direct control over position, velocity, acceleration, torque or some combination of these variables. The functional relationship determines whether control sites are related directly to assistive device axes (θ) or to other output parameters such as X, Y, Z of the endpoint. While the functional and dynamic aspects are intimately related, it is the functional relationship which becomes especially severe in multi-axis systems. The following algorithm performs a real-time coordinate conversion so that the man sees the task as moving the endpoint of the arm in an X-Y-Z cartesian coordinate space. This algorithm has been named "the Eighty-One Move Algorithm", based upon its search and optimization criteria [3], [6].

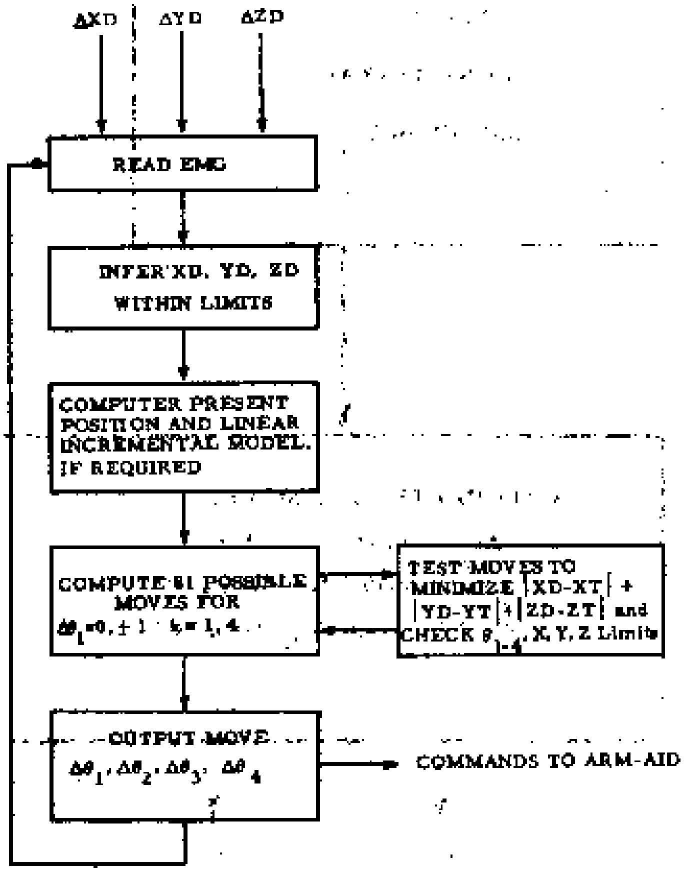

Fig. 7. Simplified flowchart of 81-move X-Y-Z algorithm

Figure 7 shows a simplified flow chart which inputs ΔX-ΔY-ΔZ EMG command information from the man and computes in real-time the required $\Delta\theta_{1-4}$ moves for the orthotic arm. Figure 6 shows a time exposure photo of the electric arm under X-Y-Z manual control with a pen light on the endpoint. An X-axis move over the operating space of the arm was made with the straightness of the path providing an overall accuracy check on the algorithm and arm.

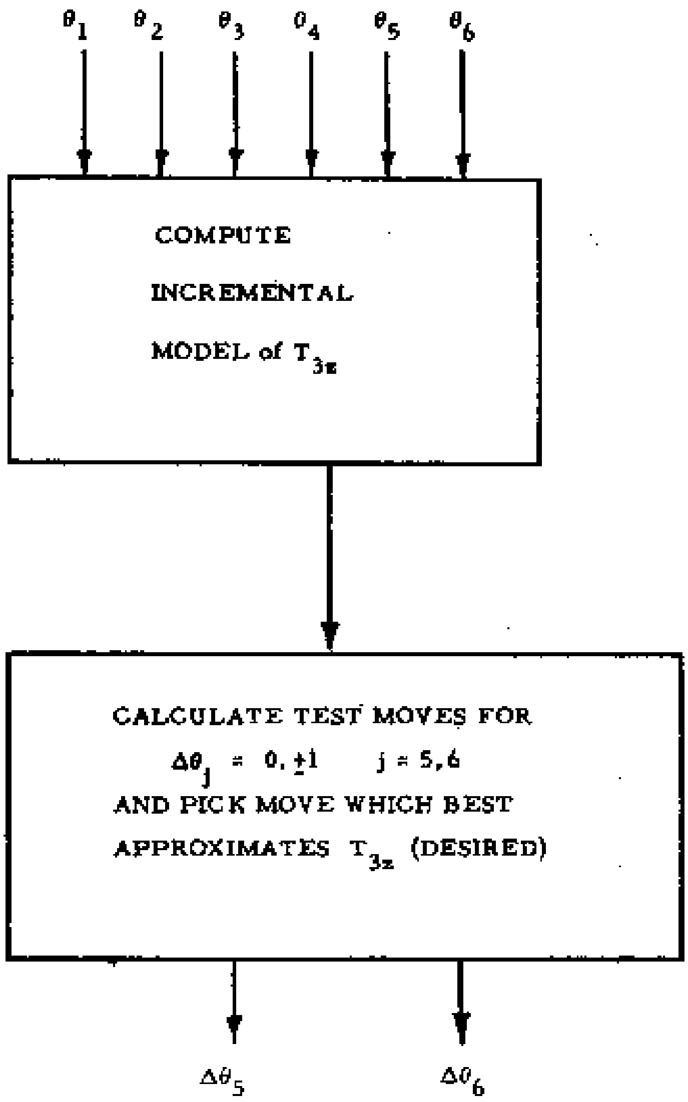

Fig. 8. Simplified level hand flowchart

To make this system feasible for many different tasks a level hand mode for θ_5 and θ_6 is necessary. Figure 8 shows a simplified flow chart which maintains the hand in a level attitude after being initialized. T_{3z} is the Z component of the vector from the wrist to the large knuckle of the middle finger. Once initialized, maintaining T_{3z} at a constant value will keep any object grasped in the hand in a level attitude. (Assuming the object was level when T_{3z} is initialized). The level hand mode can also be used with the individual axis control system. In this way, anly four axes required direct control by the patient in order to carry an object in a level mode.

Man-Adaptive Control Function

The man generates parameter sets a_1, a_2, a_3 based upon his conscious desires, observation of system behavior based on the information set x_3 and a suitable criterion of performance. Because of the extreme man-machine communication problem involved, every effort must be made to minimize the number of channels used and the date rate required by a_1 and a_2. In the same way, information rate in x_3 is small because man cannot effectively multiplex many channels. Information set x_3 is primarily visual feedback with the man perhaps estimating such variables as position and angular velocity of axes or linear position and velocity of the endpoints.

In the case of the two previous optimizing control function designs, EMG control is the primary man-machine communication technique under consideration. Several digital mode controls beyond the scope of the present discussion would also be required. Table 1 gives a comparison of the two systems in terms of the EMG requirements on the man.

Table 1.

	Proportional	Three state
Individual six axis control	12	6
Individual axis control with level hand mode	8	4
X-Y-Z control with level hand	6	3

a) Individual Axis Control

In this system, the man must control the velocity of each of the axes and also estimate the resultant move depending on the configuration of the arm. The direct and optimizing control functions provide axis limits relieving this task from the man. However, X-Y-Z coordinate obstacles such as the lapboard are not protected. In terms of EMG sites, the system with level hand mode and three state control requiring four sites was considered the most feasible. Preliminary evaluation of this system will follow in the self-organizing control function section.

b) *X-Y-Z Coordinate Conversion Control Design*

In this system, the man has the capability to control the X-Y-Z velocity of the endpoint. Elbow configuration was computed by the algorithm on an heuristic basis and level hand was maintained by correction commands on θ_5 and θ_6; supination and wrist flexion. Theta limits as well as X-Y-Z limits were incorporated in the direct and optimizing control functions. The question to be answered with this algorithm is whether or not the man can simultaneously supply the necessary EMG information to the three X-Y-Z degrees of freedom and therefore achieve "normal looking" smooth performance of tasks. Initial simulations used an X-Y-Z hand controller with the philosophy being that if the person could not control the system under manual control, EMG control would also be impossible. Results showed that the system was stable under manual control and that the man could also adaptively control the elbow position, even though it is not under direct control. Figure 9 shows the X-Y-Z coordinate system under EMG control by a normal with sites approximating those available to a quadriplegic. Similar results to the hand controller simulations were obtained [6].

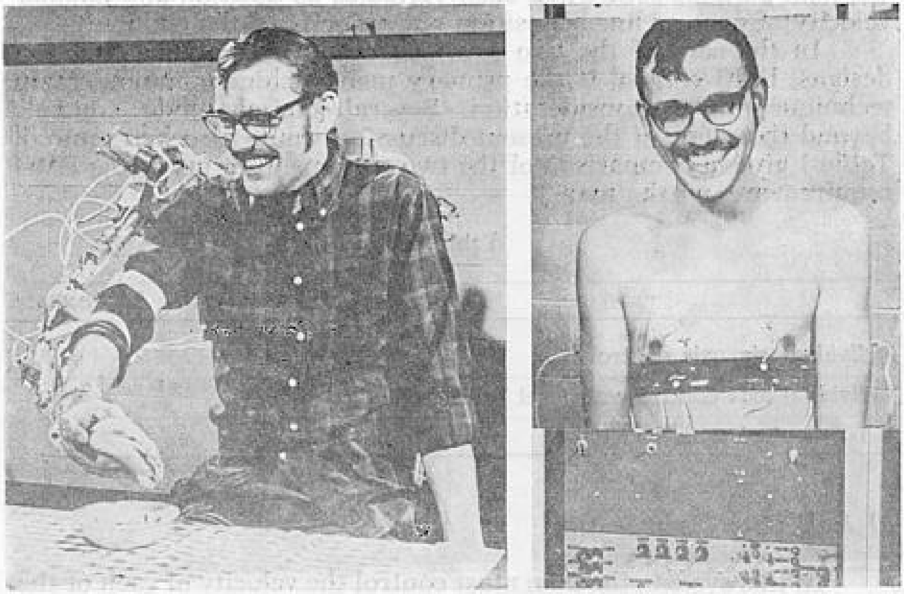

Fig. 9. Normal subject with six percutaneous EMG sites controlling endpoints of CRAA MK II under "Eighty-One Move" algorithm control

Self-Organizing System

Cybernetic Systems Group-Self Organizing Control Function at the self-organizing system level or the Cybernetic Systems Group determines the vectors v_1, v_2, v_3. These define the structures of the lower level controllers through assumptions and hypotheses concerning the system and its environment.

The generation of the design vectors by the self-organizing system has tremendous effect on the performance of the overall system. A characteristic of this research is that it is multi-discipline in nature, drawing on a broad spectrum of medical, scientific, and engineering knowledge and skills. The generation of the design vectors for this work required the collaboration of many members of CSG. As an example, one major collaborative design decision by CSG was the decision to design and implement COSP. Another important collaborative area is the engineering and clinical evaluation of alternative O/P system designs. This requires the skills of many different people; including physicians, engineers, therapists, and technicians. An evaluation procedure has been developed based on typical tasks required in an O/P system [3], [7].

Future experiments will compare specific alternative designs based on overall system performance measures. These experiments will test the usefullness of an X-Y-Z coordinate system versus individual axis control using EMG control. Preliminary data with the four site individual control and the six site X-Y-Z system under *manual control* is shown in Table 2 for a move from the lapboard area to the mouth.

Table 2.

	Individual control	X-Y-Z control
Total Average time For task Completion	68 sec.	35 sec.

It was very difficult to achieve smooth simultaneous control with the individual axis system and subjects normally adopted a sequential operation mode. The increased time to perform the task for the individual control system versus the X-Y-Z system was almost completely due to the difficulty in making fine position corrections at the endpoints of the task. Times to make the gross moves through space were approximately equal for both systems although the X-Y-Z system moves were smoother and more direct.

Conclusion

A multi-level approach to orthotic/prosthetic control system design has been presented and applied to the design of multi-axis orthotic systems. In essence, the problem is divided into a hierarchy of control functions which distribute the load and responsibility for satisfying the control objective. In general, the first layer controller is charged with the responsibility for feasible operation of the assistive device. Hence it is essential that it be sufficiently reliable and have necessary protective and fail-safe features. The levels of the hierarchy may be identified successively with direct, optimizing adaptive, and self-organizing control activities. These lead to consistent ordering characteristics in terms of frequency distribution of the pertinent disturbance inputs, period of control action and complexity of computation which enter into much of the design decisions relevant to the overall system control problem.

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