ADAPTIVE AIDING FOR ARTIFICIAL LIMB CONTROL[a]

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INTRODUCTION

Studies that were conducted by the UCLA Biotechnology Laboratory developing techniques for enhancing patient control for arm prostheses have produced a variety of upper body muscle transducer control systems, which were reported in the Bulletin of Prosthetics Research (1) and laboratory reports (2,3). In pursuing this work it was revealed that there is a basic limitation on the ability of a patient to supply the control information rate required to obtain adequate levels of performance (4). This paper describes a technique to solve the information problem by adding an aiding subsystem to the control loop. In such configuration the decision load of the patient is shared between the patient and the aiding subsystem.

In an attempt to examine the feasibility of active aided control, an aiding subsystem was developed and demonstrated at the Biotechnology Laboratory. The system utilizes upper body transducer control and a 4 deg.-of-freedom bench model prosthesis. It incorporates an Autonomous Control Subsystem (ACS) able to supplement the patient's control function while operating in parallel with him. The behavior of the ACS is established through a learning process which involves observing the patient's control function in relation to the environment and task requirements. The computer-based system establishes a decision-making policy which utilizes conditional probability. Initially, the artificial arm is controlled by the patient and the computer system is a passive observer. As the operation continues, the computer system is gradually transformed to an active controller, thereby reducing the patient's function to that of an action initiator and inhibitor. A learning model based on maximum likelihood principles constitutes the mathematical basis for the system.

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The artificial limb was capable of picking up, moving, and releasing small objects on a flat work surface. Experiments with the system have indicated that the theory is feasible. The decision load of the patient was reduced, and improved overall performance resulted.

The following sections of this paper review the problems of prosthesis control, introduce the developed system, and describe the results of experimental work.

REVIEW OF THE PROBLEM AND RELATED RESEARCH

The control of a multidimensional movement device with movement patterns similar to the human arm requires input signals of high information content. In the normal arm these signals come through voluntary control loops which are aided by reflex loops. For practical purposes, the only control signals available for operating an artificial limb are voluntary movements of residual muscles, such as those of the upper trunk, and feedback is limited to the visual mode and other indirect means. As for example, the patient may wish to use the sounds of electric motors as a means of indicating to him the speed of the arm. In special cases some other type of feedback might be used such as vibrations to indicate speed or a variety of tactile feedback mechanisms to indicate force feedback. Control of the position of such a device in its working space is therefore accomplished by a sequence of decisions based on feedback data from the instantaneous state of the device. To direct a prosthesis/orthosis to a particular end point, the operator must continuously generate an error signal for each dimensional movement and add the signal component vectorially until the desired position is obtained. Such a procedure places a decision load on the operator which is proportional to the level of skill required for task success and, in the process of controlling such a device, the human operator acts as an information processing system. As processor, his ability to receive information, process it, and generate control signals is limited. Such inherent psycho-physiological characteristics of the operator as bandwidth, fatigue limits of the muscular system, sensitivity and ability to maintain perceptual vigilance, all regulate human system capacity and hence limit the patient's information-handling abilities. When a patient is asked to control a system that requires an information content beyond his system capacity, poor performance and emotional frustration may be the result.

One indication of the difficulty of controlling artificial limbs comes from studies of remote manipulators where the control problems are similar but somewhat simpler. Taking the normal movement of the human arm as a bench-mark comparison, the most advanced remote manipulator systems are able to operate at speeds which, at best, are

only one-fourth of the speeds of the human arm (5). More typically, task performance times are increased by an order of magnitude when manipulators substitute for direct human performance.

Experimental data obtained in studies with conventional servo-controlled prostheses tend to emphasize the control problem from the information-exchange point of view. For example, Groth and Lyman (6) reviewed the operation of both the IBM Alderson IV-E electric arm and the Heidelberg pneumatic prosthesis. The IBM-Alderson Arm required the amputee to operate an extremely complex system of nine control switches. The amputee had to select and actuate the correct switch or set of switches, then turn them off after completion of the motion. Each selection had to be made independently. Only one motor was available, and it had to be separately coupled by a clutch for each arm function. The Heidelberg pneumatic prosthesis was equipped with two sequential control valves. Although there was a separate source of power to each valve, their sequential arrangements permitted selection of only one function at a time from each valve. Since control selection and operation for both prostheses required that very careful discriminations be made by the amputee, his full attention was needed to achieve a given elementary function. Detailed evaluation studies (7,8) revealed that the decision load on the amputee was excessive and degraded system performance in simple and complex test situations.

In coping with the problem of information deficiencies in prostheses control a subsystem able to assume a portion of the decision and control functions of the patient can be added to the control loop. "Aiding" of this type has been partly realized in such man-machine control systems as autopilots, predictor displays, and tape-programed machine tools. One example in the area of manipulative devices is the Case Institute Arm Aid in which a handicapped operator selects from a repertory of desired functions with a minimum input information requirement (9). An example of an industrial programed manipulator is the Unimate, developed by Unimation, Inc., which is controlled by a recorded human movement pattern stored on a magnetic drum (10). Also of interest here is the work on "Supervisory control" being conducted at M.I.T. in which a computer capable of making certain subdecisions is added to the control loop, while major decisions are made by the "supervisor," or operator (11). Devices such as the Case Arm Aid and the Unimate might be classified as preprogramed systems. Although they minimize the control burden of the patient, these systems are limited to the rigid operation sequences preprogramed in memory. Supervisory control can be considered as a form of serial aiding in which the operator sets goals and the control subsystem organizes the detailed steps necessary to meet them.

Autonomous control was first demonstrated by the computer-operated

mechanical hand of Ernst (12). His system, equipped with a sense of touch, was able to locate a stack of blocks and load them into a box without operator assistance. The inclusion of "visual" inputs for object recognition was pursued by Minsky and his colleagues (13) as part of the Machine Aided Cognition Project at M.I.T.

Current research on computer aiding in prosthesis and orthosis control has been reported by Apple and Reswick (1970). In this work a computer was used to generate the optimum trajectory of movements which were required to move an orthosis between specified points in three dimensional space. The patient specified the movement rate in X-Y-Z coordinates while the computer calculated the required angular axial movement.

Other related work is currently being performed by Whitney (1970) in trying to establish a relationship between the speeds of the joint angles and the endpoint of the arm. This relationship could be used in the future for the generation of joint angle rotation by a single command, thus reducing the complexity of control. Experiments with the control configuration are currently performed by Whitney using a PDP8 computer and a Rancho Los Amigos arm. A similar approach was also reported by Gavrilovic and Maric (1970) where two inputs were used to control 5 deg. of freedom.

The approach described in the following section represents an attempt to explore a concept for adaptive aiding based on the development of autonomous control capabilities within a trainable control subsystem. The objective of the system is to establish on-line cooperation between the patient and a decision-making subsystem.

THE AUTONOMOUS CONTROL SUBSYSTEM CONCEPT

System Description

The Autonomous Control Subsystem (ACS) concept is a means to aid the patient in complex manipulative device control. As illustrated in Figure 1, it is based on an autonomous element in the control loop—the ACS. This element, programed on a digital computer, works to unburden the human operator by "learning" through observation of the tasks being done, and progressively assuming the majority of control responsibility.

Artificial limb control in this system includes two main control loops, an external loop, which incorporates the operator and his means of feedback, and an internal loop, which involves only the Autonomous Control Subsystem. The actuators of the limb respond to either the operator or the autonomous subsystem.

Initially, the autonomous control subsystem acts as a passive observer, trying to "understand" how the operator controls the manipu-

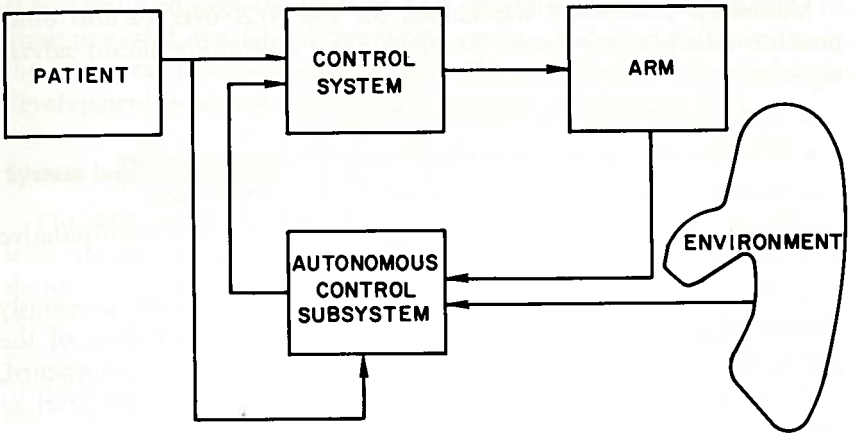

FIGURE 1.—The proposed control system.

lator and developing an "awareness" of the operating environment. In this phase, the ACS defines the relationship between the operator's responses and the external world.

After the acquisition of this passive experience, the internal loop begins to participate in the control of the manipulator. In this second phase, the operator acts mainly as an instructor letting the internal loop control the manipulator whenever possible, and correcting its decisions when they are wrong. In time, for certain classes of tasks, the function of the operator may be reduced to that of an initiator and inhibitor, who provides occasional start and override commands. In such an arrangement, the decision load associated with controlling the manipulator is substantially reduced, giving significant advantages in completion time, efficiency of manipulator use, and operator satisfaction.

The ACS is designed with the ability to forget what it has learned, and to learn new tasks in place of old unused ones. This feature provides the adaptive capability to change behavior in response to changes in the operator's control policies and in the environment. It makes the ACS a powerful tool, applicable to a large variety of teleoperator functions.

Theoretical Basis

The theoretical basis for the ACS is the Maximum Likelihood decision principle. Its structural organization is a conditional probability matrix relating future states of the manipulator device to its past and present states. Spatial movement of a manipulator is non-random for practical tasks. That is, patterns of movements in the past lead to predictable movements in the future. In the ACS, prediction is based on the likelihood of occurrence of a particular position in space or of a movement path computed from the conditional probability matrix.

Maximum Likelihood was chosen for the ACS over various other possible classification systems because it has several significant advantages in manipulator applications. These include:

- Training is rapid and relatively simple
- Decision strategy can be changed while the system is active
- Classification categories are not restricted to disjoint sets
- The model fits well the observed character of actual manipulative movements

As the ACS acquires more and more information about previously observed states, the current state, and the next observed state, of the teleoperator it controls, the conditional probability matrix is sharpened, and the ACS achieves its control decisions with a higher level of confidence.

In one sense, the ACS is a redundancy machine, able to extract redundant aspects of a task even if they are hidden in a scatter of apparently random motions. In manipulatory operations, however, the element of redundancy is quite high. Movements from place to place tend to be repeated, certain paths are followed, certain areas avoided. This makes the ACS a shrewd predictor of teleoperator action.

Through a built-in function termed "List Control," the ACS is also able to recognize repetitive sequences (or lists) of teleoperator movements, add these lists to the probability matrix decision space and retain them as long as they are needed. Thus, the ACS can at times handle a complete subtask as a single decision. There are marked advantages to this approach in practical arm prosthesis control.

Redundancy is highest in repetitive operations, and the ACS learns extremely fast under these conditions. But it is important to understand that the ACS organization allows it to comprehend much more subtle task factors after long-term operation. For example, as the ACS builds up a depth of experience with a certain general class of tasks, learning of specific subtasks occurs much more rapidly than it did initially. Furthermore, the ACS is able to move among the separate subtasks without losing its adaptation to each. An operator working on rocket engine disassembly, for example, might spend some time on fastener removal, then on fastener transport, then on another subtask, and return to fastener removal. He would receive ACS aiding at each step. Likewise, the ACS is able to recognize patterns of movement, or implicit movement "rules," and adapt to changes in such patterns. An operator placing objects sequentially in locations A, B, C, D . . . will find that the ACS learns to predict . . . E, F, and so on, even though it has not yet observed that particular movement.

The power of this approach is in the ability of the ACS to operate with a limited amount of input data. By using long-term experience it is

able to operate autonomously with a minimum amount of sensory cues. It is difficult to gage the limit of ACS capability when implemented on more powerful, specialized computing systems and after extensive training with practical manipulative tasks. The mathematical details of the development work are covered in a separate publication (14).

System Implementation

The ACS was implemented on an IBM 1800 computer and integrated with the control loop of an arm-like, 3 deg.-of-freedom manipulator as shown in Figure 2. The operator is linked to the manipulator through a control logic state which interprets operator responses and decides whether to give control of the manipulator to the computer or to the operator. The manipulator is controlled in either a position mode or a rate control mode. When the manipulator is driven by the operator it is set in rate mode, when driven by computer it is set in position mode. The 3 deg. of freedom of the manipulator are shoulder rotation, shoulder flexion-extension, and elbow flexion-extension. The manipulator claw is controlled by a separate controller, a foot pedal. The operator's control consists of strain gage transducers combined with a Go/override switch and a light indicator. In addition to providing the operator with control of the 3 deg. of freedom of the manipulator, the switch allows the operator to generate a "Go" signal that shifts control of the

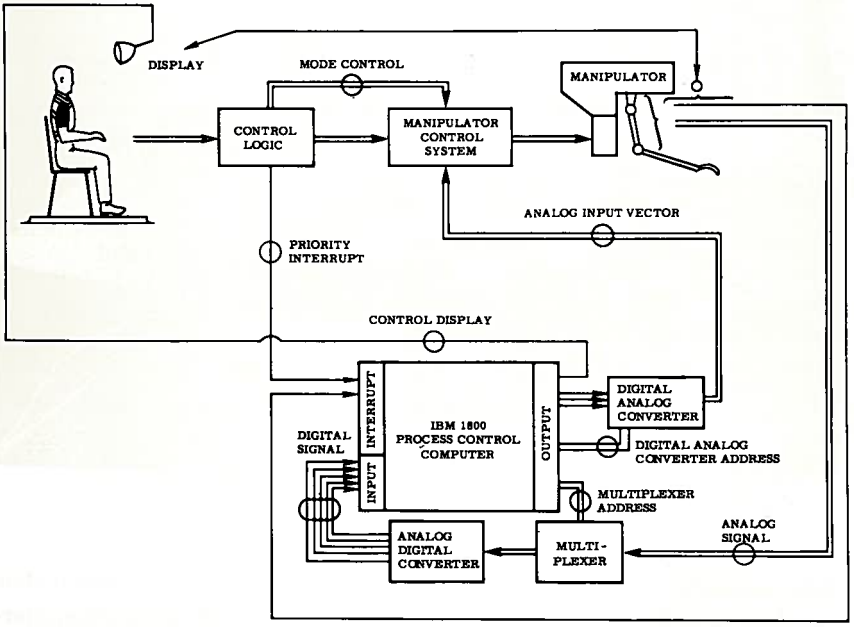

FIGURE 2.—The complete system.

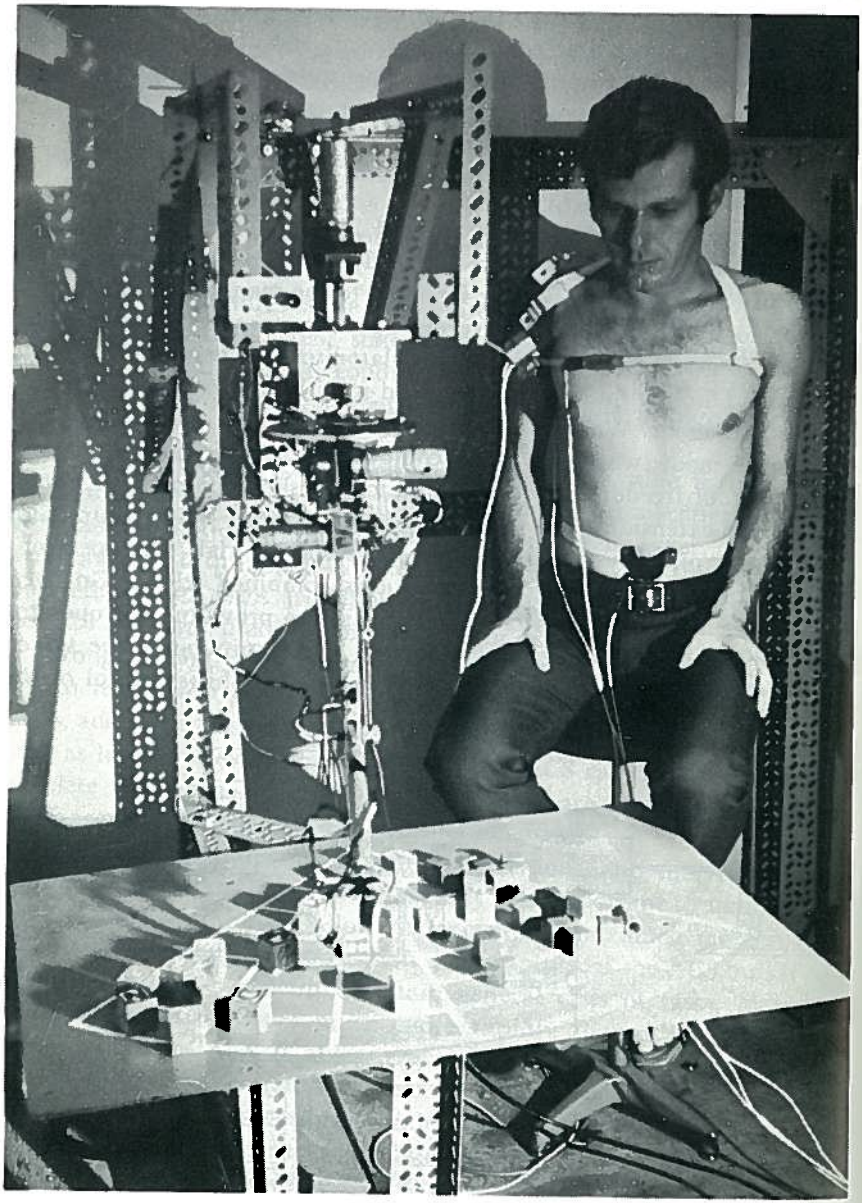

FIGURE 3.—Body transducer control system.

manipulator to the computer, and to generate an "override" signal that transfers control back to the operator at the completion of the computer-generated movement. The light indicates to the operator whether or not

the computer has the required (preset) level of confidence for executing its decision.

For an assessment of the value of the aiding system in prosthesis control, a nonmanual transducer control system was used. The transducers were attached to the upper torso by a harness. There were three transducers, one for each degree of freedom as shown in Figure 3.

On his right shoulder the subject wore a plastic shell which simulated a prosthesis. The shell was held on by a Figure-8 harness in a configuration similar to a prosthesis harness. He also wore a strap across his chest and a belt around his abdomen; a strap connected his right shoulder to the belt in the center of his back. The transducers were strain gages attached to the harness straps. A low-force pull on the strap was interpreted by the control logic as a positive control signal, while a larger force was interpreted as a negative control signal. Thus each transducer could control the corresponding arm actuator in two directions. Chest expansion operated the shoulder flexion-extension, shoulder elevation corresponded to lateral rotation, and abdomen expansion actuated elbow flexion-extension.

EXPERIMENTAL EVALUATION

An experimental study was performed to evaluate the capabilities of the ACS to reduce the decision load of the human operator. The following two tasks were selected.

1. Movement of objects from a fixed location to a bounded area, unloading the objects to an ordered formation as shown in Figure 4a.
2. A sequential movement of the manipulator between four locations —loading an object at the first location, unloading it at the second, loading another object at the third location, and unloading at the fourth location. The task was continued by returning back to the first location as shown in Figure 4b.

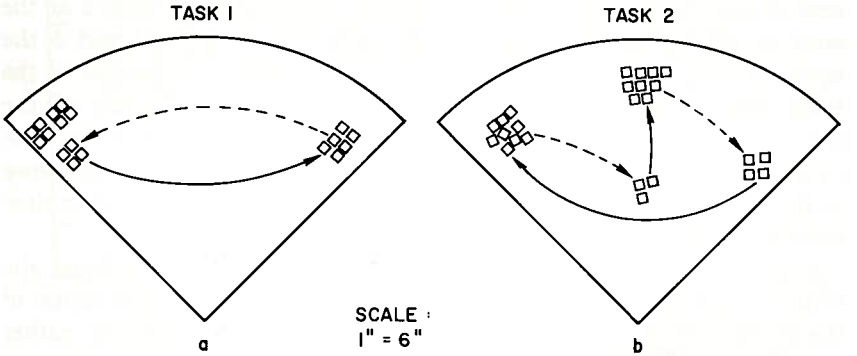

FIGURE 4.—The experimental tasks.

The objects to be transported were identical 1½ in. by 1½ in. red cubes. Task 1 consisted of the relocation of 16 objects. Task 2 consisted of the relocation of 10 objects from the first location to the second and 10 objects from the third to the fourth location.

A pilot study, using the nonmanual control arrangement described earlier, was performed using one subject. Testing was organized into blocks termed RUNS, which consisted of one complete performance of each task performed in the order Task 1, Task 2. The subject performed three RUNS with a 15-minute break between each RUN and a 5-minute break between tasks within each RUN. The entire testing period for one subject covered about 2 hours.

For purposes of data collection, each task was subdivided into a series of trials corresponding to separate, distinguishable actions of the arm. For example, in Task 1, the initial unloaded movement of the manipulator across the task space followed by grasp of an object was defined as a trial. The return of the loaded manipulator and release of the grasped object constituted a second trial. Thus, in Task 1, manipulation of the 16 cubes involved 32 discrete trials, while Task 2 involved 40 trials.

Trial completion time was the basic measure of performance taken. In addition, trial completion time was divided into two segments, 1. computer control time and 2. override time. Computer time is that portion of trial time in which the computer controlled the manipulator. Override time is the portion in which the manipulator was under operator control. Training consisted of about 2 hours' practice on tasks that resembled the experimental tasks. The subject used computer aiding in all cases. Performance of the 32 trials of Task 1 was followed by a break of 10 minutes and then the 40 trials of Task 2.

A measure of the system effectiveness in unburdening the operator control load can be obtained from Figures 5 and 6 which illustrate the mean percentage of time during a trial that the arm was controlled by the operator and by the computer in Tasks 1 and 2 respectively.

The results show that while the operator was in active control 85 percent of the time in Task 1 and 65 percent of the time in Task 2 at the start of exposure, by the end of the third run of Tasks 2 and 3 the operator's control load was reduced to 50 percent and 45 percent of the time, respectively. These results are in agreement with those of the manual control tests used in an earlier study (14), which show that the computer tends to assume the majority of the control burden as exposure to the task is provided, although the reduction in operator override time was not as rapid with the nonmanual control system.

Since the transducer control system is a "first-working" prototype, the results of the pilot study should be considered only as a demonstration of the potential capabilities of the Autonomous Control Subsystem, rather than as a definition of its capabilities. Further experimentation to evalu-

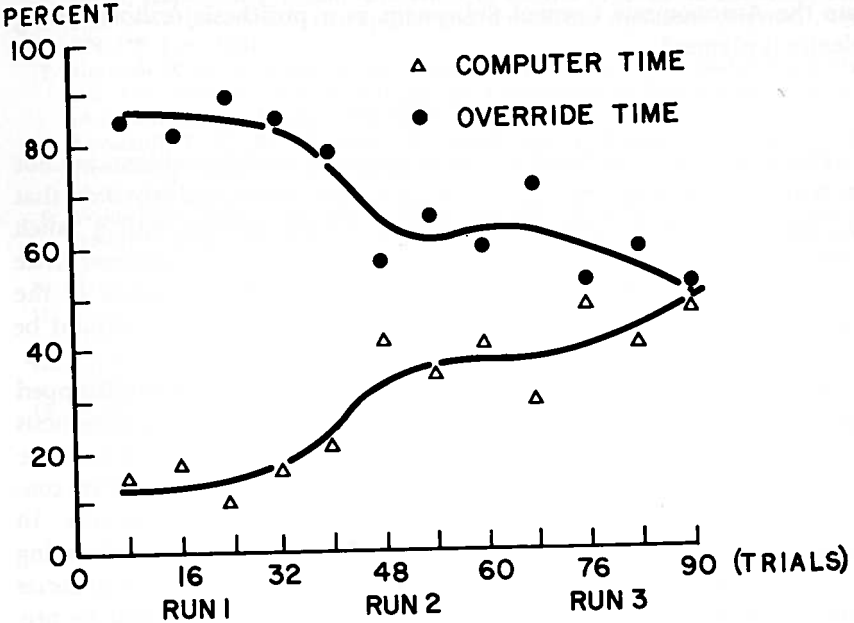

FIGURE 5.—Distribution of trial time between operator and computer (Task 1).

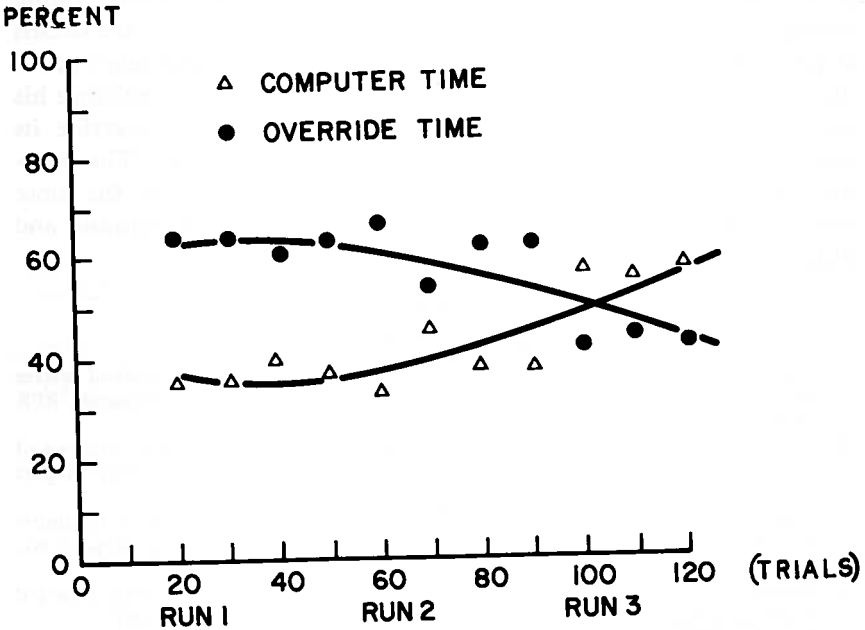

FIGURE 6.—Distribution of trial time between operator and computer (Task 2).

ate the Autonomous Control Subsystem as a prosthesis/orthosis-aiding device is planned.

CONCLUSION

Practical applications of the ACS to amputee control problems are not as remote as one might assume. This is basically due to the provision that a "special purpose" type aiding system can be realized with a much smaller memory requirement than that of the experimental system. Once the significant parameters associated with the movement space of the manipulator are defined, the Autonomous Control Subsystem could be microprogramed for this specific space.

By its nature the aiding system could serve the severely handicapped person who is very limited with an ability to control an arm prosthesis or an orthosis. However, the system could also be used with less severe cases with the function of enhancing the patient's capabilities in controlling his artificial limbs, thus giving him superior performance. In such application the system could act as an aiding device in performing a special type of manipulation as required by specific job categories and housekeeping tasks. In such cases the aiding system would be pretrained in the performance of the specific task category, as, for example, operating a telephone switchboard or eating. In very severe cases the function of the aiding system might be somewhat different, since the patient would have a very limited ability to override the adaptive aiding system and control it. Thus, the system must be pretrained in the details of performing a specific task that will be required. On the other hand, the less severe patient who would use the adaptive aiding to enhance his capability, would have the ability to retrain the device, override its control functions, and take over control whenever necessary. The adaptive nature of the aiding subsystem will be less utilized by the more severe patient, more pretraining of the subsystem will be required and its behavior will be less variable.

REFERENCES

1. Lucaccini, L. F., A. Freedy, P. Rey, and J. Lyman: Sensory Motor Control System for an Externally Powered Artificial Arm. Bulletin of Prosthetics Research, BPR 10–8: 92–111, Fall 1967.
2. Freedy, A., L. F. Lucaccini, and J. Lyman: Information and Control Analysis of Externally Powered Artificial Arm Systems. Department of Engineering Report No. 67–44, University of California, Los Angeles, Aug. 1967.
3. Freedy, A., L. F. Lucaccini, and J. Lyman: An Adaptive Approach to Optimum Switching Control of Artificial Arms. Department of Engineering Report No. 67–47, University of California, Los Angeles, Aug. 1967.
4. Freedy, A.: An Information Theory Approach to Control of Externally Powered Artificial Arms. M.S. Thesis, University of California, Los Angeles, 1967.
5. Goertz, R. C.: Manipulators Used for Handling Radioactive Materials. Human Factors in Technology, McGraw Hill, New York, 1963.

6. Groth, Hilde, and J. Lyman: Evaluation of Control Problems in Externally Powered Arm Prostheses, Orthopedic and Prosthetic Appliance Journal, 15(2): 174–177, June 1961.
7. Gottlieb, N. S., W. Santschi, and J. Lyman: Evaluation of the Model IV-E2 Electric Arm. Memorandum Report No. 18, Department of Engineering, University of California, Los Angeles, Feb. 1953.
8. Lucaccini, L. F., R. Wisshaupt, H. Groth, and J. Lyman: Evaluation of the Heidelberg Pneumatic Prosthesis. Bulletin of Prosthetics Research, BPR 10–5: 58–115, Spring 1966.
9. Wijnschenk, M. J.: Engineering Evaluation and Preliminary Studies of the Case Research Arm Aid. Report No. EDC 4–64–3, Medical Engineering Laboratory, Case Institute of Technology, Cleveland, Ohio, 1964.
10. Balmer, T. R.: Unimate. Design News, 22: 36–38, July 5, 1967.
11. Ferrell, W. R. and T. B. Sheridan: Supervisory Control of Remote Manipulation. IEEE Spectrum, 4(10): 81–88, Oct. 1967.
12. Ernst, H. A.: MH–1 Computer Operated Mechanical Hand. Proceedings of the Spring Joint Computer Conference, pp. 39–51, May 1962.
13. Minsky, M. L.: An Autonomous Manipulator System. Project MAC Progress Report III, M.I.T., July 1965–July 1966.
14. Freedy, A., F. Hull, and J. Lyman: The Application of a Theoretical Learning Model to a Remote Handling Control System. School of Engineering and Applied Science, Report No. 70–7, University of California, Los Angeles, Jan. 1970.