MANIPULATORS

SUPERVISORY CONTROL OF COMPUTER-MANIPULATORS

T. B. Sheridan

Summary

This paper describes a man-computer-manipulator system for doing a variety of exploration and assembly tasks for space, undersea, hazardous terrestial environments, warehousing, and medical applications. Implications for future externally powered prostheses are discussed. Emphasis is placed upon the allocation of functions to man and machine and the nature of their on-line interaction. The human operator through a combination of analogic commands (hand movements to specify direction magnitude, time relative to his view of the task) and symbolic commands (typewritten alphanumeric characters) sets subgoals, subroutines, and stopping conditions in terms of the manipulator's position and touch sensors. The computer interprets the human commands, reads data from the manipulator's own sensors, performs geometric transformations and executes optimal or heuristic procedures to drive the manipulator actuators. Laboratory experiments with such a system are described, and problems of organizing command languages, designing touch sensors and manipulators are detailed.

Introduction and Problem Statement

The problems of a limb prosthesis and of manipulation for space, undersea and industrial applications are coming to have more and more in common. Both for nuclear "hot cells" and for undersea vehicles direct mechanical linkages or electromechanical servomechanisms have slaved the movements of the mechanical hand to those of a handle guided by a human operator a relatively few feet away. The U. S. Surveyor spacecraft was commanded in very simple discrete movements to dig the surface of the moon and to position experimental apparatus. General purpose manipulators have recently been employed in production tasks, wherein the manipulator repeats a stored motion sequence "taught" it by a human operator who moves its degrees of freedom through the desired path to record the important points along it. An extensive historical review of developments in remote manipulation has recently been written by Johnsen and Corliss [1].

Research supported by National Aeronautics and Space Administration under grant NGR 22-009-002.

Beginning with the experiments of Ernst [2] several developments of autonomous robots have begun at MIT, Stanford University, and Stanford Research Institute [3, 4, 5] which make use of artificial intelligence and automatic environmental sensing. Completely autonomous devices will surely be practical for some recognition and control tasks eventually. It is the author's contention that in the immediate future it will be economically expedient to utilize for a variety of functions, including medical prostheses, manipulators having a low level of artificial intelligence but supervised by a human operator.

The pioneering experiments of Tomović [6] utilized artificial intelligence in a prosthetic manipulator. The system here proposed would go one step further and transmit to the human relatively simple sense data and other information for his interpretation and for use as the basis of further instructions. Generally it is believed that non-routine (not exactly the same each time) mechanical handling or assembly tasks too remote or too hazardous or scaled too large or too small for direct manipulation by normal man can best be controlled by a mixture of human and artificial intelligence. Lack of a limb or muscular function necessarily makes the manipulation task "remote" and subject to many of the same constraints. The problem is how man and computer should interact.

This paper describes laboratory simulation experiments involving human subjects together with computers in real-time control of two, three and seven degree-of-freedom mechanical manipulator devices. In these experiment the computer continuously recognizes simple patterns and effects control trajectories to achieve relatively near subgoals, whereas the man intermittently observes system states and sets subgoals. The paper also illustrates by example the ways in which a human operator and a computer can efficiently complement one an other in planning and executing task strategies.

Loop Delays from Attention Sampling Signal Transmission, Coding and Process Dynamics

A continuous control system usually becomes unstable when loop delays exceed one half cycle at signal frequency for which loop gain exceeds unity. In control of a prosthesis there is no mandatory reason why the human operator cannot monitor feedback continuously. However, for practical reasons of attending to other matters it is clear that the human may monitor control variables intermittently.

Our experiments thus far have been based upon a fixed time delay, as would be encountered in space applications, for example 2.6 seconds round-trip transmission to the moon plus 5.0 seconds for signal coding and decoding. Using a simple manipulator (two-dimensional translation and grasp) with only visual feedback, experiments have shown that human subjects can accommodate to fixed time delay by adopting a move-and-wait strategy, whereby limited open loop moves (without feedback) are punctuated by waits of one loop delay time in order to gain feedback and confirmation or reorientation [7]. Task completion time can be accurately predicted from completion times and measures of open-loop performance taken when there is no delay. Completion time increases linearly with delay.

These results suggested that when time delays are necessarily present or when it is inconvenient to attend to control variables continuously, the human operator should not control in a continuous closed loop but should serve instead as a supervisor or intermittent monitor and setter of subgoals for an automatic or computer-control loop [8]. The dynamic movement of the manipulator would be under control of a computer. Then the completion time would become far less sensitive to delay since the operator would command relatively long segments of the task, reducing the number of waits for correct feedback.

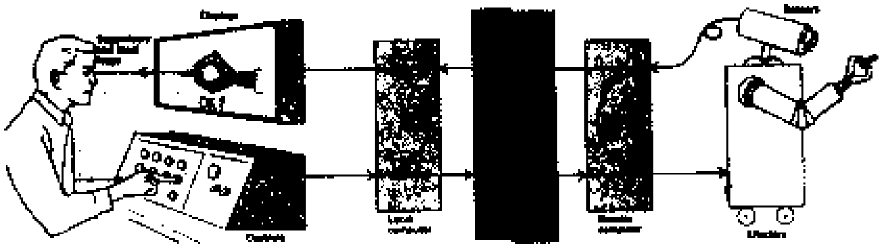

Fig. 1. Schematic diagram of supervisory control of remote manipulation.

Such a system is illustrated in Figure 1. A laboratory simulation has been implemented consisting of an American Machine and Foundry Model 8 master-slave manipulator driven by stepping motors through an augmented PDP-8 computer.

Man-Machine Console Interface

The human supervisor may issue his commands as strings of alphanumeric characters through a keyboard or conventional teletype (such commands we call "symbolic commands"). He may also indicate direction, magnitude, and time through moving a multi-degree-of-freedom joystick which may even have articulations corresponding to those of the manipulator (these we call "analogic commands"). Experiments by Verplank [9] suggest it is quicker and certainly more natural for the human operator to demonstrate to the computer certain movements or positions by the analogic mode than symbolically. He employed a device isomorphic with both the human operator's arm and the mechanical manipulator. However, in each degree of freedom, motion only actuated a switch (plus, minus, null) and in each articulation the operator adjusted his own arm and body to achieve the position correspondence. Conceivably the analogic control could also take the form of a scaled physical model of the task environment. The human operator's goals could then be communicated to the computer by his manual rearrangement of the model.

We have experimented with sensing and display of both visual and tactile feedback. As one would expect, ordinary television feedback is quite satisfactory provided the human operator can, at will, call either for a close-up or a comprehensive view. The close-up is needed for details of grasp or position of tool relative to object, while the comprehensive plan or profile view shows the manipulator base or absolute reference frame, the mechanical hand and the manipulated objects all in relation to one another.

Even the crudest of tactile sensors such as a simple electrical contact is useful for automatically stopping the arm motion if an object is touched. The manipulator arm has sufficient elasticity to render collision with fixed objects harmless, and transient shocks are quickly damped out. We have also developed a prototype touch sensor having on its surface a deformable mirror which distorts a regular grid pattern. The human operator observing the reflected image through closed circuit television can infer the point by point pattern of normal forces on the gripping surface of the manipulator hand. This device is shown in Figure 2.

Command Language

In order to develop, on-line, the commands appropriate to a particular task from a small set of primitive commands, a simple compiler called MANTRAN has been written by Barber [10]. It accepts typed commands to the manipulator to move at a specified rate to a specified position or in a specified direction until certain specified conditions occur, allowing the operator to combine these into "programs" that can be called by name. Such programs may have within them various searching or grasping or emergency conditional subroutines. A simple but useful mode is to be able to assign a name to a given manipulator configuration (simultaneous set of relative positions or angles at each articulation) and at some arbitrary time later to simply type the configuration name and have the manipulator automatically return there. This requires, of course, that the computer maintain a tsate vector for the current manipulator configuration with which to compare the stored state vector corresponding to the named configuration. Alternatively, the system can be commanded to respond to the analogic controller until certain positions are obtained or until the hand contacts an object, at which time the program branches out of the analogic mode. An example of MANTRAN is shown in Figure 3.

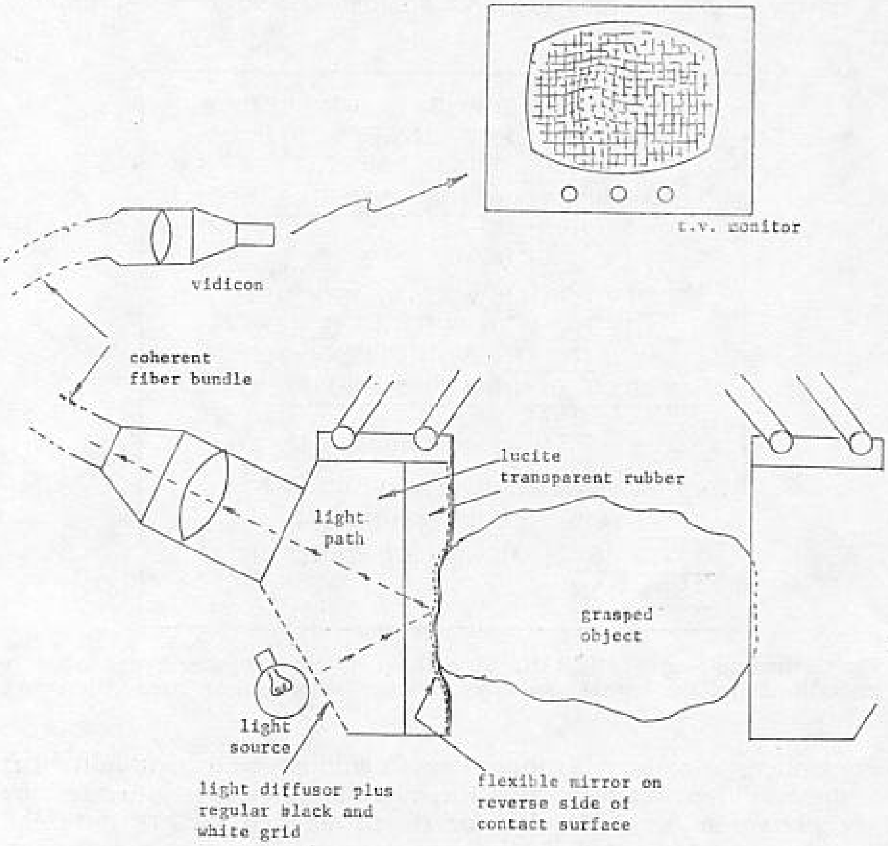

Fig. 2. Touch sensor. Grasped object deforms flexible mirror which causes distorted grid pattern to occur as human operators visual (not tactile!) display

Functional Organization of the Computer-Manipulator System

It is convenient to represent the breakdown of functions in the computer manipulator system as in Figure 4. Whereas Figure 1 illustrates the physical location of major components, Figure 4 indicates the various kinds of logical processing necessary for supervisory control. Most but not all of these functions are implemented in the laboratory system described above.

Beginning at the left, the ill-defined function of evaluating and setting subgoals is performed by the human operator. He interacts with the symbolic (keyset) and analogic (local physical model) controllers to convey his intentions. A computer element called the command interpreter converts these human responses into a unique concatenation of commands, or if certain criteria are not met, returns to the operator via the display with a query or a reminder.

```
ST 1 MOVE FORWARD 10 AND LEFT 500.
     UNTIL A) TOUCH LEFT
           OR B TOUCH FRONT.
IF MOVE CONDITION SATISFIED, DO 2
           IF A) DO 3
           IF B) DO 4.
ST 2 MOVE FORWARD 10 AND RIGHT 500
     UNTIL A) TOUCH RIGHT
           OR B) TOUCH FRONT
IF MOVE CONDITION SATISFIED, DO 1
           IF A) DO 5
           IF B) 4.
ST 3 MOVE BACK 40 AND LEFT 24*
ST 4 TYPE "DONE" AND STOP*
ST 5 MOVE BACK 40 AND RIGHT 24*
ST 6 DO 4 $
```

Fig. 3. Example of MANTRAN. At each step the computer types what is underlined and the human operator responds to set subgoals or procedures

The operator, and in turn the interpreter, can give four kinds of commands to an executive controller: 1) he can instruct the exteroceptors (receptors which sense the external environment) to be positioned, oriented and focussed in a certain way and to tell him what they sense; 2) he can request that certain "what would happen if... "experiments be conducted within an abstract representation of the manipulator and task internal to the computer; 3) he can request the execution of certain moves–simple ones like "move manipulator angle A plus-two degrees", or complex ones like "search region R for part P and assemble it with Q", 4) he can request that certain transformations available within the computer system be applied to data and that the results then be displayed to him.

The block labelled "task model" is itself worthy of far more discussion than can be given it in the present paper emphasizing the nature of the human operator's supervisory control, and its

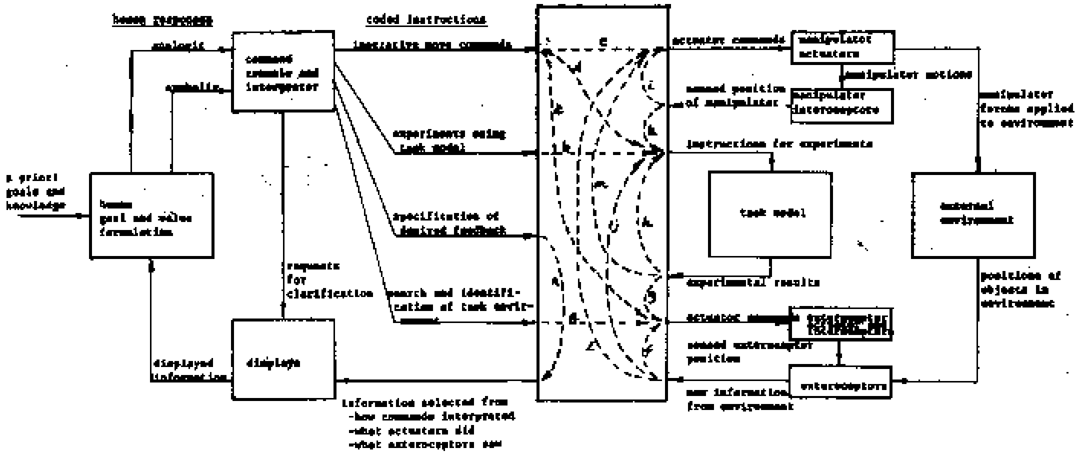

Fig. 4. Functional taxonomy of supervisory control of computer/manipulator

a. direct instructions to exteroceptor actuators
b. direct instructions to perform experiments on task model
c. instructions to exteroceptor actuators as part of move strategy
d. instructions to perform task model experiments as part of move strategy
e. direct instructions to manipulator actuators
f. modification of exteroceptor positions as a function of what exteroceptors sensed
g. modification of exteroceptor positions as a function of task model experiments
h. execution of task model experiments as a function of previous experiments results
i. manipulator position feedback control
j. updating of task model as a function of new information on the environment
k. updating of task model as a function of where manipulator is
l. manipulator control as a function of new information on the environment
m. manipulator control as a function of task model experiment results
n. information selection for display

internal organization is discused much more fully in separate papers by Whitney [11, 12]. In summary, however, one can say that if the positions in six degrees of freedom of all rigid elements of both manipulator and environment are represented by a single vector, then any interactive movements of the manipulator with the environment can be represented by a series of vectors or by a trajectory in vector space. In theory, then, optimal control strategies are those for finding minimal cost trajectories from initial state to goal state in the state space.

While a finely reticulated state space for a system having many motor sates, many sensor states, and many environment (manipulated object) states is clearly far too large to be useful for overall control, the state space model provides a formal norm or baseline to which other techniques can be compared. State space models of a tractable size can be used to perform simple manipulations, or to perform parts of more complex ones. In any case an important practical problem concerns the definition of what are rigid elements, what are costs, and what discrete resolution is appropriate to represent the real world in the state space model.

A simple example of interaction of the human operator with the task model is described in a subsequent section of the paper.

It is important to note that the executive controller oversees many "automatic" feedback loops and interactions which are not under direct control by the human supervisor. As indicated by dotted lines and letters in Figure 4, the executive controller mediates direct or straight through requests for (a) sensory analysis of the environment or for (b) task model experiments. Imperative move commands automatically call for, in sequence, (c) search and identification of objects in the environment, (d) task model experiments, and finally (e) manipulator movements.

The executive controller mediates (f) the feedback from the exteroceptor actuators (actually the interoceptors of the exteroceptor subsystem, analogous to the position sensors of the muscles of the eye!) and the (g) signals from the task model to control where to look next. Similarly (h) the feedback control of the experiments of the task model or internal representation of the manipulator as well as (i) the feedback control of the actual manipulator are handled by the executive controller.

The task model is updated by (j) the sensed state of the environment and (k) the sensed state of the manipulator. Knowledge of (l) the sensed state of the environment and (m) the results of the task model experiments are automatically used in optimal or sub-optimal control of the manipulator. A significant part of this latter function is the decision as to what individual angular changes of actuator movements within the manipulator will achieve the final desired position. The reverse transformation from component angles to gross configuration is easy trigonometry but the required transformation from joint or hand position to component angles can require complicated matrix inversions, or approximation methods, or worse yet (in the case of redundant degree of freedom manipulators), be undrefined. This specific problem has been the subject of several prevoious papers [13, 14].

Finally the operator can ask for a variety of information (n) to be displayed to him. The organization of this aspect of the system is probably very important but, since as yet no experiments have been done emphasizing it, it is left indeterminate.

Note that the executive controller, the task model, the command console interpreter and also the display boxes must all be implemented largely by digital logic. Which computer functions belong to the "local" computer and which belong to the "remote" computer are unsolved engineering problems and will surely depend upon, among other thing, the specific task context, the amount of telemetry processing required for signals of the necessary precision and the like.

Human Intervention in Computer Control Procedures

Because of the economic limits on multi-dimensional state space or other formal models of whole manipulation tasks referred to above, a primary goal of our research is identification of the ways human operators and computers can interact in planning and executing manipulation tasks. This will be presented by example. Suppose (Fig. 5) that for a 20×20 grid a manipulator M and two objects X and Y must interact. At the outset suppose we (the human operator) know that M must be transported through bounded area 1, then M and X interact in some way within area 2, pass to 3, and be assembled as a unit with object Y already there, then be transported to 4. We could consider a state space of size $(10 \cdot 10)$ (for each of three objects requiring optimum search through $(20 \cdot 20)^3 = 4 \cdot 10^8$ states. Alternatively we could break the task into two ad hoc or heuristic transport tasks and do an optimal search only wihin areas 2 and 3, in terms of 2 elements in area 2 and 2 elements (one an assembly of M and X) in area 3. This means a state space of only $(10 \cdot 10)^2 + (10 \cdot 10)^2 = 2 \cdot 10^4$ plus enough computer for storing transport heuristics is required– a space at least two orders of magnitude less.

In general, a task involving n objects, each of which can assume any one of S states, requires a state space of S^n. Breaking the task down into m subtasks in the i^{th} of which only r_i of the objects can move and each is limited to O_i states requires a state space of $\sum_{i=1}^{m} O_i^{r_i}$. This wil, except in unusual circumstances, represent a savings in both computational time and storage, since $r_i \leq n$ and $O_i \leq S$.

To implement in this exact form such man-machine cooperation in control requires means by which the human operator may delimit the sétate space and assign costs to transitions between all possible states. The latter is clearly not possible for each new manipulation task encountered. Simplified procedures must be developed for permitting the operator to tell the computer what sequence of subtasks appears to make common sense, what parts of physical space and what objects are *not* involved in each subtask. Further, some simplified procedures must be developed for assigning state transition costs in common manipulation tasks--based on resources such as distance, acceleration, energy and time.

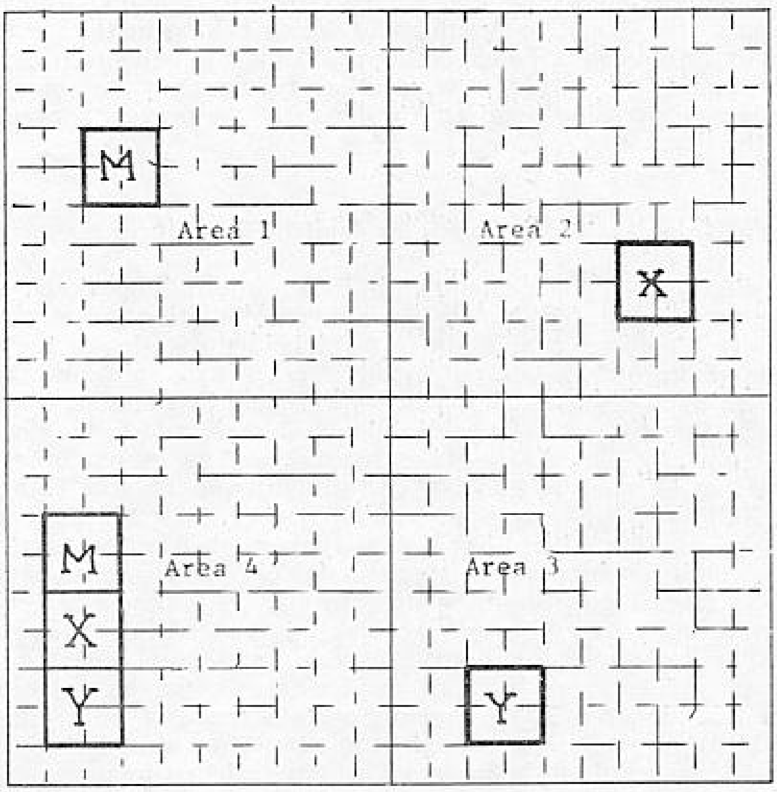

Fig. 5. Example of state space reduction. Task is to attach M to X, then assemble this to Y, move final assembly to position shown. Most general search is through all combinations of 20 by 20 physical space for each of 3 objects, a total state space of $4 \cdot 10^6$. Reduced search is sequence of two searches through $10 \cdot 10$ physical space in areas 2 and 3 for 2 objects each, a total state space of $2 \cdot 10^4$

Our understanding of supervisory control is yet primitive and many experiments remain to be done before a human wearer of a prosthesis will be able to concatenate strings of optimal searches to perform the rather complex manipulations normally used in daily living routines. Supervisory control of computer-manipulators in the *simpler* applications of space, undersea and industry will probably precede.

Conclusion

A laboratory simulation and some empirical evidence have been described which suggest the promise of having human operators operate as supervisory controllers of computer-manipulators, where the man sets subgoals and procedural constraints and the machine does the rest automatically. Many advantages of such man-machine interactive systems are foreseen, not only to speed up remote manipulation tasks with inherent time delay and to provide true flexibility not near to achievement by completely autonomous machines, but in the future to enhance prosthesis control where continuous human attention to visual monitoring of control variables is inconvenient.

REFERENCES

1. Johnsen, E. G. and Corliss, W. R., "Teleoperators and Human Augmentation", NASA, SP-5047, December 1967.
2. Ernst, H. S., "MH1: A Computer Operated Mechanical Hand", M. I. T. ScD Thesis, 1961.
3. *Application of Intelligent Automata to Reconnaissance*, (C. A. Rosen and N. J. Nilsson, Eds) SRI report dated Nov. 1966.
4. M. Green, S. Wahlstrom, G. Forsen (same title), Tech. Report No. RADC TR-66-822, Rome Air Development Center, Griffis Air Force Base, N. Y., May 1967.
5. C. Rosen, N. Nilsson, (same title) RADC TR-67-657, Jan. 1968.
6. Tomović, R. and Boni, G. "An Adaptive Artificial Hand," *Trans.* IRE Vol. AC-7, April 1962, pp. 3—9.
7. Ferrell, W. R., "Remote Manipulation with Transmission Delay," *IEEE Trans. Human Factors in Electronics*, Vol. HFE-6, pp. 24—32, Sept. 1965.
8. Ferrell, W. R. and Sheridan, T. B., "Supervisory Control of Remote Manipulation," *IEEE Spectrum*, pp. 81-88, Oct. 1967.
9. Verplank, W. L., *Symbolic and Analogic Command Hardware for Computer-Aided Manipulation*, S. M. Thesis, M. I. T., 1967.
10. Barber, D. J., "MANTRAN: A Symbolic Language for Supervisory Control of a Remote Manipulator," S. M. Thesis, M. I. T., 1967.
11. Whitney, D. E., "State Space Models of Remote Manipulation Tasks," paper in *Proc. of the International Joint Conference on Artificial Intelligence*, Washington, D. C., May 1969, pp. 495—507.
12. Whitney, D. E., "State Space Models of Remote Manipulation Tasks," Ph. D. Thesis, M. I. T., January 1968.
13. Mergler, H. W. and Hammond, P. W., "A Path Optimization Scheme for a Numerically Controlled Remote Manipulator" *6th Annual Symposium of the IEEE Human Factors in Electronics Group*, May 1965.
14. Whitney, D. E., "Methods of Rate and Position Control of Remote Manipulators and Human Prostheses," paper submitted to *IEEE Trans. on Man-Machine Systems.*