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The Southampton Hand: An intelligent myoelectric prosthesis

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Abstract—The form of the control and structure of the mechanism of an artificial hand are important factors which tend to dictate the prosthesis' level of use. Conventional prostheses are simple devices with limited functional range and a control format that requires high levels of user concentration for successful operation. The Southampton Adaptive Manipulation Scheme (SAMS) is a hierarchical control format that allows a larger number of independent motions to be controlled while requiring a smaller degree of user input. The SAMS control has been applied to different hand mechanisms, both custom-made and modified commercial systems. Their application with users shows them to have a performance on a par with, or superior to, other conventional devices. The form of prostehsis control is reviewed and the development of, and clinical experiments with, the Southampton Hand are outlined.

Key words: *artificial hand, microprocessor control, myoelectric prosthesis control, prehension.*

INTRODUCTION

A prostheses can be either actuated by an operator, using his/her own body to power the device, or it can derive its power from an external source. The control of the device is then dictated by this choice (1,2). Body-powered prostheses use the direct mechanical link between the operator and the device to control them. Good control is possible, and complex manipulation can be achieved if an effective design is employed. Generally, the commercial designs that are functional are not aesthetic, although this is now beginning to change (3,4), and functional hands are never anthropomorphic. In addition, actuation is generally bulky, requiring straps or cables which chafe against the clothes and become dirty. The range of movement or power of the device can be compromised by the geometry of the system. Despite these drawbacks, bodily powered prostheses are the most common form of terminal device, due to their functional range, robustness, light weight, and low cost.

The only practical external power source is electric; this is due to the ease by which the power source can be recharged compared with the difficulties of recharging any other safe source (5,6). Electronics also provide a compact controller. The resulting device can be more cosmetic in appearance, needing no straps to open it and much smaller bodily actions to operate it; in addition, it is less tiring to use. However, the major feedback path from the device to the operator that exists with body powered prostheses is severed. It must either be reestablished or circumvented to allow good control of the device. Current electric hands do not use any feedback except visual and incidental forms of motor vibration (7), thus the control burden is higher in the electric hands than in the mechanical ones.

Some forms of feedback have been investigated, such as the coding of the force or hand flexion in vibrations (8,9) but this mental transformation is burdensome. If the feedback is applied to the correct point in an appropriate manner by using, for example, extended physiological proprioception (EPP), good tracking performance of an arm can result (10–13). The shortcoming of such a method is that it works well for the large actions that control a serial line of joints (for example, in an arm), but cannot as easily control the parallel joints in a hand mechanism.

Commercial artificial hands have a single degree of freedom that allows them to open and close. The cosmetic versions generally are anthropomorphically shaped hands in the form of a precision grip. They cannot open wide enough to admit many common objects or flex far enough

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to hold small objects in a power grip. This limits their functional range. Although different manufacturers' hands have subtly different geometries, they do not vary greatly in prehensile performance. All commercial hand-like devices have the same limitations on size and grip forms. The standard configuration is an anthropomorphic hand in a three-point chuck grip (14,15). These can hold large objects in a power grip or precision-type grip, but do not perform so well with the smaller objects (5,16). Changes in hand geometry to a more anthropomorphic form circumvent this drawback as the fingers can curl around small objects, or alternatively, the tips of the index finger and thumb can oppose each other (17–19). Even more adaptive is the hand where the thumb can abduct to oppose the side of the index finger (20,21). However, the matter of the control of the device still is problematical.

In principle (everything else being equal), increased function could come from an increased number of independent motions, but conventional control requires too much concentration from the user, needing one independent input channel for each degree of freedom. An alternative method, developed in the Department of Electrical Engineering at the University of Southampton, mimics the natural control method of the human hand and so frees the user from making detailed decisions about the hand (22,23).

METHOD

The Southampton Adaptive Manipulation Scheme (SAMS) was developed to address the problems related to the control of the multi-degree-of-freedom and multifunction hand prosthesis. The basic form of the central nervous system (CNS) of a human being is hierarchical, as the tasks of controlling the hand and digits are broken up into three layers (**Figure 1**). At the lowest level the force and position of individual fingers are managed. These reflexes are then commanded by an intermediate level that coordinates the fingers to create a hand shape and grip force in response to the shape of the target object and the action that is intended for it. Above this is the strategic control of the hand. This is the level of the consciousness of the individual. The person simply desires to move an object, and the system coordinates the action to achieve this goal with very little conscious thought. SAMS was designed to restore the level of control of a prosthesis up to this level (**Figure 2**).

The user issues simple instructions to open the hand, normally through a single electromyographic (EMG) channel. In this example, the flexor and extensor muscles on the forearm are used (**Figure 3**). The EMG channel is regarded as a single bipolar signal ranging from full extension at one extreme to full flexor tension at the other. In the center both muscles are relaxed. The degree of opening is proportional to the muscular tension (on the positive vertical axis); therefore, when the muscle relaxes, the hand closes natu-

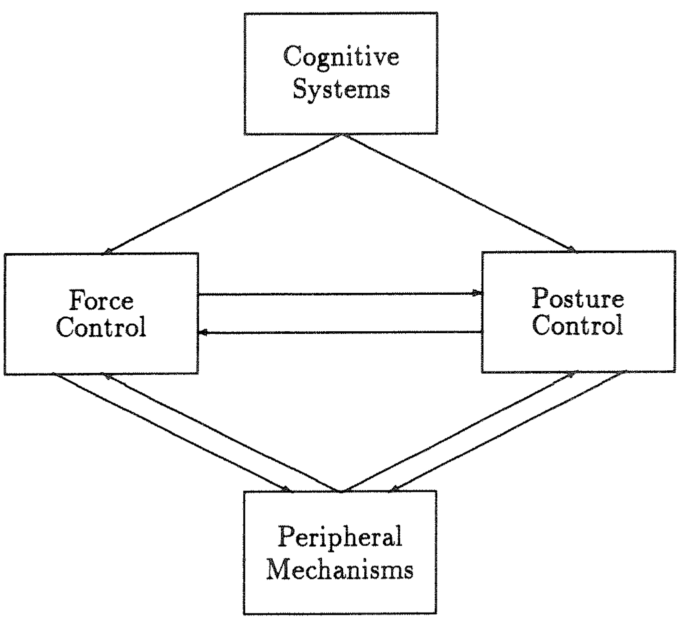

Figure 1.
The Southampton Adaptive Manipulation Scheme, (SAMS). It is arranged in a hierarchical form analogous to the human Central Nervous System.

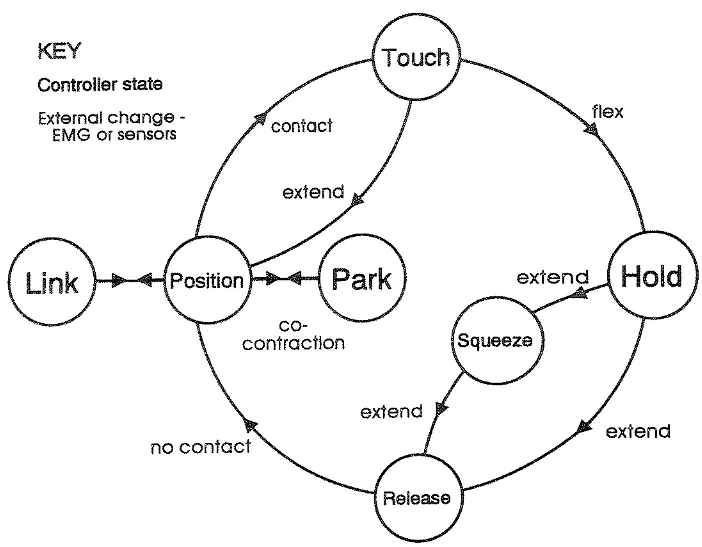

Figure 2.
State diagram of the SAMS hands. Control is mediated by electromyographic input or contact with sensors on the palmar surface of the hand.

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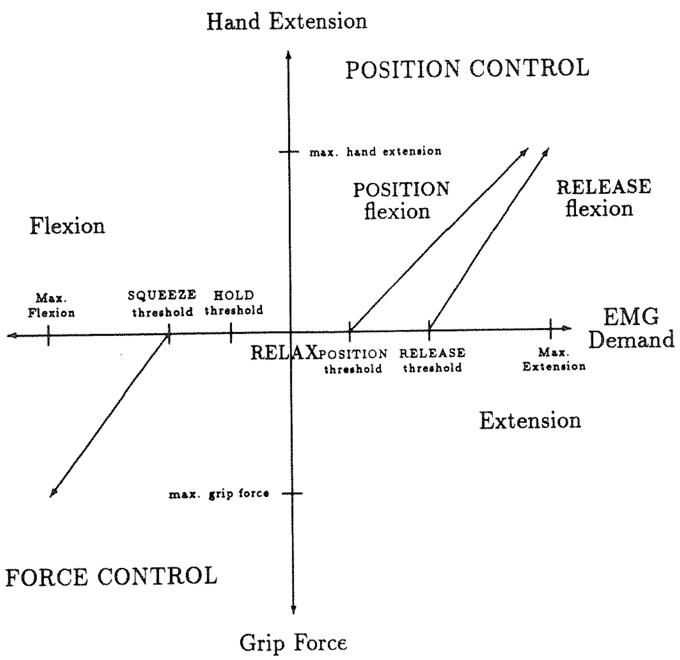

Figure 3.
EMG control for the Southampton Adaptive Manipulation Scheme (SAMS). The flexor and extensor signals are arranged as a continuous range from full flexion to full extension, the vertical axis is hand position or grip for demand, depending on controller state.

rally upon the object (POSITION). The shape of the object is detected by sensors on the palmar surface of the hand while a computer controller selects a grip posture from a small repertoire to suit the most appropriate general shape. The controller then makes detailed corrections of that shape to suit the exact shape of the object. This maximizes the contact area while minimizing the contact force. In this phase, a light touch is maintained so the operator can maneuver the object within the hand to obtain the best attitude (TOUCH). Then the user can instruct the computer to hold the object (HOLD). If the grip tension is too low, the object slips within the grasp, the slippage is detected by sensors on the hand, resulting in an increase in the force in proportion to the time that slippage occurs. At any time, the operator can either instruct the hand to increase the grip force, overriding the slip reflex (SQUEEZE, the negative going arm of the y-axis, **Figure 3**) or to open (RELEASE). The threshold when this occurs can be set higher than for when the hand is opened empty, so that holding or releasing objects becomes a more deliberate act than opening the hand when empty. With conventional prostheses this point has to be set at the same muscular tension so that it is either too easy to drop an object, or too difficult to use the hand without tiring. A LINK phase can also be implemented in the SAMS scheme so that the third, fourth, and fifth fingers are moved out of the way and the hand adopts a two-digit pinch grip for manipulating small objects. Finally, a PARK state allows the hand to be powered down when not in use.

This scheme has been realized on a range of prostheses known generically as the "Southampton Hand." The Southampton Hand is the entire system, comprising the adaptive control scheme, the proportional instructions controlling a terminal device with feedback to the controller. Analysis of the type of action required to perform the majority of prehension tasks showed that for an anthropomorphic hand, four degrees of freedom are sufficient (20). These motions are: index finger flexion and extension; thumb flexion/extension and abduction/adduction; and flexion of the other three digits as a closely coupled group. Using the terminology described by Napier (24), the design allows the hand to perform *precision* prehension with two or more digits, *power* grip, as well as *side* prehension, where the thumb opposes the side of the index finger. The hand was designed to look and move in an anthropomorphic way to provide a pleasing cosmesis for the device. It was also designed to fit all four drives within the natural envelope of the hand so it could be worn by the widest range of possible users.

The slip detection and response realized on the Southampton Hand is based on detecting the vibrations set up when an object slides past the finger tips (23), or the changes in the forces between the hand and the object (7). These techniques mirror those of natural systems (25,26). The advantages of the vibrotactile detection have been recognized and are being implemented in a number of other devices (18,19,27,28).

Early Clinical Demonstration

The original Southampton Hand was built in 1969 (20) and was controlled by using discrete logic components. A realistic clinical application requires the electronics to be reduced to a size and cost that is acceptable to the user population and the limb-providing authorities. In the early 1970s, the electronic devices and packaging technology were not sufficiently small to allow the production of a clinically practical device. In the interim, laboratory versions of the hand were fitted to an individual who usually used a split hook (Dorrence heavy duty hook, number 7, voluntary opening configuration). He had a congenital, below-elbow right hand loss (29). A conventional myoelectric hand (Viennatone MM3 with digital control of velocity and force) was fitted, so a comparison of the control methodologies could be made (**Figure 4**).

The subject was trained prior to performing various tests to assess his ability to use the hand. The provision of the myoelectric hand also allowed the subject to accustom himself to myoelectric control between training sessions and prior to the laboratory tests. The procedure was in the form of progressively introducing more of the functions to him, spread over a number of visits to the center:

1. Fitting of prosthesis.
2. Familiarization of EMG scheme without hand.
3. Familiarization of hand functions.
4. Grasping of everyday objects.
5. Evaluation:

- Abstract prehension objects
- Positional prehension on standard objects on open shelves
- Practical activities outlined in **Table 1**.

Familiarization of EMG Scheme

Initially, an oscilloscope trace of the smoothed EMG output was displayed for the subject and used to indicate the command level achieved. Once the subject was sure of the operation, this was replaced by lights that indicated the state the controller was in. This was found to be a very clear way to train the user. Once the error rate was below 6 percent (after 2.5 hours), the subject progressed to the next phase.

Familiarization of Hand Functions

Familiarization was achieved by separating the functions into each grip category and progressively introducing them by use of a range of abstract objects. Practical tasks are difficult to assess objectively; therefore, the abstract objects were adopted. Compressible foam items were designed to test the force control. These were made of strips of plastic foam glued together at their centers only. The foam was a light color with the ends colored a darker shade. Thus, pressure on the central region caused the strips to splay out progressively relative to the force imparted, betraying the level of force to the outside observer. Competence was achieved at these tasks after a further 4.25 hours.

Evaluation

Prior to the start of the evaluation, the subject was advised that he would be scored on the time taken to complete the task and the number of grasp errors. No period of practice was allowed before the first run of the test. This was to enable a measure of the competence of the control to be made. Any subsequent improvement in the times would betray this fact. The positional tasks consisted of moving abstract objects, such as cylinders and blocks, from lower shelves to higher ones, or vice versa. The practical tests were based on ones devised by the Department of Health and Social Security (DHSS) in the United Kingdom to assess artificial limbs. They consisted of abstract prehension tasks and simulated real tasks of daily living. The tasks were recorded, observed by an independent, experienced observer, and timed (29); the results are outlined in **Table 1**. The following ratings were given to the hands based on the scores given by the observer:

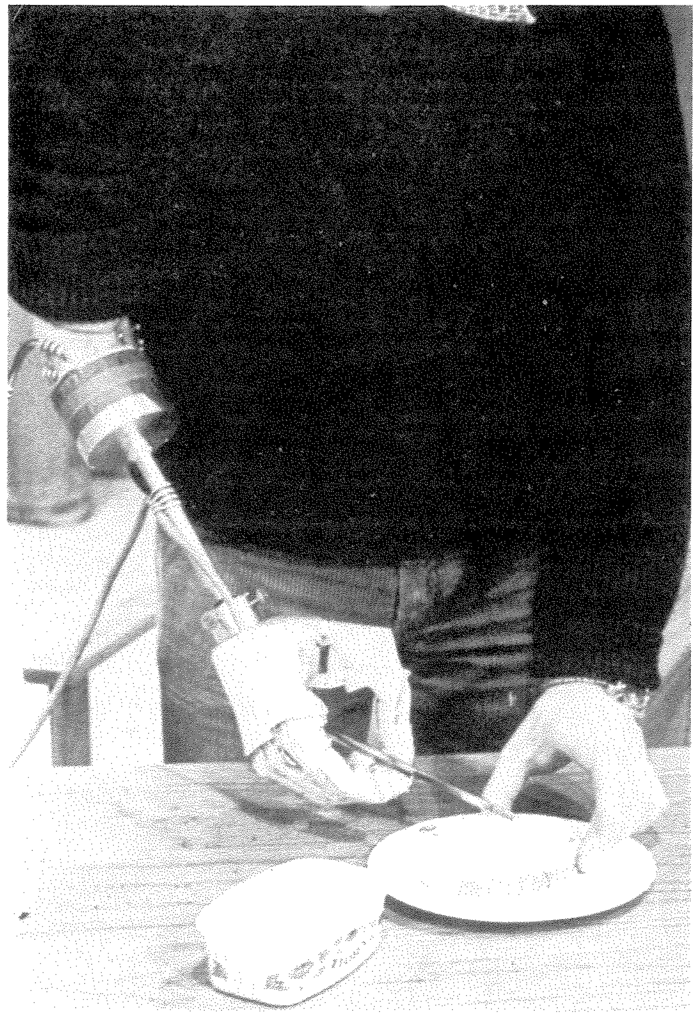

Figure 4.
Third generation four degree of freedom SAMS hand under test.

Table 1:
Comparative tests with the SAMS hand.

	Time(s)			Rating	
Task	**Sams**[1]	**Hook**[2]	**Myo**[3]	**SAMS**	**Myo**
Cutting					
Fork LH Knife RH	57	26	—	2	1
Fork RH Knife LH	49	42	—	2	1
Change grip, Spear to scoop	12	14	—	2	1
Open bottle and pour					
Top LH Bottle RH	26	29	—	3	1
Top RH Bottle LH	11	12	12	3	1
Carry tray	21	17	18	2	2
Cut slice of bread					
Loaf LH Knife RH	41	42	—	3	1
Loaf RH Knife LH	17	26	17	3	2
Butter bread					
Bread RH Knife LH	16	19	20	2	1
Bread LH Knife RH	36	31	29	3	2
Fasten belt	32	29	31	3	2
Toothpaste onto brush					
Brush LH Tube RH	36	21	20	3	2
Brush RH Tube LH	42	—	15	3	2
Grasp telephone receiver	19	5	5	3	2
Grasp pen and write	30	20	22	2	2
Cigarette from pack					
Pack LH Cig RH	28	20	44	2	2
Pack RH Cig LH	12	11	13	2	2
Use mallett and chisel					
Mallt LH Chis RH	16	11	9	3	3
Mallt RH Chis LH	18	—	15	3	3
Pick up coins	34	17	27	3	2
Lift and pour kettle	29	15	—	3	1
Tear and fold paper	46	46	26	2	2
Put paper in envelope					
Paper LH Env RH	19	18	22	2	2
Paper RH Env LH	13	18	20	2	2
Grasp cup	8	6	7	2	2

[1]A hierarchically controlled four degree of freedom Southampton prosthesis.
[2]Dorrence heavy duty split hook (no. 7), voluntary closing.
[3]Viennatone single degree of freedom hand with two myoelectric channels.

1. The hand was inferior to the split hook.
2. The hand was as successful as the split hook.
3. The hand was superior to the split hook.

The total assessment was spread over 3 months with a total of 31.25 hours use of the hand.

Recent Progress

More recent work has concentrated on two areas: The first is sensor design and signal processing of the input signal for improved performance and speed (30,31). The second is development of a simple Southampton Hand that could be used clinically (7,32).

The device was based on a Viennatone MM3 hand. The standard control electronics were removed and sensors added to detect object slip, contact force, and hand flexion angle. A simple microprocessor-based computer was built from CMOS low-power components and the device was fitted to an individual who had suffered a traumatic amputation of the left wrist and usually used a myoelectric hand (Steeper 2-channel myoelectric hand).

After three familiarization/training sessions at the Arm Training School at Queen Mary's University Hospital, Roehampton, London, UK, the individual was able to use the hand at home and at work. In addition, pick-and-place tests were performed on a standard set of shapes and the standard bimanual tasks used at the center. These were recorded on video tape and observed.

RESULTS

Four Degree of Freedom Hand

For trials on the multifunction hand, the subject was able to learn the operation of the hand quickly (within half an hour). A few hours of use then refined the familiarity with the controls still further. For the larger abstract prehension tests, all three devices worked equally well. As the items became smaller, the grasp limitations of the standard myoelectric hand were more pronounced. On the real objects, the myoelectric hand was not as easily or quickly used, as the wider range of shapes were more readily adopted by the Southampton Hand. In addition, wrist prosupernation was not necessary as the adaptive shape of the grasp allowed these to be accommodated as well.

The split hook was limited to the largest size of its grasp and it was also very tiring for the user to repeatedly open the hook to a sufficiently wide gape to admit many of the large objects.

Neither of these drawbacks was noted with the Southampton Hand. The observers' assessment of the hand was that it was superior in performance to the hook in just under half of the practical activities (12 out of 25, or 48 percent) and it was equal in the rest. The standard myoelectric hand was seen to be on a par with, or worse than, the hook. The area where the Southampton Hand showed the greatest advantage over the split hook was where the actions required a power grip with a large grasp. However, some of the other tasks were not possible at all (**Table 1**). The user was allowed to practice with the training objects until his times between runs tended toward a constant value. However, there were improvements in the times for the practical tasks, showing further improvement was still taking place.

Single Degree of Freedom SAMS Hand

These results were borne in mind when the experiment with the single degree of freedom Southampton Hand was commenced. Since the functional range of the device was obviously limited, the comparisons were made in terms of the ease of teaching and use of the device. The user's own device was a Steeper myoelectric hand with two channel digital input. Given that the hands were very similar in design and construction, the differences in use could be more directly attributable to the control philosophy than in the previous experiment.

The individual found the Southampton scheme easy to learn. However, the difference in control between the Southampton Hand and his normal prosthesis needed to be explained. Habit had taught him to use flexor tension to close the hand and extensor tension to open it. The Southampton Hand is of the normally closed form with the opening on the extensor tension alone; the flexor is used for switching to the hold state and SQUEEZE override, once HOLD is established. Only a little practice was required before he began to allow the hand to close of its own accord rather than to instruct it like his usual hand. Once this was achieved, he easily used the flexor tension to invoke HOLD or SQUEEZE. The subject became an enthusiastic user of the device and readily appreciated its advantages (**Figure 5**).

Figure 5.
The single degree of freedom SAMS hand in clinical application.

DISCUSSION

The ease with which individuals control prostheses show how adaptable human beings are. They can learn to use a range of non-natural inputs to assist in their control of the devices, for example, using the vibrations of the motor in the conventional myoelectric hand as it stalls to detect contact with the object (7). However, using the existing structures in the way most appropriate to the action is preferable.

Users of conventional, two-channel myoelectric hands can learn to apply muscular tension from opposing muscle groups to open and close their hands. The more natural occurance is to proportionately relate the flexion angle with the extensor muscle's tension, as with the voluntary opening aspect of the Southampton Hand.

That nonanthropomorphic methods work at all is an illustration of the adaptability of the individual. However, the average prosthesis user is not willing to invest a great deal of long-term effort in controlling a hand unless the benefits are substantially greater. Thus, a solution with minimal user effort is preferred.

In an experiment with limited numbers and time, it is difficult to draw firm conclusions about the efficacy of a particular system. The Southampton Hand has a number of factors that are different from the other devices. First is the proportional control, which has an important effect on the ease of control of the device (5,16); at that time no commercial devices offered such a facility, although in recent years it has become more common.

A second factor is the device's geometry. The more anthropomorphic hand can afford a wider range of grip postures, under any control philosophy. But the effectiveness of the control scheme is harder to demonstrate. A more direct comparison is possible with the single degree of freedom hand. A computer controlling the hand directly is "aware" when the fingers are touching each other or when the hand is touching an object. So the controller can respond to different situations, and the threshold for opening an empty hand can be set to require a small muscular tension, but releasing an object is made a much more deliberate act. Users of normal myoelectric hands do complain that it is too easy to inadvertently release a held object when the extension level is set low enough to make opening the hand less tiring.

As is apparent, the factors that dictate the acceptance or rejection of a prosthesis are many, varied, and unpredictable (33). One user may accept a prosthesis enthusiastically for precisely the same reason that another rejects it out of hand. Appearance, weight, action, ease of use, and cost all contribute to the decision. The Southampton Hand and its derivatives attempt to address the problems of ease of operation and appearance. Many of the other factors can only be addressed in a near-production, robust field version of the device.

Finally, as the hand is a semi-autonomous manipulator, it can be used in other fields beyond prosthetics. A robot manipulator need not look like a hand, but if it is to be used in a domestic environment it must hold objects found in that arena. Most such objects are designed to be held by human hands. Thus, a basically anthropomorphic shaped gripper is useful. In addition, if the users are individuals who have a restricted range of input, such as those with dysfunction brought on by a neuromuscular disorder (e.g., muscular dystrophy), then a simple high-level control channel for the gripper is an advantage, enabling an operator to make the most of his limited physical abilities. Such a philosophy will form a part of the Oxford Robot Assistant project (**Figure 6**) being conducted at the Oxford Orthopaedic Engineering Centre to develop different technologies to help people with special needs (34).

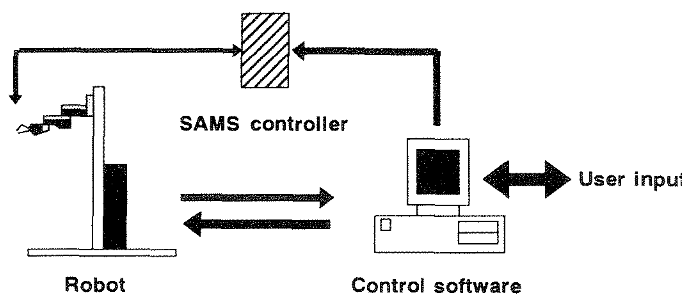

Figure 6.
Oxford Robot Assistant System, this combines the control of a SCARA robot with a semi-intelligent mobile base and a SAMS based gripper.

CONCLUSION

Dexterous manipulation of a range of objects is possible if a selection of special tools is used. A general manipulator must be adaptable in its geometry if it is to handle a wide range of objects. One such device is the Southampton Hand. The control is kept simple by divorcing the supervision of the device from the detailed management of the hand. In limited field experiments the combination of a multi-degree of freedom hand and hierarchical control showed improved performance in the range of objects grasped and the tasks performed compared with the standard devices of the time.

This demonstrates the importance of the Southampton Adaptive Manipulation Scheme as a control technique for prostheses. It leaves an imperative to conduct more rigorous tests on the scheme in the field. The SAMS philosophy formed part of a collaboration funded by the European Community under the TIDE initiative, between centers in the UK and Italy, to develop a two degree of freedom intelligent myoelectric hand for clinical evaluation in both countries which began in 1993 (35).

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