ADAPTIVE PREHENSION CONTROL FOR A PROSTHETIC HAND

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Summary

This paper considers normal hand action and how it can be replaced by an artificial hand. An adaptive hand with four powered movements is suggested. The operator is relieved of detailed control and simply supervises the progress through a task by command signals derived from electromyographic signals of two muscles. Communication with the operator and the classification of tasks are discussed, and some details are given of an adaptive hand control system which has been constructed.

Introduction

This paper outlines the work done by the Control Group at the University of Southampton on an adaptive control system for an artificial hand. It has been assumed that the hand can be positioned in space by the operator, either directly or by use of another control system, and effort has been concentrated on producing a functional hand, rather than one of good appearance.

The human hand performs a wide variety of tasks which may be roughly grouped as

1) lifting, holding, carrying, etc, which will involve the application of forces to an object,
2) exploratory sensing which calls for the ability to touch a surface and register shape, smoothness or temperature etc.,
3) expressive gesturing, that is, conveying sizes or making other gestures which involve co-ordinated opening and closing of the hand.

The first of these groups, holding, carrying etc., involves very little conscious effort considering the complex nervous signalling which goes on in order to perform the task. Satisfactory performance of a gripping task is not achieved by simply controlling the force applied; the human hand changes its posture to suit the object being grasped and provides in general a much more efficient grasp than any fixed-geometry device could. Numerous control signals from the Control Nervous System (CNS) adjust the posture of the hand and often the position of the object within the hand and determine how the gripping force is distributed between the digits in order to stabilise the grip and to economise on muscle effort. The great majority of this adaptation is done subconsciously except perhaps when extreme care is being exercised. Examples of this adaptation are

1) the extension of the 3rd digit, while holding a teacup, to apply a couple with a much longer moment arm than is possible using the thumb and 2nd digit alone,

2) the way in which the thumb and 2nd digit are almost at right angles and not parallel as might be expected while using scissors, thus providing control over sideways movement of the scissors and

3) the way in which the weight of a wine glass is taken on the 4th or 5th digit at right angles to its normal plane of movement allowing the hand to be almost completely relaxed.

In some situations quite a high level of muscle activity can be maintained with little or no conscious awareness; e.g. carrying a bag or case.

In the other types of hand activity, i.e. its use as a sensor and for expression, more conscious awareness of the hand is called for; its position and contact forces being continuously monitored and controlled.

Considering hand action in this way suggests that satisfactory performance of an artificial hand cannot be achieved with a simple control system or with only one degree of freedom. The Southampton Group believes that a hand prosthesis must have similar geometry to the human hand for several reasons:

1) most everyday tasks are implicitly related to the human hand shape, for example handles, car controls etc.,

2) a hand which not only looks like a human hand but does tasks in the same functional way is more socially acceptable,

3) it is difficult to imagine a more versatile or adaptive structure if we were to deviate from the human pattern.

The introduction of several degrees of freedom into an artificial hand calls for several control signals but, while these could sometimes be obtained from an equal number of control sites on the operator, this approach calls for very high levels of mental effort and skill in order to produce co-ordinated movements.

This effort is quite different to that used in normal hand action because of the lack of detailed sensory information feedback to CNS. It would seem that artificial feed-in of sensory information cannot replace this adequately (except where feed-in takes the form of control lever "feel" and hence provides sensory feedback along a natural path) because the information has to be evaluated and acted upon consciously. This makes fast corrections to the grip impossible.

The lack of control sites and of fast subconscious communication with the operator suggests the use of an automatic system to control those movements of the hand which are normally performed subconsciously, with only conscious supervision and monitoring by the operator.

Supervision can be achieved by use of an EMG signal, and artificial feed-in can allow the hand to be used as a sensor. This implies little departure from normal hand function as decisions both to actively use the hand and to perform exploratory sensing are normally made consciously.

The problems posed by such a hand are mainly:

1) the construction of such a complex mechanical structure, light in weight, strong, quiet, of good apperance and fitted with numerous transducers and
2) its overall control.

The latter involves communication with the operator, classification of the task, and the control of posture and applied forces. An experimental hand has been built with sufficient mechanical performance to test the proposed control system, and another improved version is at present under construction.

Communication

To date our work has been largely concerned with *feed-out* or with obtaining a suitable supervisory signal rather than with feed-in. EMG signals from two opposing forearm muscles were chosen as a suitable feed-out. The signal from each muscle is amplified in a differential amplifier and fed to a diode clamp and averaging circuit. The two signals so produced are then subtracted in another differential stage whose output provides a continuously variable voltage level centred about the relaxed condition and extending in opposite polarity up to vigorous flexion and extension of the digits controlled by the muscles. By treating the signal in this way the output level is a noisy indication of muscle effort. Voltage deviations are around 25 per cent during a constant large effort but in the range of muscle contractions used in digit positioning with no load, the signal is much steadier although small. Further amplification of this central portion of the range provides a signal of 0 to 10 volts depending on the unloaded position of the digit. This position dependence is due to the digit being constrained by tissues which act as weak return springs pulling towards the relaxed position.

It was decided to use position rather than velocity control for conscious movements as this seemed more natural, left no doubt as to where the artificial digits were when the muscles were relaxed and allowed large muscle efforts to be achieved without attaining high artificial digit velocities. However, position control does imply passing through a fully flexed condition but forces can be limited during position control to overcome this difficulty.

A double time constant filter is used to increase the stability of the output signal level. Deviations of less than 0.6 V in either direction are filtered using a long time constant (1.5 secs) but for larger deviations diodes reduce the time constant to about 90 mS. This makes steady position control possible while still allowing fast movements.

While the central portion of the EMG output range is used for position control, the signal is also fed to a set of four Schmitt triggers which are adjusted to switch at four fixed levels, two beyond each end of the position control range. This enables four command signals to be produced at will and these are labelled -1 and -2 for extension and $+1$ and $+2$ for flexion.

During the development of the control system, a further command was found necessary to effect a choice between two digit or full hand grips. An automatic choice was possible but could not be relied upon to give what the wearer wants. The extra command was achieved by summing the outputs of the two diode clamp and averaging circuits and using further trigger and logic circuits to indicate when both muscles were contracted together. This corresponds to the simple action of stiffening the digit and is called the precision command.

Tests on this system showed that, after a little practice, any position or command could be produced easily. However, there was a tendency to relax from the extreme levels to the inner ones after a time. This was thought to be unimportant as the control system would not require the extreme levels to be maintained for long periods.

Task Classification

Tasks are classified into both hand postures and types of force control. The various categories are shown below:

Touch — The application of sufficient force to stimulate pressure receptors and to maintain contact with an object as used in exploration. This level of force is the maximum possible during position control.

Weight Balancing — A relaxed grip using just sufficient force to avoid slip.

Holding — A firm grip in readiness for moving an object or resisting an external force.

Arrest — The application of maximum available force to stop object slip as quickly as possible.

Squeeze — Variation of force up to maximum value in order to deform an object at a controlled speed.

Manoeuvre — A grip with accurately controlled force such that an object is allowed to slip at a steady speed under an external force.

Posture

Continuous co-ordinated control of hand opening and closing under conscious position control used when not performing a grip.

Tips — With precision— the thumb opposes the tip of the forefinger or without precision — the thumb opposes the fingertips.

Side — The thumb opposes the side of the forefinger.

Chuck — The thumb and first two fingers provide a 3-corner chuck.

Hook — With precision — the forefinger hooked, the rest fully flexed or without precision — all four fingers crooked for pulling or carrying.

Fist — The fingers flexed to hold an object in the palm followed by the thumb wrapping round the outside of the fingers if the object is small.

Flat hand — The hand is flattened with the fingers fully extended and the thumb flexed and adducted.

The selection of the type of force control is partially determined by the supervisory signal and partially by feedback from the hand-object interface. A suggested block diagram for this is shown in Figure 1.

Posture selection is determined by the points of contact between hand and object and by the supervisory signal. The outputs from pressure sensing pads on the hand (Fig. 2) are fed to a series of Schmitt triggers which provide an on/off signal, representing contact or no contact, for each pad. The trigger levels are arranged to be lower than those produced during "touch" force control and the on/off signals are fed to a logic unit which makes the decision as to which posture to adopt as soon as the operator changes from position control to the grip command +1. The table in Figure 3 shows how this decision is related to points of contact and the logic arrangement which performs this is shown in Figure 4. The system provides the facility of changing from a thumb and forefinger precision grip to a full hand grip on receiving an EMG command to stop using precision. If, on closing the other fingers no object is encountered, a three finger chuck is formed and adjusted to the object.

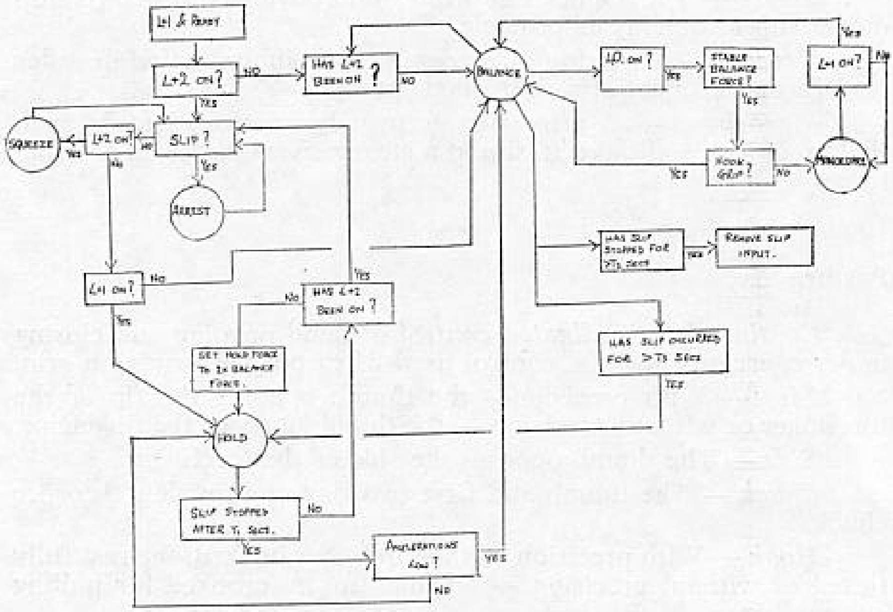

Fig. 1. Suggested Force Logic Diagram.

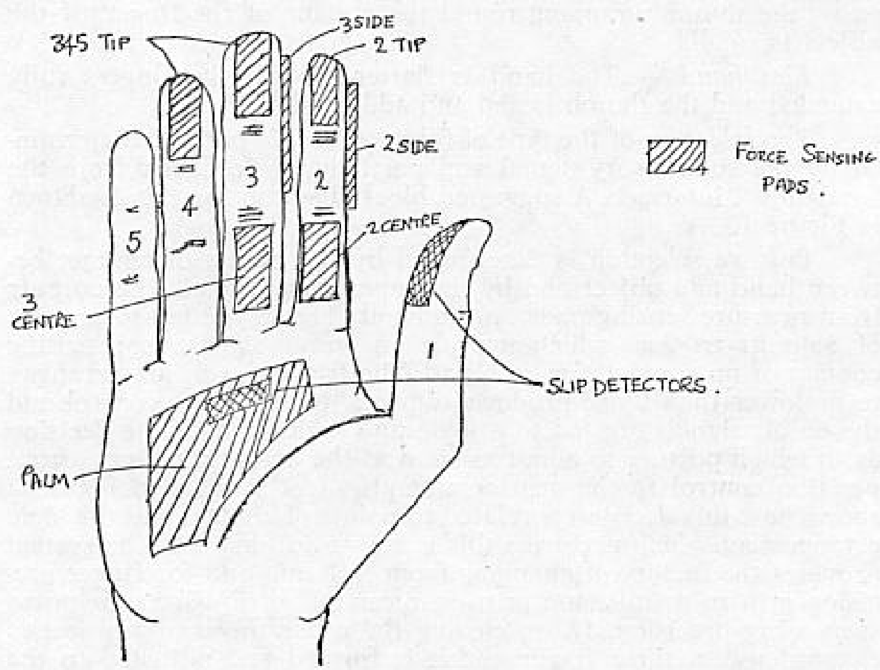

Fig. 2. Sensor Positions.

INPUTS

SWITCHING FUNCTION	2 SIDE	2 TIP	2 CNTR	345 TIPS	345 CNTRS	3 SIDE	PALM	'P'	'O'	'-2'	POSITION 3>2	j	l	a	f
a	O	1	X	X	X	X	O	X			X	X	O		
or a	O	X	X	1	X	X	O	O			X	X	O		
b								O						1	
d				O				O			1			1	
e	ON AT START OF d, OFF WITH START OF 3 SIDE.														
f	1	X	X	X	X	X	X	X			X	O	O	X	
c	DELAYED FROM f														
g								O							1
h	O	X	X	X	X	X	1	X	X	X	X	X	X		
i	DELAYED FROM h														
j	X	O	1	X	X	X	O	X	X	X	X		X		
j+l	X	X	X	X	1	X	O	X	X	X	X	X			
4j													1		
m									1						
n								1	1						
o										1					

Fig. 3. Determination of posture switching function from sensor inputs and command signals.

Control of Posture and Force

Interpretation of Commands

It has been explained how five EMG levels from "−2" through "0" (position control) to +2 are obtained together with an extra precision signal. The policy adopted in interpreting these was to make the resulting actions as similar as possible to the natural action originating the EMG Command "−1" was allotted to opening the hand after a grip had been performed and "−2" to opening the hand further to produce a "flat hand" posture. Moving from "−1" through "0" into "+1" was allotted to weight balancing or holding while "+2" was given to "arrest" or "squeeze". Manoeuvring was then achieved by relaxing from "+1" or "+2" back to level "0" which previously corresponded to position control. Opening the hand was then possible by selecting "−1". This is shown diagramatically in Figure 5.

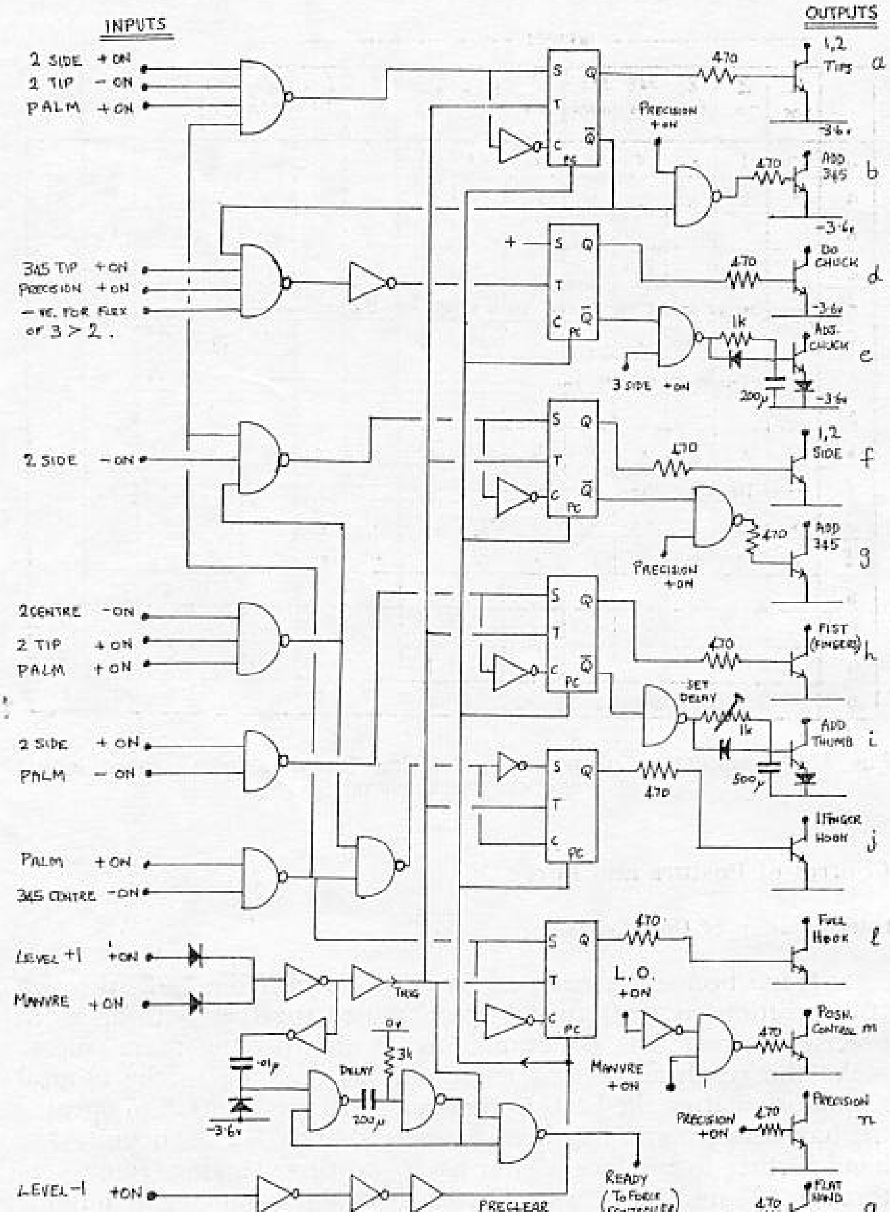

Fig. 4. Posture logic diagram.

The dual use of level "0" was thought to be acceptable because once an object has been gripped, the only reasons for relaxing the

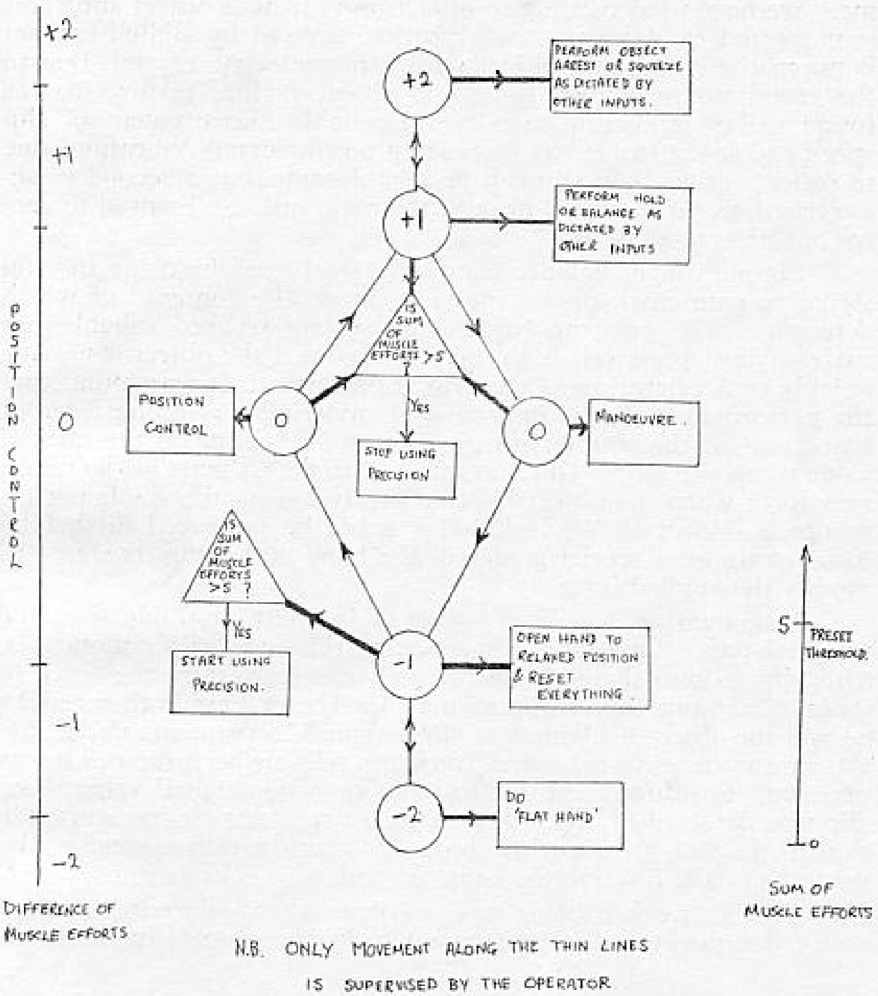

Fig. 5. Flow diagram of commands.

grip are for manoeuvring and releasing the object both of which are possible without further use of position control.

Force Control

The only force control present in our prototype hand at the moment is "touch" control. Nevertheless some work has been done on weight balancing and manoeuvring on a simple electromagnetic clamp. The types of feedback which can be used to achieve control are limited entirely by what can be measured. The only measurement we have used relating to object movement is object slip. This is measured by detecting the vibrations caused by sliding contact between the clamp and object with a piezoelectric crystal. Due to the variations in contact force and object surface texture, it was found to be impossible to obtain a reliable measurement of slip speed and so control is based on a slip/no slip signal. Vibrations due to sources other than slip can be troublesome, but a second piezoelectric detector mounted near to the main one can be used to cancel out unwanted signals.

Simple weight balance control was achieved by using the slip signal to gate clock pulses into a counter, the contents of which determined the gripping force. This system worked reliably but suffers from excessively high force estimates if the object is moving quickly or accelerating as the grip is performed. It was found that the performance can be improved by applying a gripping force of twice that in the counter during slip and reverting to the normal value when slip stops. This can cause an underestimate of the necessary force when the object is lifted gently but on the whole performance is improved. We feel that it could be improved further by incorporating an accelerometer in the hand and using its signal to modify the applied force.

Manoeuvring has been achieved by first attaining a stable weight balance force and then relaxing this until slip commences. This slip is immediately detected and used to restore the force to its original value thus stopping the slip. The process is then repeated and the object is allowed to slip in small increaments under gravity or another external force. To obtain reliable performance it was necessary to return the force to more than its original value when slip was detected in order to provide a deccelerating force in addition to the weight balancing force. This can be done as before, by using twice the force in the counter while slip is occurring.

Further work is being done to try to obtain more information about the object and its movement from transducers in the hand.

The Control Loops

To achieve the functions mentioned with the artificial hand, two switching systems are necessary; one forms the appropriate feedback loops around each of the four servomotors and amplifiers, and another selects the appropriate input for each loop. The loops used in the prototype are:

Force F/B — from hand pressure pads for control of grip force.

Non-linear Force F/B — control of touch force.

Position F/B

Velocity F/B — derived from position signal.

Non-linear Velocity F/B — used to maintain slow closing speed when necessary.

Non-linear shaping is used so that, despite other inputs to the amplifiers, force or velocity can be maintained below a fairly accurate upper limit. The inputs available for the loops are, the position signal from the EMG, the signals determined by the force logic and preset constants.

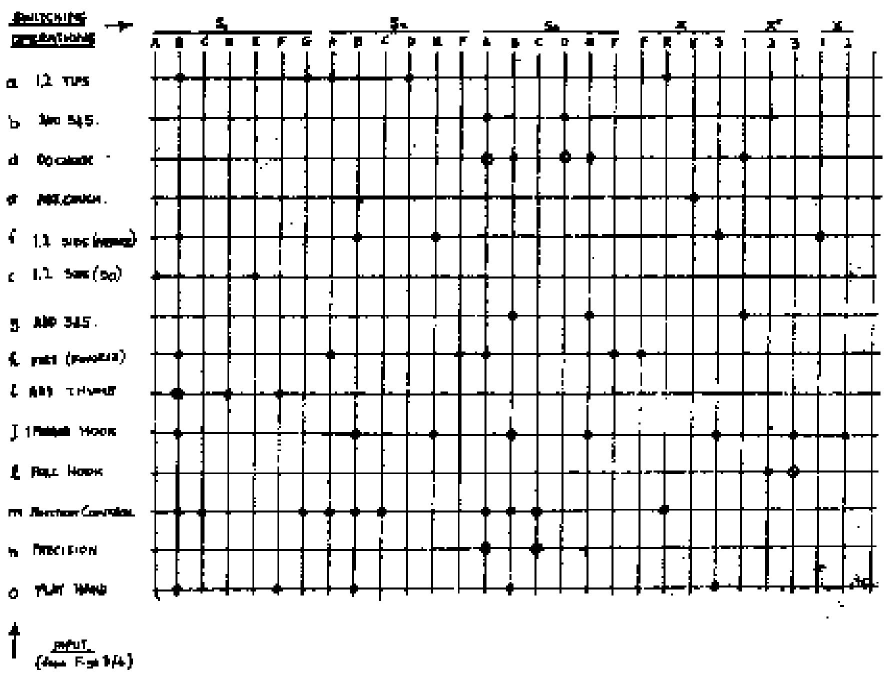

Fig. 6. Selection of feedback loops.

In the prototype, the loops and their inputs are selected by relays for simplicity when dealing with low level signal voltages. Selection is made according to the table of Figure 6. The switching operations $S_{1,2}$; $_{A,B}$ etc. refer to the realy contacts shown in Figure 7 which shows both the input and loop switching circuits. The complete control system is shown in block diagram form in Figure 8.

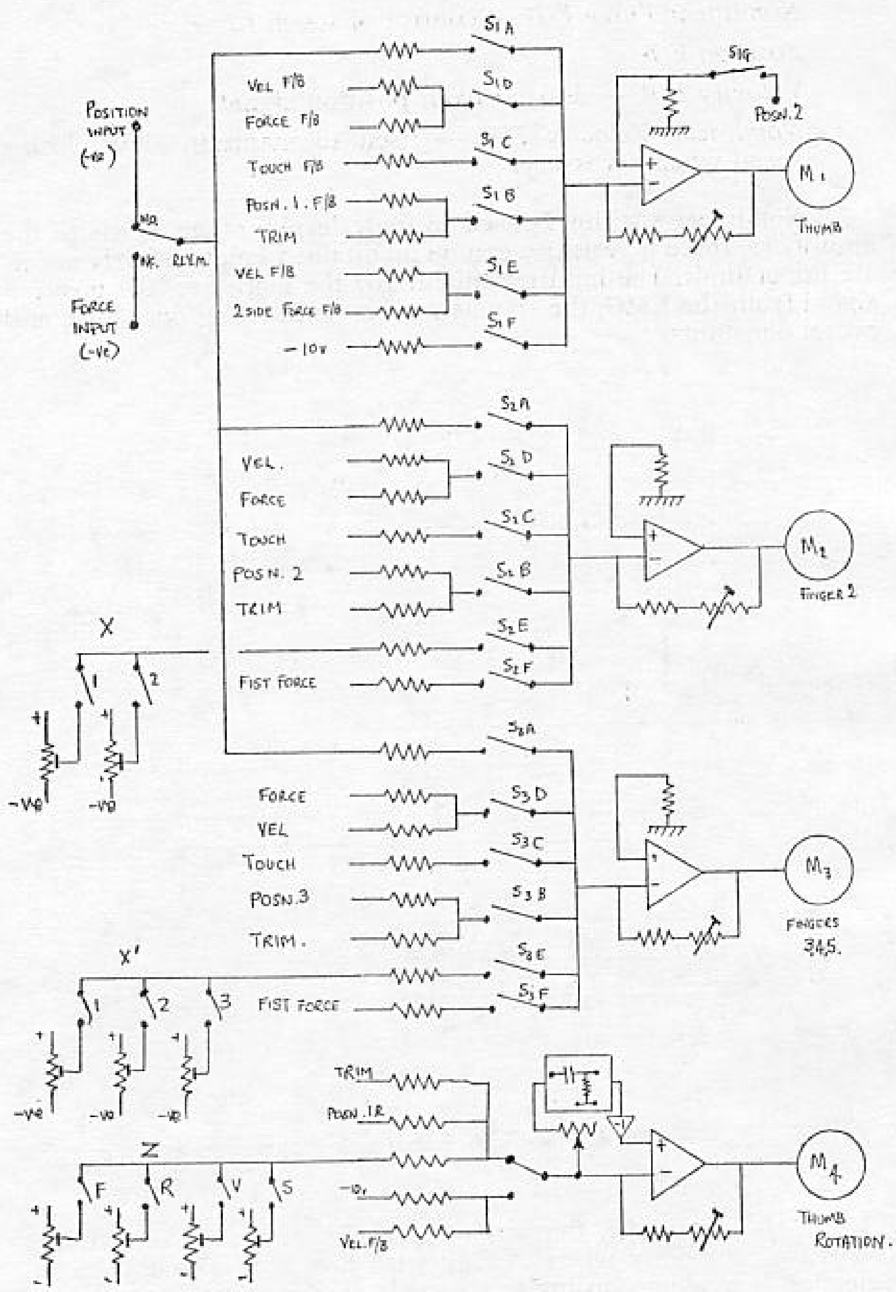

Fig. 7. Feedback loop switching.

Conclusions

The system constructed to date has demonstrated the feasibility of obtaining direct position control and command signals from one muscle pair. Experiments with the solenoid operated clamp have shown the possibilities and advantages of supervisory control by achieving stable weight balancing and controlled slip, impossible with direct control of the force by the operator. Nevertheless there are many difficulties to be overcome before this type of control could be incorporated in a clinically acceptable hand.

The choice of four motors to operate the digits seems to give adequate flexibility for most everyday tasks, provided that intricate jobs are excluded.

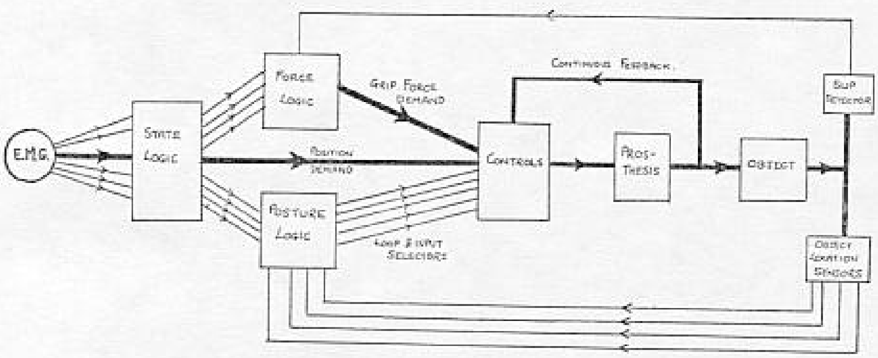

Fig. 8. Complete control system.

The automatic posture selection circuitry operates reliably as far as it has been tested but no tests under real conditions have yet been performed.

The type of control system adopted makes possible the simple addition of special grips along with those mentioned to suit a particular need without mechanical modification.

Completion and testing of our prototype hand is continuing while a second model with improved mechanical capabilities and better integration of the transducers is being developed. A new type of transducer is also under consideration in order to allow weight balancing without slip occurring first.