THE CONCEPT OF A NEUROLOGICAL PROSTHESIS IN THE CONTROL OF HUMAN EXTREMITIES

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Summary

The work we wish to present extends our previous work on Powered Limb and Functional Stimulation. The paper will consider general problems in the control of the upper limb, including the hand, from the viewpoint of achieving an optimum compromise between functional flexibility and the conscious involvement of the wearer.

To simplify the control and communication problems between patient and prosthesis for multi degree of freedom limbs a hierarchical system has been considered which can be likened to a neurological prosthesis. The system consists of low-level reflex loops, discriminatory and adaptive intermediate levels and upper level perception elements which interpret simple signals from the wearer as commands to the control system. Most of the signals for the lower levels are obtained from skin and joint angle sensors.

Whereas the principles have been successfully applied to the study of a prosthetic hand, the concept of a similar system for use in conjunction with multi-channel stimulation of a paralyzed hand is comparatively untried. The paper attempts to establish a logical approach to the specification of such a system. In particular it pays attention to the complete measurement system which is necessary together with the logical processing required at the upper levels. Experimental results will be presented.

Introduction

This paper reports extensions to the application of functional stimulation. Whereas earlier work /1, 2/ was concerned with repetitive activity in single joint mechanisms (footdrop), the work presented here is a beginning to the more difficult task of achieving a range of differing functions where several degrees of freedom are involved - for example in the paralyzed hand. Control of the latter poses problems of a higher order of difficulty than the former.

A very common disability from upper motorneurone lesions is wrist drop which is loss of ability to open the hand and extend the wrist voluntarily. The cause of this is twofold: Firstly, control over hand extensors is lost and, secondly, there is often spasticity in the flexors of the hand. If inhibition of the spasticity is achieved then stimulation of the hand could form a basis for useful function. The hand and wrist present severe problems owing to the number of degrees of freedom. A sufficient set of stimuli must be available and these in turn require a coordinating set of command signals some of which may be obtained indirectly by external measurements. While a general control structure is sought, the diverse requirements of individual patients will demand a programmable capability. This suggests a hierarchical control structure with local reflex loops, capable of continuous, rapid variations in movement or force, being coordinated by a supervisory logical network.

Signals available as inputs can be obtained from the following measurements: i) EMG, ii) movement, and iii) force. In principle these may be used as command inputs or feedback signals. However experiment suggests that EMG feedback, from surface electrodes, is less effective in hand control than in other applications due to cross-talk from adjacent muscles. Stimulating electrodes have priority for the sites which this permits.

The most obvious force sensors which can be used are touch pressure sensors. Their use in a hierarchical control system for a prosthetic hand has been extensively studied by the Southampton Control Group. Possible variants include: i) foam-spaced capacitors, ii) RF balanced transformers, iii) conductive foam pads, and iv) strain gauges. While being preferred in the prosthesis work for its high stability, the strain gauge method requires a rigid mounting for its load cell and therefore seems impractical for the present application.

All transducers relying on deformation of plastic foam suffer from mechanical creep in the material and, in addition, resistive foam appears to have electrical creep. However, the basic simplicity of construction and associated circuitry led to the choice of resistance foam force transducers in the present application.

The relevant movement sensors measure joint angles. Practically it is not feasible to use a potentiometer coupled by a mechanical linkage to the appropriate joint. However, it was found to be possible to measure joint angles through the mutual coupling between coils mounted on each moving part. The associated circuitry is shown in Figure 1. Figure 2 shows the location of the pick-up coils. Surprisingly the method is quite insensitive to the proximity of metal objects except in extreme cases. An advantage of this type of transducer is its low noise level which would permit differentiation of the output within a limited frequency band, thus giving a some measure of velocities.

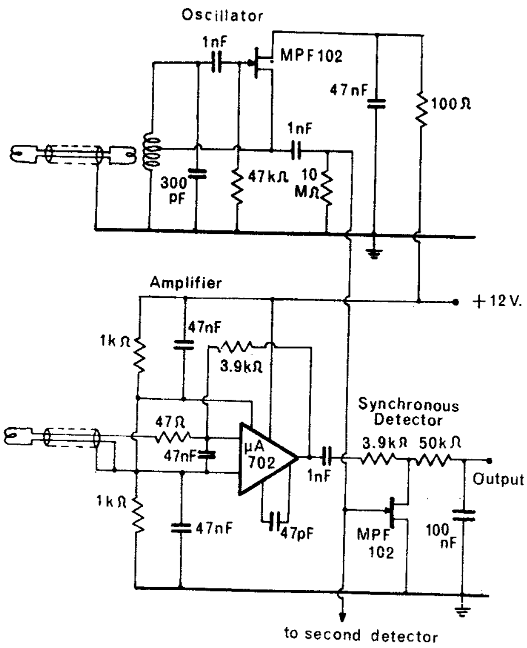

Fig. 1. Circuit diagram of goniometer.

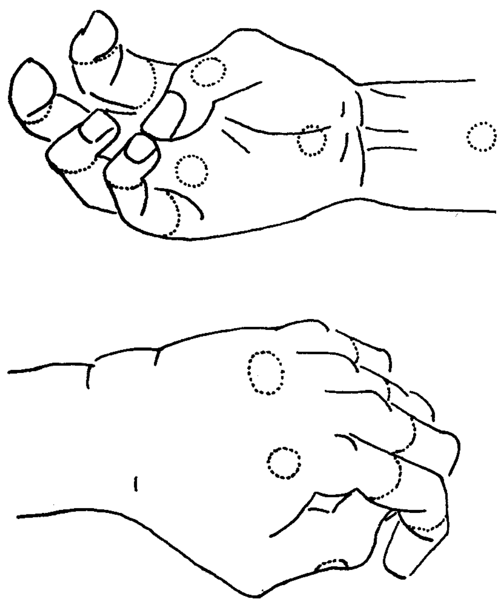

Fig. 2. The positions of the sensing coils.

Finger functions are defined, from a control viewpoint, by the loading condition. There are two basic cases. The first - free movement - involves no external loading. Assuming no spastic or voluntary contraction the force developed by the muscle is balanced by

1. Gravitational forces - constant for a given hand position;
2. Elastic reaction to joint movement and elastic reaction to muscles stretch;
3. Viscous reaction to muscle stretch (velocity dependent);
4. Inertia forces (acceleration dependent).

Since the hand normally weighs less than 0.5 kg.f. gravitational and inertia forces are small except, perhaps, at the wrist. Normally the elastic forces are also small and it seems that the dominant reaction forces are the viscous ones. With these assumptions we can suppose that it is the speed of movement which is proportional to stimulation, at least within a limited range. Thus, for movements produced by single muscles rather than an antagonistic pair simultaneously.

$$\dot{\underline{x}} = M\underline{\sigma} \tag{1}$$

where $\underline{x}$ represents the band configuration, each component of which indicates a degree of freedom. $\underline{\sigma}$ represents the induced muscle activity state and each component is associated with a specific muscle.

If position feedback is employed, $\underline{\sigma}$ depends on the difference between an input $\underline{z}$ denoting the desired hand configuration and $\underline{x}$. Thus

$$\dot{\underline{x}} = MA\ (\underline{z} - \underline{x}) \tag{2}$$

A indicates a specific control configuration. We should qualify the apparent linearity of Equation 2 by remarking that no component of $\underline{\sigma}$ may be negative and hence A is strictly a state dependent matrix. This is a multi-variable control problem and ideally the controls should not interact. If the system were linear it would be possible to diagonalize MA. However, here it is first necessary to effectively linearize the control system. This we may achieve by means of a further state dependent matrix operator B (Fig. 3), which ensures that an effect equivalent to negative $\underline{\sigma}$ components may be obtained although this is achieved by selection of another muscle set. The combined operations MBA should result in a single linear matrix operator K which is of order nxn, where n is the number of components in $\underline{x}$. Since however $\underline{\sigma}$ may contain many more components than n, matrix A may be of order mxn, m>n and therefore the realisation MBA=K is not unique.

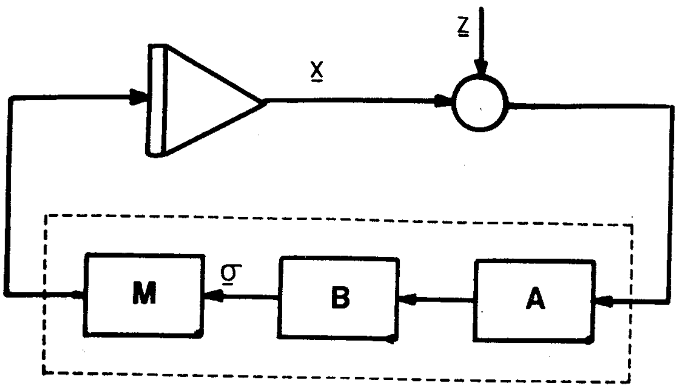

Fig. 3.

A design strategy for B is necessary, although possibly this is most realistically achieved by experimental techniques. However, the basis of this is the use of sign detectors in each channel at the output of A together with decision matrices calling for particular groups of muscle activities. The problem of choosing the elements of K is now one of the design of a stable, non-interacting multi-variable control system for which analytic techniques exist. In principle this will give, in the free movement condition, independent control over each degree of freedom.

The second case concerns the control of the hand when gripping an object. Here we assume that the forces developed in the muscles are balanced entirely by static reactions at the interface with the object. The relationship between the moments $\underline{q}$ developed at the joints involves a matrix M, which is related to M. Thus

$$\underline{q} = M_s\underline{\sigma}$$

The force control system at the moment is conceived as an open-loop system in which input signals $\underline{\omega}$ are related to $\underline{\sigma}$ through a matrix C (Fig. 4).

As in the case of the artificial hand /3/ the use of the hand is considered as consisting of a sequence of actions each of which would be implemented by its own control law. These can be of a position control nature, such as the movement of the hand to a flat hand configuration, or controlled closing of a hand for a precision grip. Alternatively they can be force controlled actions, such as that involved in maintaining as appropriate grip on an object.

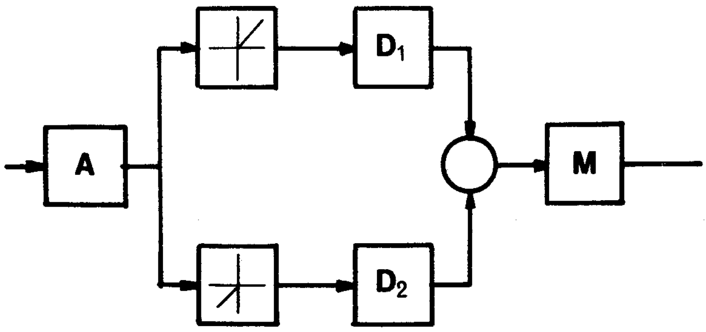

Fig. 4.

It must be remembered that wrist drop patients often have some control over their hand. If any spasticity present is inhibited by sub-threshold stimulation or other means, they are likely to be able to perform several of the actions which they require of their hand (especially force control tasks, which often only require the control of the flexor muscles). Obviously any capability of this kind should be utilized to the full.

However, it is possible that in other actions it may be difficult, if not impossible, for the patient to coordinate the muscles he has control of with those under external control. This would be because of the delays in the nervous system and the possibly unnatural nature of the task. If this were the case it would be necessary to stimulate the muscles under voluntary control, as well.

The choice of which action is to be implemented at any instant is decided by the supervisory controller. This makes decisions based upon the information it receives from the transducers. If for example the hand is closed and an object is "felt" on the back of the fingers it would be reasonable to assume that the object was to be grasped. This would mean, first, that the hand would have to be opened. The position error caused by voluntary contraction of the flexors could be used, then, to select the grip configuration to be used. Sudden relaxation of the grip, detected by the touch sensors could be used to initiate release of the object.

Such a system would be difficult to set up, particularly the parameters of the linear loops. Adjustments might have to be made each time the system was fitted to the patient. However it is feasible that an adaptive system might be designed which could overcome these difficulties, as well as being more tolerant of electrode failures. Such a system would make the concept of multichannel FES a much more practical possibility.

References

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