ADAPTIVE CONTROL OF AN ARTIFICIAL ARM

J.M. NIGHTINGALE AND I.D. SWAIN

SUMMARY

An important aspect of the overall problem of prosthetic arm design is the provision of input signals. These must be independent, repeatable, easily generated by the wearer and preferably, related to the movement they are to iniate. This paper discusses the control of an arm with six degrees of freedom by means of three inputs obtained directly from body movements and three generated indirectly by the control system. The latter arise from a constraint on elbow movement together with data from the wrist trajectory supplemented by prehensile feedback from the hand. An instrumented harness has been developed suitable for this and similar orthortic applications and early results are encouraging.

INTRODUCTION

For a number of years work has been undertaken at Southampton University on the development of a multi-degree of freedom prosthetic hand. Recently this has been complemented by a study of a fully articulated artificial arm. In the complete hand/arm system there are two distinct problems. Firstly, the gripping device must have adequate and stable prehension while, secondly, the arm must offer sufficient flexibility in the positioning and movement of the terminal gripping device. In each case the approach has involved the development of an autonomous control system requiring only limited supervisory intervention from the wearer thus reducing his voluntary effort and the resulting fatigue.

In the hand system (1) (2) the wearer provides a set of basic commands labelled *hold*, *squeeze*, *manoeuvre*, *release*, *flat hand*, etc, which are obtained from a single EMG source. These commands are supplemented by signals from an array of sensors in the hand relating to static and dynamic relationships between the hand and the object being gripped. These latter feedback signals are used for detailed control actions and so the overall system is a hierarchy in which functions are iniated at the conscious level but are performed without conscious effort in a manner analogous to normal human activity. Clinical trials indicate that flexibility can be achieved with very limited prior training.

It is the second problem involving control of arm trajectories that is the subject of this paper. The approach again involves an electronic controller to reduce the voluntary effort required from the wearer. Body movements were chosen as the basic source of signals since residual proprioception clearly provides a valuable feedback. These signals are assumed to be related to the demanded wrist position and control algorithms generate the required joint angles. In order to orientate and manoeuvre the the hand it was felt that two degree of freedom (wrist flexion and forearm ratation) were adequate. However, it was considered impossible to relate these naturally to a residual body movement and also the need for feedback from the hand is apparent. The provision of suitable signals will be considered later in the paper.

THE CONTROL SYSTEM

A cartesian co-ordinate system is chosen, the origin being a 'body' reference point at the shoulder. The position of a point at the wrist is given by co-ordinates (x,y,z) and movement of the hand is related to displacement of the shoulder such that relative hand motion is always in the same direction as the input motion, regardless of the absolute hand position. Thus raising the clavicle raises the hand (z), forward shoulder movement moves the hand forward (x) and lateral spine flexion moves the hand sideways (y).

The elbow constraint required to reduce the number of input signals is arbitrarily chosen so that its vertical displacement, relative to the shoulder, is half that of the wrist. The elbow co-ordinates (x_e, y_e, z_e) are thus

$$x_e = \tfrac{1}{2} \{x \pm y \left[(4r^2 - R^2)/(x^2 + y^2)\right]^{\frac{1}{2}}\},$$

$$y_e = \left[r^2 - x^2\ z^2/4\right]^{\frac{1}{2}}, \quad z_e = z/2 \qquad \ldots \quad (1)$$

Where $r^2 = x_e{}^2 + y_e{}^2 + z_e{}^2$ ... (1a)

and $R^2 = x^2 + y^2 + z^2$ ... (1b)

Equation (1) gives four sets of elbow co-ordinates only two of which satisfy condition 1a. From these two solutions xe is chosen to maximize y_e when $x > 0$ and to minimize ye when $x < 0$. This gives the more natural arm posture and leads to the following expression for x_e.

$$x_e = \operatorname{sgn} x \{|x| + |y| \left[(4r^2 - R^2)\ (x^2 + y^2)\right]^{\frac{1}{2}}\} \qquad \ldots \quad (2)$$

The rotations needed to position the wrist and elbow, figure 1, are given by

$$\theta_1 = \tan^{-1} y_e/x_e \qquad \text{(shoulder rotation)}$$

$$\theta_2 = \sin^{-1} z_e/r \qquad \text{(shoulder flexion)} \qquad \ldots \quad (3)$$

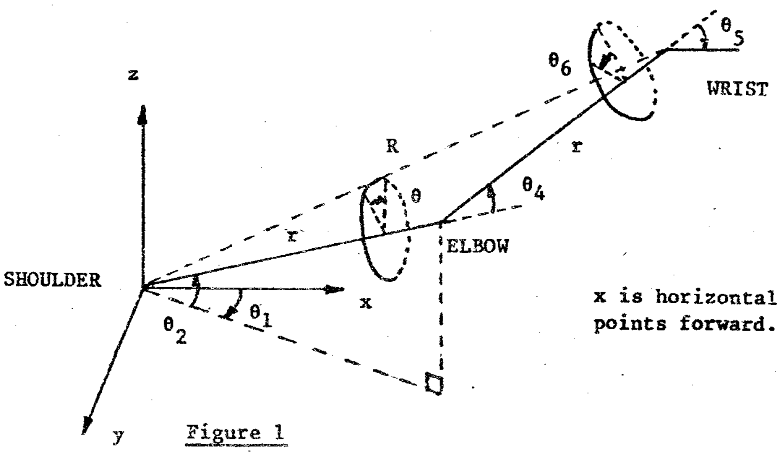
$$\theta_3 = \cos^{-1} \{(z - r \sin \theta_2\ (1 + \cos \theta_4))/r \cos \theta_2 \sin \theta_4\} \qquad \text{(elbow rotation)}$$

$$\theta_4 = \pi - 2 \sin^{-1} R/2r \qquad \text{(elbow flexion)}$$

Hand orientation, relatively more difficult, can be approached in two ways.

i) Alignment of the hand with an object prior to contact by controlling the wrist position and using trajectory curvature to control hand orientation.

ii) Corrective manoeuvring of the hand when the object has been gripped using tactile sensory feedback from the hand control system.



x is horizontal and points forward.

Figure 1

Defination of co-ordinate system and Joint Angles.

A system involving both methods sequentially is proposed. It is considered adequate that two signals be generated to control wrist flexion θ_5 and forearm rotation θ_6. To achieve orentation of the moving hand from the trajectory it has been necessary to define two effective measures of the curvature of the trajectory. Elements of the curved tragectory are projected onto two moving planes such that the angles of curvature $\delta\alpha$, $\delta\beta$, are independent of rotations $\delta\phi$, $\delta\psi$ respectively about the y,z reference axes. Then total curvature is considered to be $\int d\alpha$ and $\int d\beta$ respectively.

In practice points on the trajectory are sampled and the integrals are approximated by $\sum \delta\alpha$ and $\sum \delta\beta$.

The angles $\delta\alpha$ and $\delta\beta$, figure 2, may be calculated from the equations

$$\delta\alpha = \pm \sin^{-1} \left[(s_1t_3 - s_2t_1)^2 + (s_2t_3 - s_3t_2)^2\right]^{\frac{1}{2}}/|s|\,|t|$$

$$\delta\beta = \pm \sin^{-1} \left[(s_2t_1 - s_1t_2)^2 + (s_2t_3 - s_3t_2)^2\right]^{\frac{1}{2}}/|s|\,|t|$$

The sign of the angles $\delta\alpha, \delta\beta$ can be determined by mapping the tragectory onto the xz and xy planes respectively.

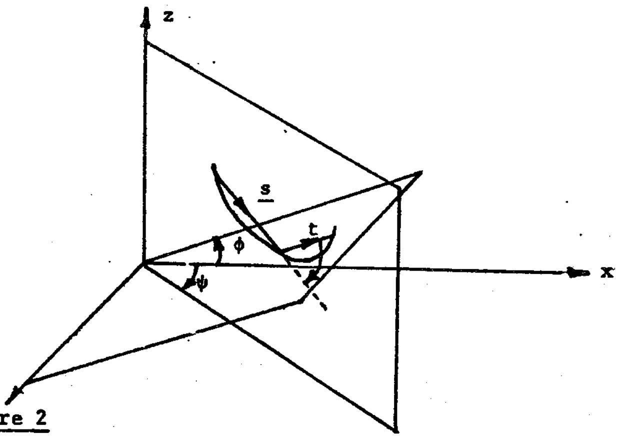


Figure 2

Mapping of the Wrist Trajectory

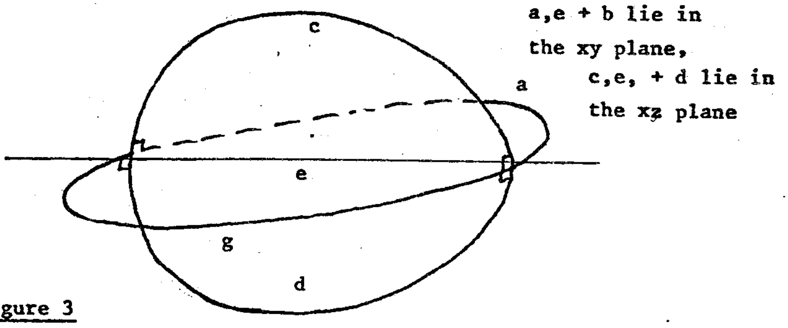


Figure 3

Possible Wrist Trajectioies

Figure 3 illustrates the limiting cases of curves which lie only in vertical or horizontal planes and therefore cause either wrist flexion or rotation.

The fine adjustments mentioned - (ii) can be achieved by using the sensors incorporated in the tactile hand. While these are normally used in active control of gripping, they may be used passively (when no grip command signal is present) to provide wrist movement input. Thus index finger contact along can control clockwise rotation of the wrist and little finger contact causes anti-clockwise rotation. Similarly finger tip contact causes dorsiflexion while contact with the heel of the hand causes palmar flexion. Preliminary studies have shown that conductive rubber sensors are insensitive to spurious vibrations and are therefore suitable.

PROVISION OF INPUT SIGNALS

To test the feasibility of the proposed control system it is essential that the signals provided by the patient should be independant, of high resolution and capable of producing repeatable results over a long period of time. These criteria necessitate the use of a fixed frame of reference which is stationary while the patient is moving his shoulder or flexing his spine. To this end a harness was made using stainless steel as it did not corrode and, being strong, provided a robust frame that, once bent and machined to fit the wearer, was easy to put on and needed no adjustment. The transducers chosen were linear potentiometers as they needed no external circuitry. At the shoulder the two transducers were connected between the harness and a fibre glass shoulder cap. The transducer to measure spinal flexion was connected between a waist belt and the harness, figures (4,5).

RESULTS OBTAINED USING THE HARNESS

The movement in the Y direction (spinal flexion) was found to be independant of the two movements of the shoulder, so detailed tests were carried out on the x + z inputs using a graph plotter. These tests were all performed on one of the authors since the harness was initially constructed to fit his person. The x + z inputs from the harness driving the x + y channels of the plotter respectively. The tests performed were:

a) Co-ordinated Movements - This was the first test tried as it gave the wearer practice in controlling the inputs independently. The first result is shown in Figure 6. After 1½ hours good control could be obtained enabling writing as shown in Figure 7.

b) Static Positional Control - A matrix of points (3) was used and the and the gain of the plotter adjusted so that all the points could just be reached by moving the shoulder over the whole range. The pen was then moved to above each of the points in turn, the pen lowered and the shoulder held in position for 30 secs (Figure 8.).

c) Dynamic Positional Control - The same matrix of points was used and the subject moved the pen from one point to another as quickly as possible upon a command naming the next point to go to the sequence 7,5,6,12,2,1,9,11,3,10, 8,13,4,7 was chosen to cover a variety of distances and directions. The time taken to move through the sequence was 28 secs. (Figure 9.).

d) Proprioceptive control - In order to test the amount of feedback the wearer obtained from the harness, two experiments were carried out. Firstly drawing squares and writing letters (the letter S was chosen) with eyes closed (Figure 10) and secondly repeating test (b), closing the eyes once the pen was lowered (Figure 11).

One of the problems with these tests was the fact that there was a considerable amount of stiction in the x-y plotter, which made smooth, co-ordinated movements of the pen difficult.

RESULTS USING AN ARM PROSTHESIS

To test the proposed control scheme a four degree of freedom, (shoulder

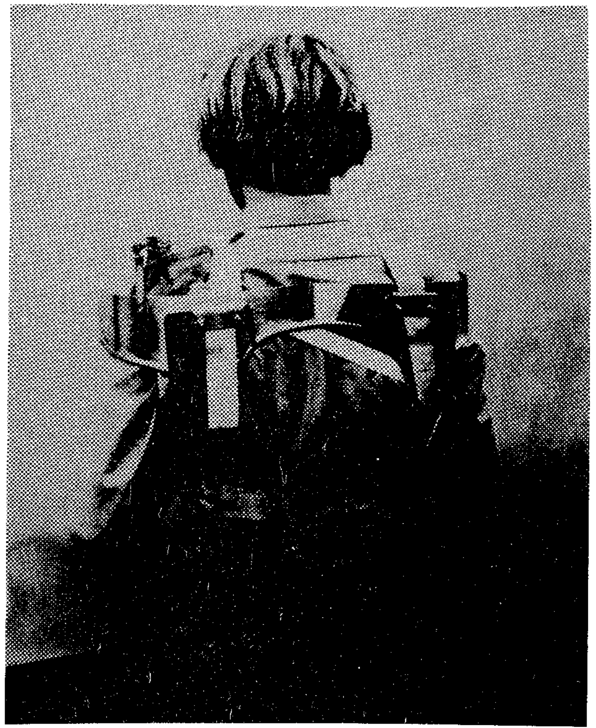


Figure 4

Back View of Harness

Figure 5

Front View of Harness

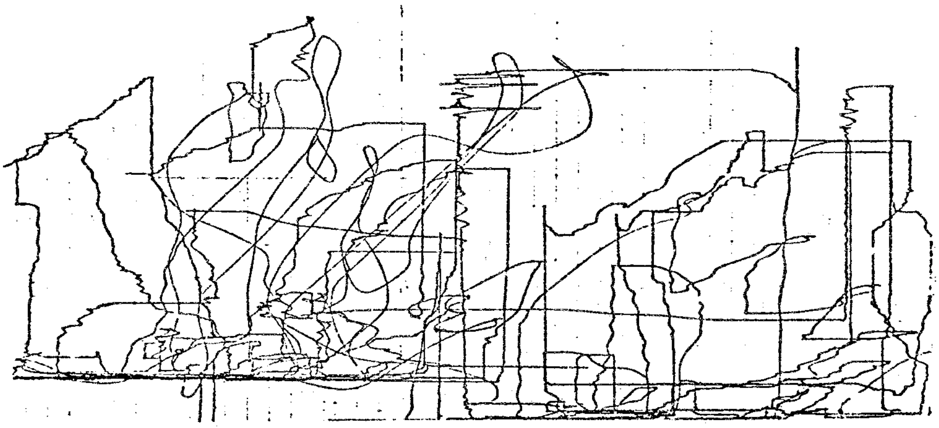


Figure 6

First Attempt at Co-ordinated Control

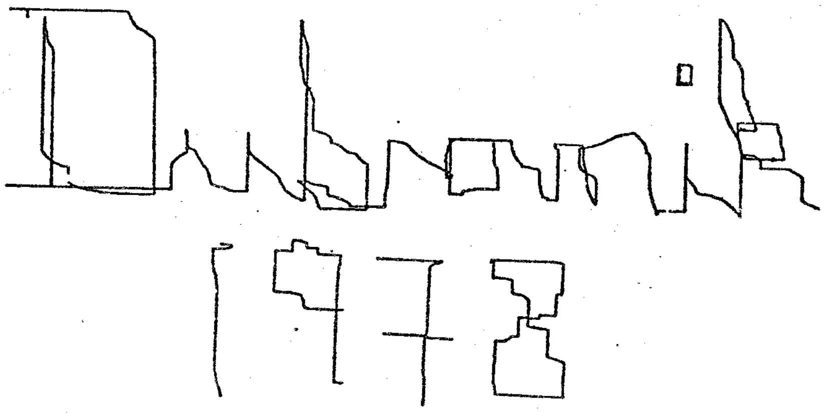


Figure 7

Co-ordinated Control after 1½ hours Practice

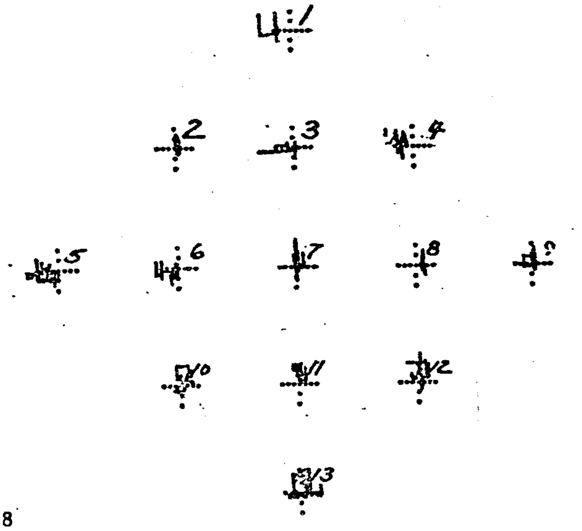


Figure 8

Static Positional Control

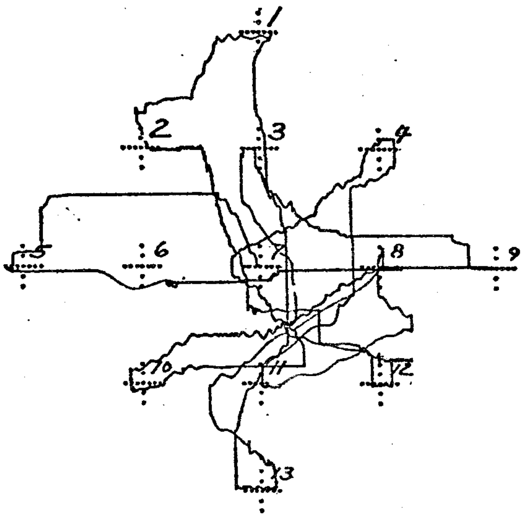


Figure 9

Dynamic Positional Control

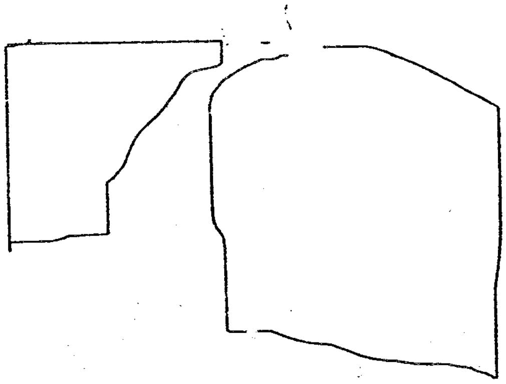


Figure 10

Drawing Squares with Eyes Shut

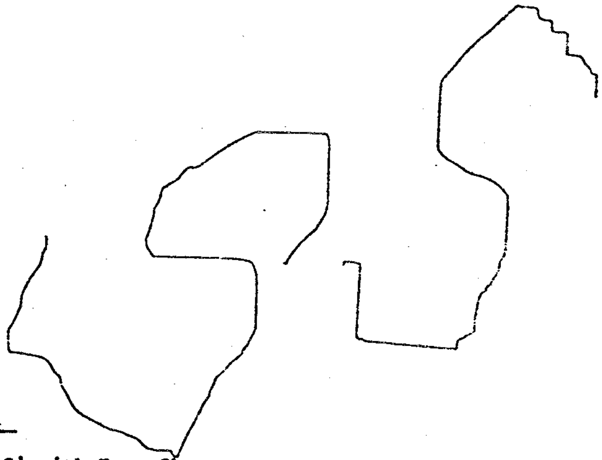


Figure 11

Drawing 'S' with Eyes Shut

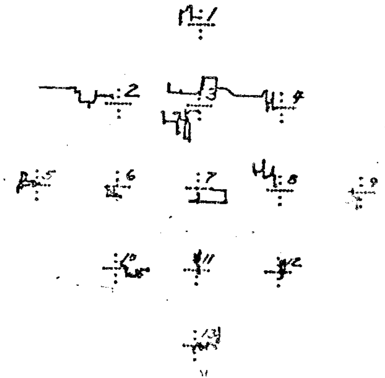


Figure 12

Static Positional Control with Eyes Shut

flexion and rotation, and elbow flexion and rotation) electrically powered arm was built(4). So far tests have been carried out without the constraint on elbow position. Due to the increased complexity of the co-ordinate transfer equations a computer controlled system was not possible as the time taken to calculate the joint angles was prohibitively long. To overcome this an analogue controller of known stability was designed.

The results of the tests on the prototype prosthesis have been very encouraging. Although only a small number of subjects were tested, the uniformity of their opions gave a measure of confidance in the validity of the results obtained. When controlling the prosthesis by body movement the subjects were aware of thinking of the required wrist position rather than the necessary position of the shoulder. This implies that the arm is being controlled at a largly subconscious level, as in this case of a human arm. A short 16mm film has been made which shows the characteristics of the prototype system in operation.

CONCLUSION

A control scheme has been proposed to control a six-degree of freedom arm requireing only three input signals from the wearer and with sufficiently related movements to enable subconscious control. The arm has been designed to interface with the Southampton Adaptive Hand Prosthesis and sensory signals from this hand are required to provide final alignment of hand orientation through movements at the wrist.

A platform through which the limb may be joined to the human frame has been constructed in the form of a harness. The harness was found to be comfortable to wear, the author feeling no fatigue after wearing it for three hours. It was easy to put on and required little adjustment. After a short training period the control was subconscious, with the wearer thinking of moving the pen rather than his shoulder. The results obtained were very encouraging and compare favourably with those obtained in other research centres.

REFERENCES

1. TODD, R.W. : 'Adaptive control of a Hand Prosthesis' Ph.D. Thesis, Department of Electronics, University of Southampton, October 1970.

2. CODD, R.D. : 'Development and Evaluation of Adaptive Control for a Hand Prosthesis', Ph.D. Thesis, Department of Electronics, University of Southampton, March 1975.

3. MORTIMER, J.T., BAYER, D.M., LORD, R.M. and SWANKER, J.W. : 'Shoulder Position Transduction for Proportional Two Axis Control of Orthotic/Prosthetic Systems,' Control of Upper Extremity Prosthesis and Orthoses, edited by P. Herbert et al.

4. STOREY, N. : 'Control of an Arm Prosthesis', Ph.D. Thesis, Southampton University, April 1977.