A STUDY ON THE FLEXIBLE VISUAL POINT CONTROL OF A COMPLETE ARM PROSTHESIS

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Abstract

In the present paper, a flexible control system for a shoulder disarticulation prosthesis is proposed. Information of head orientation and shoulder motion are used as control signals in our system. The control algorithm is so made as to move the terminal device of the prosthesis to the visual point by information of head orientation and shoulder motion. The materialized system was tested on several normal subjects and one upper limb amputee with an electrically powered prototype shoulder disarticulation prosthesis with six degrees of freedom.

The results showed that the subject could move easily the terminal device anywhere within the reach at his will, except extreme neighborhood of the face. As a complement for such a case, a modified fixed program control scheme was introduced and a prototype of the control system comprising the above two control schemes was implemented electronically with a microcomputer. By the patient's tests, it was proven that the control system proposed here had more adaptability and flexibility than, and as good reliability as the pure fixed program control system.

1. Introduction

The control of shoulder disarticulation prosthesis(SDP) is becoming an increasingly important problem as engineering advances in hardware production have made a SDP available in practical use.

This report briefly summarizes the results of several years' work by the authors and many co-workers at Tokushima University and Takuma Radio Technical College on the development of coordinated motion control of electically powered artificial upper limbs[1∿4]. We developed a coordinated motion control system using the well known fixed program control(FPC) scheme and investigated for improvement on the basis of experimental fitting on an amputee. As a result, it became clear that this method had the advantage of simplicity and reliability, but it had also reduced adaptability. The above disadvantage seemed to be covered by introducing a flexible control scheme, which could drive the terminal device of the prosthesis(TD) to an arbitrary point in space at his will. From this point of view, our later efforts have been aimed at the research on such a flexible control scheme. Furthermore, a good control scheme is thought to involve the patient's participation in the control system, thus making minimum the patient training, concentration and efforts to operate. Therefore, our efforts also have been done to this point.

So far, several reports concerned with flexible control of an upper limb prosthesis have been published. The position control method using motion of the clavicle was adopted to pneumatically powered arm with five degrees of freedom by Simpson[5]. Storey[6] extended this method of control to include extra degrees of freedom. And, Potter[7] adopted end control method using head orientation to control an upper-extremity orthotic system. These control methods satisfy extended physiological proprioception(E.P.P.) conditions[8] and have superior flexibility.

On the other hand, we observed activities of daily living(A.D.L.) of normal subjects in regard to cooperated motions among the eyeballs, head, shoulders and upper limbs. According to our observations, we got the following knowledge. As partly pointed out by Engen[9], the head, the shoulder and the line of vision always move in assosiation with the motion of a moving upper limb. Particularly, the eyes are almost always turned towards the handled object, thus making easy the setting of visual point on the object. Also, the head and the shoulder always move in such a way to help the movement of the line of vision and the motion of upper limb, respectively. Based on these understandings, we adopted the nearly ideal scheme which can lead the TD to the visual point with the information from head orientation and shoulder motion.

A new system, named a flexible visual point control(FVPC) system, was constructed using analog electronics. The result of laboratory evaluation shows that the subject can move the TD to the arbitrary visual point at his will. For any motions of the TD extremely near the face, such as eating, enough reliability is required for safety. In this case, we use the modified FPC scheme in addition to the above FVPC scheme. The motion pattern selection in the former is carried out by applying pattern recognition techniques to the information about wrist rotation and hand prehension. Then, one of six kinds of patterns can be selected. A prototype of the control system comprising the above two control schemes was implemented electronically with a micro-computer.

Six degrees of freedom were expected to be controlled. They are shoulder rotation, shoulder flexion-extension, humeral rotation, elbow flexion-extension, wrist rotation and hand prehension. Experimental results by several normal subjects and one upper limb amputee have demonstrated that this control system has both flexibility and reliability. If the head orientation and the shoulder motion transducer is miniaturized, this will become one of very useful methods for controlling an SDP.

2. Flexible Visual Point Control(FVPC) System

2.1 Control Algorithm

It seems very favourable to use the visual sensation to the control of a SDP. To do this, the line of vision may be the first to be taken up. The line of vision can be determined by the eyeball orientation, but the measurement of the latter is not an easy matter so far as practical application is concerned.

For these reasons, we preferred a system in which the natural direction of the line of vision was evaluated from head orientation, and the TD was led to the direction of the line of vision by the head orientation. By this system, an amputee is able to control the prosthesis without watching the TD. The control signals, the head orientation and shoulder motions, are shown in Fig.1. The modelized upper-limb system is shown in Fig.2.

Though the joint part of a human head and spinal column has a complex construction enabling the head to perform delicate motions, in this model, the intersection of atlas and axis is supposed to be an imaginary head fulcrum. In Fig.1 and Fig.2, this point is shown as O. The head orientation is assumed to be the orientation of the straight line OF in Fig.1, which is drawn right in front of the face through O. Thus the head azimuth rotation angle ϕ_3 and elevation angle ϕ_4 indicate the head orientation. In Fig.2, the azimuth angle and elevation angle of the line of vision are assumed ϕ_1 and ϕ_2, respectively. The reference point of ϕ_1,ϕ_2 is the same as that of ϕ_3,ϕ_4.

In Fig. 1, δ_2 and δ_4 represent forward and backward motion of the shoulder, and δ_1 and δ_3 represent elevation and depression motion of the shoulder.

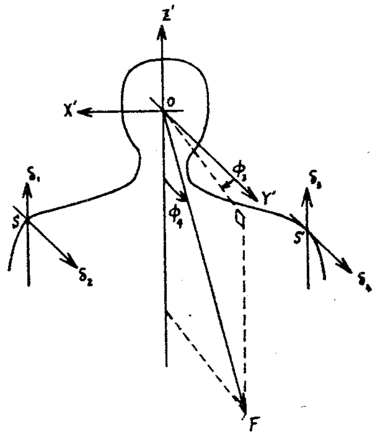

Fig. 1. Control signals.

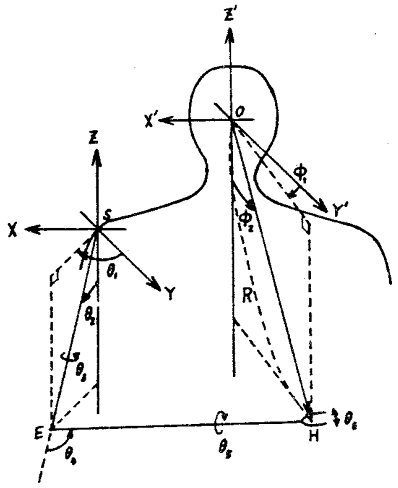

Fig. 2. Mathematical model of upper limb system.
O: center of head rotation S: center of shoulder joint
E: center of elbow joint H: center of TD

In Fig. 2, $\theta_1 \sim \theta_6$ are the joint angles of a SDP and are defined as follows;

θ_1: shoulder rotation angle, θ_2: shoulder flexion-extension angle,
θ_3: humeral rotation angle, θ_4: elbow flexion-extension angle,
θ_5 : wrist rotation angle, θ_6 : hand prehension angle.

An approximate relationship between the head orientation and the line of vision can be represented experimentally by the following equations;

$$\phi_1=k_0\phi_3+k_1 \quad (1)$$
$$\phi_2=m_0\phi_4^2+m_1\phi_4+m_2 \quad (2)$$

where $k_i(i=0,1)$, $m_j(j=0,1,2)$ are parameters dependent on an individual. For simplicity and practicality, the linear relations are supposed in equations (1),(2) by putting $m_0=0$. The direction of the line of vision is decided by the equations (1),(2) after linearization. In Fig. 2, the two spherical polar coordinate systems used are shown. One with origin O is named the operation coordinate system, the other with origin S is named the prosthesis coordinate system.

It is arranged that forward and backward motion of the shoulder on the same side as the SDP being controlled results in extension and contraction of the artificial arm, thus causing increase and decrease in the distance R between O and H in Fig. 2. Then we face two problems, one is the construction of the transform algorithm which defines the relations between the operation coordinate system and the coordinate system of the prosthesis. The other is how to determine the orientation of the prosthesis. Concerning with the latter, we can solve the problem by making the assumption that, the prosthesis is controlled to simulate the natural motion of a human arm. Consequently, the number of necessary signals can be reduced. However, considering that the essence of the flexibility of upper limb exists in the capability of controlling the upper limb orientation at his will, this function has been carefully reserved.

According to our observations, the shoulder of a normal subject is lifted by raising his elbow. Then, it is natural to arrange so that, under the condition that the TD is held at the indicated point, elevation and depression of the shoulder result in elevation and lowering of the elbow, respectively. Concerning with the former problem, as the exact control equations are relatively complex trigonometric expressions, a simplified set of control equations is used for miniaturizing the system. As the result of this simplification, some errors are caused, but the errors can be cancelled by visual feedback. The simplified control equations are as follows;

$$\theta_1=(a_1\theta_3^2+a_2\theta_3+a_3)\theta_4^2+(a_4\theta_3^2+a_5\theta_3+a_6)\theta_4+a_7\phi_1^2+a_8\phi_1+a_9 \quad (3)$$
$$\theta_2=(b_1\theta_3^2+b_2\theta_3+b_3)\theta_4^2+(b_4\theta_3^2+b_5\theta_3+b_6)\theta_4+b_7\phi_2^2+b_8\phi_2+b_9 \quad (4)$$
$$\theta_3=c_1\delta_1+c_2 \quad (5)$$
$$\theta_4=d_1\delta_2+d_2 \,. \quad (6)$$

Equations(3),(4) are based on the condition that the TD is in front of the body. We have calculated the errors with a mini-computer. The result shows that the equations are a fairly good approximation except when the TD has approached extremely near the face.

Equations (5),(6) are determined by considering the range of stump's motion. θ_5 and θ_6 are controlled by δ_3 and δ_4 using the step by step control scheme, respectively.

2.2 Transducer

A number of motion transducers have been reported, and we are especially interested in the semiconductor strain element[10]. Nevertheless, as the main purpose of this paper is to confirm the performance of control scheme, we used single turn potentiometers in a transducer for usefulness and simplicity without respect to miniaturization.

2.2.1 Shoulder Motion Transducer(SMT)

The fundamentals of the structure is shown in Fig. 3. The SMT is fixed to the axilla, and the point P is attached to the shoulder. The motion of shoulder elevation and depression δ_1 or δ_3 is converted to the rotation of the potentiometer P_2 through the linear displacement of the point P. Forward and backward motion of the shoulder δ_2 or δ_4 is converted to the rotation of the potentiometer P_1 through the horizontal displacement of the point P. Consequently, two-dimensional shoulder motion is converted into output voltages of P_1 and P_2. In order to combine the output of P_1 and P_2 to represent the site of P in a rectangular coordinate system with origin S, it is necessary to seek the relationship between the potentiometer outputs and the coordinate of P. Clearly the relationship is linear within a small range of motion.

2.2.2 Head Orientation Transducer(HOT)

The structure of HOT is the same as that of SMT in the fundamentals. The HOT is fixed to the Proc. xiphoideus which is not susceptible to any change of posture, and the point P is situated beneath the chin. The angles of head azimuth and elevation are sensed by the potentiometer P_1 and P_2. The characteristic curves are shown in Fig. 4. As seen from the figure, the relation between angle and output voltage is approximately linear.

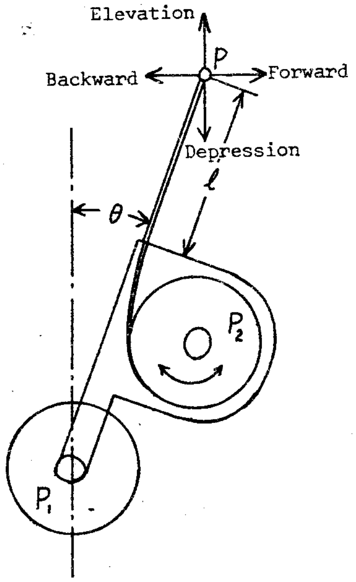

Fig. 3. Fundamental structure of a transducer.

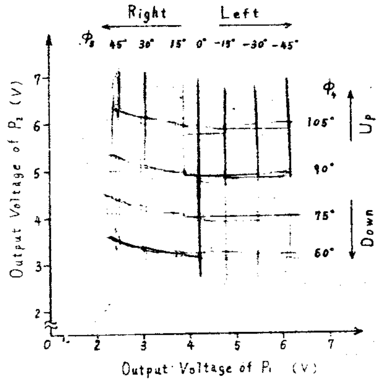

Fig. 4. Characteristic curves of the HOT.

3. Modified Fixed Program Control(modified FPC)

The well known fixed program control is the completely automatic scheme in which a patient need only select one of several programmed motions to be performed. The demerit of this scheme is that it reduces the patient's participation. Then, the multi-mode approach by Carlson et al.[11∿13] and the control system described by Sword and Hill[14] that uses one proportional and one binary or code selector control site to control a 7-df arm prosthesis seems to be useful. From this point of view, the fixed control scheme was modified not to reduce the patient's participation. This control scheme is called the modified FPC scheme.

3.1 Method 1

An orthosis developed by us was used in order to analyse coordinated motions of an upper limb. In Fig. 5, the orthosis during usage is shown. It has an exo-skelton structure which is similar to the Golden Arm[15]. By this orthosis, it is possible to measure $\theta_1 \sim \theta_5$. They are generally the functions of time t. The control signal δ_2 is substituted for time t in order that the patient will participate in the control. As the result of analysing the A.D.L., the relation between each angle and time is sufficiently approximated with a cubic equation. Consequently, control equation of a motion pattern becomes as follows;

$$\begin{pmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \\ \theta_5 \end{pmatrix} = \begin{pmatrix} \theta_1(\delta_2) \\ \theta_2(\delta_2) \\ \theta_3(\delta_2) \\ \theta_4(\delta_2) \\ \theta_5(\delta_2) \end{pmatrix} = \begin{pmatrix} e_1 & f_1 & g_1 & h_1 \\ e_2 & f_2 & g_2 & h_2 \\ e_3 & f_3 & g_3 & h_3 \\ e_4 & f_4 & g_4 & h_4 \\ e_5 & f_5 & g_5 & h_5 \end{pmatrix} \begin{pmatrix} \delta_2^3 \\ \delta_2^2 \\ \delta_2 \\ 1 \end{pmatrix} . \qquad (7)$$

These control equations are necessary as many as the numbers of motion patterns. The forward terminal position and backward terminal position of the shoulder correspond to a start position δ_2^s and end position δ_2^e respectively, in the range of light motion. By means of the equation (7), one can control the speed of SDP with forward and backward motion of the shoulder.

Fig. 5. Mr. Nagaoka wears the orthosis for motion analyses.

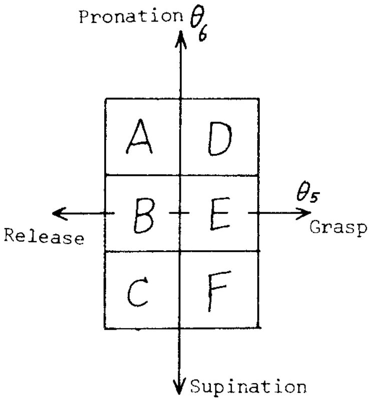

Fig. 6. Practical assignment of motion patterns.

3.2 Method 2

Method 1 has the advantage of reproducibility of complex patterns, but it has also the least flexibility because of fixed start position. We prepared another method in which the start position is arbitrary for such motion as the course is not a serious problem, for example putting a receiver to one's ear. We simplify the equation (7) to linear form neglecting δ_2^3 and δ_2^2. The equation becomes as follows;

$$\theta_i = g_i \delta_2 + h_i \quad (i=1\sim 5). \tag{8}$$

If the start angles of each joint on prosthesis are taken as θ_i^s $(i=1\sim 5)$, end angles as θ_i^e, then we get with a micro-computer the coefficients g_i, h_i by substituting θ_i^s, θ_i^e into equation (9),(10).

$$g_i = \frac{\theta_i^s - \theta_i^e}{\delta_2^s - \delta_2^e} \tag{9}$$

$$h_i = -\frac{\theta_i^s - \theta_i^e}{\delta_2^s - \delta_2^e}\delta_2^s + \theta_i^s . \tag{10}$$

3.3 Selection of Motion Pattern

For a patient who is short of the number of signal source such as a high level spinal cord injury patients, the motion pattern selection problem is solved by applying pattern recognition techniques to the information about wrist rotation and hand prehension. This is based on the fact that the hand orientation varies naturally for easy starting. A step by step control method is adopted for the above two motions so that a patient could change their angles easily.

As this system is used jointly with the FVPC scheme, six patterns are considered. The assignment of practical motion patterns(A∼F) are shown in Fig. 6. By this method one of six patterns can be selected.

4. Total System

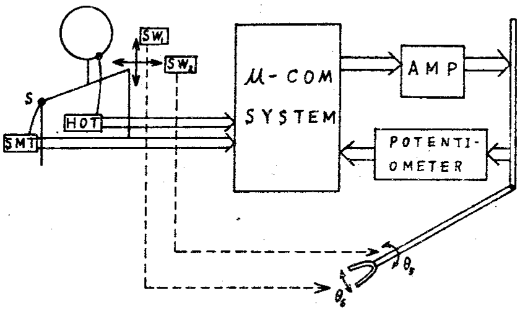

Fig. 7. Total system.

An electrically powered prototype arm prosthesis with the six degrees of freedom mentioned in 1 was produced for estimating the several control scheme. Though, we took careful notice of its function on making the prototype prosthesis, we didn't pay special attention to cosmetic acceptability. For the purpose of miniaturizing the total system in the future, the trial control system was produced using a micro-computer. Fig. 7 is a block diagram of the total system.

This control system uses the FVPC scheme with the modified FPC scheme. The prosthesis is usually controlled by the FVPC scheme. According to request, a patient stops the prosthesis and moves θ_4 and θ_5 to select a desired pattern. Then, he can practice the desired motion pattern using the modified FPC scheme. The total memory in our control system requires about 1.5k bytes and the calculation time for obtaining a signal driving the SDP is less than 0.1 sec.

5. Experimental Results and Evaluation

The system has been tested on one patient and several physically normal people, and the test scenes were filmed.

First, the subject performed the motion of eating, drinking, and putting a receiver to his ear using the modified FPC scheme. Motions of drinking water with a cup and of eating with a spoon were performed by method 1. The motion of putting a receiver to one's ear was also performed easily by method 2. And each motion was smooth and natural. Test scenes

Fig. 8. Drinking water with a cup by the modified FPC scheme method 1.

Fig. 9. Eating with a spoon by the modified FPC scheme method 1.

Next, the subject was asked to move the TD to the indicated point using the FVPC system. After short time training, the subject could move the TD to an arbitrary point without any mental effort. A test scene is shown in Fig. 10. Also, the subject was able to change the SDP orientation with little effort by the shoulder elevation and depression. The subject was asked to grasp, move, and release an object on the desk. In this case, the subject could operate the SDP easily after little training. After a few hours training, one of the subjects could pull a desk drawer and grip out an object in it. A test scene is shown in Fig. 11. Motions of the SDP controlled by the FVPC scheme were also smooth and natural. Because of the error caused when the TD comes extremely near the face, drinking and eating motions are not so easy as merely positioning the TD in space. At present, it seems preferable for simplicity and safety to use the modified FPC scheme for drinking and eating, etc.

The amputee's reactions to the whole system were very favorably positive.

Fig. 10. Moving the TD to the indicated point by the FVPC schme.

Fig. 11. Pulling a desk drawer by the FVPC scheme.

6. Conclusion

a) Two important factors, flexibility and reliability, are principally satisfied in our control system comprising the above-mentioned two control scheme. As the results of our test by amputee, it is shown that this system is useful to control the SDP.

b) The total memory in our control system requires about 1.5k bytes and the calculation time for obtaining a signal driving the SDP is less than 0.1 sec. These conditions present us no problem in practical use.

c) Our system can be constructed, if necessary, by using analog circuits.

d) Further development requires miniaturization and fitting improvement of the signal transducers.

7. Acknowledgment

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