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DEVELOPMENT OF HYDRAULICALLY POWERED WHOLE ARM PROSTHESIS

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Summary

In order to produce a whole arm prosthesis, we select a hydraulic power supply and develop a new rotary actuator named R.S.A. which has a rotary valve in itself. Using these actuators, we make a model of whole arm prosthesis which has 7 degrees of freedom. As a result of EMG analysis on the normal shoulder, we get 10 patterns from 4ch electrodes. We develop an end point control method. Using these 10 patterns, we can easily select an end point of the terminal device and can move the prosthesis towards an object during a meal. The motion is now controlled by a mini computer, but we wish to use a portable micro computer in the near future.

1. Introduction

The prosthesis should have a beatiful appearance, flexibility and portability. But these conditions interfere with one another, putting a great obstacle especially in the delelopment of a prosthesis with a high degree of freedom, concerning both hardware and software. First in order to attain portability in powering many degrees of freedom, we should check an increase of weight by using a device which has high power density. For this purpose firstly we selected hydraulic power supply for our prosthesis/1/. In this part, we prodused and developed micro hydraulic devices.

Secondary in order to give satisfactory functions to the prosthesis, we decided to develop a control system. The whole arm prosthesis is required to have more fuctions than the forearm prosthesis, but the region of the body from which to select control signals is more restricted. In order to overcome this difficulty, we tried an appraisal of EMG analysis. We newly adopted an end point control technique and introduced a coplanar condition aiming at a development of control technique for hand positioning. As a result, a control system admitting of all-round appraisal was developed.

This paper deals not only with the problem of hardware which accompanies hydraulic prosthesis of multi functions, but also with that of software concerning control signal detecting, a planning control system, and a development of coordinated motion technique. Our object was to find the guide line for putting to practical use a multi functional prosthesis.

2. Hardware System of the Hydraulic Whole Arm Prosthesis which has 7 Degrees of freedom

2.1 Hardware System

The experimental prosthesis has 7 degrees of freedom: shoulder abduction (Θ_1), shoulder flexion (Θ_2), external humeral rotation (Θ_3), elbow flexion (Θ_4), forearm supination (Θ_5), wrist flexion (Θ_6), and prehension (Θ_7). [Fig. 1.]. The terminal device can select passively two thumb positions of pinch and lateral pinch. We selected a hydraulic device experimentally. We made a light rotary servo actuator (R.S.A.) and, by using a micro motor, made a very compact electro hydraulic servo mechanism which was applied to every joint. This mechanism excels the usual hydraulic devices. We were able to construct a prosthesis system of such a weight and shape as to make its maintenance and operation easy.

We used duralmin for the main material to make the parts for the structure light, which was reinforced by carbon fiber. We modularized the parts of our prosthesis and made similaly three joints of the shoulder, the trunnion and a support mechanism of thrust bearings. We adopted a manifold and trunnion and support mechanism of thrust bearings. We adopted a manifold and a beam with oil lines in it for hydraulic piping. Applying an involute serration to the output shafts of R.S.A.'s for shoulder flexion, and elbow flexion, we obtained high mechanical strength per volume, and avoided an increase in weight/2/.

By adopting modularization of the prosthesis, we are easily able to construct the upper limb prosthesis and the forearm one. (We had a large space in the prosthesis by adopting the beam structure.) The total weight of our prosthesis is about 2.5 kg. That of forearm is from 300 g (1 degree of freedom) to 650 g (3 degrees of freedom). The upper-limb which has 5 degres of freedom weighs 1370 g. These values do not include the weight of the socket and cosmetic cover. The size of the prosthesis correspondes to the body demensions of the average Japanese male adult, and the total length is 645 mm. The length from the tips of the fingers to the wrist is 120 mm, that from the wrist to the elbow is 235 mm, and that from the elbow to the shoulder is 290 mm [Fig. 2.].

2.2 Rotary Servo Actuator (R.S.A.)

The R.S.A. is composed of a hydraulic oscillating motor and a rotary spool valve [Fig. 3.]. The hydraulic pressure in the oscillating motor is changed by the rotary spool valve or the input shaft and makes the valve or the output shaft follow the vane position, so we can say the R.S.A.has a mechanical feedback loop in itself and is a mechanical torque amplifier, because we can move the input shaft by a very small force less than 1 kg cm in valve and we can hope to attain at a few hundred times as large torque at the output shaft as that of the input shaft. Therefore the input shaft can be operated by a micro servo motor, and we can utilize the R.S.A. as a micro electo-hydraulic servo actuator. The R.S.A. is proof against the dust of oil and is maintained more easily than a servo valve. In this paper we conclude the R.S.A. is suitable for the actuator of the prosthesis which has many degrees of freedom, because it has a very compact shape and is excellent in controllability, so we tentatively made some light R.S.A.'s. In planning it we attended to the design of the shape so that the power density might become maximum, and we also adopted a manifold, and module design. We used dularmin for the main material and hardened the surface by anodic film treatment so that we could easily grind the surface and maintain high power processing. Table 1 shows the experimental R.S.A.'s specification. When the deflexion between the input shaft and the output shaft is zero or in a neutral condition, the total leakage inside the R.S.A. is about 20 cc/min. On the other hand when the deflexion between the shaft is maximum when they are in the overloaded or overrun condition, the total leakage inside the R.S.A. is about 1000 cc/min. To achieve the total efficiency of the prosthetic system, it is possible to improve the R.S.A. by changing the seal from metal seal to the plastic seal at the vane of the hydraulic oscillating motor. The torque of the output shaft is more than 80 % of theoretical torque at 20 kg/cm^2.

In order to move the input shaft, we use D.C. motors or a pulse motor (for handling). The driving torque of the shaft holds low torque, so the necessary power of the drive motor is less than a few hundred milli watts.

The load torque of the input shaft is largely changed at the starting point and is interfered with by the load on the output shaft. But when we use the warm gear on the power transmission, we can ignore the influence of the load variation and correct the delay of the phase of the system and stabilize it. [Fig. 4.] shows the frequency characteristic of the position servo system at the shoulder flexion.

2.3 Hydraulic Pump

The pump is a rotary piston type and can get high pressure in a small volume. The piston which slides on the surface of eccentric cam works one stroke per one round of the rotor/3/4/5/. In order to increase the power density, we think it necessary to raise the usual pressure to about 30 kg/cm^2. We select a coreless motor which has a high output power per weight, and matching it to the pump mechanically by using a planet gear, we get the characteristic in [Fig. 5.]. The weight of the unit is 330 g and its diameter is 23 mm and its total length is 110 mm. At the high pressure the pump has a large noise and low efficiency. So there is still much to improve so far as power source for the prosthesis is concerned.

3 EMG Analysis

The control signal should fulfil two conditions: it must be influenced only by the motion of the signal region and the region of each shoulder must be operated independently.

From these points of view, we examined the region of the shoulder and the shoulder girdle (the region of the collarbone and the shoulder-blade). We observed the relation between several control motions and the EMG patterns which were detected by the several electrodes on the surface of the living body. Supporting the prosthesis by a corset, we get a free space where the shoulder can control the movement, and we can ignore the influence from the constraint and the load, assuming the control posture is vertical both in a sitting position and in a standing position.

On the shoulder and the shoulder girdle, we select 8 muscles: deltoid, trapezius, pectoralis major, teres minor, teres major, serratus anterior, latissiumus dorsi, and infraspination. Some of the eight muscles occupy a large region and are devided into several parts. And the control motion of the shoulder and the shoulder girdle are defined by basic motions and their combinations as shown in [Fig. 6]. The basic motion is defined only by the course irrespectively of the size of the motion from the standard posture in the condition of dropping freely. The control posture is defined by the control motion and its size. We observed the relation between these control postures and the EMG patterns. In order to ascertain whether ordinary motions had a significant influence on the EMG patterns, we examined their influence upon the control muscles at the time of the flexion, extension, lateroflexion, and rotation of head, spinal column, and waist and during deep breathing. From the result of the examination, we consider the control motion to be special EMG patterns. It is easy to hold and reproduce the each level of the patterns. The result of our experiment is stated below:

The EMG pattern and the control posture

1. The EMG pattern dose not change even if the size of the control posture is changed.
2. The EMG amplitude of each channel varies with the size of the control posture, and preserves the same level so long as the posture is static.
3. Some muscles have a close connection with the control posture. The front part and the rear part of the deltoid are respectively connected with the flexion and extension. The upper part and lower part of the trapizius are respectively connected with the elevation and extension.

The influence from the ordinary motion

1. The ordinary motion has a relatively small influence on the selected muscles in the erect posture. So we think we ensure the independence of these signals.
2. In the ordinary motion of the special rotation of the spinal column and the waist, a remarkable EMG activity appears, so we should take care not to move coordinately the zero point of the shoulder in order to help the motion.

Then in order to know how many signal patterns we can get, we examined the on-off patterns by setting a threshold level on each channel. From this result we learned that if the number of combined motions or the number of electrodes increases, the number of the special patterns increases but it becomes difficult, as a matter of fact, to set the threshold level or to select control motion. We detected EMG pattern signals from the signal regions of the deltoid and the trapezius which are closely connected with the standard motion, and there was a fair prospect of separating eleven or twelve sorts of signal through simply combined motions. So we constructed a system to examine the technique of making patterns by setting a threshold level [Fig. 7.]. The EMG signals detected by 4 channel electrodes are rectified, smoothed, changed to 4 level signals and, by the help of a comparator with a threshold level on each channel, were recorded with a visigraph. At the same time, 4 level signals were recorded in order to check the setting level of the threshold. A subject under examination studies the control patterns by using lamps.

From this experiment we can ascertain 10 reliable signals from the 4 regions, that is, the upper part and the lower part of the trapigius and the front and back part of the deltoid. In order to judge these signals, we defined the pattern appearing rate as the time rate of the same pattern during the time that purpose control posture is held. The appearance rate of these 10 patterns is very high and the more than half of them are 100 % and the time of holding the same control posture is a few seconds. The rest are more than 75 %. The signal delay time on the transient state is fixed by the rate of the threshold level and the maximum EMG level, and there is no problem concerning the 4 muscles. The 10 patterns detected by this technique correspond to the actual control motion as shown in Table. 2.

These corresponding pairs are conceived on the assumption of introducing the end point technique which is referred to in the latter part of this paper. High appearance rate patterns are connected with the individual control of three degrees of freedom below the forearm and the other four are connected with four wrist positions or four end points.

4. Control Modes

Considering the control modes of the prosthesis, we can distinguish two kinds of mode, that is, the conscious control and unconscious control correspondingly to the user's consciousness. In each case we can distinguish the control mode by a detecting signal which is used for the control, as shown in [Fig. 8.]. The coordinated controls and the individual controls are distinguished by noticing whether a single signal controls several degrees of freedom at a time or separately. The coordinated controls are divided into three sorts of control; position, velocity and force. One of the position control mode is the path memory control which memorizes the analysis data of the ordinary motions and plays back the memory sequentially. This paper newly introduced the end point memory mode.

This means that the movement path from the present position to the positions of the prosthesis are memorized previously and are selected by the 10 control signals. Arriving at the objective position according to the algorisms mentioned below, two degrees of freedom on the wrist and one degree of freedom on the hand are controlled respectively when the hand is oriented and handled at each position.

4.1 Direct Interpolation Algorism

The end point can be defined with the angular coordinates inherent in the prosthesis unless we take in account the movement path of the wrist. This means that the end point can be defined by the 4 degrees of freedom for wrist positioning θ_1, θ_2, θ_3, θ_4 [Fig. 1.]. The position aimed at in the movement path is calculated by a direct linear interpolation. The result of the calculation can be directly used for the servo system of each joint. Because no coordinates transformation is needed, the structure of movement algorism is extremely simplified.

The direct interpolation algolism is constructed by the next steps.

1. At the request for motion (i.e. when there is a EMG signal) the present position of 4 joints is observed on the shoulder and elbow. θi_0 is the angle which gives the present position (i = 1, 2, 3, 4).
2. θik is the selected end point, i = 1, 2, 3, 4.
3. When there is the request signal for a motion, the calculation of the path and outputting are repeated until the wrist arriving at about the objective position. Defining that T_0 is a total motion time from the present position to the objective position (for about 2 seconds) and the number of interpolation or that of outputting is N (about 25 times), the $\theta ik(t/T)$ which is the object value after t second is calculated as follows:

$$\theta ik(t/T)= \begin{cases} \theta i_0+(\theta ik-\theta i_0)[t/T]1/N & (0\leq t<NT) \\ \theta ik-N\delta\theta & (NT\leq t) \end{cases} \qquad (1)$$

Then $T=T_0/N$. $\delta\theta$ is the calculation error of $(\theta ik-\theta i_0)/N$ and is cancelled if θik is put out at the time of N+1.

4.2 Indirect Interpolation Algolism

In ordinary motion there are several movements in which the movement path of the wrist position is very important. For the example, in order to conduct the movement on a surface like the writing movement, a straight motion is needed. For this purpose we introduce a rule to converse the coordinate between hand oriented coordinates and rectangular coordinates, and to fix the elbow position.

If X_0, X_1, X_2, X_3 are coordinates proper to each joint from the shoulder, then we can define the coordinate conversion matrix as follows:

$$Xn = Rm(n+1)\,Xn+1 \qquad (2)$$
$$n = 0, 1, 2, \text{ or } 3 \qquad m = i, j, \text{ or } k$$

In this coordinated system we defined: $ci = \cos\theta i$, $si = \sin\theta i$, then the elbow position is :

$$Xe = Ri(\theta_1)\cdot Rj(\theta_2)\cdot(0, 0, 0, 1)^t$$
$$= \begin{bmatrix} l_1c_1 \\ l_1s_1c_2 \\ -l_1c_1s_2 \\ 1 \end{bmatrix} \qquad (3)$$

The wrist position is :

$$X_w = Ri\ (\theta_1)\cdot Rj\ (\theta_2)\cdot Ri\ (\theta_3)\cdot Rj\ (\theta_4)\cdot(\ l_2,\ 0,\ 0,\ 1\ )^t$$

$$= \begin{bmatrix} l_1c_2c_4 - l_2s_2c_3s_4 + l_1c_2 \\ - l_2s_1s_2c_4 - l_2c_1s_3s_4 - l_2s_1c_2c_3s_4 - l_1s_1s_2 \\ l_2c_1s_2c_4 - l_2s_1s_3s_4 + l_2c_1c_2c_3s_4 - l_1c_1s_2 \\ 1 \end{bmatrix} \qquad (\ 4\ )$$

Now l_1 is the upper-limb length and l_2 is the forearm length. From this we can observe the present position of the prosthesis.

To restrict voluntary elbow guiding, we fixed on a geometric limiting. Aiming at human-like movements of a normal man, we assume that in uncoscious motions 4 points, L, S, E and W (i, e, Lip, Shoulder, Elbow, and Wrist) are usually on the corplanar surface. This means that in ordinary motions the rotational axis of elbow flexion stands almost vertically on the surface which is made by the three end points, L,S, and E. We suppose that in this way a man can smoothly carry out a reach motion at a meal. If we fix the shoulder position as the origin, and define like this: S(0,0,0), L(X_L,X_L,X_L), E(X_E,X_E,X_E) and W(X_W, Y_W, Z_W), the coplanar condition is :

$$(L\times E)\cdot W = 0 \qquad (\ 5\ )$$

From the restriction imposed by the prosthetic structure :

$$\begin{aligned} |E| &= l_1 \\ |E-W| &= l_2 \end{aligned} \qquad (\ 6\ )$$

Rewriting the above equations

$$aX_E + bY_E + cZ_E = 0$$

here

$$\begin{aligned} a &= X_LZ_W - Z_LX_W \\ b &= Z_LX_W - X_LZ_W \\ c &= X_LY_W - Y_LX_W \end{aligned} \qquad (\ 5\ )'$$

$$X_E^2 + Y_E^2 + Z_E^2 = l_1^2 \qquad (\ 6\ )'$$

$$(X_W - X_E)^2 + (Y_W - Y_E)^2 + (Z_W - Z_E)^2 = 1 \qquad (\ 7\ )$$

From the equations (6)' and (7)'

$$\begin{aligned} X_WX_E + Y_WY_E + Z_WZ_E &= L/2 \\ L &= l_1^2 + X_W^2 + Y_W^2 + Z_W^2 - l_2^2 \end{aligned} \qquad (\ 8\ )$$

From the equations (5)' and (8)

$$Y_E = \frac{L}{2e} - \frac{d}{e} X_E$$

$$\begin{aligned} d &= X_W - aZ_W/c \\ e &= Y_W - bZ_W/c \end{aligned} \qquad (\ 9\ )$$

From the equations (5)'and (9)

$$Z_E = \left(\frac{bd}{ce} - \frac{a}{c}\right) X_E - \frac{B}{2ce} L \qquad (\ 10\ )$$

From the equation (6), (9) and (10)

$$AX_E^2 - BX_E + C = 0$$

$$\begin{aligned} A &= 1 + \frac{d^2}{e^2} + \left(\frac{bd}{ce} - \frac{a}{c}\right)^2 \\ B &= \frac{L}{e}\left(\frac{d}{e} + \frac{b^2d}{c^2e} - \frac{ab}{c^2}\right) \\ C &= \frac{L^2}{4e^2}\left(1 + \frac{b^2}{c^2}\right) - l_1^2 \end{aligned} \qquad (\ 11\ )$$

so

$$X_E = \frac{B \pm \sqrt{B^2 - 4AC}}{2A} \qquad (12)$$

In order to fix the elbow position from the equation (12), it is necessary to make simple selecting rules. Moreover, considering the equations (3) and (4), the object value of each joint can be calculated from (X_E, Y_E, Z_E) and (X_W, Y_W, Z_W)

$$\begin{aligned} \theta_1 &= \sin^{-1} - \frac{Y_E}{l_1 \sin \theta_2} \\ \theta_2 &= \cos^{-1} \frac{X_E}{l_1} \\ \theta_3 &= \sin^{-1} \frac{Y_E Z_W - Y_W Z_E}{l_1 l_2 \sin\theta_2 \sin\theta_4} \\ \theta_4 &= \cos^{-1} \frac{X_E(X_W - X_E) + Y_E(Y_W - Y_E) + Z_E(Z_W - Z_E)}{l_1 l_2} \end{aligned} \qquad (13)$$

In the indirect interpolation algorism the end point is defined by the rectangular coordinates which stand for the wrist position. If the values are Wi (i = 1, 2, 3) then the algorism is shown as follows:

1. First we observe the wrist position for once, and fix the value represented by the rectangular coodinates, as Wi.
2. Fixing the objective end point as Wi_0, the objective wrist point in the motion path can be calculated by the equation:

$$W_{ik}\left(\frac{t}{T}\right) = \begin{cases} W_{i0} + (W_{ik} - W_{i0}) \cdot \left[\frac{t}{T}\right] \frac{1}{N} & (0 \ t \ NT) \\ W_{ik} & (NT \ t) \end{cases} \qquad (14)$$

3. Using equations (9), (10) and (12),the elbow position can be calculated by the wrist position.
4. From the equation (13), the objective angular value can be obtained to operate the prosthesis.

5. The Whole Arm Prosthesis System

Combining the result of EMG analysis and the end point control modes, we constructed the whole arm prosthetic system [Fig. 9.]. The flow chart of the total program is shown in [Fig. 10.]. The program is composed of six parts: (a) signal refreshing part when there was no EMG signal; (b) routine deciding the motive motion by analizing input EMG signal; (c) routine for controlling each joint separately; (d) end point control routine for moving wrist position coordinately; (e) routine for observing the signal in each motion; (f) timer routine for taking program timing. We decided to have the prosthesis take a meal successively by dividing the 10 sorts of EMG signal into the individual control and the coordinate control. When we use the direct interpolation method, the program shown in [Fig. 10.] needs less than 400 steps including the memory area. And by this method, it is possible to stop or change the motion mode at any desired point in the motion path. Now we use a mini computer, but it is possible to utilize a 12 bit micro computer with arithmetic logic unit. The calculating time of one cycle is less than tens of m sec, and offers no problem in operating the prosthesis. Concerning the indirect interpolation algorism, there is still room left for reconsidering the calculating time.

6. Conclusion

Aiming at developing a harmonized system of the prosthesis which has many restrictions in software and hardware, we were able to get a promising prospect. Moreover, introducing the idea of the end point method we could easily and rapidly conduct the movement of the wrist. From this we can suggest a useful method for controlling the multi functional prosthesis.

Acknowledgment

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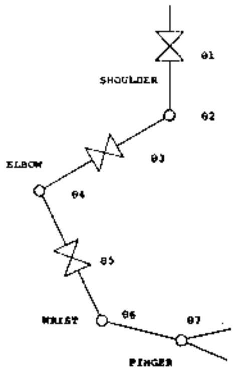

Fig. 1. Arrangement of Degree of Freedom

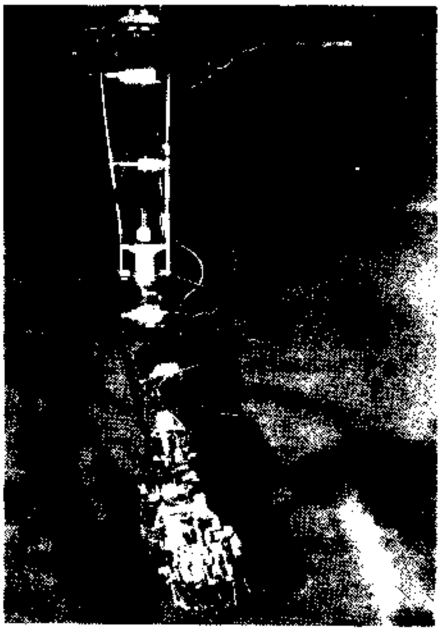

Fig. 2. Whole Arm Prosthesis

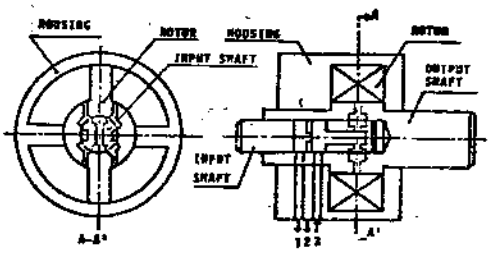

Fig. 3 Standard Structure of R.S.A.

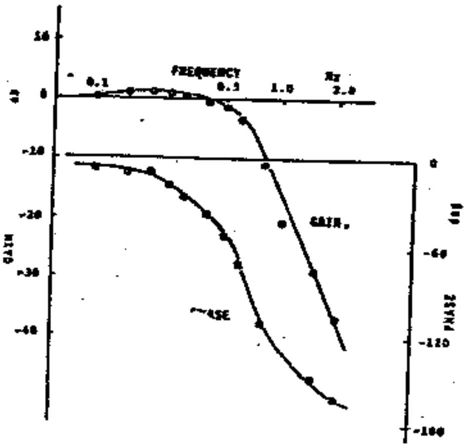

Fig. 4. Frequency Characteristic

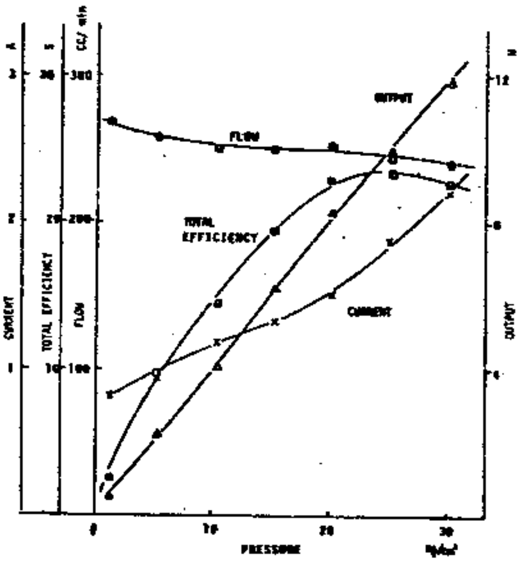

Fig. 5. Pump Unit Performance

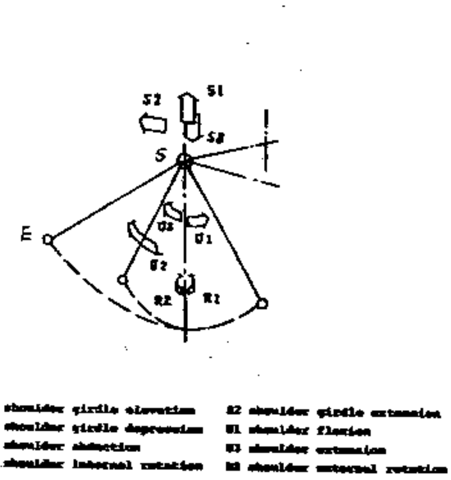

Fig. 6. Standard Control Motion

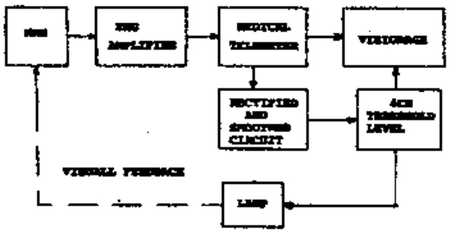

Fig. 7. EMG Vauation System

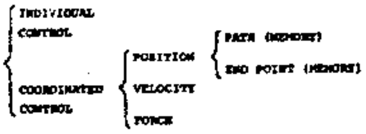

Fig. 8. Control Method

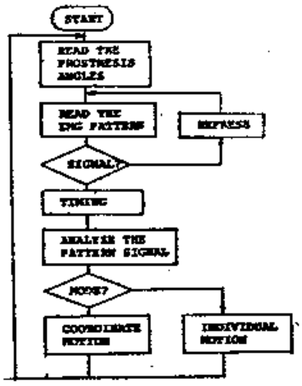

Fig. 10. Program Flow Chart

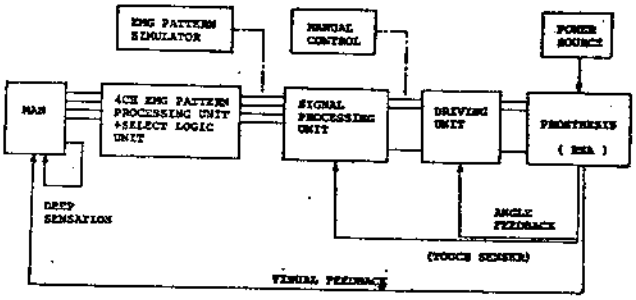

Fig. 9. Control System of the Whole Arm Prosthesis

Specification of R.S.A.

SPEC. / JOINT	TYPE	MAX. ANGLE deg	WEIGHT g	INPUT TORQUE gcm	OUTPUT TORQUE kgcm	VOLUME cc
PREHENSION	MA0.4	100	64	36	14.3	1.7
WRIST FLEXION	MA0.4	100	64	36	14.3	1.7
FOREARM SUPINATION	MB0.4	360	103	36	14.3	4.4
ELBOW FLEXION	MA1.5	100	175	134	53.6	5.9
EXTERNAL HUMERAL ROTATION	MA1.5	100	175	134	53.6	5.9
SHOULDER FLEXION	MA1.5	100	175	134	53.6	5.9
SHOULDER ABDUCTION	MA3.0	100	246	268	107	10.7

Table. 1.

Pattern and Movement

SELECT PATTERN		MOVEMENT
S0	0000	STOP
S3	0011	HAND OPENING
S2	0001	HAND CLOSING
U3	1100	WRIST EXTENSION
U1	1000	WRIST FLEXION
U3	1000	FOREARM INTERNAL SUPINATION
S0U3	1001	FOREARM EXTERNAL SUPINATION
S1U1	0110	FORWARD POINT
S1U2	1110	UP POINT
S1U3	1010	RIGHT POINT
S1	0010	LEFT POINT

Table. 2.

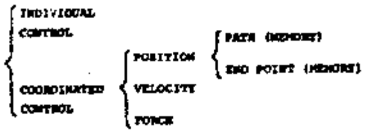

Fig. 8. Control Method

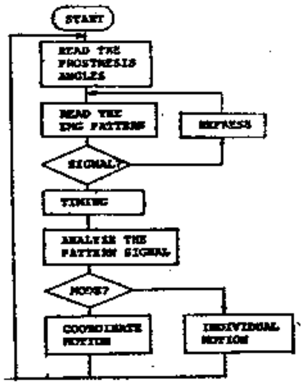

Fig. 10. Program
Flow Chart

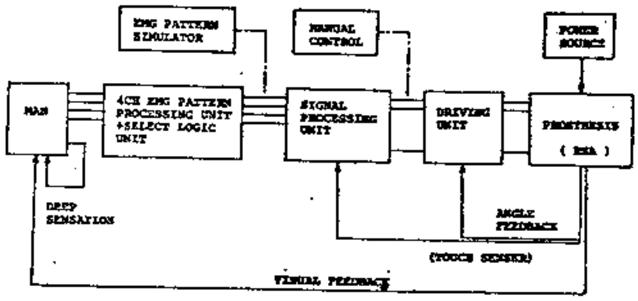

Fig. 9. Control System of the
Whole Arm Prosthesis

Specification of R.S.A.

SPEC. / JOINT	TYPE	MAX ANGLE deg	WEIGHT g	INPUT TORQUE gcm	OUTPUT TORQUE kgcm	VOLUME cc
PREHENSION	MA0.4	100	64	36	14.3	1.7
WRIST FLEXION	MA0.4	100	64	36	14.3	1.7
FOREARM SUPINATION	MB0.4	360	103	36	14.3	4.4
ELBOW FLEXION	MA1.5	100	175	134	53.6	5.9
EXTERNAL HUMERAL ROTATION	MA1.5	100	175	134	53.6	5.9
SHOULDER FLEXION	MA1.5	100	175	134	53.6	5.9
SHOULDER ABDUCTION	MA3.0	100	246	268	107	10.7

Table. 1.

Pattern and Movement

SELECT PATTERN		MOVEMENT
S0	0000	STOP
S3	0011	HAND OPENING
S2	0001	HAND CLOSING
U3	1100	WRIST EXTENSION
U1	1000	WRIST FLEXION
U3	1000	FOREARM INTERNAL SUPINATION
S0U3	1001	FOREARM EXTERNAL SUPINATION
S1U1	0110	FORWARD POINT
S1U2	1110	LIP POINT
S1U3	1010	RIGHT POINT
S1	0010	LEFT POINT

Table. 2.