Proc. of 5th Int. Symp. on External Control of Human Extremities, ETAN, Yugoslavia, Dubrovnik 1975.

A HYDRAULICALLY POWERED PROSTHETIC ARM WITH SEVEN DEGREES OF FREEDOM (PROTOTYPE-1)

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Abstract

This paper is concerned with a hydraulically powered prosthetic arm with seven degrees of freedom (Prototype-1). A rotary-servo actuators is used for every degree of freedom.From the standpoint of controlling,three actuators are arranged at the shoulder joint so that the axes of forward-backward elevation of the shoulder and of elbow flexion-extention always keep parallel to each other during reach-motion of the hand. Most of the oil-paths are designed to go through inside of the structures of the prosthetic arm, i.e. actuators and beams, so that troublesome external piping of oil-tubes are not to be used.

Introduction

As a first step to develop powered prosthetic arm with multi degrees of freedom, a hydraulically powered prosthetic arm with seven degrees of freedom (Prototype-1) was built, so as to investgate the way of arrangement of degrees of freedom that would provide the prosthetic arm with functions similar to those of a natural arm and that would make it easy to control the prosthetic arm with EMG signals, and so as to define problems which should be researched and developed for practical application of the powered prosthetic arm with multi degrees of freedom.

Basic Design Concept

It is said that a natural arm has twenty seven degrees of freedom from the shoulder joint to the tips of fingers and most of the degrees of freedom, however, are concentrated in the hand/1/. So that to reduce the number of degrees of freedom, function of the hand is limited only to grasp adaptively an object with complicated figure. Then, one degree of freedom was given to the hand.

The functions of the shoulder are to be decomposed into three elements, i.e. roation, forward-backward elevation and inward-outward elevation, so that three degrees of freedom are required for the shoulder joint unit of the prosthetic arm. In addition to these, one degree of freedom for flexion-extention of the elbow joint, one for rotation of the forearm and one for flexion-extention of the wrist are required. So that seven degrees of freedom, in total, are provided for the prosthetic arm. And one actuater is to be provided for each degrees of freedom, seevn actuaters in total.

The way of arranging three degrees of freedom in the shoulder joint unit is the most difficult in stand point of controlling, function and appearance. As shown in Fig.1, there are six alternative ways of arranging them. The arrangiment is to be chosen among these six alternatives that can made the prosthetic arm as similar as possible to the natural arm both in appearance and functions, and that can make it easy to control.

Now considering reach-motion on the hand-oriented coordinates, it is assumed that positioning of the hand is performed on the plane which is defined by the shoulder joint, the elbow joint and the wrist joint. .

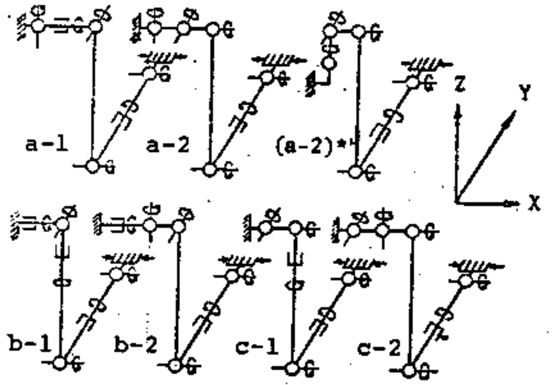


Fig.1 Arrangements of Degrees of Freedom

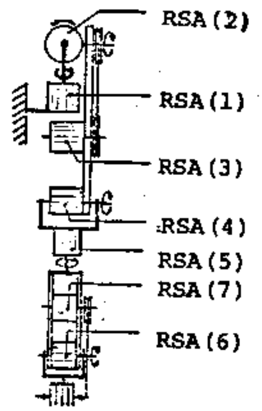


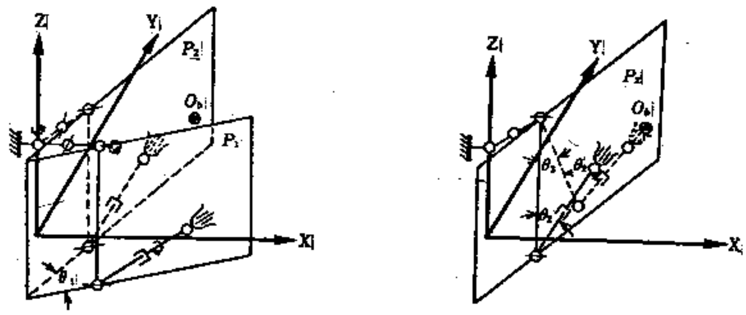
Fig.2 Arrangement of Actuators

In Fig.3 is shown away of positioning of the hand by reach-motion. At first, the hand is oriented from a plane (P1) to a plane (P2) by shoulder rotation (a), and next the hand is positioned on the plane (P2) by foward elevation of the shoulder joint unit and the elbow extention (b). The arrangiment of degrees of freedom of the arm is that of (a-2) in Fig.1.

Performing in this way, the positioning of the hand, that is mostly a problem of three dimensional control, can be converted into a problem of two dimensional control, then the control of the prosthetic arm may be performed definitely easier. For this, the degrees of freedom must be arranged in such a way that the axes of forward-backward elevation of the shoulder and flexion-extention of the elbow keep parallel to each other independently of the situations of the other degrees of freedom. There two alternative ways of arranging the degrees of freedom which can satisfy these conditions, i.e.

a-2 and c-2 in Fig.1.

Considering appearance, the modulated version of a-2, i.e. (a-2)* in Fig.1 is chosen as a arrangement of the degrees of freedom for the prosthetic arm. The actuaters are arranged as shown Fig.2 basing on the arrangement (a-2)* in Fig.1. The three axes of the actuaters for the shoulder joint unit are to meet at one point so as to control the arm easily. Also, with a stand point of making the prosthetic arm similar to a natural arm, the actuater for foward-backward elevation of the shoulder is installed at the middle of the upper arm, and power from the actuater is transmitted via a cable and pulleys.



a) Orientating b) Positioning

Fig.3 Positioning of the Hand in Reach Motion

Driving System

Hydraulic pressure is used as the source of driving power for the actuaters (30 kg/cm^2), and rotary servo actuaters (RSA) are employed for each degrees of freedom/2/.

The principle of performance of the RSA is shown in Fig.4, input shaft of the RSA itself is designed to accomplish the function of a flow control valve. Differing from the conventional actuators of cylinder type and rotary type, it can do without any control valve or servo valve, and therefore proves very effectiveness in simplifying the hydraulic circuit. The specification of the RSA used for each degrees of freedom are shown in Table 1.

Stop Left Neutral Right Stop

Fig.4 Principle of Performance of RSA/3/

In general, feeding of pressure oil to actuators and return of oil from actuators to oil tank are made to go through external piping and distributors. But external piping is anseemly in appearance furthermore, it often privent the prosthetic arm from performing smooth motions. So that internal oil paths which go through inside the structures themselves of the prosthetic arm are employed in place of external piping, and oil paths are branched inside the actuaters or beems themselves.

Table 1. Specication of RSA

Function	Type	Swing Angle (degree)	Outputs* Torque (kg-m)	Weight (g)	Quantity of Flow (cm^3/rad)
Shoulder Rotation	MB15	280	0.64	610	2.72
Shoulder Elevation For.-Back.	MB30	280	1.28	387	5.32
Shoulder Elevation In.-Out.	MB30	280	1.28	380	5.32
Elbow Flex.-Ext.	MB15	280	0.64	650	2.72
Forearm Rotation	MB04	280	0.17	155	0.73
Grasp	MA04	100	0.17	110	0.80
Wrist Flex.-Ext.	MA04	100	0.17	110	0.80

* Value is in the case of oil pressure 30 kg/cm^2

In Fig. 5 is shown the upperarm beam made of FRP, inside of which oil paths are provided. The oil paths inside the beames are made by milling three grovees on a FRP plate and by sealing them off with FRP plate cover of 2mm in thickness. And some ports are opened

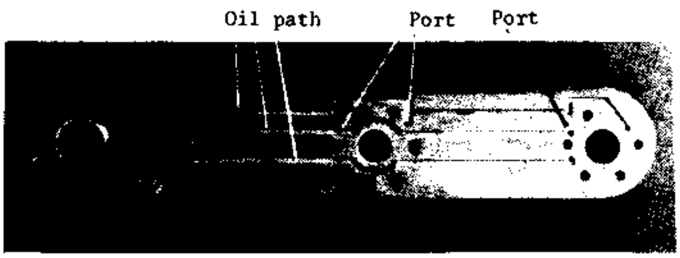


Fig. 5 Oil Paths in the Upperarm Beam

on the beams for feeding pressure oil into RSA or returning oil from RSA. The three grooves are for pressure oil, return oil and drain oil. But oil paths between RSA (2) for inward-outward elevation of shoulder and RSA (3) for foward-backward elevation of shoulder are provided with synflex tubes of external piping, since in this portion it is difficult to provide the oil paths in side the structures. The hydraulic circuit is shown in Fig.6.

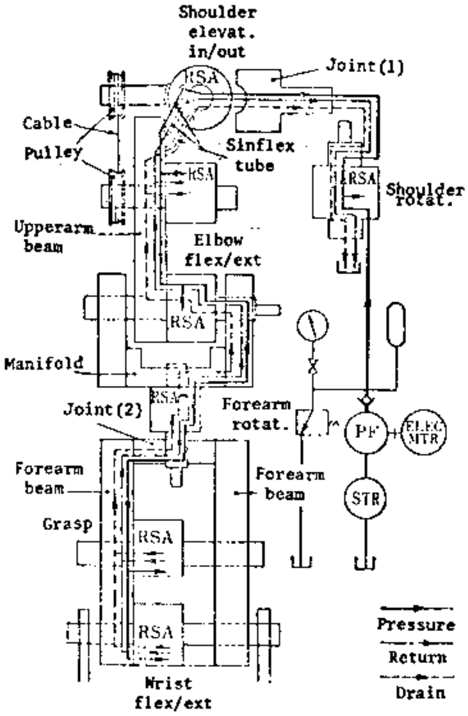


Fig.6 Hydraulic Circuit

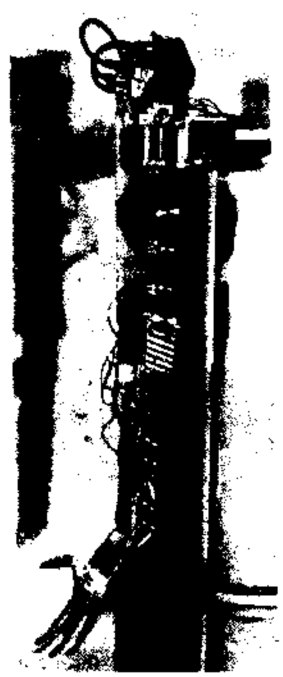


Fig.7 Photograph of the Prosthetic Arm

Construction of the Prosthetic Arm

An overall view of the prosthetic arm is shown in Fig.7. The construction of the shoulder joint unit except forward-backward elevation unit, are shown in Fig.8. To simplify the method of controlling the prosthetic arm, the three units of shoulder are designed in such a way that the axes of there rotation meet with each other at one point.

A joint (1) made of duralumin, inside of which oil paths are provided, is fastened to the output shaft of the RSA (1) for shoulder rotation, and on the top of the joint output shaft of the RSA (2) for inward-outward elevation of shoulder is mounted. Method of application of the RSA (2) differs from other RSA, i.e. the output shaft of it is fixed to the joint (1) and housing rotates. On the housing a joint (2) made of steel is fixed, which a shaft for foward-backward elevation of showlder is integrated with. And on the joint (2) the upper arm beam is mounted with a ball bearing. RSA (3) for foward-backward elevation is mounted on the beam, and power to elevate shoulder foward and backward is transmitted with pulleys and a cable.

The oil paths provided inside the joint (1) are connected to ports which open on periphery of the output shafts of RSA (1) and RSA (2). And the connected potions are sealed with O-ring.

An input shaft of RSA (1) for shoulder rotation is driven by a DC motor, which is controlled with EMG signals, via gears and a connecter, when the connecter and the input shaft start revolution in one body, the joint (1) and the output shaft of RSA (1) follow them.

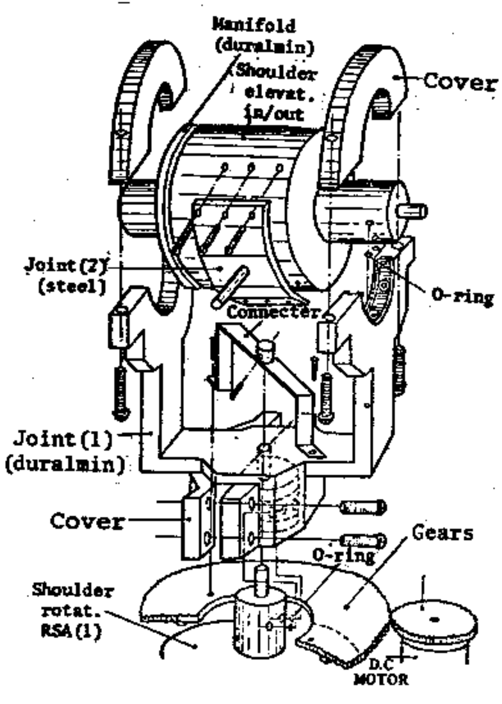


Fig.8 Shoulder Joint Units

Constraction of the forearm rotation unit is shown in Fig.9. A manifold is fixed to joint (3) and (4) those are fixed to the output shaft of RSA (4) for elbow flexion-extention. And RSA (5) for rotation of the forarm is mounted on the manifold. Halved joints (5) are fastened to the output shaft of RSA (5), and then two forearm beems made of FRP are fixed to the joints. The input shaft of RSA (5) is driven in the same way as that of RSA (1) for shoulder rotation.

The hand unit of the prosthetic arm (prototype-1) is equiped with an adaptive grasping mechanism composed of links and springs, after the model of WASEDA HAND 4P/4/. The motions of the fingers are controlled by RSA (7) via a cable. RSA (7) for fingers operation is located not in the hand unit but in the forearm between RSA (6) for wrist flexion-extention and RSA (5) for forearm rotation. With the choise of this arrangement appearance of the hand unit becomes so smart (Fig.10).

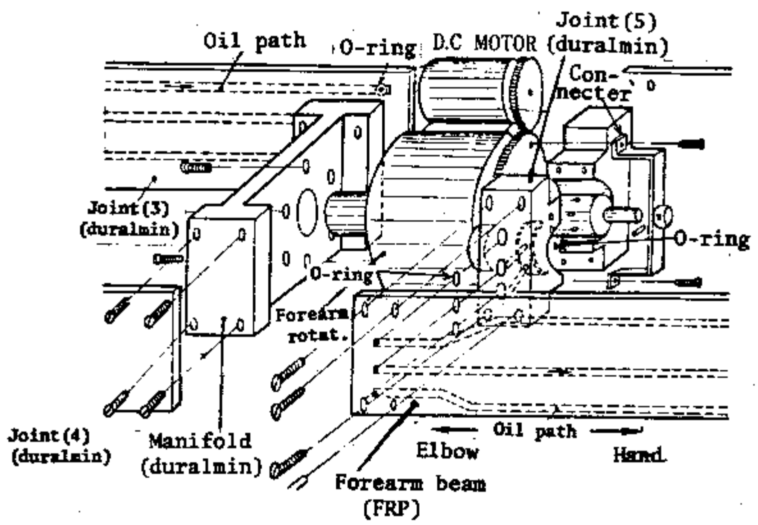


Fig.9 Forearm Rotation Unit

Dynamic Characteristics of RSA and RSA-DC Motor System

Frequency response of RSA individual and RSA-DC motor system were examined (Fig.11). In the case of RSA individual, the frequency response of both gain and phase are rather satisfactory, but in the case of RSA-DC motor system, gain falls down rapidly over 0.1 [Hz], and phase delays 90[deg.] up to 1[Hz], and amount of delay increases rapidly over 1[Hz]. These seem to be the delay of phase caused by 90[deg.] delay inherent in integrating elements, folling down of gain caused by inertia of reduction gears, loosening and elongation of belt of pulley.

In order to compensate the delay in the phase, it is necessary to feedback into this system the phase advancing facters. And as for the foll down in gain, cause of it seems to be mainly due to the inertia of reduction gears of DC motor, so it is necessary to use

DC motors with lower speed and higher torque and reduction gears with small reduction ratio.

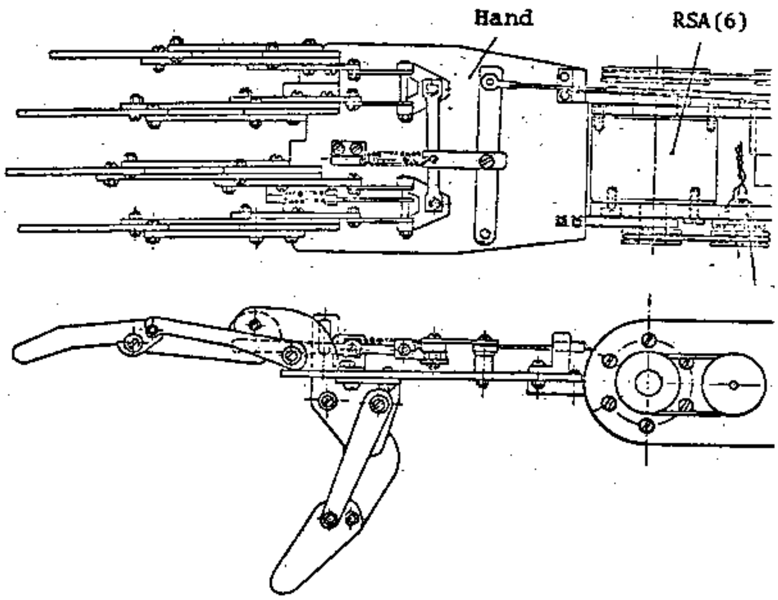


Fig.10 Hand Unit

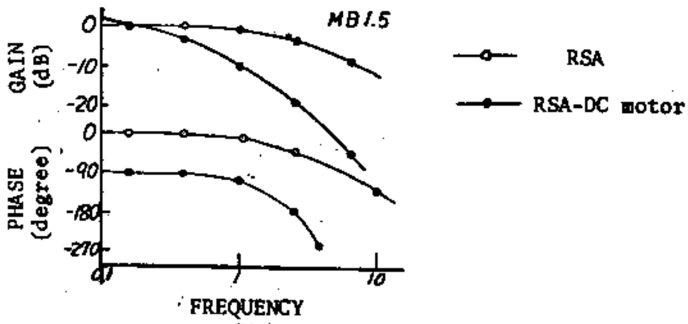


Fig.11 Bode Diagram

Assessment of the Structure of the Prosthetic Arm

To avoid as far as possible using oil tubes of external piping and to adopt the system of oil paths built inside the structure of the prosthetic arm has turned out to be quite a success as the new system has not only made the arm smart appearance but has also eliminated the kind of problems that have been almost an avoidable in the external piping such as the twisting of tubes caused by the motions of the arm.

The arrangement of the RSA employed seems to be rather satisfactory with regard to the appearance of the arm and to the functions. Appearance of shoulder unit is also favorable considering that three RSA being installed here. Another factor of importances is that the RSA for finger control is installed in the forearm unit rather than in the hand unit, thereby the piping system in the forearm is able to be simplified and the appearance of the hand becomes favorable.

The most serious probrem inherent in this prosthetic arm is that its weight is about 4[kg] and that the RSAs are so heavy that thire weight occupy 60[%] of the total weight. To improve the present prosthetic arm it is necessary to develop the RSA smaller in size, lighter in weight and more efficient than what is.

Conclusions

As the first step to develop the powered prosthetic arm with multi degrees of freedom, the hydraulically powered prosthetic arm with seven degrees of freedom was manufactured.

Three degrees of freedom are provided to shoulder joint, and with the aim to control the prosthetic arm easily they are arranged in such a way that the axes of foward-backward elevation of shoulder and elbow rotation always keep parallel, and then positioning of the hand by reach motion can be performed on a plane.

The RSA is provided for every degree of freedom. The RSA for operating the fingers is located not in the hand unit but in the forearm, thereby piping system in forearm is simplified and the appearance of the hand unit becomes relatively favorable.

The piping system of the prosthetic arm can be designed internly, and, asthe result, the interference between piping lines and moving arm be eliminated.

Acknowledgment

We would like to expressed our thanks to Dr. Y.Saida, Mr. K.Imanaga(Mitubishi Metal Co.), Dr. S.Simamura, Mr. S.Noguchi(Mechanical Engineering Lab.) and Mr. T.Yamanaka(Waseda Univ.) for technical help and advice at various stage of the project.

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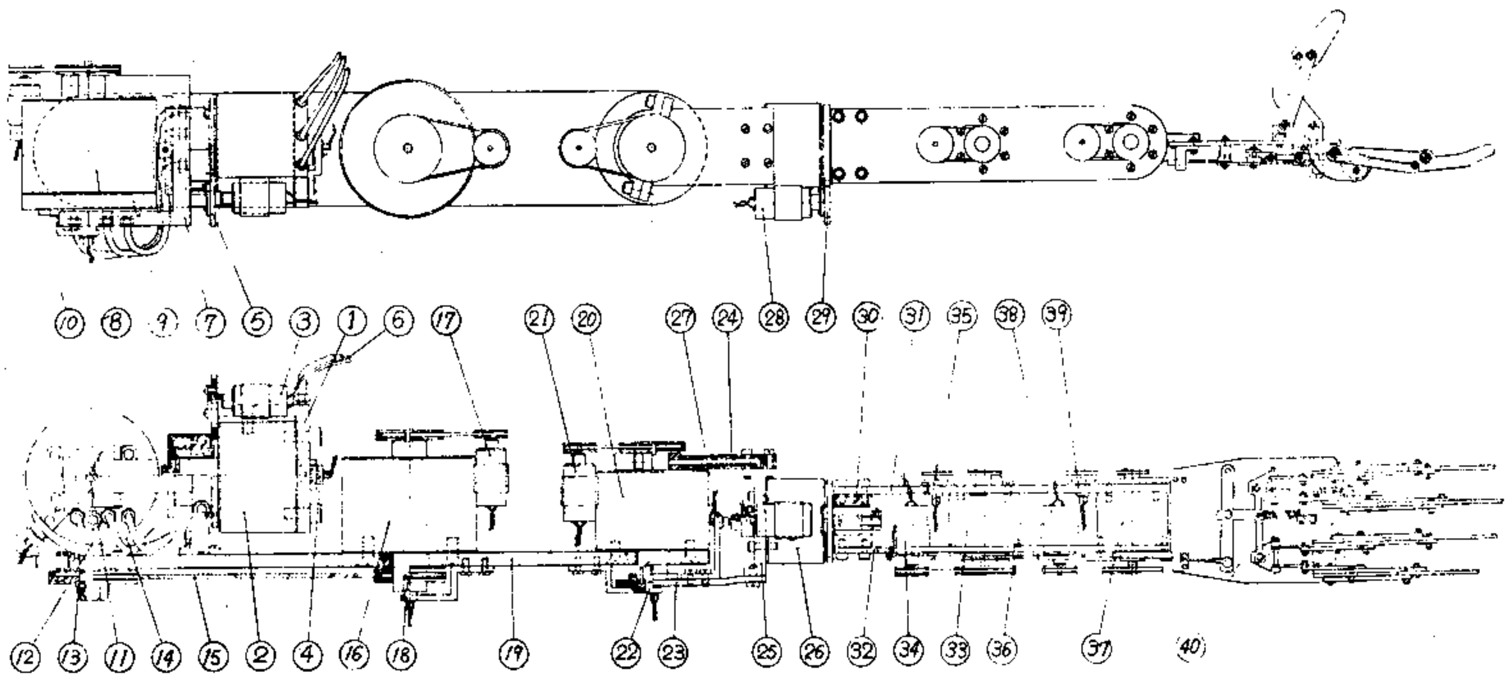
Appendix

View of Hydraulically Powered Prosthetic Arm with Seven Degrees of Freedom (PROTOTYPE-1)



Appendix

View of Hydraulically Powered Prosthetic Arm with Seven Degrees of Freedom (PROTOTYPE-1)