COOPERATIONAL CONTROL OF THE ANTHROPOMORPHOUS MANIPULATOR "MELARM"

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ABSTRACT

Studies on a pair of anthropomorphous manipulators "MELARM" were conducted mainly to achieve manipulation of objects, without human intervention, by the effective use of two mechanical arms.

In a multi-degree of freedom manipulator there are two significant problems—one being how to coordinate all the actuators to produce movement in a space of a lower dimension, and the other being how to make two arms cooperate to do effective work.

A minimum potential energy criterion is used here to select an elbow position of the MELARM and a cooperational control procedure using force sensors is proposed for determining the movements of a pair of manipulators without human intervention when as an example a box is carried by them.

1. INTRODUCTION

Recently there has been a growing interest in the control of multi-jointed manipulators. Since these manipulators often consist of several linkages and many actuators, the control problem is significant and not easy solved.[1),2),3)] Also, in most cases the problem was the control of only one manipulator.

However, humans can do very effective work by using two arms easily. If we can control two manipulators cooperatively and automatically, we can reasonably expect that such manipulators can advance the progress of work.

The human-like manipulator MELARM used in the work reported here is shown in Fig.1. The features of this manipulator system are as follows; (1) It has a symmetric pair of manipulators. (2) Each manipulator has seven joints and a hand. (3) Each joint has a force sensor and the hand has many tactile and pressure sensors. (4) The manipulators are controlled by a mini-computer. (5) They also can be controlled manually by a master manipulator and joysticks.

Fig.2 shows the joint structure of the MELARM. As shown in Fig.2 and Fig.6, the following notations will be used throughout this paper; S, E, W, H — shoulder, elbow, wrist, vise grip hand; ℓ_1, ℓ_2, ℓ_3 — lengths of upper arm, forearm and hand, respectively, where ℓ_3 describes the distance between the wrist point (W) and the prehension point (H) ; $\underline{i}$, $\underline{j}$, $\underline{k}$ — unit vectors in fixed coordinates at the shoulder point; $\theta_1,..,\theta_7$ — seven degrees of freedom, i.e.,

θ_1 : shoulder flexion	θ_5 : forearm supination
θ_2 : shoulder abduction	θ_6 : wrist flexion
θ_3 : external humeral rotation	θ_7 : wrist abduction
θ_4 : elbow flexion	

Table 1 shows the specification of the manipulator. The working space of the manipulator is shown in Fig.3. The wrist position is determined by four degrees of freedom, θ_1, θ_2, θ_3, θ_4, which are driven by hydraulic actuators and the direction of the hand is determined by three joints (θ_5, θ_6, θ_7) that are driven by electric motors. Force sensors are composed of torsion bars and semi-conductor strain gauges, as shown in Fig.4. The torque applied on a joint is detected by the force sensors and we shall be able to calculate the amount of the force applied on the hand if we can subtract the torque generated by gravity which acts on the far side of the arm from the joint.

2. BASIC MOVEMENT PROCEDURE OF THE MANIPULATOR

If we represent the 3×3 coordinate transformation matrix by $\underset{\sim}{C}$, the coordinate transformation matrices $\underset{\sim}{C}_e$ between S and E, $\underset{\sim}{C}_w$ between S and W and $\underset{\sim}{C}_h$ between S and H may be written by

$$\underset{\sim}{C}_e=\underset{\sim}{C}_x(\theta_1)\underset{\sim}{C}_y(\theta_2)\underset{\sim}{C}_z(\theta_3)\equiv\left[e_{ij}\right] \tag{1}$$

$$\underset{\sim}{C}_w=\underset{\sim}{C}_e\underset{\sim}{C}_x(\theta_4)\equiv\left[w_{ij}\right] \tag{2}$$

$$\underset{\sim}{C}_h=\underset{\sim}{C}_w\underset{\sim}{C}_z(\theta_5)\underset{\sim}{C}_y(\theta_6)\underset{\sim}{C}_x(\theta_7)\equiv\left[h_{ij}\right] \tag{3}$$

where $\underset{\sim}{C}_x(\theta_i)$, $\underset{\sim}{C}_y(\theta_i)$, $\underset{\sim}{C}_z(\theta_i)$ are 3×3 matrices which are given by

$$\underset{\sim}{C}_x(\theta_i)=\begin{bmatrix}1&0&0\\0&c_i&-s_i\\0&s_i&c_i\end{bmatrix},\quad \underset{\sim}{C}_y(\theta_i)=\begin{bmatrix}c_i&0&s_i\\0&1&0\\-s_i&0&c_i\end{bmatrix},\quad \underset{\sim}{C}_z(\theta_i)=\begin{bmatrix}c_i&-s_i&0\\s_i&c_i&0\\0&0&1\end{bmatrix} \tag{4}$$

in which $c_i=\cos\theta_i$, $s_i=\sin\theta_i$ and θ_i is the i-th joint angle and x, y, z show the directions of the joint axes.

To calculate $\underline{P}_e=[x_e,y_e,z_e]^T$, $\underline{P}_w=[x_w,y_w,z_w]^T$ and $\underline{P}_h=[x_h,y_h,z_h]^T$ which are position vectors of the elbow point, wrist point and prehension point, we need to define three vectors $\underline{y}_{10}$, $\underline{y}_{20}$ and $\underline{y}_{30}$ which are vectors from S to E, from E to W and from W to H, respectively, as illustrated in Fig.6.

Those are

$$\underline{y}_{10}=\underset{\sim}{C}_e\begin{bmatrix}0\\0\\-\ell_1\end{bmatrix}=-\begin{bmatrix}e_{13}\\e_{23}\\e_{33}\end{bmatrix}\ell_1,\quad \underline{y}_{20}=\underset{\sim}{C}_w\begin{bmatrix}0\\0\\-\ell_2\end{bmatrix}=-\begin{bmatrix}w_{13}\\w_{23}\\w_{33}\end{bmatrix}\ell_2,\quad \underline{y}_{30}=-\begin{bmatrix}h_{13}\\h_{23}\\h_{33}\end{bmatrix}\ell_3 \tag{5}$$

and $\underline{P}_e$, $\underline{P}_w$ and $\underline{P}_h$ are related by

$$\underline{P}_e=\underline{y}_{10},\quad \underline{P}_w=\underline{y}_{10}+\underline{y}_{20},\quad \underline{P}_h=\underline{y}_{10}+\underline{y}_{20}+\underline{y}_{30}\,. \tag{6}$$

As this human-like manipulator has a redundant degree of freedom to decide the wrist position, as mentioned before, we need to introduce a certain criterion to decide all four joint angles when the wrist position is given in terms of conventional three-dimensional coordinates.

For the first step we decided as the criterion that while the manipulator moves it keeps the minimum potential energy configuration, namely it moves with the "lowest elbow" movement. Then the relations between $\underset{\sim}{P}_e=[x_e, y_e, z_e]^T$ and $\underset{\sim}{P}_w=[x_w, y_w, z_w]^T$ are shown by following equations (see Fig.5).

$$\frac{x_e}{x_w}=\frac{y_e}{y_w},\quad x_e^2+y_e^2+z_e^2=\ell_1^2,\quad (x_e-x_w)^2+(y_e-y_w)^2+(z_e-z_w)^2=\ell_2^2,$$

$$\ell_1^2+\ell_2^2-R^2=-2\ell_1\ell_2\cos\theta_4,\ \text{where}\ R^2=x_w^2+y_w^2+z_w^2. \tag{7}$$

From Eq. (6) and (7) we may obtain θ_1, θ_2, θ_3, θ_4 :

$$\tan\theta_1=-\frac{y_e}{z_e},\quad \sin\theta_2=-\frac{x_e}{\ell_1},$$

$$\sin\theta_3=\frac{(x_e-x_w)/\ell_2-\sin\theta_2\cos\theta_4}{\cos\theta_2\sin\theta_4},\quad \cos\theta_4=\frac{\ell_1^2+\ell_2^2-R^2}{-2\ell_1\ell_2} \tag{8}$$

in which $x_e=x_w(sr+Dz_w)/rR^2$, $y_e=x_e y_e/x_w$, $z_e=sz_w-rD$,

$$R^2=x_w^2+y_w^2+z_w^2,\quad s=R^2+\ell_1^2+\ell_2^2,\quad D=R^2\ell_1^2-s_2^2,\quad r^2=x_w^2+y_w^2.$$

To obtain θ_5, θ_6, θ_7, let us define the fixed coordinate system at the shoulder point as ${}^c\chi_0$, the last coordinate system at the hand point as ${}^c\chi_7$ and the direction cosines of x_7-, y_7-, z_7- axes in frame ${}^c\chi_0$ as $\underset{\sim}{k}_1=[\ell_1, m_1, n_1]^T$, $\underset{\sim}{k}_2=[\ell_2, m_2, n_2]^T$, $\underset{\sim}{k}_3=[\ell_3, m_3, n_3]^T$, respectively. Then the direction of the hand $\underset{\sim}{K}$ is written by $\underset{\sim}{K}=[\underset{\sim}{k}_1, \underset{\sim}{k}_2, \underset{\sim}{k}_3]$. And ${}^c\chi_0$ is written by

$${}^c\chi_0=\underset{\sim}{C}_1\underset{\sim}{C}_2\underset{\sim}{C}_3\underset{\sim}{C}_4\underset{\sim}{C}_5\underset{\sim}{C}_6\underset{\sim}{C}_7\,{}^c\chi_7. \tag{9}$$

Then, following equations are obtained:

$$\underset{\sim}{C}_w^{-1}[\ell_1, m_1, n_1]^T=\underset{\sim}{C}_z(\theta_5)\ \underset{\sim}{C}_y(\theta_6)\ \underset{\sim}{C}_z(\theta_7)[1,0,0]^T,\ \text{etc.} \tag{10}$$

$$\therefore\ \tan\theta_5=\frac{w_{12}\ell_1+w_{22}m_1+w_{32}n_1}{w_{11}\ell_1+w_{21}m_1+w_{31}n_1},\quad \sin\theta_6=-(w_{13}\ell_1+w_{23}m_1+w_{33}n_1),$$

$$\tan\theta_7=\frac{w_{13}\ell_2+w_{23}m_2+w_{33}n_2}{w_{13}\ell_3+w_{23}m_3+w_{33}n_3}. \tag{11}$$

3. COMPUTATION OF EXTERNAL FORCES

This section describes a basic computation theroty of external forces which are applied on the manipulator hand. First, it will be necessary to calculate the torque generated by gravity on each joint.

We must first define the following notations illustrated in Fig.6.

$\underline{y}_1(=\lambda_1\underline{y}_{10})$, $\underline{y}_2(=\lambda_2\underline{y}_{20})$, $\underline{y}_3(=\lambda_3\underline{y}_{30})$: Vectors from E to G_1, from E to G_2 and from W to G_3, respectively, where G_1, G_2, G_3 describe the center of gravity of the upper arm, forearm and hand, respectively.

$\underline{z}_1=\left[0,0,-m_1g\right]^T$, $\underline{z}_2=\left[0,0,-m_2g\right]^T$, $\underline{z}_3=\left[0,0,-m_3g\right]^T$: Gravity vectors which apply on the upper arm, forearm and hand, respectively, where m_1, m_2, m_3 describe their weights.

Then the torque T_1 applied on the first joint is described as follows, $T_1=(\underline{i}\cdot\lambda_1\underline{y}_{10}\times\underline{z}_1)+\underline{i}\cdot(\underline{y}_{10}+\lambda_2\underline{y}_{20})\times\underline{z}_2+\underline{i}\cdot(\underline{P}_w+\lambda_3\underline{y}_{30})\times\underline{z}_3$

$$=\underline{i}\cdot(\underline{y}_{10}\times\underline{z}_a+\underline{P}_w\times\underline{z}_b+\underline{P}_h\times\underline{z}_c) \qquad (12)$$

where $\underline{z}_a=\lambda_1\underline{z}_1+(1-\lambda_2)\underline{z}_2$, $\underline{z}_b=\lambda_2\underline{z}_2+(1-\lambda_3)\underline{z}_3$, $\underline{z}_c=\lambda_3\underline{z}_3$.

The torques $T_2,\cdots,T_7$ applied on each joint are also written as follows,

$$T_2=\underset{\sim}{C}_x(\theta_1)\underline{j}\cdot(\underline{y}_{10}\times\underline{z}_a+\underline{P}_w\times\underline{z}_b+\underline{P}_h\times\underline{z}_c) \qquad (13)$$

$$T_3=\underset{\sim}{C}_x(\theta_1)\underset{\sim}{C}_y(\theta_2)\underline{k}\cdot(\underline{P}_w\times\underline{z}_b+\underline{P}_h\times\underline{z}_c) \qquad (14)$$

$$T_4=\underset{\sim}{C}_x(\theta_1)\underset{\sim}{C}_y(\theta_2)\underset{\sim}{C}_z(\theta_3)\underline{i}\cdot\{\underline{P}_w\times\underline{z}_b-\underline{y}_{10}\times(\underline{z}_b+\underline{z}_c)+\underline{P}_h\times\underline{z}_c\} \qquad (15)$$

$$T_5=\underset{\sim}{C}_e\underline{k}\cdot(\underline{P}_h-\underline{P}_w)\times\underline{z}_c \qquad (16)$$

$$T_6=\underset{\sim}{C}_e\underset{\sim}{C}_z(\theta_5)\underline{j}\cdot(\underline{P}_h-\underline{P}_w)\times\underline{z}_c \qquad (17)$$

$$T_7=\underset{\sim}{C}_e\underset{\sim}{C}_z(\theta_5)\underset{\sim}{C}_y(\theta_6)\underline{i}\cdot(\underline{P}_h-\underline{P}_w)\times\underline{z}_c. \qquad (18)$$

Although, in practice, we must add other complicated corrective terms to the above due to the peculiarity of the configuration of the manipulator, in this paper we will omit them.

Next, it is necessary to calculate the incremental torques $T_{1\delta},\cdots,T_{7\delta}$ when a general external force $\underline{z}_\delta$ is applied on the prehension point $\underline{P}_h$, shown in Fig.7. Those are written as follows:

$$T_{1\delta}=\underline{i}\cdot\underline{P}_h\times\underline{z}_\delta \qquad (19)$$

$$T_{2\delta}=\underset{\sim}{C}_x(\theta_1)\underline{j}\cdot\underline{P}_h\times\underline{z}_\delta \qquad (20)$$

$$T_{3\delta}=\underset{\sim}{C}_x(\theta_1)\underset{\sim}{C}_y(\theta_2)\underline{k}\cdot(\underline{P}_h-\underline{P}_w)\times\underline{z}_\delta=\underset{\sim}{C}_x(\theta_1)\underset{\sim}{C}_y(\theta_2)\underline{k}\cdot\underline{P}_h\times\underline{z}_\delta \qquad (21)$$

$$T_{4\delta}=C_x(\theta_1)\cdots C_z(\theta_3)i\cdot(P_h-y_{10})\times z_\delta \quad (22)$$

$$T_{5\delta}=C_w k\cdot(P_h-P_w)\times z_\delta \quad (23)$$

$$T_{6\delta}=C_x(\theta_1)\cdots\cdots C_z(\theta_5)j\cdot(P_h-P_w)\times z_\delta \quad (24)$$

$$T_{7\delta}=C_x(\theta_1)\cdots\cdots C_y(\theta_6)i\cdot(P_h-P_w)\times z_\delta . \quad (25)$$

In Fig.8, the theoretical external forces about θ_4 is compared with the experimental values which were obtained by gradual movement of θ_4 from vertical straight configuration of the manipulator.

Similar tendencies were observed in force sensors of other joints.

4. COOPERATIONAL TRANSFER PROCEDURE USING "MELARM"

This section deals with the procedure and results of the transfer of a large box by using two arms, as an example of cooperational control of a pair of anthropomorphous manipulators, as shown in Fig.9.

The task name and the goal point are given by an operator. Then, the two manipulators search and grip the box by means of the tactile sensors of the hand and transfer it to the goal point. In this case the right arm is used as a master side manipulator and the left arm as a slave side manipulator. Though the right arm can be moved to the goal point irrespective of the extermal force, the left arm have to be moved while always giving due consideration to the external force and keeping the box toward the same direction. Equations (19)∿(25) cannot be used in their original form because additional torque apart from the force z_δ is applied on the prehension point from the box. Therefore the left arm should be moved while correcting its path so as to eliminates the force $F=[F_x, F_y, F_z]'$ which is applied on the box at right prehension point P_h by the right hand as shown in Fig.10. Position P_h is written in frame S' which is the fixed coordinate at the left shoulder (see Fig.10) as follows:

$$\begin{aligned} P_h &= P_h' + [h_{ij}][-\ell_0, 0, -\ell_3]^T = P_h' - [h_{11}, h_{21}, h_{31}]^T \ell_0 \\ &\quad - [h_{13}, h_{23}, h_{33}]^T \ell_3 \\ &= P_w' - [h_{11}, h_{21}, h_{31}]^T \ell_0 \end{aligned} \quad (26)$$

where a dash denotes position of the left arm in frame S'.

The incremental torques applied on each joint owing to F are to be calculated by replacing z_{δ} by F and P_h by P'_w in equations (19)∿(25).

The correcting path procedure of the left arm is as follows. First, the master side arm (right arm) is given the goal point P_g and it begins to move ΔP by ΔP. Next, the left arm moves while calculating force F at each time j and while correcting its path by $\Delta P'_{\delta,j+1}$ from the next aiming point $P'_j+\Delta P'_j$, as follows and as shown in Fig.11.

$$P'_{j+1}=P'_j+\Delta P'_{j+1},\quad \Delta P'_{j+1}=\Delta P'_j+\Delta P'_{\delta,j+1},$$

$$\Delta P'_{\delta,j+1}=\begin{bmatrix} F_{xj}/(F_{xj}-F_{xj-1}) & 0 & 0 \\ 0 & F_{yj}/(F_{yj}-F_{yj-1}) & 0 \\ 0 & 0 & F_{zj}/(F_{zj}-F_{zj-1}) \end{bmatrix}\Delta P'_{\delta,j} \qquad (27)$$

This procedure was practiced by using "CRS(Core Realtime System) Monitor" provided in the "FACOM U-200" system which enables us to carry out multi-level and multi-task processing of programs.

5. CONCLUSIONS

1. We can decide seven joint angles of a computer-driven human-like manipulator when the wrist position and the hand direction are given in terms of conventional three-dimensional coordinates.

2. We have presented a theory of computing the i-th torque applied on the i-th joint of the manipulator when external force is applied to the prehension point. Also we can find the amount and direction of the external force by examining the torques.

3. We have presented a basic method of cooperational control using a pair of manipulators.

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	WEIGHT	LENGTH	MOVEMENT		DEGREE OF FREEDOM	WORKING RANGE	ROTATION RATE	CONTROL METHOD
UPPER ARM	81 Kg	630 mm	S	FLEXION	θ_1	+60°~-30°	12°/Sec	ELECTRO-HYDRAULIC SERVO
				ABDUCTION	θ_2	+30°~-60°	10	
				ROTATION	θ_3	+60°~-60°	75	
			E	FLEXION	θ_4	+60°~-60°	20	
FOREARM	18	550	W	SUPINATION	θ_5	+150°~-150°	31	ELECTRIC SERVO
				FLEXION	θ_6	+90°~-45°	33	
				ABDUCTION	θ_7	+45°~-45°	7.5	
HAND	3	300	H	VICE GRIP		0~650 mm		ON/OFF

Table 1 Specification of MELARM

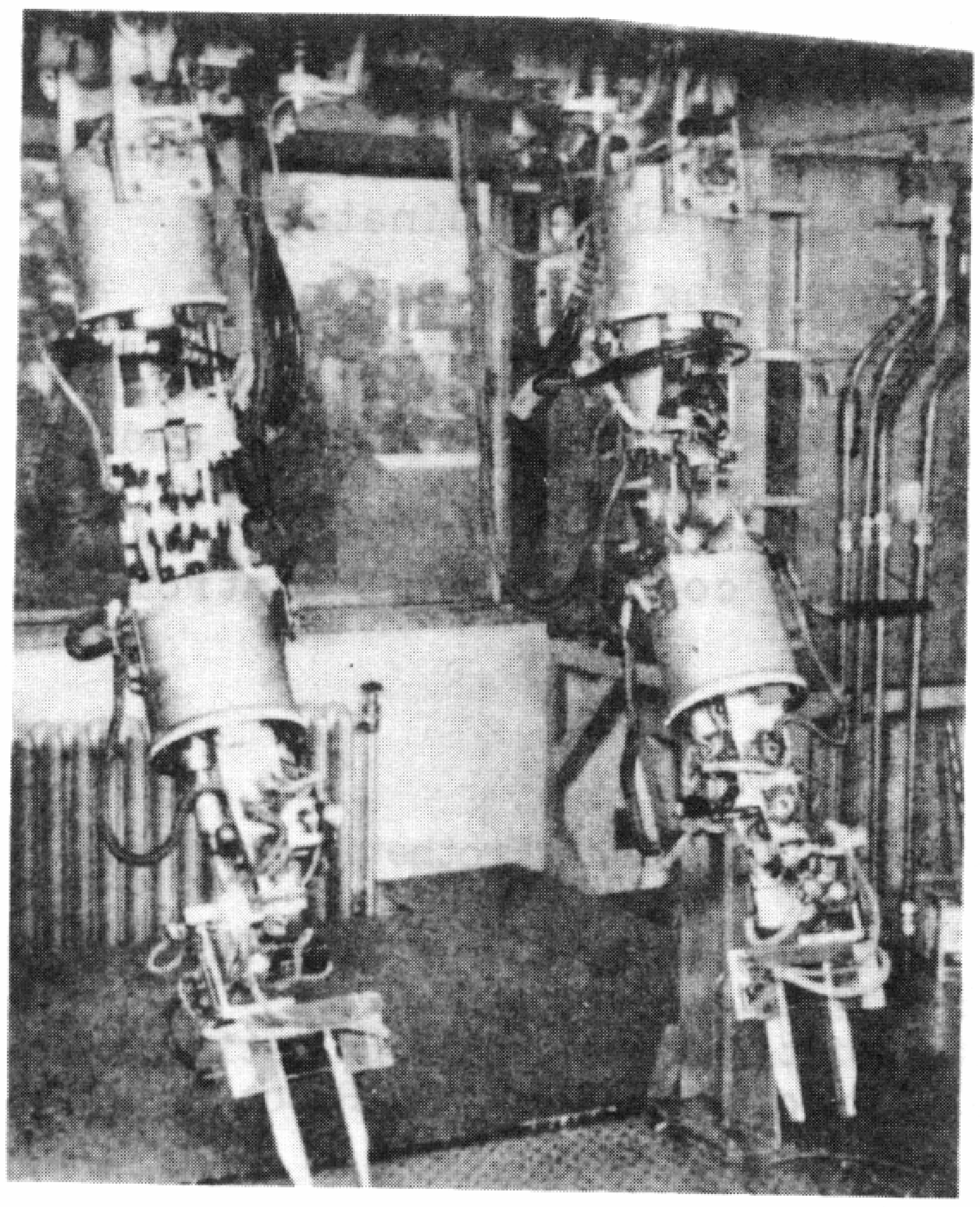


Fig.1 Photo of MELARM

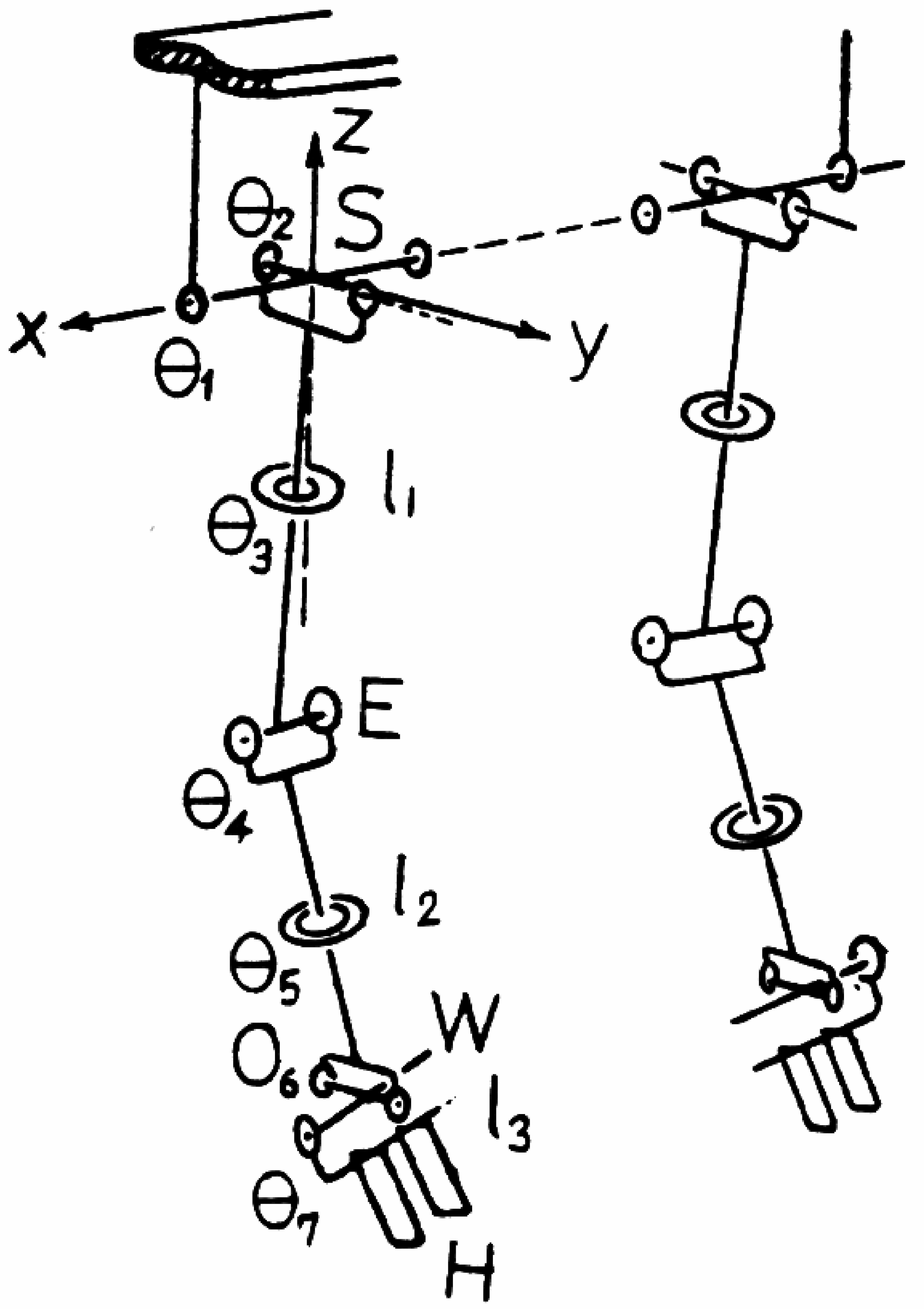
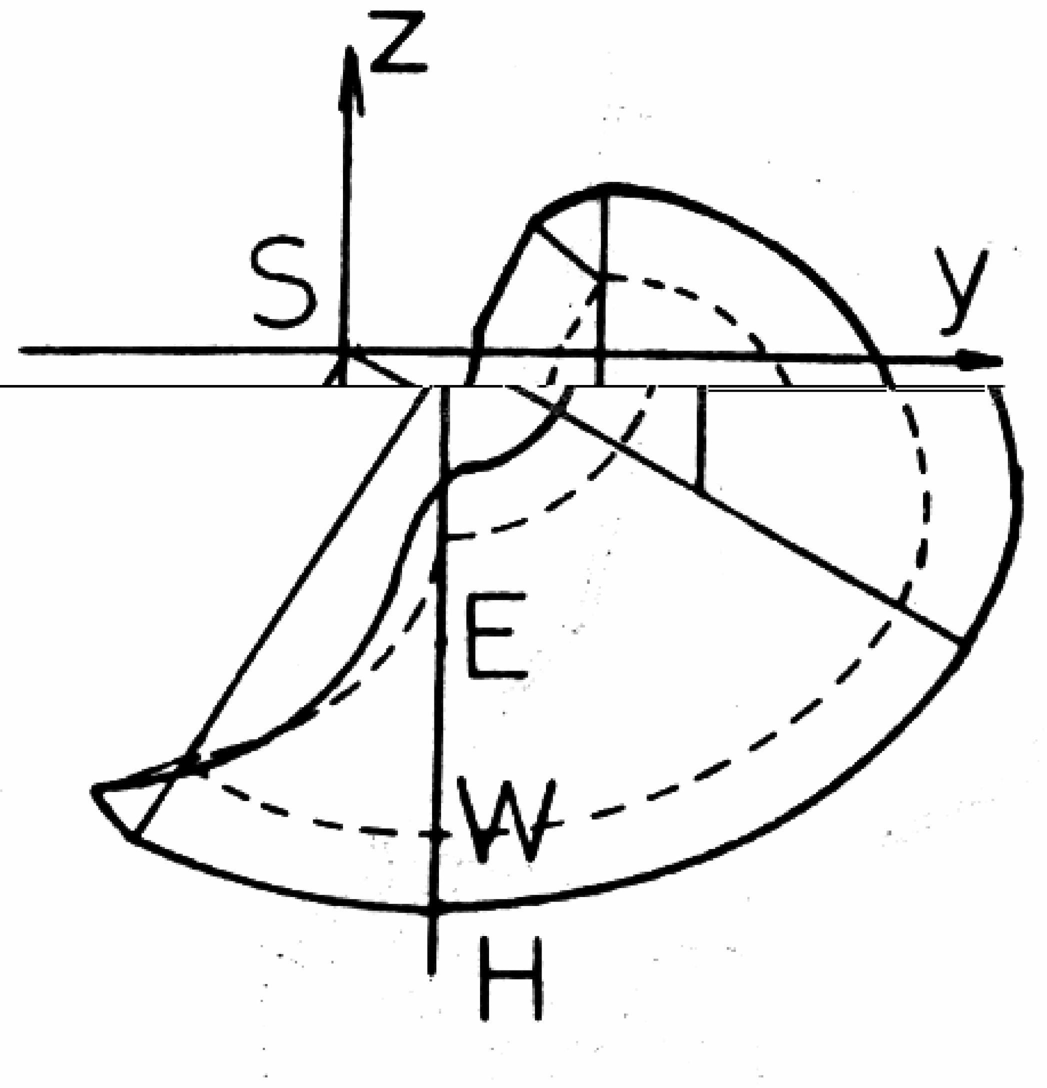
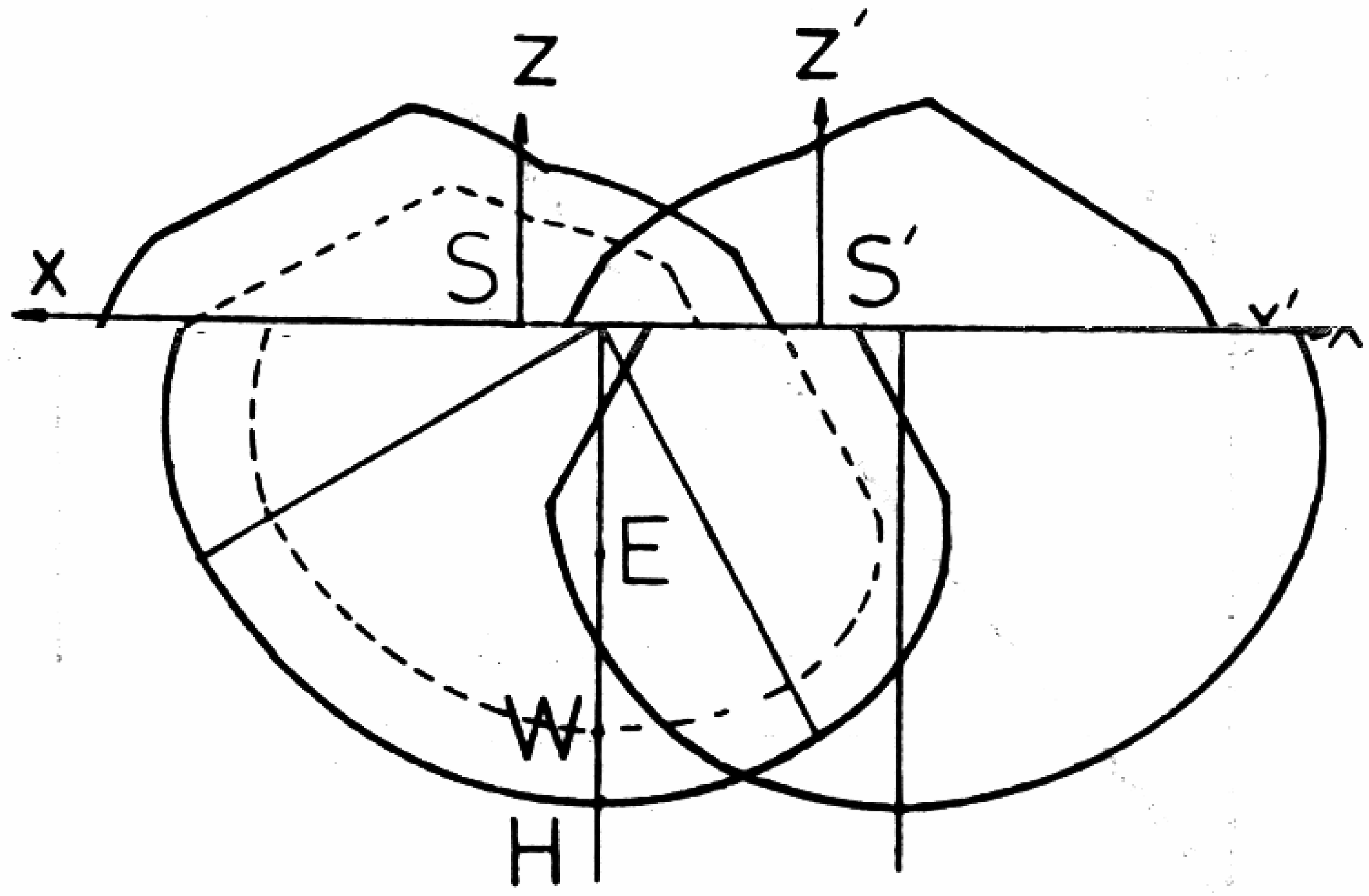


Fig.2 MELARM joint structure



(a) Sagital plane



(b) Front view

Fig.3 MELARM working space

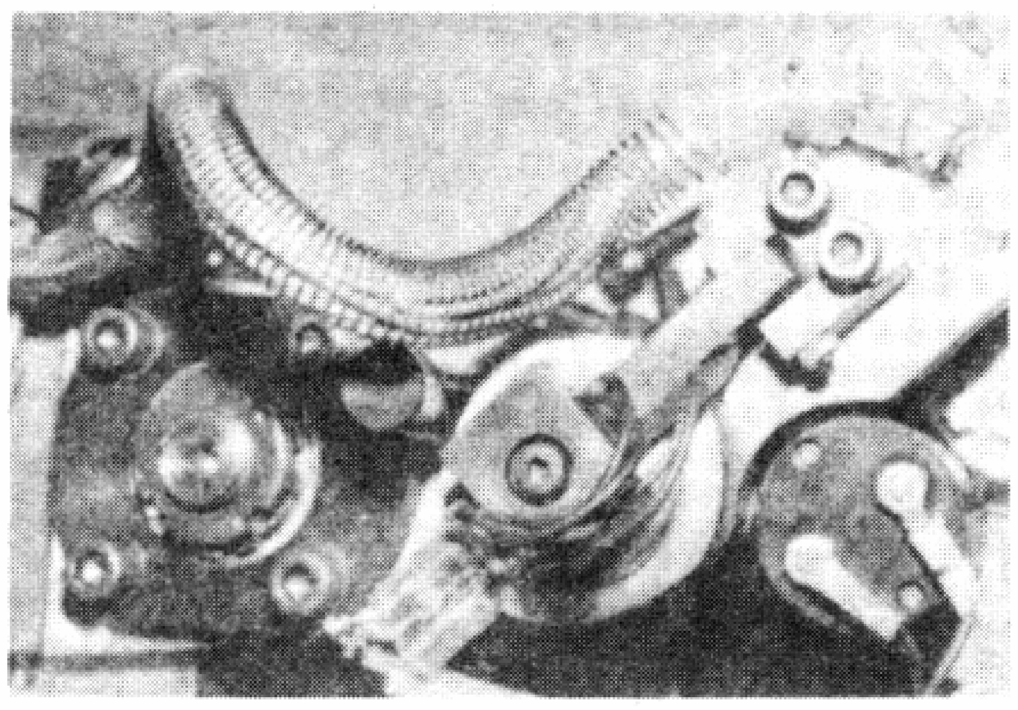


Fig.4 Sixth-joint force sensor

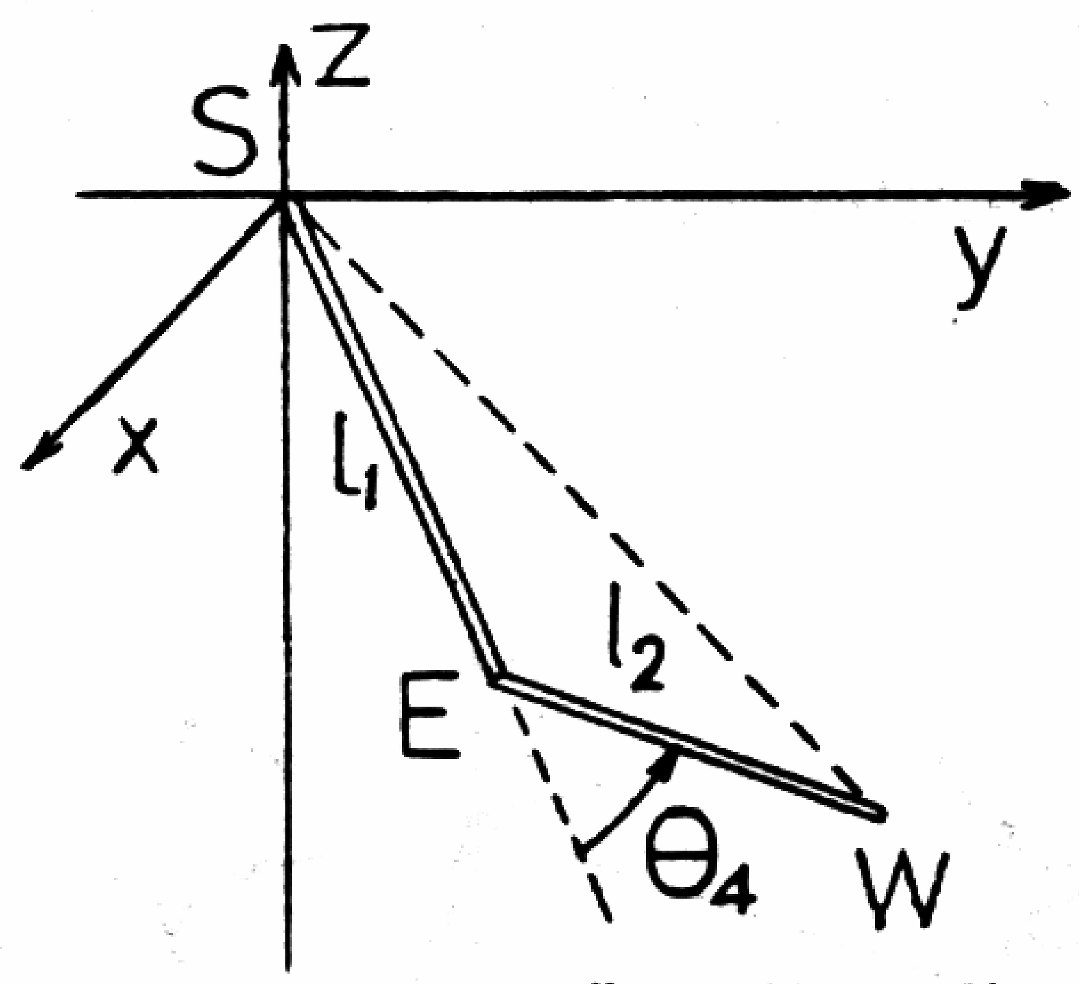


Fig.5 "Lowest elbow" configuration of the manipulator

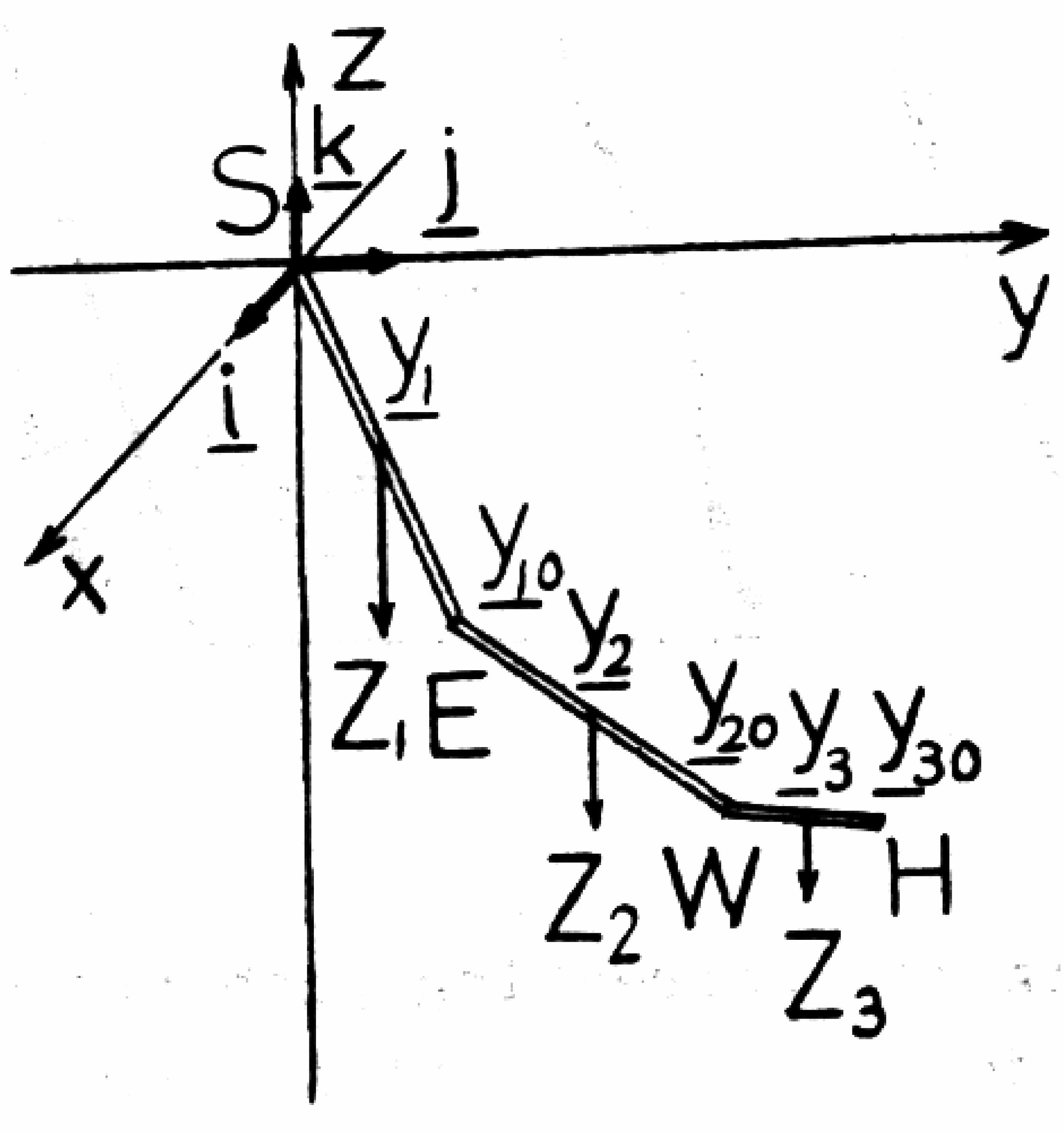


Fig.6 Notations

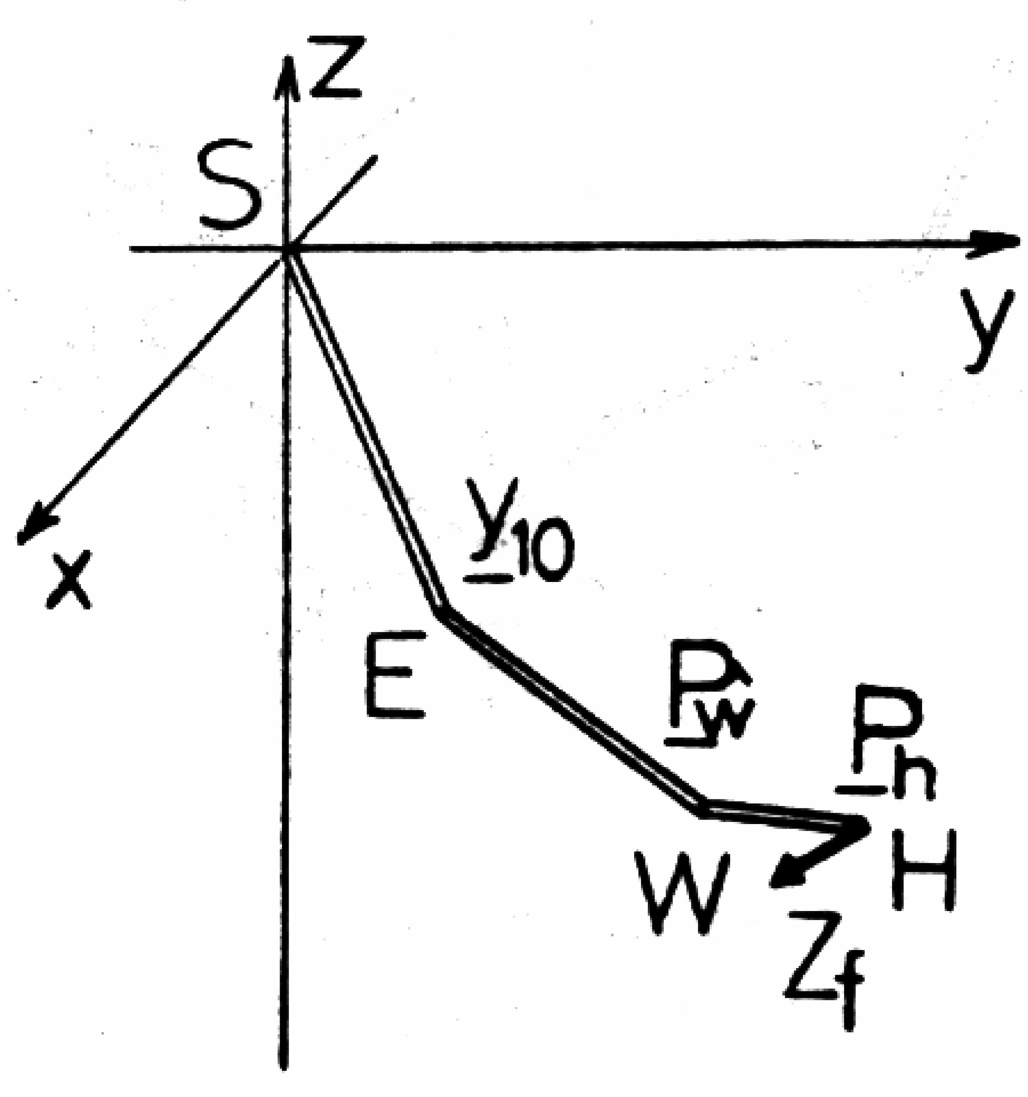


Fig.7 Torque applied on prehension point

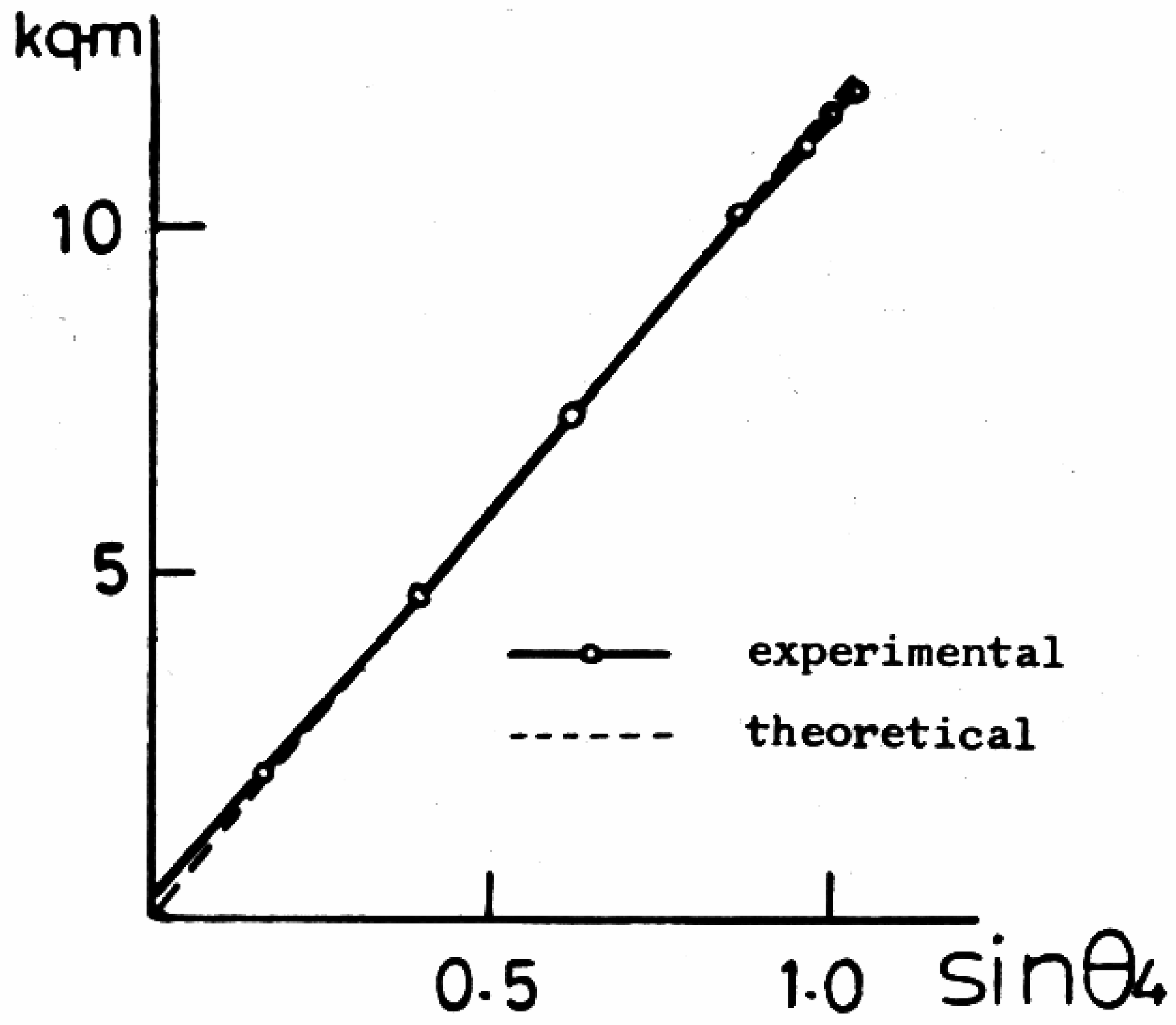


Fig.8 Comparison of theoretical force and strain gauge output concerning θ_4

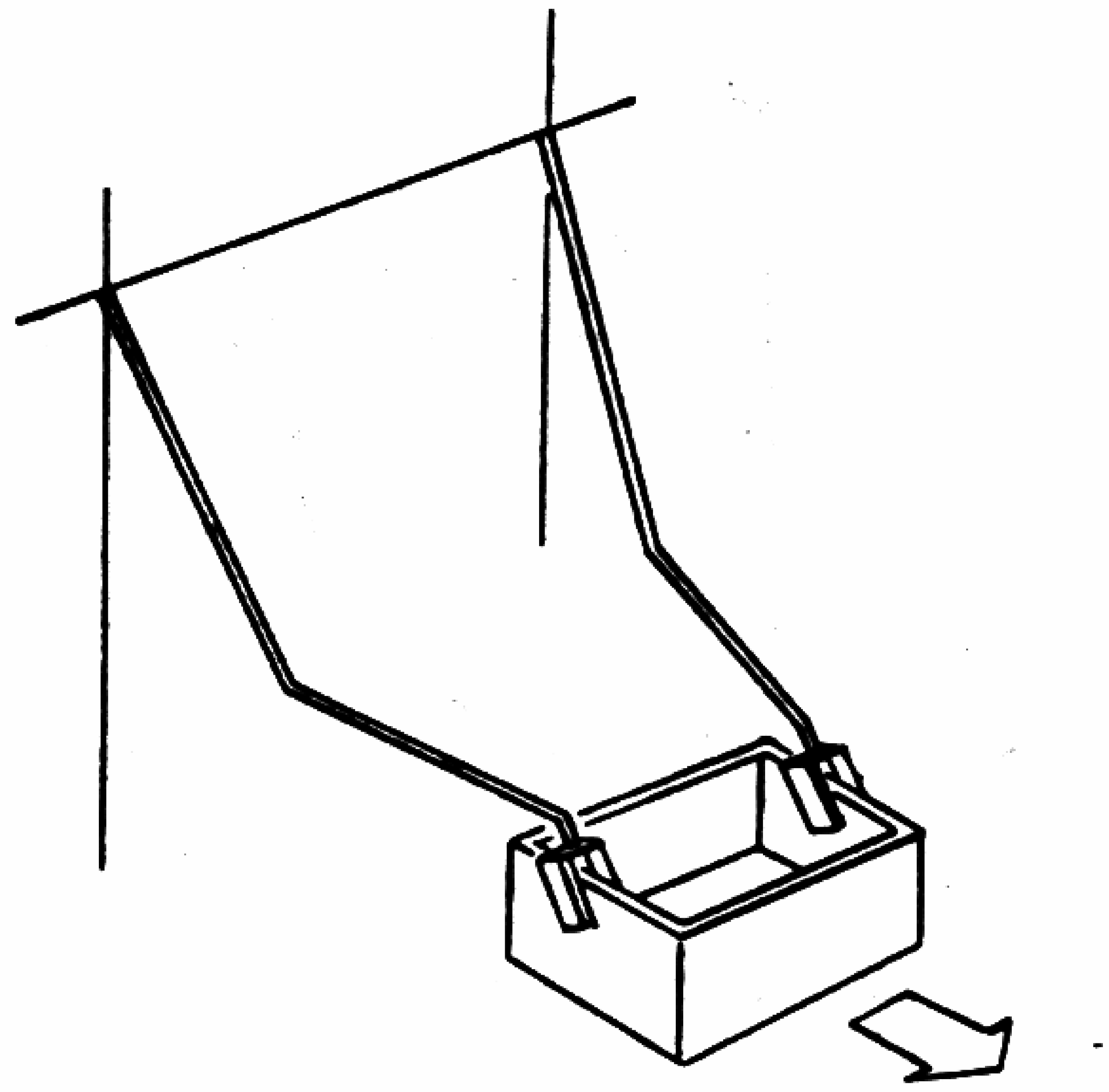


Fig.9 Example of cooperational control using a pair of manipulators

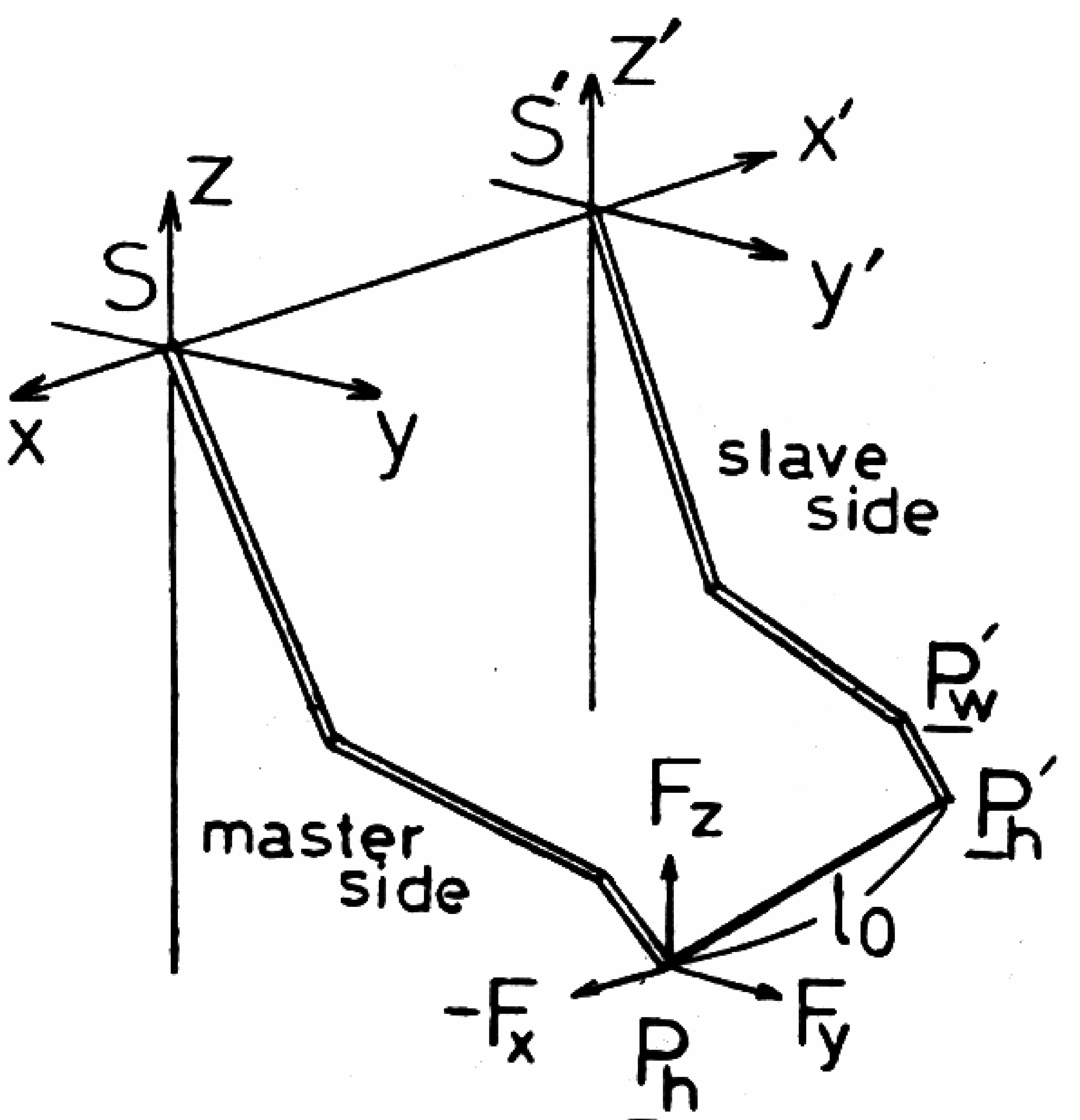


Fig.10 Forces under the cooperational transfer

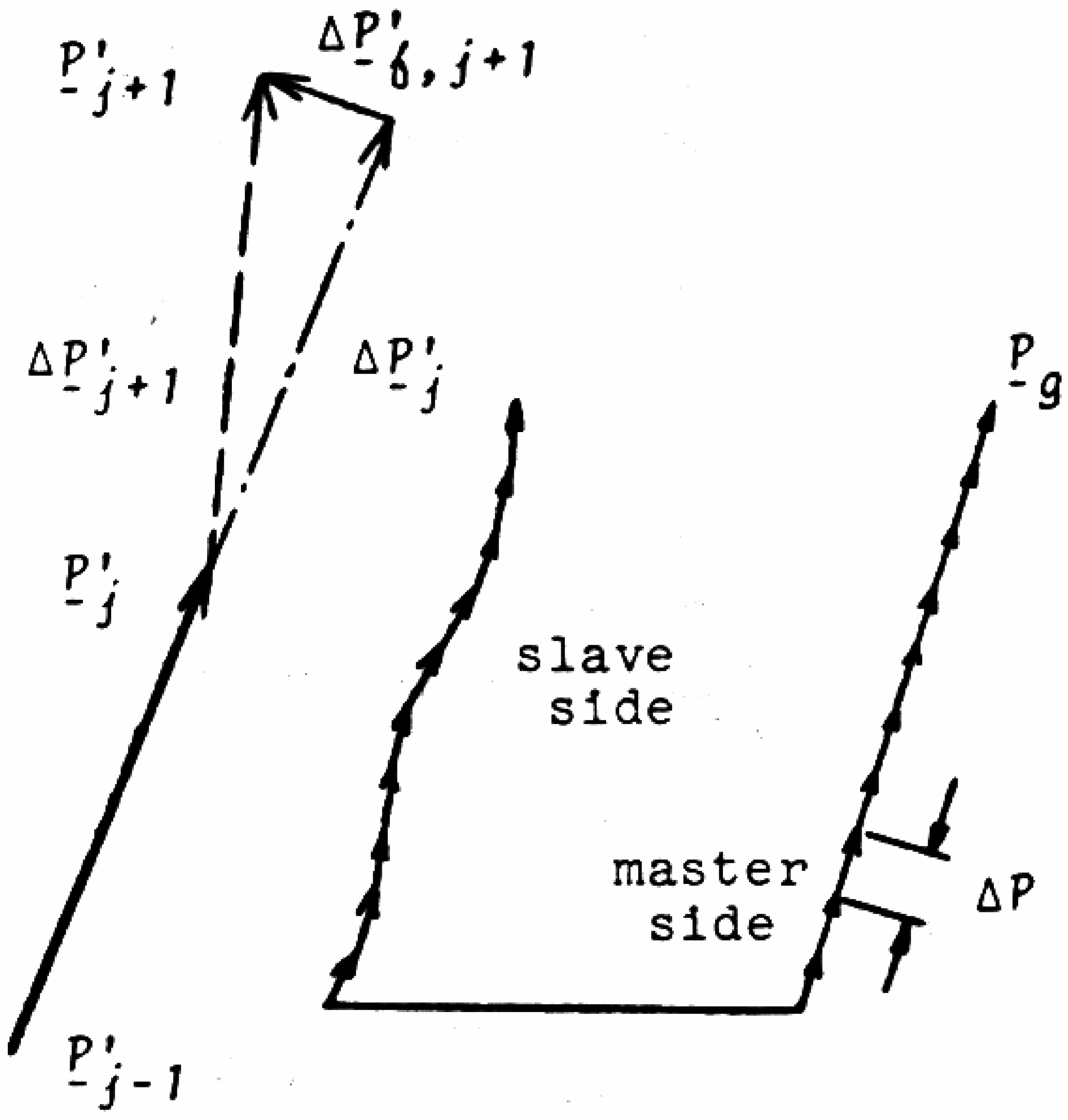


Fig.11 Correcting path procedure under the cooperational trnsfer