

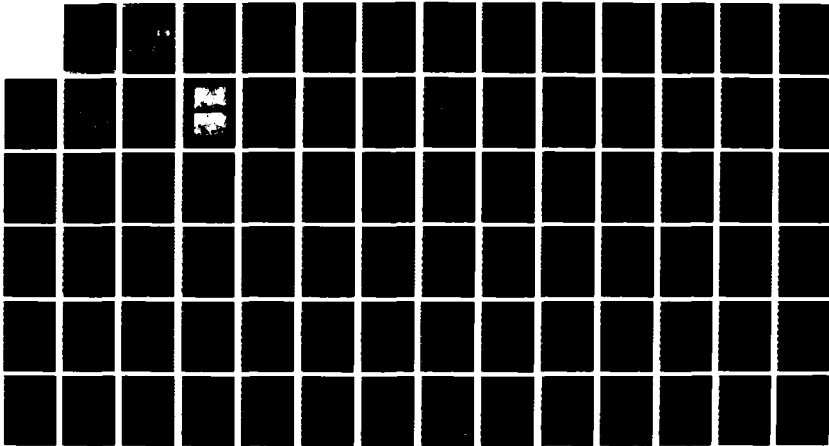
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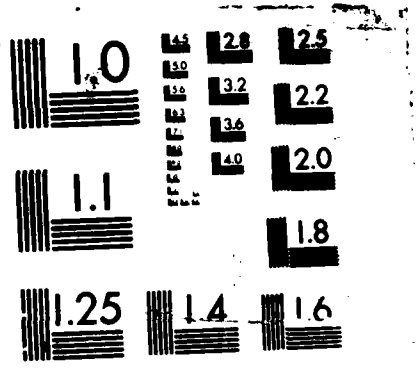
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SUPERVISORY MANIPULATION FOR
ASSEMBLING MECHANICAL PARTS
WHILE COMPENSATING FOR
RELATIVE MOTION

HISAKI HIRABAYASHI

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Supervisory Manipulation for Assembling Mechanical
Parts While Compensating for Relative Motion

by

Hisaaki Hirabayashi

Kogakushi, Waseda University
(1972)

Kogakushushi, Waseda University
(1974)

SUBMITTED TO THE DEPARTMENT OF
MECHANICAL ENGINEERING
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DEGREE OF

MASTER OF SCIENCE IN
MECHANICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1981

c Hisaaki Hirabayashi

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Signature of Author

Hisaaki Hirabayashi

Department of Mechanical Engineering
June 22, 1981

Certified by

Thomas B. Sheridan

Thomas B. Sheridan
Thesis Supervisor

Accepted by

Warren M. Rohsenow

Warren M. Rohsenow
Chairman, Departmental Graduate Committee

Supervisory Manipulation for Assembling Mechanical
Parts While Compensating for Relative Motion

by

Hisaaki Hirabayashi

Submitted to the Department of Mechanical Engineering
on June 22, 1981 in partial fulfillment of the
requirements for the Degree of Master of Science in
Mechanical Engineering

ABSTRACT

This research is to develop and demonstrate the capability for a manipulator system to automatically compensate for random motion of the object being manipulated. This is done by means of a computer and a "measurement arm", a multi-degree-of-freedom position sensor independent of the manipulator itself.

Following preliminary experiments of Dr. K. Tani which pre-supposed perfect measurement, we developed the position sensor and the Jacobian matrices of approximation necessary to interject and transform the measurement to enable control. This report describes the interaction of the 6 degree-of-freedom sensor, and the Jacobian matrices of first order approximation. Evaluation tests were done for simple motions. As the result of the tests, we found the errors acceptable, and believe that this technique is useful for this type of compensation.



Thesis Supervisor: Dr. Thomas B. Sheridan
Title: Professor of Mechanical Engineering

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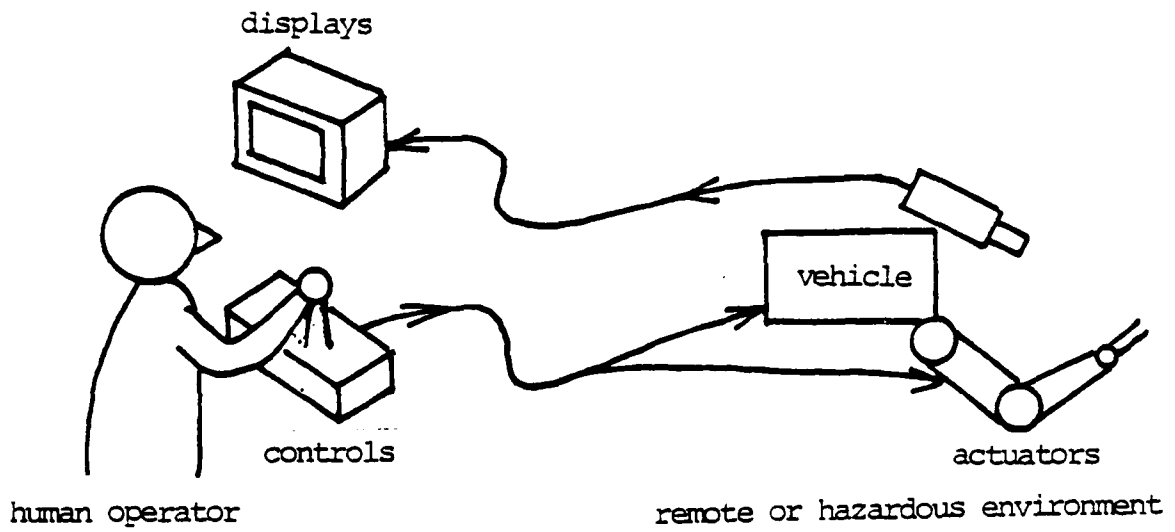
CHAPTER 1

INTRODUCTION TO SUPERVISORY MANIPULATION

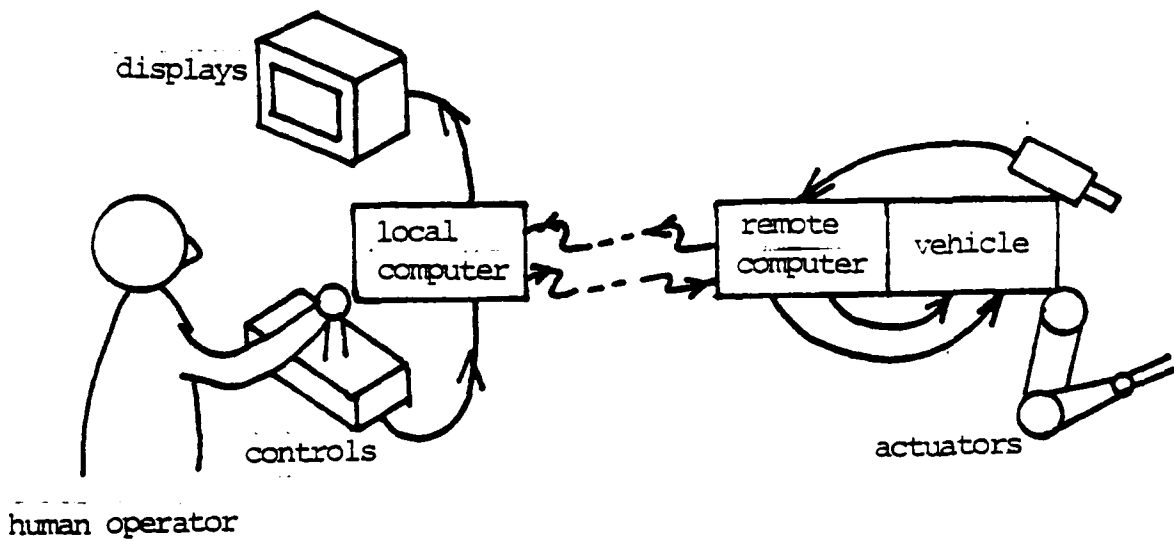
1.1 Supervisory Control

Recently the need has increased for operating vehicles and devices far from the surface of the earth, such as underwater submersibles and space shuttles. These operations are so difficult that fully unmanned systems can not carry out them. Consequently, for these operations the man is required to be within the systems to make some decisions. These manned systems are divided into two categories: one is direct control and another is supervisory control. We can explain the difference as follows, by making use of Fig. 1.1.[1] In direct control, the human directly controls, over the communication link, the separate propulsive actuators of the vehicle, the actuators for the separate degrees of freedom of the manipulator and the actuators of the video camera. The video picture is sent back directly to the operator. The "hand control" can be a master-slave positioning replica or a rate joystick. In supervisory control a computer is added to the teleoperator, and for short periods and limited circumstances the teleoperator can function autonomously. Then the terminology, teleoperator, is defined as follows: A vehicle having sensors and actuators for mobility and/or manipulation, remotely controlled by a human operator, and thus enabling him to extend his sensory - motor function to remote or hazardous environments.

One example of direct control is the conventional master - slave arm system, where the operator has to make all decisions for control on the basis of all information from teleoperator in a short time. It will



a) Direct Control



b) Supervisory Control

Fig. 1.1 Direct and Supervisory Control of a Teleoperator

make him do too much work and might lead to misoperations in complicated systems. Alternatively, supervisory control may be advantageous to achieve faster or more accurate control, or to control simultaneously in more degrees - of - freedom than the operator can achieve by direct control, or relieve him of tedium. This is why a computer is included to carry out a part of the work in addition to the operator. Strictly speaking these computer roles are divided into four categories, as in Fig. 1.2 [1]:

- 1) it can extend his capabilities to help the teleoperator accomplish more than he alone were in control.
- 2) it can relieve him of some control tasks.
- 3) it can provide back-up by taking over control for a short time if feedback is lost.
- 4) it can replace him when a task is too dull.

We have explained supervisory control so far in comparison with the counterpart which is the manned direct control without computer. Next it is also important to explain supervisory control in comparison with the work of divers or manned submersibles in the sea.

About ten years ago divers seemed to have an advantage over manned work - vehicles with manipulators in terms of maneuverability, manipulation, tactile sensing, and covertness. Because of smaller unmanned vehicles and computers, only manipulation, sensing and cognition still remain the primary advantage for the divers.

As to the comparison between teleoperators and manned submersibles, because of the remarkable progress in television cameras and communication channels, the major difference remaining between manned submersibles and

Roles of Computer
(L-load or task, H-human, C-computer)

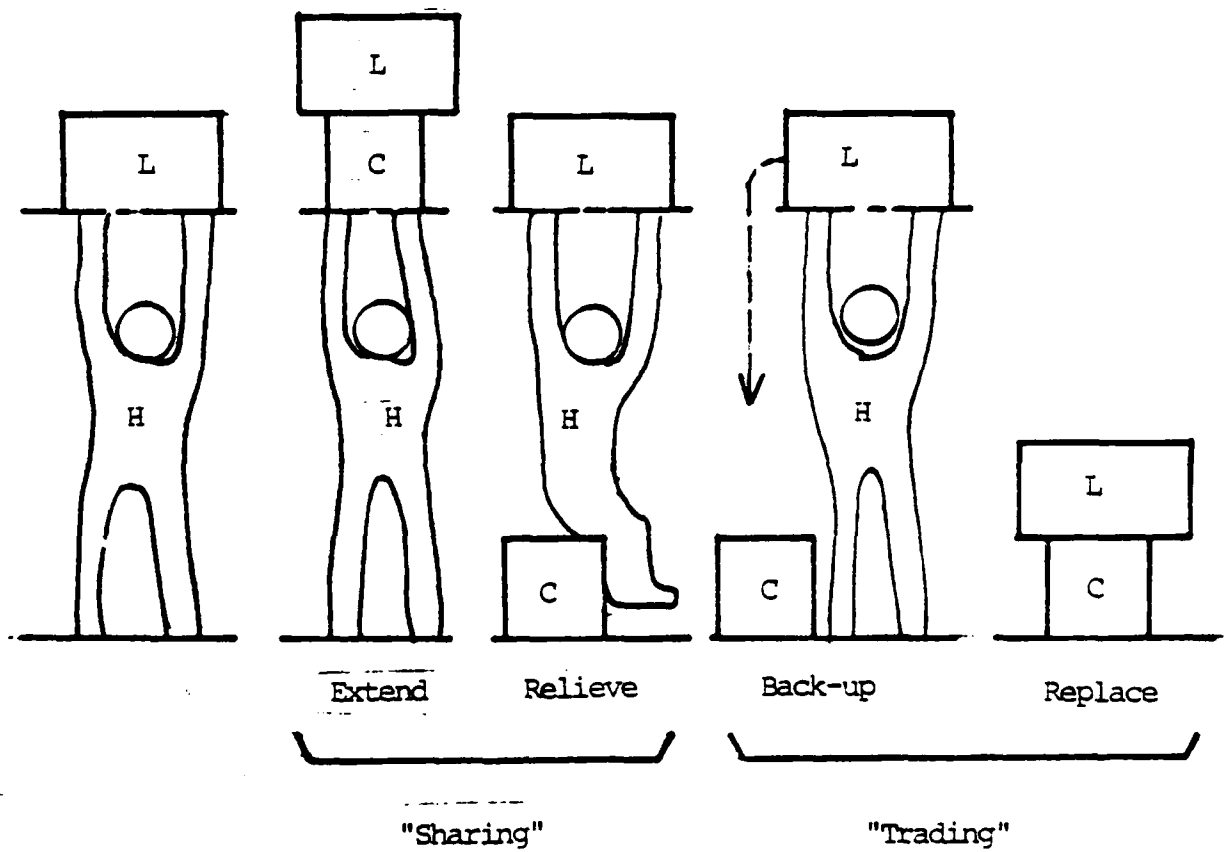


Fig. 1.2 Roles of Computer

teleoperators are cost and safety. The pressure vessel and life-support equipment make the manned submersible much more costly than the same vehicle without the pressure vessel and life-support equipment but with remote control instead.

The above-mentioned explanations show that supervisory control is getting to have an advantage in terms of technology and cost compared with divers and manned submersibles.

1.2 Compensation

There are many problems to be solved in the field of the supervisory control. As an example, in the project we concentrate on remote manipulation by the supervisory control, particularly on manipulation with automatic compensation, which belongs to the 1st category in computer roles said in 1.1, for moving targets.

As far as compensation is concerned, a first step has been achieved so far in our laboratory by Tani.[2] His work demonstrated that automatic manipulator compensation for relative motion between manipulated object and manipulator base made master - slave manipulation easier. For his work, he used a hardware system which consisted of master/slave manipulator, a moving table for the moving objects, and a computer controlling both the manipulator and the table. By means of the method of resolved motion rate control, his software system allowed the master/slave operation with object motion compensation under computer control. Tani's experiments were of three kinds: no object motion, compensation for the object motion, and no compensation. The comparison of the situations with the compensation without it showed that the compensation reduced the operation time or increased the accuracy in some tasks.

CHAPTER 2

PURPOSE OF THIS RESEARCH

2.1 Compensation with Position Measuring

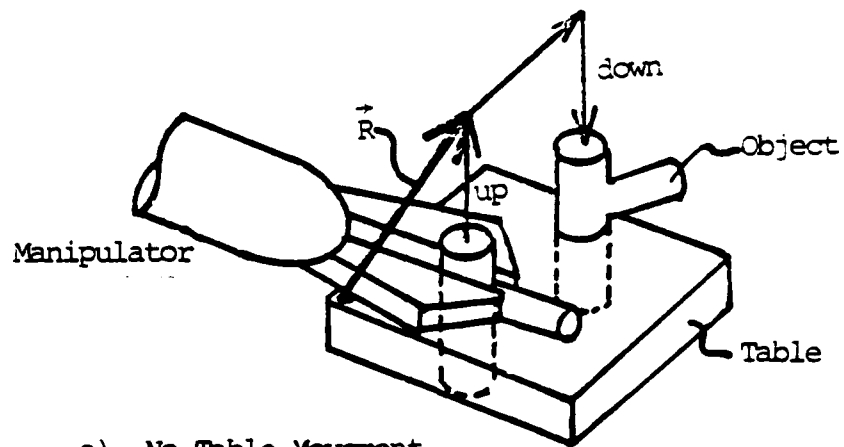
The manipulator compensation done so far presupposed a perfect measurement of the relative motion between manipulated object and manipulator base. The purpose of this project is to extend the compensation by using an experimental 6 degree-of-freedom passive "measurement arm" having a simple gripper, but otherwise flaccid. The operator positions it with the actual manipulator. We explain it in Fig. 2.1.

$$\vec{A} = \vec{T} + \vec{R} \quad (2.1)$$

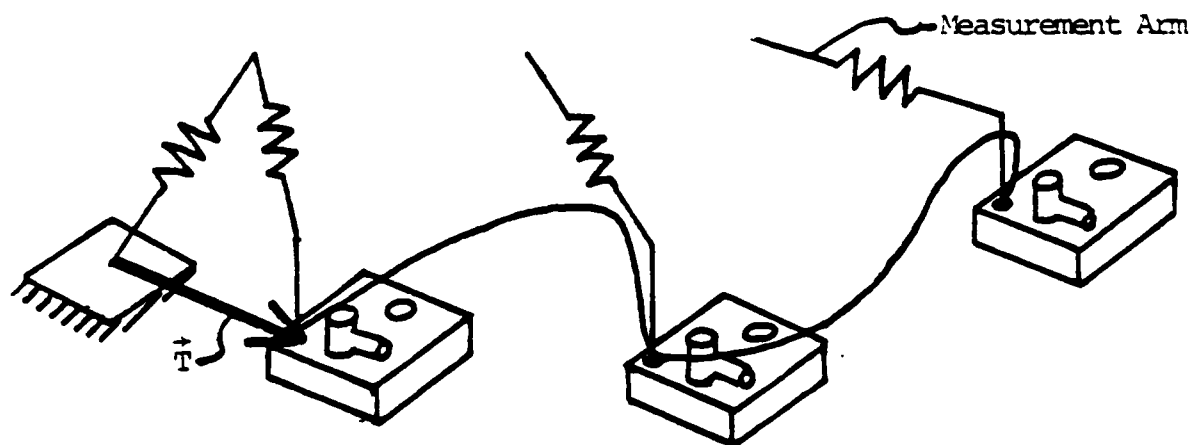
where

- \vec{A} : Absolute Position of the Object with respect to the Manipulator Base
- \vec{T} : Table Position with respect to the Manipulator Base
- \vec{R} : Relative Position of the Object with respect to the Table

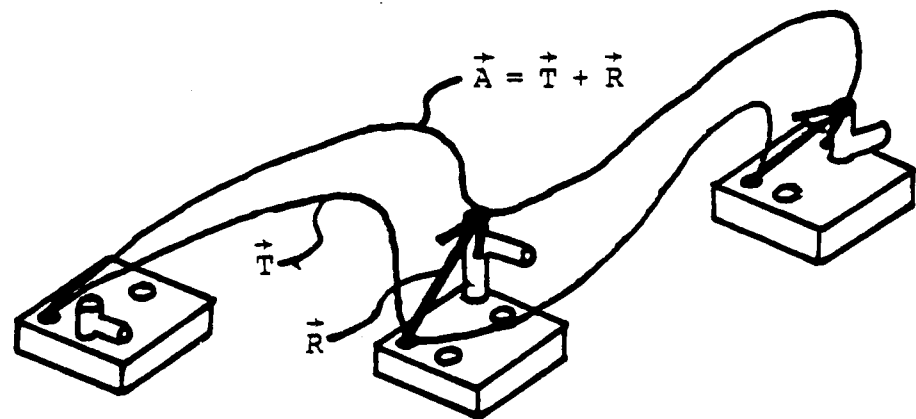
As shown in Fig. 2.1.a, in the case that the table where the object is mounted is fixed, all the operator has to do is to pick up and place the object with direct visual feedback. On the other hand, as shown in Fig. 2.1.b, in the case that the table moves, he is required to do more to achieve the same operation. That is, as we showed in Fig. 2.1.c he has to pick it up and to place it by taking account of the movement of both table and object. If there were some function which enabled him to operate as if the table were fixed, it would be very convenient for him.



a) No Table Movement



b) Table Movement with Position Measuring



c) Compensation with Position Measurement

Fig. 2.1 Compensation with Position Measuring

In this project, I define compensation as this function. According to the above mentioned notation, the compensation means to change A from $\vec{T} + \vec{R}$ to \vec{R} . In other words it means subtraction of \vec{T} from \vec{A} .

2.2 Function of Measurement Arm

When it comes to subtraction of \vec{T} from \vec{A} , \vec{T} has to be measured while \vec{A} can be controlled by the operator. In order to measure \vec{T} , that is, table position with respect to the manipulator base, we introduced the measurement arm to the system. Fig. 2.2 by means of 6 potentiometers, are set in each joint of the arm, we can measure each joint angle; therefore, we can estimate the position and orientation of the table with the help of some geometrical calculations. With the aid of computation and by making use of the measurement arm, the operator can pick up and place the object on the moving table as if the table were fixed.

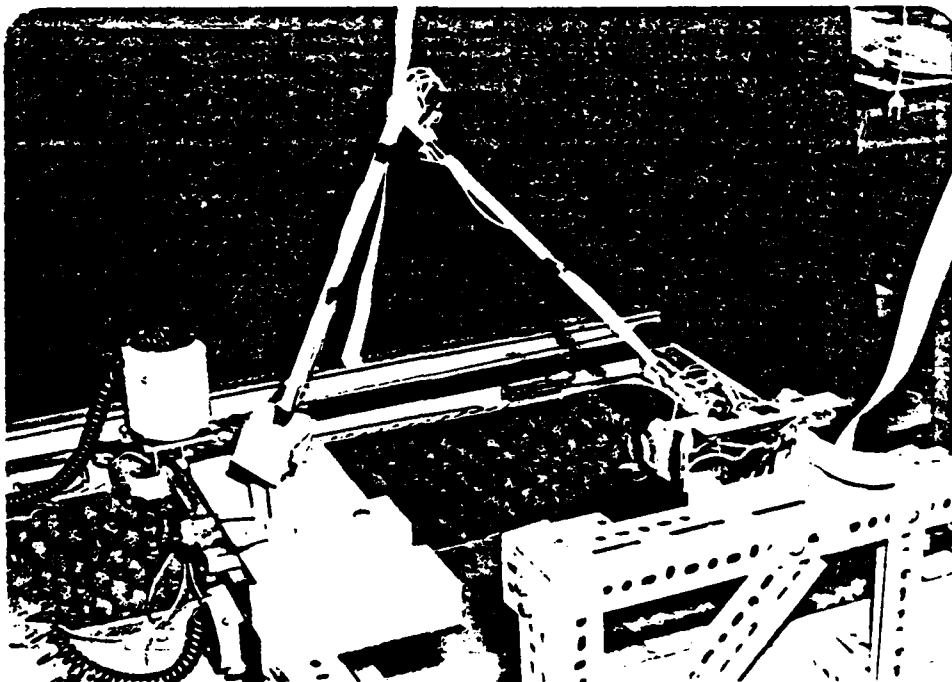


Fig. 2.2 Measurement Arm

CHAPTER 3

METHOD

3.1 Control Theory of Manipulation

At first, we explain the control of manipulation. It is the control of \vec{A} : Absolute Position of the Object with respect to the Manipulation Base, illustrated in Chapter 2. In Sec. 3.1 the general method is stated and in Sec. 3.2 the approximated method we used is stated.

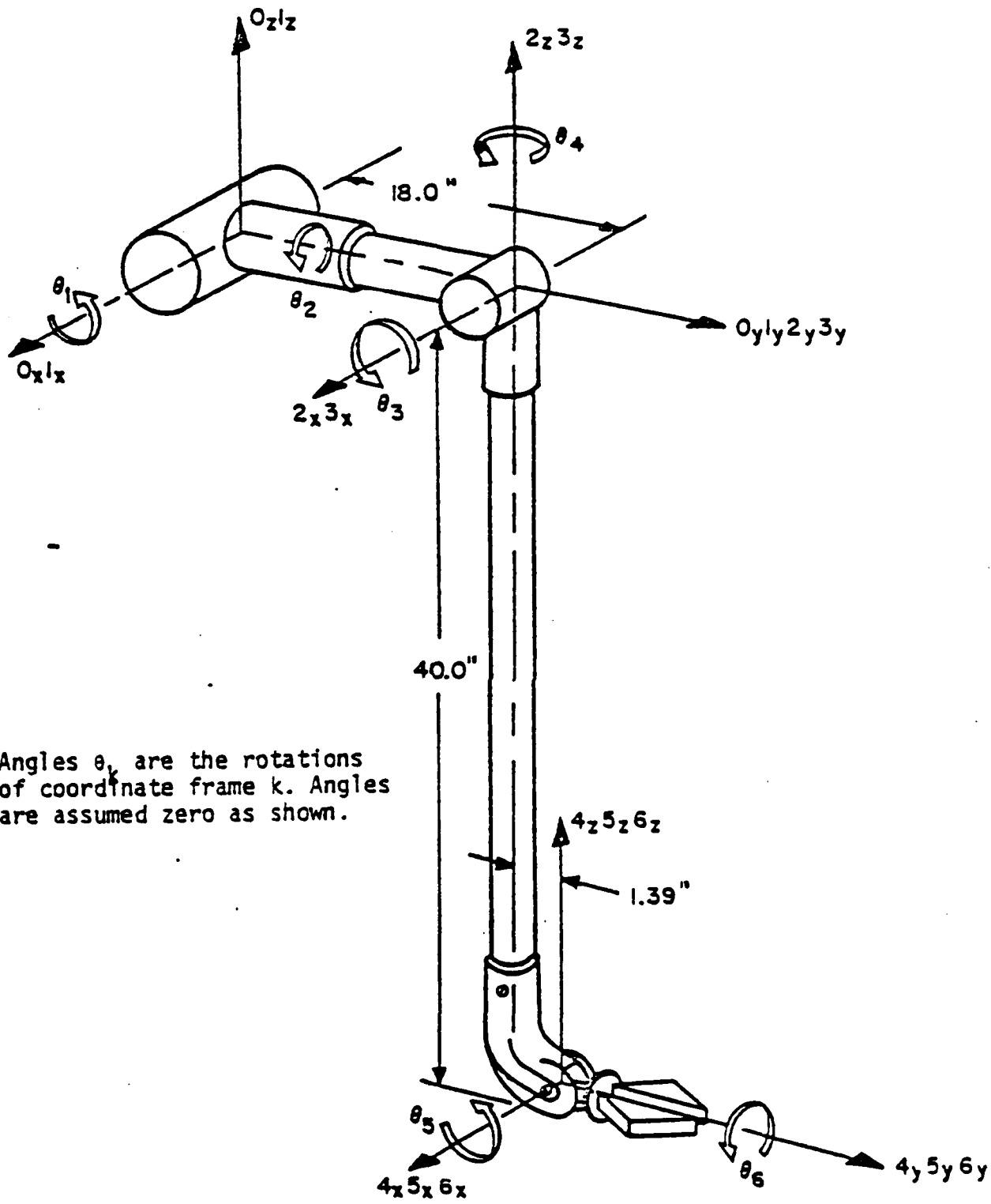
Generally speaking, an unconstrained rigid body has six independent degree of freedom: three independent translation components and three independent rotation components.[3]

Since the hand of a manipulation is rigid body, it needs six independent components to be fixed in the space. We define the following six components: x , y and z which show the translation P of the hand and α , β and γ which show the orientation or rotation of the hand. In order to describe these six parameters, we use the coordinate system whose notation is given by T. Brooks.[4] Matrix ${}^m A_n$ means the transformation from the m th frame to the n th frame. For example the transformation from the hand frame (6th) to the vehicle frame (0th) is given as

$${}^0 A_6 = {}^0 A_1 {}^1 A_2 {}^2 A_3 {}^3 A_4 {}^4 A_5 {}^5 A_6 \quad (3.1)$$

Each frame is defined in Fig. 3.1 and components of each matrix are shown in Table A.1.

According to this notation, x , y and z are the vehicle coordinates at point P . With the definitions that the x_m axis means the x axis in the



Angles θ_k are the rotations of coordinate frame k . Angles are assumed zero as shown.

Fig. 3.1 Definitions of Coordinate Systems and Rotation Angles of the Manipulator (from Brooks [4])

mth frame and the $x_m y_m$ plane means the plane containing the x_m axis and the y_m axis, we define the rotation α , β and γ in Fig. 3.2. The rotation α is the angle between the $y_0 z_0$ plane and the plane which contains the y_6 axis and which is perpendicular to the $x_0 y_0$ plane. The rotation α , β and γ are defined in Fig. 3.2.

If all joints θ_p through θ_6 (θ_k specifies the rotation of the kth frame with the respect to the k - 1 the frame) are given, these six parameters are found as follows.

$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = {}^0A_6 \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} = {}^0A_4 \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \quad (3.2)$$

$$\alpha = \tan^{-1} \left(\frac{x_{hy} - x}{y_{hy} - y} \right) \quad (3.3)$$

$$\beta = \tan^{-1} \left(\frac{z_{hy} - z}{\sqrt{(x_{hy} - x)^2 + (y_{hx} - y)^2}} \right) \quad (3.4)$$

$$\gamma = \tan^{-1} \left(\frac{z_{hx} - z}{\sqrt{(x_{hx} - x)^2 + (y_{hx} - y)^2}} \right) \quad (3.5)$$

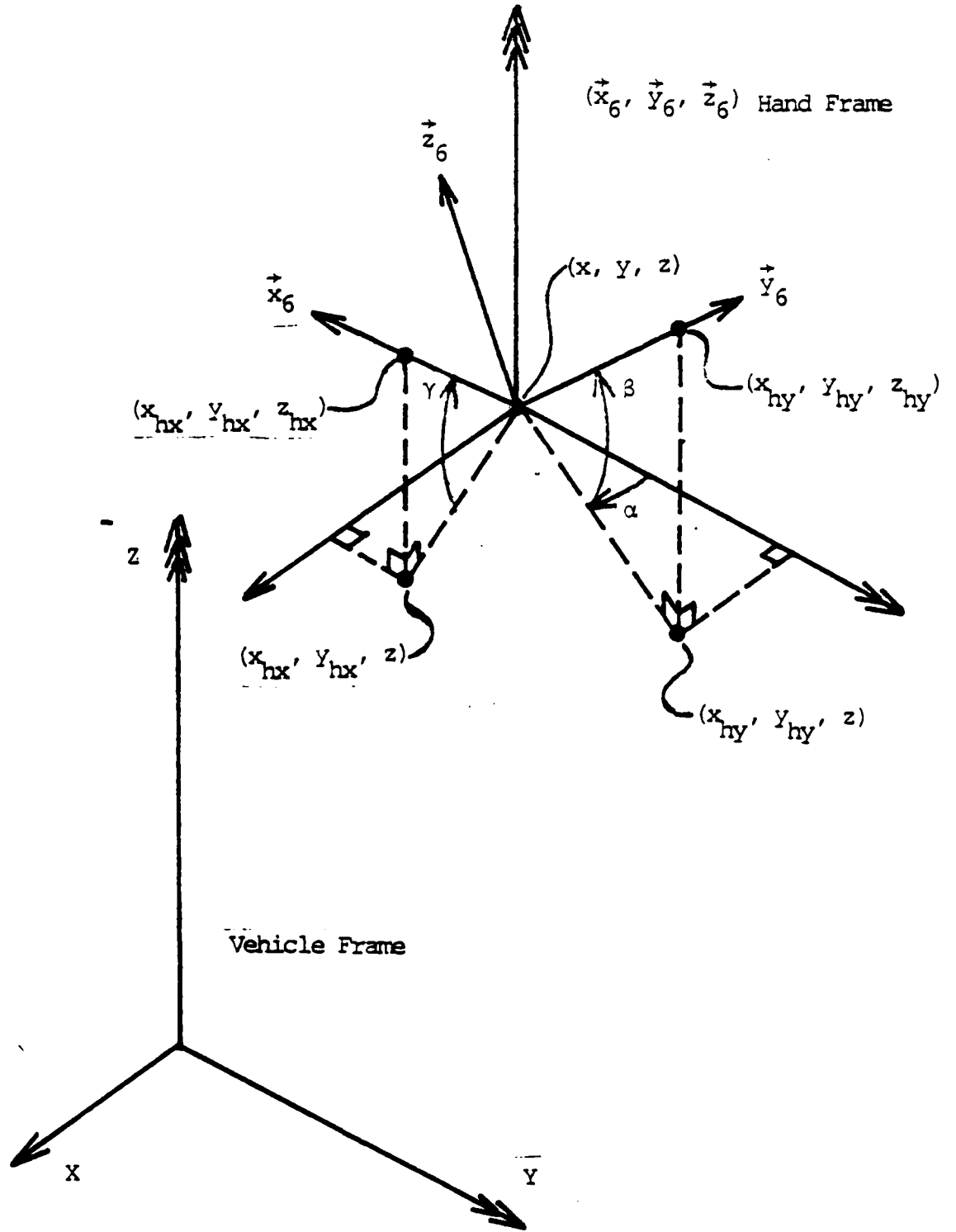


Fig. 3.2 Orientation of Hand

where

$$\begin{bmatrix} x_{hy} \\ y_{hy} \\ z_{hy} \\ 1 \end{bmatrix} = {}^0A_6 \begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \end{bmatrix} = \vec{y}_6 \quad (3.6)$$

$$\begin{bmatrix} x_{hx} \\ y_{hx} \\ z_{hx} \\ 1 \end{bmatrix} = {}^0A_6 \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \vec{x}_6 \quad (3.7)$$

In contrast with above procedure, it is difficult to find θ_1 through θ_6 when x, y, z, α, β and γ are given. Since we want to keep the orientation of the hand parallel to the x_0y_0 plane, we have to give

$$\beta = 0 \quad (3.8)$$

$$\gamma = 0 \quad (3.9)$$

From those equations, we find θ_5 and θ_6 as follows. From equations (3.4) and (3.5), $\beta = 0$ and $\gamma = 0$ mean $z_{hy} - z = 0$ and $z_{hx} - z = 0$, respectively. That is,

$$z_{hy} - z = (0,0,1,0) {}^0A_6 \begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \end{bmatrix} - (0,0,1,0) {}^0A_6 \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$= (0,0,1,0) {}^0A_6 \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} = a_{32} = 0$$

$$\therefore \theta_5 = \tan^{-1} [-(\sin\theta_1 \cos\theta_3 \cos\theta_4 + \cos\theta_1 \cos\theta_2 \sin\theta_3 \cos\theta_4 + \cos\theta_1 \sin\theta_2 \sin\theta_4) / (\cos\theta_1 \cos\theta_2 \cos\theta_3 - \sin\theta_1 \sin\theta_3)] \quad (3.10)$$

$$z_{hx} - z = (0,0,1,0) {}^0A_6 \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix} - (0,0,1,0) {}^0A_6 \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$= (0,0,1,0) {}^0A_6 \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} = a_{31} = 0$$

$$\therefore \theta_6 = \tan^{-1} \left\{ (-\cos\theta_1 \sin\theta_2 \cos\theta_4 + \sin\theta_1 \cos\theta_3 \sin\theta_4 + \cos\theta_1 \cos\theta_2 \sin\theta_3 \sin\theta_4) / [\cos\theta_1 \cos\theta_2 \cos\theta_3] \right.$$

$$\begin{aligned}
& - \sin\theta_1 \sin\theta_3) \cos\theta_5 - (\sin\theta_1 \cos\theta_3 \cos\theta_4 + \\
& \cos\theta_1 \cos\theta_2 \sin\theta_3 \cos\theta_4 + \cos\theta_1 \sin\theta_2 \cos\theta_4) \\
& \sin\theta_5] \} \qquad (3.11)
\end{aligned}$$

Where a_{mn} represents an element in matrix 0A_6 . On the other hand, from (3.3) α is expressed as

$$\begin{aligned}
\tan \alpha &= \frac{(1,0,0,0) {}^0A_6 \begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \end{bmatrix} - (1,0,0,0) {}^0A_6 \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}}{(0,1,0,0) {}^0A_6 \begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \end{bmatrix} - (0,1,0,0) {}^0A_6 \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}} \\
&= \frac{a_{12}}{a_{22}} = [\sin\theta_2 \sin\theta_3 \cos\theta_4 - \cos\theta_2 \sin\theta_4 \\
&+ \sin\theta_2 \cos\theta_3 \tan\theta_5] / [\cos\theta_1 \cos\theta_3 \cos\theta_4 \\
&- \sin\theta_1 \sin\theta_2 \sin\theta_4 - \sin\theta_1 \cos\theta_2 \sin\theta_3 \cos\theta_4 \\
&- (\cos\theta_1 \sin\theta_3 + \sin\theta_1 \cos\theta_2 \cos\theta_3) \tan\theta_5] \qquad (3.12)
\end{aligned}$$

To eliminate θ_5 , substitution of (3.10) to (3.12) gives

$$\begin{aligned} \tan \alpha &= (-\cos\theta_1 \cos\theta_3 \sin\theta_4 - \sin\theta_1 \sin\theta_2 \cos\theta_4 \\ &+ \sin\theta_1 \cos\theta_2 \sin\theta_3 \sin\theta_4) / (\cos\theta_2 \cos\theta_4 \\ &+ \sin\theta_2 \sin\theta_3 \sin\theta_4) \\ &= S \end{aligned} \tag{3.13}$$

By means of S instead of α , we define P.

$$\begin{aligned} P &= S(\cos\theta_2 \cos\theta_4 + \sin\theta_2 \sin\theta_3 \sin\theta_4) \\ &+ \sin\theta_1 \sin\theta_2 \cos\theta_4 + \cos\theta_1 \cos\theta_3 \sin\theta_4 \\ &- \sin\theta_1 \cos\theta_2 \sin\theta_3 \sin\theta_4 \end{aligned} \tag{3.14}$$

Now that we give four parameters: x, y, z and P, to find θ_1 through θ_4 , the equations are rearranged as

$$x = 1.39 (\sin\theta_2 \sin\theta_3 \cos\theta_4 - \cos\theta_2 \sin\theta_4) - 40 \sin\theta_2 \cos\theta_3 \tag{3.15}$$

$$\begin{aligned}
y = & 1.39 (\cos\theta_1 \cos\theta_3 \cos\theta_4 - \sin\theta_1 \cos\theta_2 \sin\theta_3 \cos\theta_4 \\
& - \sin\theta_1 \sin\theta_2 \sin\theta_4) + 40 (\sin\theta_1 \cos\theta_2 \cos\theta_3 \\
& + \cos\theta_1 \sin\theta_3) + 18 \cos\theta_1
\end{aligned} \tag{3.16}$$

$$\begin{aligned}
Z = & 1.39 (\sin\theta_1 \cos\theta_3 \cos\theta_4 + \cos\theta_1 \cos\theta_2 \sin\theta_3 \cos\theta_4 \\
& + \cos\theta_1 \sin\theta_2 \sin\theta_4) + 40 (-\cos\theta_1 \cos\theta_2 \cos\theta_3 \\
& + \sin\theta_1 \sin\theta_3) + 18 \sin\theta_1
\end{aligned} \tag{3.17}$$

$$\begin{aligned}
P = & S(\cos\theta_2 \cos\theta_4 + \sin\theta_2 \sin\theta_3 \sin\theta_4) \\
& + \sin\theta_1 \sin\theta_2 \cos\theta_4 + \cos\theta_1 \cos\theta_3 \sin\theta_4 \\
& - \sin\theta_1 \cos\theta_2 \sin\theta_3 \sin\theta_4
\end{aligned} \tag{3.18}$$

It is quite difficult to solve equations (3.15)-(3.18), then we introduce the relation between the total differential and the partial differential of a function.[5]

The total differential of f is defined by the equation,[6]

$$df = \frac{\partial f}{\partial x} dx + \frac{\partial f}{\partial y} dy + \frac{\partial f}{\partial z} dz \tag{3.19}$$

where f is a function of three variables x , y and z , and $\frac{\partial f}{\partial x}$ is the partial derivative with respect to x .

If x , y and z are all functions of a single variable, say t , then the dependent variable f may also be considered as truly a function of the one independent variable t .

Since only one independent variable is present, df/dt has a meaning and it can be shown, by appropriate limiting processes, that

$$\frac{df}{dt} = \frac{\partial f}{\partial x} \frac{dx}{dt} + \frac{\partial f}{\partial y} \frac{dy}{dt} + \frac{\partial f}{\partial z} \frac{dz}{dt} \quad (3.20)$$

For a short period of time Δt , it can be replaced by

$$\frac{\Delta f}{\Delta t} = \frac{\partial f}{\partial x} \frac{\Delta x}{\Delta t} + \frac{\partial f}{\partial y} \frac{\Delta y}{\Delta t} + \frac{\partial f}{\partial z} \frac{\Delta z}{\Delta t} \quad (3.21)$$

Consequently, we get

$$\Delta f = f_x \Delta x + f_y \Delta y + f_z \Delta z \quad (3.22)$$

where $f_x = \partial f / \partial x$.

Applying the relation to our problem gives

$$\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta p \end{bmatrix} = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ y_1 & y_2 & & \\ z_1 & & & \\ p_1 & - & - & p_4 \end{bmatrix} \cdot \begin{bmatrix} \Delta \theta_1 \\ \Delta \theta_2 \\ \Delta \theta_3 \\ \Delta \theta_4 \end{bmatrix} \quad (3.23)$$

$$\vec{\Delta x} = J(\vec{\theta}) \cdot \vec{\theta}$$

Provided that $|J(\vec{\theta})| \neq 0$, we have

$$\begin{bmatrix} \Delta\theta_1 \\ \Delta\theta_2 \\ \Delta\theta_3 \\ \Delta\theta_4 \end{bmatrix} = J(\vec{\theta})^{-1} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta p \end{bmatrix} \quad (3.24)$$

Each component of Jacobian matrix is shown in Table A.3.

3.2 Jacobian of 1st Order Approximation

By looking over components of the Jacobian matrix, we find it contains many trigonometric functions. Decreasing the trigonometric functions in number will cause more efficiency in terms of mechanism and time for calculation. Then we introduce the appropriate Jacobian matrix so that we may eliminate the trigonometric functions, provided that θ is limited in the neighborhood of θ_0 : $\theta_s (= \theta - \theta_0)$ is small.

At first we consider the 0th order approximation: $\sin\theta_s$ and $\cos\theta_s$ are expressed as $\sin\theta_s = 0$ and $\cos\theta_s = 1$, that is,

$$\left. \begin{aligned} \sin \theta &= \sin (\theta_0 + \theta_s) \doteq \sin \theta_0 \\ \cos \theta &= \cos (\theta_0 + \theta_s) \doteq \cos \theta_0 \end{aligned} \right\} \quad (3.25)$$

The 0th order approximation makes Jacobian matrix constant so that we do not need estimate it after the manipulator starts moving as well as we get $\vec{\theta}$ with ease. But it causes much error.

The 1st order approximation: $\sin \theta_s$ and $\cos \theta_s$ are expressed as $\sin \theta_s = \theta_s$ and $\cos \theta_s = 1$, that is,

$$\left. \begin{aligned} \sin \theta &= \sin (\theta_o + \theta_s) = \sin \theta_o + \theta_s \cos \theta_o \\ \cos \theta &= \cos (\theta_o + \theta_s) = \cos \theta_o - \theta_s \sin \theta_o \end{aligned} \right\} \quad (3.26)$$

This approximation has less complicated calculation than the conventional one and less error than the 0th order approximation. The final form we get is expressed as

$$\Delta \theta_n = \frac{(\Delta x, \Delta y, \Delta z, \Delta p) [C_n]}{(D_1, D_2, D_3, D_4)} = \frac{\begin{bmatrix} \theta_{1s} \\ \theta_{2s} \\ \theta_{3s} \\ \theta_{4s} \\ 1 \end{bmatrix} \Delta \vec{x}^{-1} [C_n] \vec{\theta}_s}{\vec{D}^{-1} \vec{\theta}_s} \quad (3.27)$$

where

$$\vec{\theta}_s = \vec{\theta} - \vec{\theta}_o$$

$$J(\vec{\theta}) = \vec{D}^{-1} \cdot \vec{\theta}_s$$

$[C_n]$ is constant

Next, as an example of higher order approximation, we consider the 2nd order approximation $\sin\theta_s$ and $\cos\theta_s$ are expressed as $\sin\theta_s = \theta_s$ and $\cos\theta_s = 1 - \frac{\theta_s^2}{2}$, that is,

$$\left. \begin{aligned} \sin \theta &= \sin (\theta_o + \theta_s) = \left(1 - \frac{\theta_s^2}{2}\right) \sin\theta_o + \theta_s \cos\theta_o \\ \cos \theta &= \cos (\theta_o + \theta_s) = \left(1 - \frac{\theta_s^2}{2}\right) \cos\theta_o - \theta_s \sin\theta_o \end{aligned} \right\} \quad (3.28)$$

These equations prove that the higher order approximation needs more complicated calculation compared with the 0th and 1st order ones, though it is more accurate. Accordingly, we conclude that the 1st order is the most appropriate in terms of simplicity and accuracy. The components of the 1st order approximation are expressed as

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} & x_{15} \\ \vdots & & & & \vdots \\ x_{41} & \dots & \dots & \dots & x_{45} \end{bmatrix} \begin{bmatrix} \theta_{1s} \\ \theta_{2s} \\ \theta_{3s} \\ \theta_{4s} \\ 1 \end{bmatrix} \quad (3.29)$$

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} y_{11} & \dots & \dots & \dots & y_{15} \\ \vdots & & & & \vdots \\ y_{41} & \dots & \dots & \dots & y_{45} \end{bmatrix} \begin{bmatrix} \theta_{1s} \\ \theta_{2s} \\ \theta_{3s} \\ \theta_{4s} \\ 1 \end{bmatrix} \quad (3.30)$$

$$\begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} = \begin{bmatrix} z_{11} & \dots & z_{15} \\ \vdots & & \vdots \\ z_{41} & \dots & z_{45} \end{bmatrix} \cdot \begin{bmatrix} \theta_{1s} \\ \theta_{2s} \\ \theta_{3s} \\ \theta_{4s} \\ 1 \end{bmatrix} \quad (3.31)$$

$$\begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{bmatrix} = \begin{bmatrix} p_{11} & \dots & p_{15} \\ \vdots & & \vdots \\ p_{41} & \dots & p_{45} \end{bmatrix} \cdot \begin{bmatrix} \theta_{1s} \\ \theta_{2s} \\ \theta_{3s} \\ \theta_{4s} \\ 1 \end{bmatrix} \quad (3.32)$$

where $x_1 = \partial x / \partial \theta_1$.

Details are shown in Table A.4. Consequently, we have θ , through $\Delta\theta_4$

$$\Delta\theta_n = \Delta_n / \Delta \quad (n = 1, \dots, 4)$$

where

$$\Delta = \begin{vmatrix} x_1 & x_2 & \dots & x_4 \\ y_1 & & & \vdots \\ z_1 & & & \vdots \\ p_1 & \dots & \dots & p_4 \end{vmatrix} \quad (3.33)$$

$$\Delta_n = \begin{vmatrix} \overbrace{x_1}^n & \Delta x & \dots & x_4 \\ y_1 & \Delta y & & \vdots \\ z_1 & \Delta z & & \vdots \\ p_1 & \Delta p & \dots & p_4 \end{vmatrix} \quad (3.34)$$

In reference to θ_5 and θ_6 , they are much influenced by the posture of the hand so that they change more than others. Therefore, introducing the approximate calculus for θ_5 and θ_6 is not suitable. So we get θ_5 and θ_6 by the basic expression.

$$\theta_5 = f(\theta_1, \theta_2, \theta_3, \theta_4), \theta_6 = f(\theta_1, \theta_2, \theta_3, \theta_4, \theta_5) \quad (3.35)$$

According to those methods, we can get $(\theta_1, \theta_2, \dots, \theta_6)$, consequently x, y, z and S by means of equations (3.15) - (3.18).

As the result, we can control \vec{A} .

3.3 Compensation

According to Chapter 2, \vec{T} is measured by the measurement arm. We show the basic idea of measuring the position and orientation of the table. The measurement arm consisted of 6 joints all of which are rotational pairs. In practical use, the extreme distal link is kept perpendicular to the horizontal plane. On this condition, we can get x, y and z coordinates of point Q and angle α . For convenience, we define angles θ_1', θ_2' and length l as in Fig. 3.4 and Fig. 3.5.

Accordingly, point Q is determined by

$$\left. \begin{aligned} Q_x &= l \cos\theta_2' \\ Q_y &= l \sin\theta_2' \\ Q_z &= l \sin\theta_1' - (b \cos(\theta_1' + \theta_4) + c) \end{aligned} \right\} \quad (3.36)$$

where

$$l = a \cos \theta_1' + b \sin (\theta_1' + \theta_4)$$

$$\theta_1' = \tan^{-1} (1/(\tan\theta_1 \tan\theta_2))$$

$$\theta_2' = -\tan^{-1} (\tan\theta_2/\sin\theta_1)$$

These coordinates are determined in terms of the coordinate system which is fixed in the measurement arm. However, they need to be expressed by the common coordinate system which the slave arm can use. In terms of the common system, point Q is expressed by

$$\left. \begin{aligned} Q_x &= Q_X + \Delta x \\ Q_y &= Q_Y + \Delta y \\ Q_z &= Q_Z + \Delta z \end{aligned} \right\} \quad (3.37)$$

Where $(\Delta x, \Delta y, \Delta z)$ means the vector which shows the distance between two origins of coordinate system.

$$\alpha = \frac{\pi}{2} - (\theta_2' - \theta_6) \quad (3.38)$$

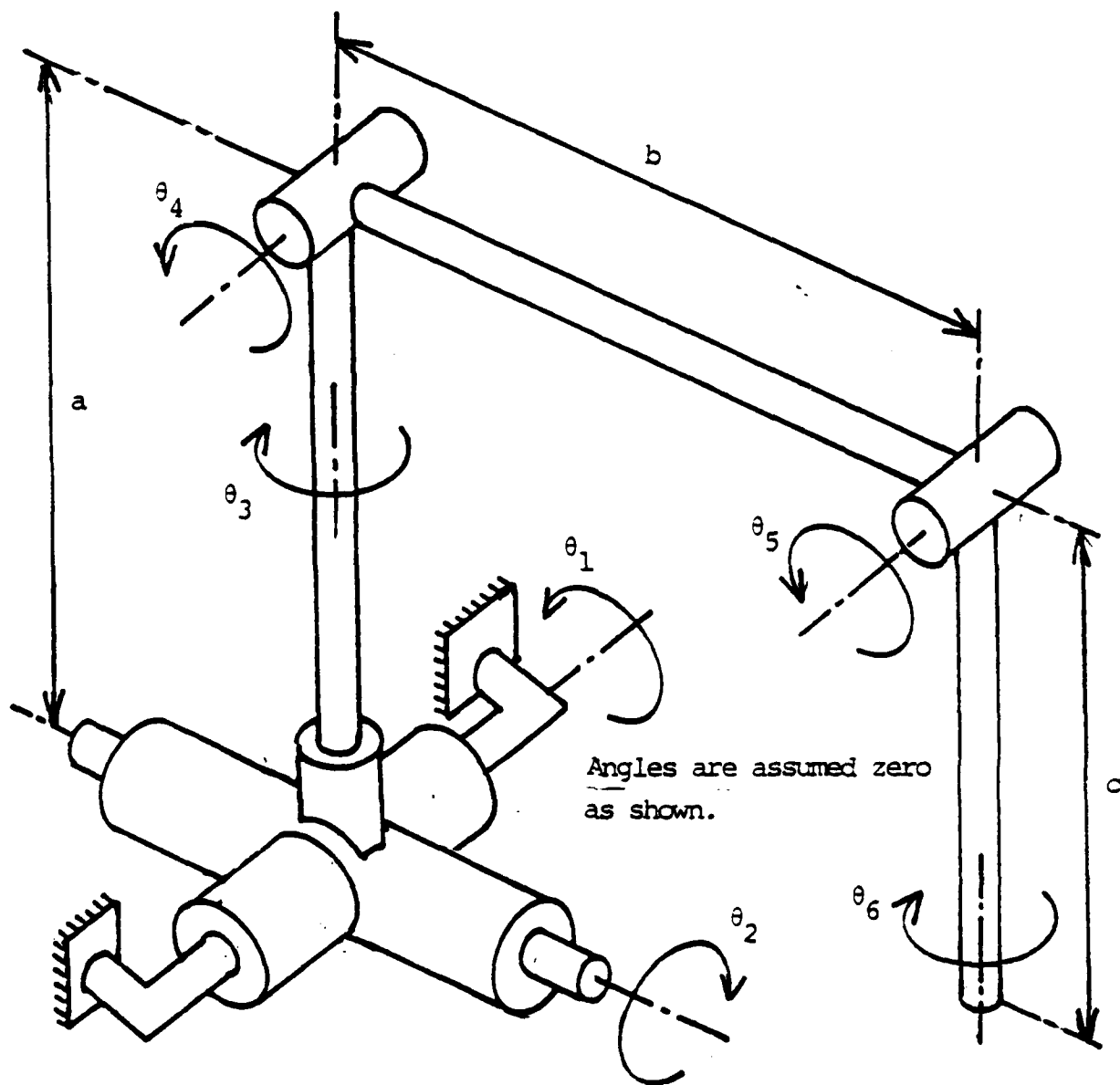
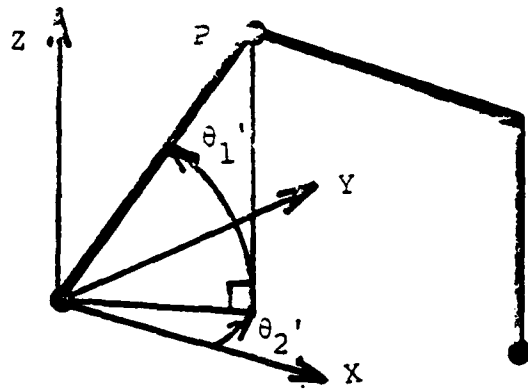
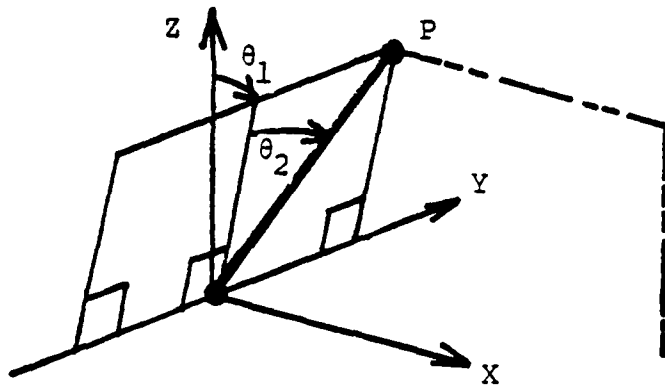


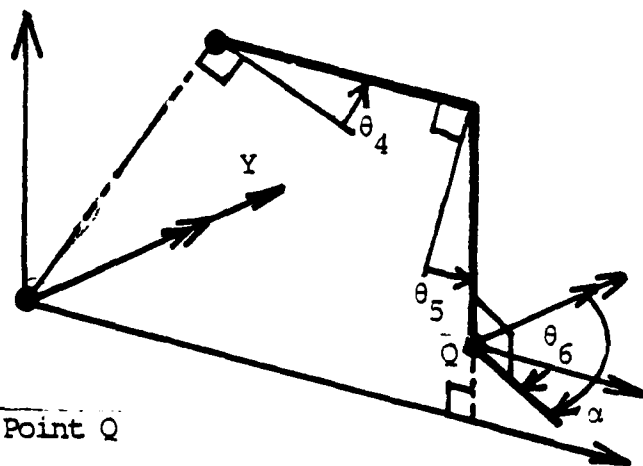
Fig. 3.3 Rotational Angles of the Measurement Arm



a) θ_1' and θ_2'

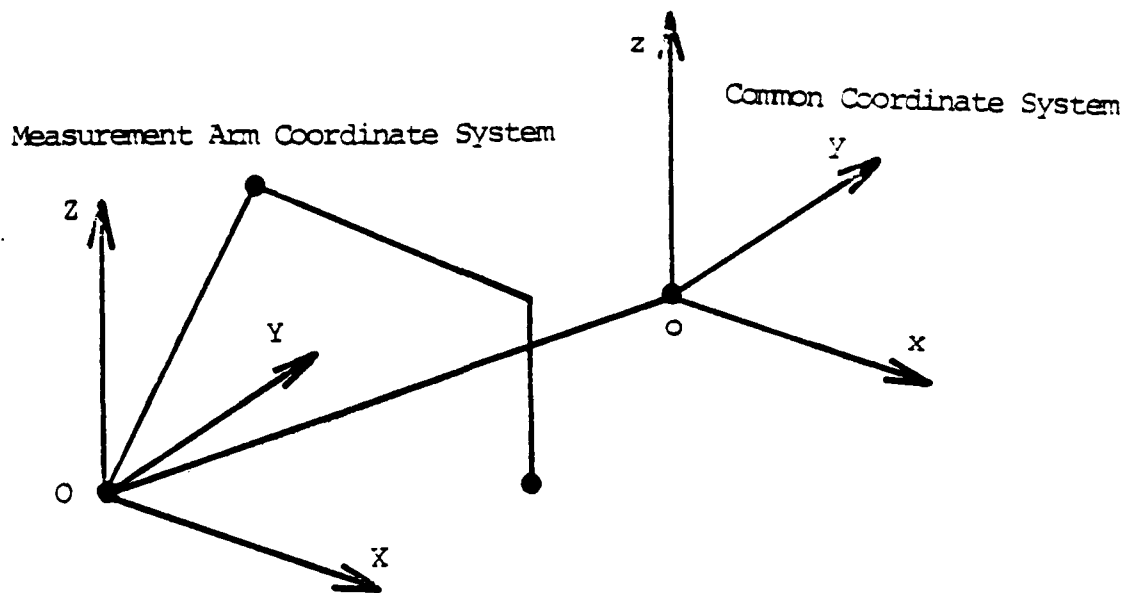


b) Point P

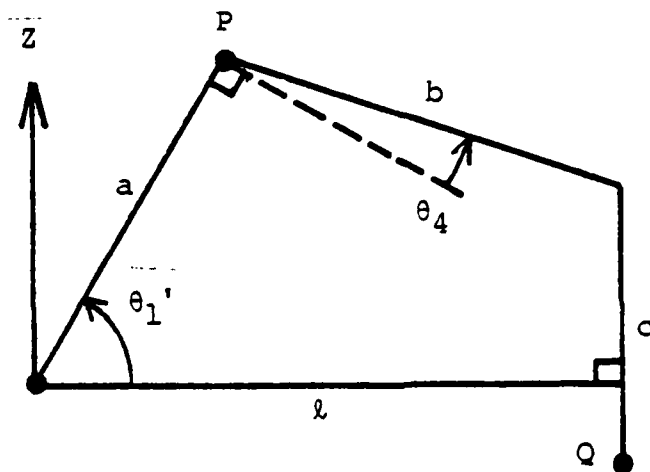


c) Point Q

Fig. 3.4 Rotational Angles in Practical Use



a) Two Coordinate Systems



b) Plane including all Links of Measurement Arm

Fig. 3.5 Rotational Angles and Some Other Parameters

CHAPTER 4

EXPERIMENTS

We mainly had two experiments: one was to measure the accuracy of the Measurement Arm; another was to measure the accuracy of the first order of approximation of Jacobian Matrices used for the straight-line motion of Slave Arm.

As to the first one, we combined the Measurement Arm with the Table illustrated in Fig. 2.1.b. and made the table move with the distance of $\Delta\vec{x}(l_x, l_y, l_z)$ by means of the program MSURE. As illustrated in Figs. 4.1 and 4.2, we got good linearity, with errors within ± 0.15 inch. This is a good result, considering the experimental mechanism of the Measurement Arm.

Next, we tried to make a straight-line motion of the Slave Arm by means of program MAIN. As illustrated in Fig. 4.3, we make the arm move from origin to point p_1 , the distance \vec{x}_1 . The results are shown in Tables 4.3, 4.4 and 4.5. For example, as to the reference $\vec{x}_1(\Delta x_1, 0, 0)$ in Table 4.3, we have the errors within 0.09 inch, 0.19 inch and 0.21 inch, along the x-axis, y-axis and z-axis, respectively. This is also a good result, considering that the Slave Arm mechanism has significant backlash. The errors along the y-axis are big compared with others. It is mainly caused by the backlash of the angle θ_1 .

In Figs. 4.1.c. and 4.2.c. we can see the increase in error, it is because the z-axis of the Measurement Arm is not in parallel with the z-axis of the Table.

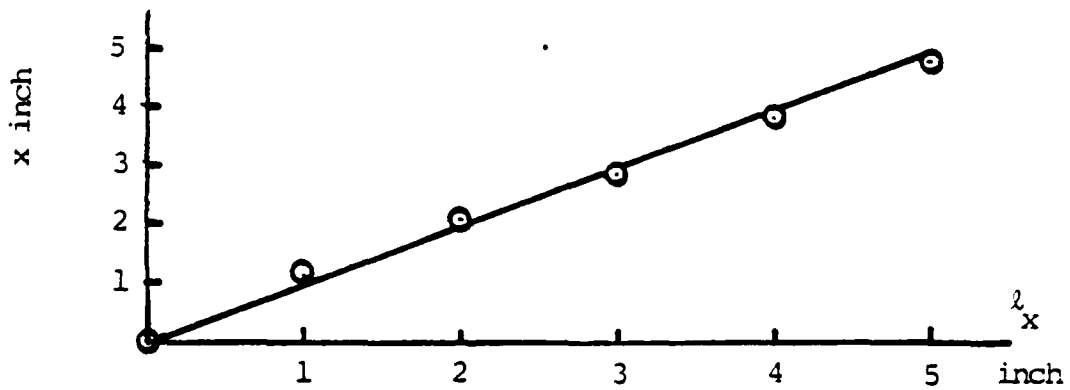
TABLE 4.1
ACCURACY OF MEASUREMENT ARM

a) Measured Data $\lambda_y = 0, \lambda_z = 0$

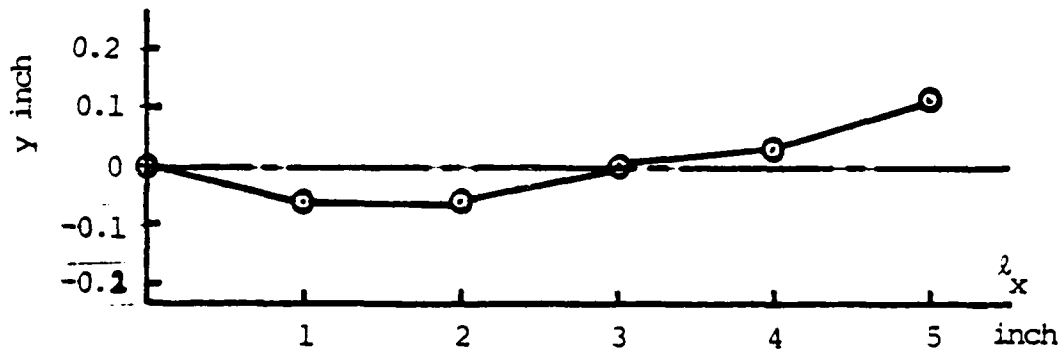
λ_x inch	x inch	y inch	z inch	S
0	4.71	-6.78	3.89	0.870
1	5.75	-6.84	3.96	0.879
2	6.73	-6.85	4.03	0.890
3	7.61	-6.78	4.10	0.908
4	8.53	-6.75	4.14	0.932
5	9.49	-6.67	4.19	0.964

b) Modified Data $\lambda_y = 0, \lambda_z = 0$

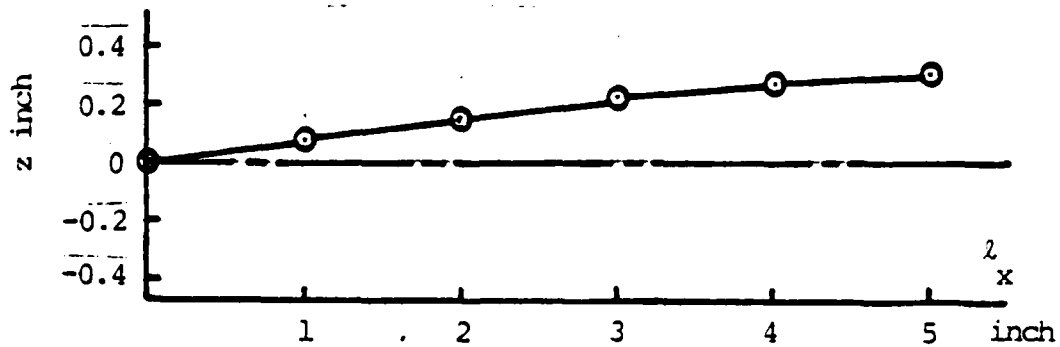
λ_x inch	x inch	y inch	z inch	S
0	0.00	0.00	0.00	0.000
1	1.04	-0.06	0.07	0.009
2	2.02	-0.07	0.14	0.020
3	2.90	0.00	0.21	0.038
4	3.82	0.03	0.25	0.062
5	4.78	0.11	0.30	0.094



a) X - Axis



b) Y - Axis



c) Z - Axis

Fig. 4.1 Accuracy of Measurement Arm, $\lambda_y = 0$, $\lambda_z = 0$

TABLE 4.2

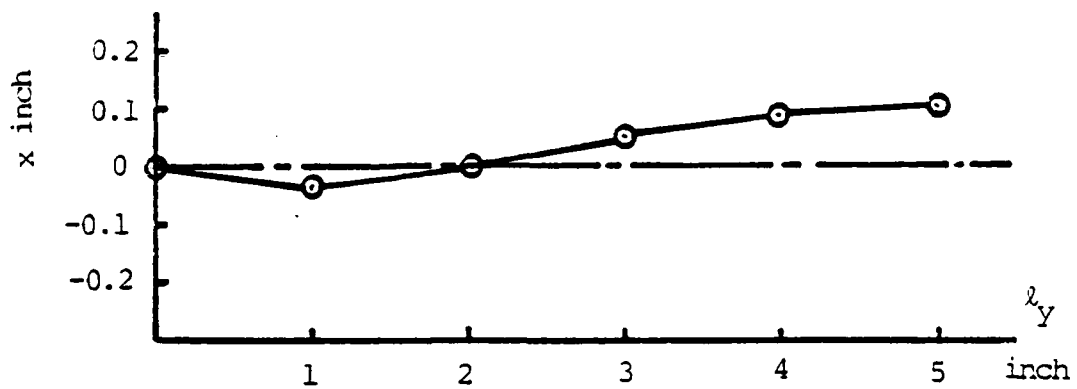
ACCURACY OF MEASUREMENT ARM

a) Measured Data $\lambda_x = 0, \lambda_z = 0$

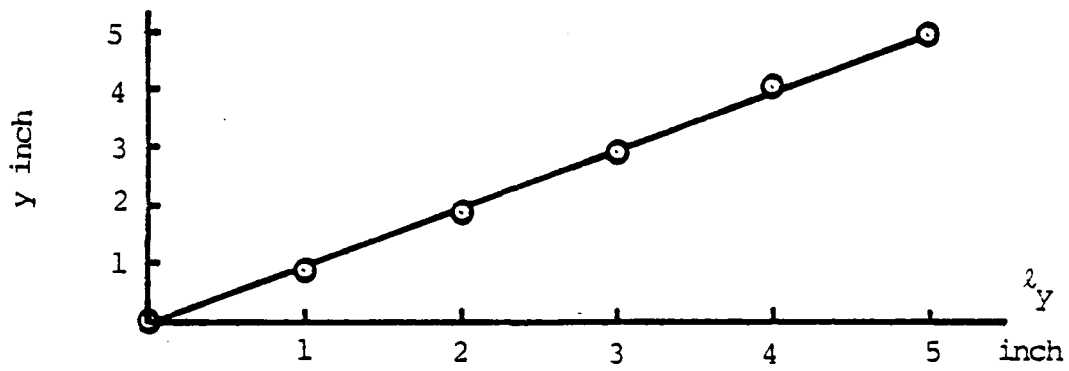
λ_y inch	x inch	y inch	z inch	S
0	3.74	-12.71	3.70	0.812
1	3.71	-11.79	3.74	0.815
2	3.74	-10.80	3.77	0.807
3	3.79	- 9.76	3.79	0.811
4	3.83	- 8.71	3.80	0.823
5	3.84	- 7.77	3.80	0.842

b) Modified Data $\lambda_x = 0, \lambda_z = 0$

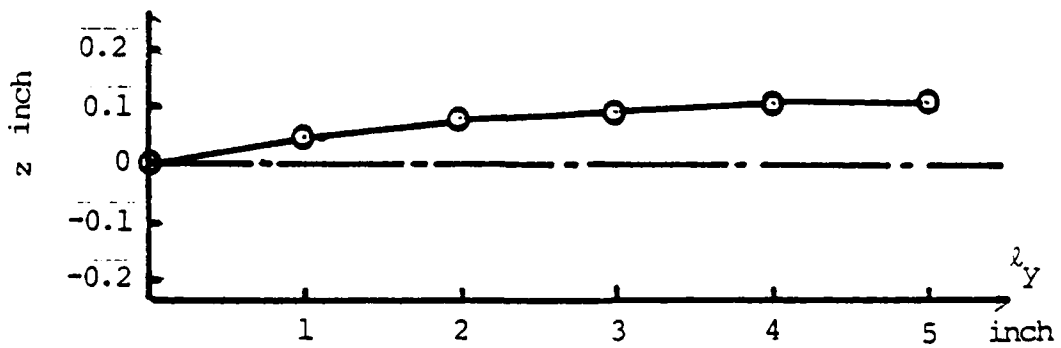
λ_y inch	x inch	y inch	z inch	S
0	0.00	0.00	0.00	0.000
1	-0.03	0.92	0.04	0.003
2	0.00	1.91	0.07	-0.005
3	0.05	2.95	0.09	-0.001
4	0.09	4.00	0.10	0.011
5	0.10	4.94	0.10	0.030



a) X - Axis



b) Y - Axis



c) Z - Axis

Fig. 4.2 Accuracy of Measurement Arm, $\lambda_X = 0$, $\lambda_Z = 0$

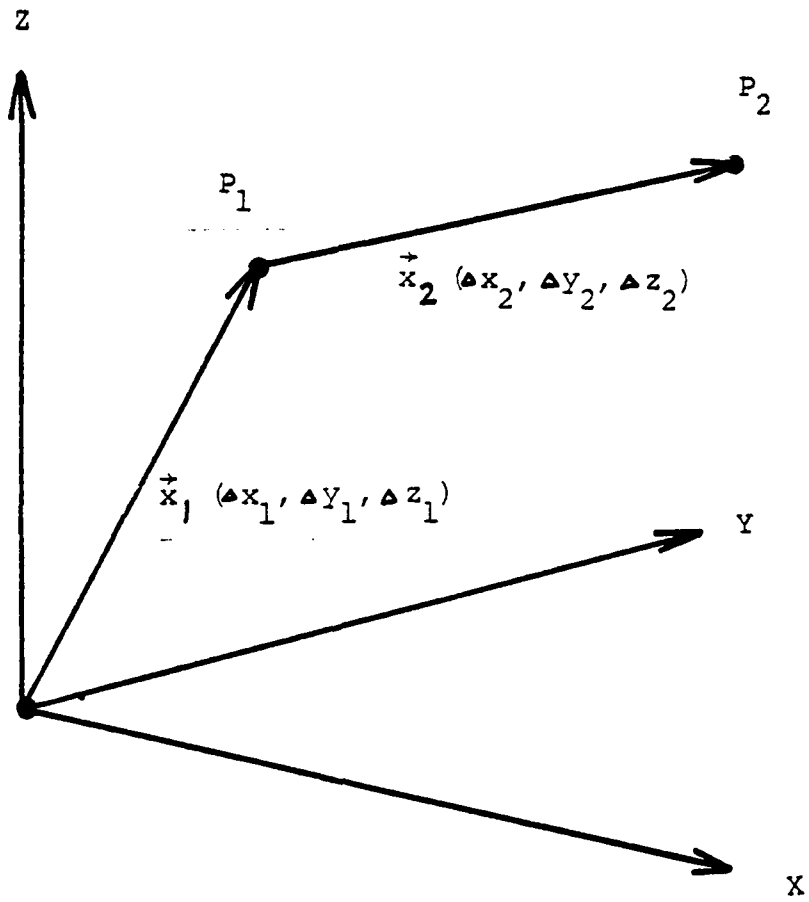


Fig. 4.3 Accuracy of Approximation Vehicle Frame

TABLE 4.3

Accuracy of Approximation \vec{x}_1 , $\Delta y_1 = \Delta z_1 = 0$

a) Measured Data

				inch
Δx_1	x	y	z	
0	-0.01	-0.13	-0.00	
0.5	0.49	-0.35	-0.04	
1	0.98	-0.17	-0.03	
2	1.98	-0.32	-0.05	
3	2.99	-0.32	0.13	
4	3.90	-0.32	0.21	

b) Modified Data

				inch
Δx_1	x	y	z	
0	0.00	0.00	0.00	
0.5	0.50	-0.22	-0.04	
1	0.99	-0.04	-0.03	
2	1.99	-0.19	-0.05	
3	3.00	-0.19	0.13	
4	3.91	-0.19	0.21	

TABLE 4.4

Accuracy of Approximation \vec{x}_1 , $\Delta x_1 = \Delta z_1 = 0$

a) Measured Data

	inch		
Δy_1	x	y	z
0	-0.00	-0.06	-0.01
0.5	-0.02	0.32	-0.03
1	-0.07	0.88	-0.09
2	-0.02	1.74	-0.15
3	-0.07	2.84	0.19
4	-0.06	3.87	0.26

b) Modified Data

	inch		
Δy_1	x	y	z
0	0.00	0.00	0.00
0.5	-0.02	0.38	-0.02
1	-0.07	0.94	-0.08
2	-0.02	1.80	-0.14
3	-0.07	2.90	0.20
4	-0.06	3.93	0.27

TABLE 4.5

Accuracy of Approximation \vec{x}_1 , $\Delta x_1 = \Delta y_1 = 0$

a) Measured Data

				inch
Δz_1	x	y	z	
0	-0.00	-0.06	-0.01	
0.2	0.03	-0.22	0.13	
0.5	-0.04	-0.16	0.45	
1	0.01	-0.31	0.97	
2	-0.05	-0.30	1.97	
3	0.01	-0.55	2.90	

b) Modified Data

				inch
Δz_1	x	y	z	
0	0.00	0.00	0.00	
0.2	0.03	-0.16	0.14	
0.5	-0.04	-0.10	0.46	
1	0.01	-0.25	0.98	
2	-0.05	-0.24	1.98	
3	0.01	-0.49	2.91	

TABLE 4.6

Accuracy of Approximation \vec{x}_2 , $y_2 = z_2 = 0$

a) Measured Data

	inch		
Δx_2	x	y	z
0	2.92	-2.22	1.15
0.5	3.46	-2.50	1.20
1	3.93	-2.19	1.14
2	4.90	-2.32	1.28
3	5.82	-2.26	1.36
4	6.88	-2.43	1.63

b) Modified Data

	inch		
Δx_2	x	y	z
0	0.00	0.00	0.00
0.5	0.54	-0.28	0.05
1	1.01	0.03	-0.01
2	1.98	-0.10	0.13
3	2.90	-0.04	0.21
4	3.96	-0.21	0.48

TABLE 4.7

Accuracy of Approximation \vec{x}_2 , $\Delta x_2 = \Delta z_2 = 0$

a) Measured Data

	inch		
Δy_2	x	y	z
0	2.92	-2.12	1.14
0.5	2.94	-1.84	1.09
1	2.93	-1.43	1.10
2	3.00	-0.48	1.11
3	3.00	0.73	1.05
4	2.88	1.77	1.16

b) Modified Data

	inch		
Δy_2	x	y	z
0	0.00	0.00	0.00
0.5	0.02	0.28	-0.05
1	0.01	0.69	-0.04
2	0.08	1.64	-0.03
3	0.08	2.85	-0.09
4	-0.04	3.89	0.02

TABLE 4.8

Accuracy of Approximation \vec{x}_2 , $\Delta x_2 = \Delta y_2 = 0$

a) Measured Data

				inch
Δz_2	x	y	z	
0	3.00	-2.32	1.19	
0.5	2.87	-2.25	1.58	
1	2.96	-2.30	2.05	
2	2.92	-2.64	3.10	
3	2.86	-2.81	4.08	
4	2.82	-3.06	5.04	

b) Modified Data

				inch
Δz_2	x	y	z	
0	0.00	0.00	0.00	
0.5	-0.14	0.07	0.39	
1	-0.04	0.02	0.86	
2	-0.08	-0.32	1.91	
3	-0.14	-0.49	2.89	
4	-0.18	-0.74	3.85	

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The purpose of this research was to extend the compensation done previously by Tani which presupposed a perfect measurement by using a sensor.

For this purpose, as a sensor we developed a 6 degree-of-freedom passive Measurement Arm having a simple gripper but otherwise flaccid. In addition to developing the sensor, we extended the control method by considering some approximated Jacobian matrices instead of complicated strict Jacobian matrices. Consequently, we developed the Jacobian matrices of first order approximation with no trigonometric functions.

We performed two experiments: one was to measure the accuracy of the Measurement Arm by moving the table; another was to measure the accuracy of the Jacobian matrices of first order approximation by moving the Slave Arm. The result showed the capability of compensation with the Measurement Arm as a sensor.

Having developed the basic hardware and software for compensation by means of the sensor, we intend to improve this compensation by using these techniques in the near future.

As an example of future work, I show the following two programs. One is the program named TTT, which will keep the same orientation of the hand of the Slave Arm and the same distance between the table and Slave Arm, regardless of the position of the table. This is to test the total error caused by the hardware and software of the system. Another is the program named HICOM which is to extend Tani's compensation by using the

sensor. These are almost completed but not yet perfect.

In order to extend the compensation with sensor, we suggest developing a program which considers the errors caused by mechanisms such as backlash in addition to present considerations.

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APPENDIX I

TRANSFORMATION MATRICES

TABLE A.1

Frame Transformation

$${}^0A_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \theta_1 & -\sin \theta_1 & 0 \\ 0 & \sin \theta_1 & \cos \theta_1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^1A_2 = \begin{bmatrix} \cos \theta_2 & 0 & \sin \theta_2 & 0 \\ 0 & 1 & 0 & 18 \\ -\sin \theta_2 & 0 & \cos \theta_2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^2A_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \theta_3 & -\sin \theta_3 & 0 \\ 0 & \sin \theta_3 & \cos \theta_3 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^3A_4 = \begin{bmatrix} \cos \theta_4 & -\sin \theta_4 & 0 & -1.39 \sin \theta_4 \\ \sin \theta_4 & \cos \theta_4 & 0 & 1.39 \cos \theta_4 \\ 0 & 0 & 1 & -40 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^4A_5 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \theta_5 & -\sin \theta_5 & 0 \\ 0 & \sin \theta_5 & \cos \theta_5 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^5A_6 = \begin{bmatrix} \cos \theta_6 & 0 & \sin \theta_6 & 0 \\ 0 & 1 & 0 & 0 \\ -\sin \theta_6 & 0 & \cos \theta_6 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

TABLE A.2

Transformation from Hand to Vehicle

$${}^6A_0 = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$a_{11} = (C2C4 + S2S3S4) C6 + (S2S3C4S5 - C2S4S5 - S2C3C5) S6$$

$$a_{12} = (S2S3C4 - C2S4) C5 + S2C3S5$$

$$a_{13} = (C2S4S5 - S2S3C4S5 + S2C) C6 + (C2C4 + S2S3S4) S6$$

$$a_{14} = 1.39 (S2S3C4 - C2S4) - 40 (S2C3)$$

$$a_{21} = (C1C3C4 - S1C2S3C4 - S1S2S4) S5S6 + (C1S3 + S1C2C3) C5S6 + (C1C3 - S1C2S3) S4C6 + S1S2C4C6$$

$$a_{22} = (C1C3C4 - S1S2S4 - S1C2S3C4) C5 - (C1S3 + S1C2C3) S5$$

$$a_{23} = (S1S2S4 - C1C3C4 + S1C2S3C4) S5C6 - (C1S3 + S1C2C3) C5C6 + (C1C3 - S1C2S3) S4S6 + S1S2C4S6$$

$$a_{24} = 1.39 (C1C3C4 - S1C2S3C4 - S1S2S4) + 40 (C1S3)$$

$$a_{31} = (C1S2S4 + S1C3C4 + C1C2S3C4) S5S6 + (S1S3 - C1S2C3) C5 + (C1C2S3 + S1C3) S4C6 - C1S2C4C6$$

$$a_{32} = (C1S2S4 + S1C3C4 + C1C2S3C4) C5 + (C1C2C3 - S1S3)$$

$$a_{33} = -(C1S2S4 + S1C3C4 + C1C2S3C4) S5C6 + (S1C3 + C1C2S3) + (C1C2C3 - S1S3) C5C6 - C1S2C4S6$$

$$a_{34} = 1.39 (S1C3C4 + C1C2S3C4 + C1S2S4) + 40 (S1S3 - C1C2C3) + 18S1$$

where $S1 = \sin\theta_1$, $C1 = \cos\theta_1$

APPENDIX II

JACOBIAN MATRICES

TABLE A.3

Jacobian Matrix

$$J(\theta) = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ y_1 & y_2 & y_3 & y_4 \\ z_1 & z_2 & z_3 & z_4 \\ p_1 & p_2 & p_3 & p_4 \end{bmatrix}$$

where $x_1 = \partial x / \partial \theta_1$.

$$x_1 = 0$$

$$x_2 = 1.39 (C2S3C4 + S2S4) - 40C2C3$$

$$x_3 = 1.39S2C3C4 + 40S2S3$$

$$x_4 = -1.39 (C2C4 + S2S3S4)$$

$$y_1 = -1.39 (S1C3C4 + C1C2S3C4 + C1S2S4) + 40 (C1C2C3 - S1S3) - 18S1$$

$$y_2 = 1.39 (S1S2S3C4 - S1C2S4) - 40S1S2C3$$

$$y_3 = -1.39 (S1C2C3C4 + C1S3C4) + 40 (C1C3 - S1C2S3)$$

$$y_4 = 1.39 (-S1S2C4 - C1C3S4 + S1C2S3S4)$$

$$z_1 = 1.39 (C1C3C4 - S1C2S3C4 - S1S2S4) + 40 (S1C2C3 + C1S3) + 18C1$$

$$z_2 = 1.39 (-C1S2S3C4 + C1C2S4) + 40C1S2C3$$

$$z_3 = 1.39 (C1C2C3C4 - S1S3C4) + 40 (S1C3 + C1C2S3)$$

$$z_4 = 1.39 (C1S2C4 - S1C3S4 - C1C2S3S4)$$

$$p_1 = 0 + C1S2C4 - S1C3S4 - C1C2S3S4$$

$$p_2 = S (-S2C4 + C2S3S4) + (S1C2C4 + S1S2S3S4)$$

$$p_3 = S (S2C3S4) + (-S1C2C3S4 - C1S3S4)$$

Table A.3 (Continued)

$$P_4 = S (S_2S_3C_4 - C_2S_4) + (C_1C_3C_4 - S_1C_2S_3C_4 - S_1S_2S_4)$$

where $S_1 = \sin\theta_1$ and $C_1 = \cos\theta_1$.

TABLE A.4
Components of Matrix

$$\begin{aligned}
 x_{11} &= 0 \\
 x_{12} &= 0 \\
 x_{13} &= 0 \\
 x_{14} &= 0 \\
 x_{15} &= 0 \\
 x_{21} &= 0 \\
 x_{22} &= 1.39 [(-S30 - C40) S20 + S40C20] + 40C30S20 \\
 x_{23} &= 1.39 (C20 + C40) C30 + 40C20S30 \\
 x_{24} &= 1.39 [(-C20 - S30) S40 + S20C40] \\
 x_{25} &= 1.39 (C20S30C40 + S20S40) - 40C20C30 \\
 x_{31} &= 0 \\
 x_{32} &= 1.39 (C20C30C40) + 40C20S30 \\
 x_{33} &= -1.39 S20S30C40 + 40S20C30 \\
 x_{34} &= -1.39S20C30S40 \\
 x_{35} &= 1.39S20C30C40 + 40S20S30 \\
 x_{41} &= 0 \\
 x_{42} &= 1.39 (S20C40 - C20S30S40) \\
 x_{43} &= 1.39S20C30S40 \\
 x_{44} &= 1.39 (C20S40 - S20S30C40) \\
 x_{45} &= -1.39 (C20C40 + S20S30S40)
 \end{aligned}$$

where $C10 = \cos\theta_{10}$, $S10 = \sin\theta_{10}$

Table A.4 (Continued)

$$\begin{aligned}
 y_{11} &= -1.39 (C10C30C40 - S10C20S30C40) \\
 &\quad + 40 (-S10C20C30 - C10S30) - 18C10 \\
 y_{12} &= -1.39 [C10 (-S20) S30 C40] + 40 [C10 (-S20) C30] \\
 y_{13} &= -1.39 [S10 (-S30) C40 + C10C20C30C40] \\
 &\quad + 40 [C10C20 (-S30) - S10C30] \\
 y_{14} &= -1.39 [S10C30 (-S40) + C10C20S30 (-S40)] \\
 y_{15} &= -1.39 (S10C30C40 + C10C20S30C40) \\
 &\quad + 40 (C10C20C30 - S10S30) - 18S10 \\
 y_{21} &= 1.39 (C10S20S30C40 - C10C20S40) \\
 &\quad - 40C10S20C30 \\
 y_{22} &= 1.39 [S10C20S30C40 - S10 (-S20) S40] \\
 &\quad - 40S10C20C30 \\
 y_{23} &= 1.39S10S20C30C40 - 40S10S20 (-S30) \\
 y_{24} &= 1.39 [S10S20S30 (-S40) - S10C20C40] \\
 y_{25} &= 1.39 (S10S20S30C40 - S10C20S40) \\
 &\quad - 40S10S20C30 \\
 y_{31} &= -1.39 (C10C20C30C40 - S10S30C40) \\
 &\quad + 40 (-S10C30 - C10C20S30) \\
 y_{32} &= -1.39 [S10 (-S20) C30C40] - 40S10 (-S20) S30 \\
 y_{33} &= -1.39 [S10C20 (-S30) C40 + C10C30C40] \\
 &\quad + 40 [C10 (-S30) - S10C20C30] \\
 y_{34} &= -1.39 [S10C20C30 (-S40) + C10S30 (-S40)] \\
 y_{35} &= -1.39 (S10C20C30C40 + C10S30C40) \\
 &\quad + 40 (C10C30 - S10C20S30) \\
 y_{41} &= 1.39 (-C10S20C40 + S10C30S40 \\
 &\quad + C10C20S30S40) \\
 y_{42} &= 1.39 [-S10C20C40 + S10 (-S20) S30S40] \\
 y_{43} &= 1.39 [-C10 (-S30) S40 + S10C20C30S40]
 \end{aligned}$$

Table A.4 (Continued)

$$\begin{aligned}
 y_{44} &= 1.39 [-S10S20 (-S40) - C10C30C40 \\
 &\quad + S10C20S30C40] \\
 y_{45} &= 1.39 (-S10S20C40 - C10C30S40 \\
 &\quad + S10C20S30S400) \\
 z_{11} &= 1.39 (-S10C30C40 - C10C20S30C40 - C10S20S40) \\
 &\quad + 40 (C10C20C30 - S10S30) + 18 (-S10) \\
 z_{12} &= 1.39 [-S10 (-S20) S30C40 - S10C20S40] \\
 &\quad + 40 [S10 (-S20) C30] \\
 z_{13} &= 1.39 [C10 (-S30) C40 - S10C20C30C40] \\
 &\quad + 40 [S10C20 (-S30) + C10C30] \\
 z_{14} &= 1.39 [C10C30 (-S40) - S10C20S30 (-S40) \\
 &\quad - S10S20C40] \\
 z_{15} &= 1.39 (C10C30C40 - S10C20S30C40 - S10S20S40) \\
 &\quad + 40 (S10C20C30 + C10S30) + 18C10 \\
 z_{21} &= 1.39 (S10S20S30C40 - S10C20S40) \\
 &\quad + 40 (-S10S20C30) \\
 z_{22} &= 1.39 [-C10C20S30C40 + C10 (-S20) S40] \\
 &\quad + 40C10C20C30 \\
 z_{23} &= 1.39 (-C10) S20C30C40 + 40C10S20 (-S30) \\
 z_{24} &= 1.39 [-C10S20S30 (-S40) + C10C20C40] \\
 z_{25} &= 1.39 (-C10S20S30C40 + C10C20S40) \\
 &\quad + 40C10S20C30 \\
 z_{31} &= 1.39 (-S10C20C30C40 - C10S30C40) \\
 &\quad + 40 (C10C30 - S10C20S30) \\
 z_{32} &= 1.39 C10 (-S20) C30C40 + 40C10 (-S20) S30 \\
 z_{33} &= 1.39 [C10C20 (-S30) C40 - S10C30C40] \\
 &\quad + 40 [S10 (-S30) + C10C20C30] \\
 z_{34} &= 1.39 [C10C20C30 (-S40) - S10S30 (-S40)] \\
 z_{35} &= 1.39 (C10C20C30C40 - S10S30C400) \\
 &\quad + 40 (S10C30 + C10C20S30)
 \end{aligned}$$

Table A.4 (Continued)

z_{41}	=	$1.39 (-S10S20C40 - C10C30S40 + S10C20S30S40)$
z_{42}	=	$1.39 [C10C20C40 - C10 (-S20) S30S40]$
z_{43}	=	$1.39 [-S10 (-S30) S40 - C10C20C30S40]$
z_{44}	=	$1.39 [C10S20 (-S40) - S10C30C40 - C10C20S30C40]$
z_{45}	=	$1.39 (C10S20C40 - S10C30S40 - C10C20S30S40)$
P_{11}	=	$-S10S20C40 - C10C30S40 + S10C20S30S40$
P_{12}	=	$C10C20C40 - C10 (-S20) S30S40$
P_{13}	=	$-S10 (-S30) S40 - C10C20C30S40$
P_{14}	=	$C10S20 (-S40) - S10C30C40 - C10C20S30C40$
P_{15}	=	$C10S20C40 - S10C30S40 - C10C20S30S40$
P_{21}	=	$C10C20C40 + C10S20S30S40$
P_{22}	=	$S [-C20C40 - S20S30S40]$ $+ S10 (-S20) C40 + S10C20S30S40$
P_{23}	=	$S [C20C30S40]$ $+ S10S20C30S40$
P_{24}	=	$S [-S20 (-S40) + C20S30C40]$ $+ S10C20 (-S40) + S10S20S30C40$
P_{25}	=	$S [-S20C40 + C20S30S40]$ $+ S10C20C40 + S10S20S30S40$
P_{31}	=	$-C10C20C30S40 + S10S30S40$
P_{32}	=	$S [C20C30S40]$ $- S10 (-S20) C30S40$
P_{33}	=	$S [S20 (-S30) S40]$ $- S10C20 (-S30) S40 - C10C30S40$
P_{34}	=	$S [S20C30S40]$
P_{35}	=	$S [S20C30S40]$ $- S10C20C30S40 - C10S30S40$

Table 4.3 (Continued)

- P₄₁ = - S10C30C40 - C10C20S30C40 - C10S20S40
- P₄₂ = S [C20S30C40 + S20S40]
- P₄₃ = S [S20C30C40]
+ C10 (-S30) C40 - S10C20C30C40
- P₄₄ = S [S20S30 (-S40) - C20C40]
+ C10C30 (-S40) - S10C20S30 (-S40) - S10S20C40
- P₄₅ = S [S20S30C40 - C20S40]
+ C10C30C40 - S10C20S30C40 - S10S20S40

APPENDIX III

LIST OF COMPUTER PROGRAMS

"MAIN": Straight-line motion of Slave Arm according to the reference (Δx , Δy , Δz , $\Delta \alpha$) in Figs. 4.3 and 3.2, by means of Jacobian Matrices of 1st Order Approximation in Secs. 3.1 and 3.2.

"MSURE": Measurement of Point Q (x , y , z , α) in Fig. 3.4 which is the extreme end of Measurement Arm, by means of the method in Sec. 3.3.

"TTT": Motion of Slave Arm so as to keep the constant distance between the table measured by "SUBME" and Slave Arm measured by "SUBS1", regardless of the position of table.

"HICOM": Extended Compensation done so far by means of Measurement Arm as a sensor.

Subroutines for "TTT" and "HICOM"

"SUBI", "SUBO": Input and Output of each angle.

"SUBS1" and "SUBM1": Present angle of Slave Arm and Master Arm.

"SUBS2" and "SUBM2": Desired angle according to the reference (Δx , Δy , Δz , $\Delta \alpha$) for Slave Arm and for Master Arm.

"SUBME": Measurement of the extreme end of Measurement Arm.

```

PROGRAM MAIN
C
C      GAIN
COMMON THXSI(7),THXMI(7),THXSO(7),THXMO(7)
COMMON IDATA(14)
DIMENSION AD(7),PA(4,3),PY(1,3),XY(4,3),YY(4,3),ZZ(4,3),PP(4,3),
1      X(4),Y(4),Z(4),P(4),TSS(5)
C
C
THXSO(1)=0.0
THXMO(1)=0.0
CALL ANINIT
CALL BOUT(24,0)
CALL BOUT(26,0)
TYPE *, 'MANIPULATOR COMPUTER CONTROL'
ACCEPT *, I
IF(I.NE.1) STOP
CALL AINSQ(16,29,IDATA)
CALL AOUTSQ(4,17,IDATA)
CALL BOUT(24,63)
C
C      CONTINUE
CONTINUE
TYPE *, 'DO YOU NEED ORIGIN SET? '
ACCEPT *, NNN
IF(NNN.EQ.1) GO TO 500
C
TYPE *, 'NO. OF. DIV. : SPEED'
ACCEPT *, N
RN=FLOAT(N)
C
TYPE *, 'POSITION INCREMENTS DX, DY, DZ, IN INCH AND IS, IN DEG'
ACCEPT *, BX, BY, BZ, IS
SS=FLOAT(IS)*(.3.14159/180.0)
SS=TAN(SS)
C
C      CALL MANGLI
CALL MANGLI
C
THS1=THXSI(5)
THS2=THXSI(7)
THS3=THXSI(6)-THS1
THS4=THXSI(2)
THS5=(THXSI(4)+THXSI(3))/2.0+0.27*THS3
THS6=(THXSI(4)-THXSI(3))/1.65
C
THM1=THXMI(5)
THM2=THXMI(7)
THM3=THXMI(6)-THM1
THM4=THXMI(2)
THM5=(THXMI(4)+THXMI(3))/2.0+0.27*THM3
THM6=(THXMI(4)-THXMI(3))/1.65
C
TYPE *, 'IDATA(1)-(3)'
TYPE *, IDATA(1), IDATA(2), IDATA(3)
TYPE *, 'THS1-3'
TYPE *, THS1, THS2, THS3
C
C
TYPE *, 'PRESENT THS'
ITHS1=ININT((180.0/3.1415)*THS1)
ITHS2=ININT((180.0/3.1415)*THS2)
ITHS3=ININT((180.0/3.1415)*THS3)
ITHS4=ININT((180.0/3.1415)*THS4)
ITHS5=ININT((180.0/3.1415)*THS5)
ITHS6=ININT((180.0/3.1415)*THS6)
TYPE *, ITHS1, ITHS2, ITHS3, ITHS4, ITHS5, ITHS6

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C
TYPE *,X,Y,Z
XF= 1.39*(SIN(THS2)*SIN(THS3)*COS(THS4)
1 -COS(THS2)*SIN(THS4)
2 -40.0*(SIN(THS2)*COS(THS3))
C
YF= 1.39*(COS(THS1)*COS(THS3)*COS(THS4)
1 -SIN(THS1)*COS(THS2)*SIN(THS3)*COS(THS4)
2 -SIN(THS1)*SIN(THS2)*SIN(THS4)
3 +40.0*(SIN(THS1)*COS(THS2)*COS(THS3)
4 +COS(THS1)*SIN(THS3))
5 +18.0*(COS(THS1))
C
ZF= 1.39*(SIN(THS1)*COS(THS3)*COS(THS4)
1 +COS(THS1)*COS(THS2)*SIN(THS3)*COS(THS4)
2 +COS(THS1)*SIN(THS2)*SIN(THS4)
3 +40.0*(-COS(THS1)*COS(THS2)*COS(THS3)
4 +SIN(THS1)*SIN(THS3))
5 +18.0*SIN(THS1)
C
YF=YF-19.39
ZF=ZF+40.0
C
TYPE *,XP,YP,ZP
TYPE *,(IF INITIAL SET NEEDS INPUT,1)
ACCEPT *,I1
IF(I1.NE.1) GO TO 100
C
THS01=THS1
THS02=THS2
THS03=THS3
THS04=THS4
C
S1=SIN(THS01)
S2=SIN(THS02)
S3=SIN(THS03)
S4=SIN(THS04)
C
C1=COS(THS01)
C2=COS(THS02)
C3=COS(THS03)
C4=COS(THS04)
C
XX(1,5)=0.0
XX(1,1)=0.0
XX(1,2)=0.0
XX(1,3)=0.0
XX(1,4)=0.0
C
XX(2,5)=1.39*(C2*S3*C4+S2*S4)-40.0*(C2*C3)
XX(2,1)=0.0
XX(2,2)=1.39*((-S3-C4)*S2+S4*C3)+40.0*C3*S2
XX(2,3)=1.39*(C2+C4)*C3-40.0*C2*S3
XX(2,4)=1.39*((-C2-S3)*S4+S2*C4)
C
XX(3,5)=1.39*(S2*C3*C4)+40.0*(S2*S3)
XX(3,1)=0.0
XX(3,2)=1.39*(C2+C3*C4)+40.0*(C2*S3)
XX(3,3)=-1.39*(S2*S3*C4)+40.0*(S2*C3)
XX(3,4)=-1.39*(S2*C3*S4)
C
XX(4,5)=-1.39*(C2+C4+S2*S3*S4)

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XX(4,1)=0.1
XX(4,2)=1.39*(S2*C4-C2*S3*S4)
XX(4,3)=-1.39*(S3*C4+C2*S3*S4)
XX(4,4)=1.39*(C2*S4-S2*C3*C4)

YY(1,5)=-1.39*(S1*C3*C4+C1*C2*S3*C4)+40.0*(C1*C2*C3-S1*S3)
1 -18.0*S1
YY(1,1)=-1.39*(C1*C3*C4-S1*C2*S3*C4)+40.0*(-S1*C2*C3-C1*S3)
1 -18.0*C1
YY(1,2)=-1.39*(C2*(S2)*S3*C4)+40.0*(C1*(S2)*C3)
YY(1,3)=-1.39*(S1*(S3)*C4+C1*C2*C3*C4)
1 +40.0*(C1*C2*(-S3)-S1*C3)
YY(1,4)=-1.39*(S1*C3*(-S4)+C1*C2*S3*(-S4))

YY(2,5)=1.39*(S1*S2*S3*C4-S1*C2*S4)-40.0*(S1*S2*C3)
YY(2,1)=1.39*(C1*S2*S3*C4-C1*C2*S4)-40.0*(C1*S2*C3)
YY(2,2)=1.39*(S1*C2*S3*C4-S1*(S2)*S4)-40.0*(S1*C2*C3)
YY(2,3)=1.39*(S1*S2*C3*C4)-40.0*(S1*S2*(-S3))
YY(2,4)=1.39*(S1*S2*S3*(-S4)-S1*C2*C4)

YY(3,5)=-1.39*(S1*C2*C3*C4+C1*S3*C4)+40.0*(C1*C3-S1*C2*S3)
YY(3,1)=-1.39*(C1*C2*C3*C4-S1*S3*C4)+40.0*(-S1*C3-C1*C2*S3)
YY(3,2)=-1.39*(S1*(S2)*C3*C4)-40.0*S1*(S2)*S3
YY(3,3)=-1.39*(S1*C2*(-S3)*C4+C1*C3*C4)+40.0*(C1*(-S3))
1 -18.0*S1
YY(3,4)=-1.39*(S1*C2*C3*(-S4)+C1*S3*(-S4))

YY(4,5)=1.39*(S1*S2*C4-C1*C3*S4+S1*C2*S3*S4)
YY(4,1)=1.39*(S1*S2*C4+S1*C3*S4+C1*C2*S3*S4)
YY(4,2)=1.39*(S1*C3*S4+S1*(S2)*S3*S4)
YY(4,3)=1.39*(S1*(S3)*C4+S1*S2*C3*S4)
YY(4,4)=1.39*(S1*S2*(-S4)-C1*C3*C4+S1*C2*S3*C4)

ZZ(1,5)=1.39*(C1*C3*C4-S1*C2*S3*C4-S1*S2*S4)
1 +40.0*(S1*C2*C3+C1*S3)+18.0*C1
ZZ(1,1)=1.39*(S1*C3*C4-C1*C2*S3*C4-C1*S2*S4)
1 +40.0*(C1*C2*C3-S1*S3)+18.0*(-S1)
ZZ(1,2)=1.39*(S1*(S2)*S3*C4-S1*C2*S4)
1 +40.0*(S1*(S2)*C3)
ZZ(1,3)=1.39*(C1*(S3)*C4-S1*C2*C3*C4)
1 +40.0*(S1*C2*(-S3)+C1*C3)
ZZ(1,4)=1.39*(C1*C3*(-S4)-S1*C2*S3*(-S4)-S1*S2*C4)

ZZ(2,5)=1.39*(C1*S2*S3*C4+C1*C2*S4)
1 +40.0*(C1*S2*C3)
ZZ(2,1)=1.39*(S1*S2*S3*C4-S1*C2*S4)
1 +40.0*(S1*S2*C3)
ZZ(2,2)=1.39*(C1*C2*S3*C4+C1*(S2)*S4)
1 +40.0*(C1*C2*C3)
ZZ(2,3)=1.39*(C1*S2*C3*C4)+40.0*(C1*S2*(-S3))
ZZ(2,4)=1.39*(C1*S2*S3*(-S4)+C1*C2*C4)

ZZ(3,5)=1.39*(C1*C2*C3*C4-S1*S3*C4)
1 +40.0*(S1*S3+C1*C2*S3)
ZZ(3,1)=1.39*(S1*C2*C3*C4-C1*S3*C4)
1 +40.0*(C1*C3-S1*C2*S3)
ZZ(3,2)=1.39*(C2*(S2)*C3*C4)+40.0*(C1*(S2)*S3)
ZZ(3,3)=1.39*(C1*C2*(-S3)*C4-S1*C3*C4)
1 +40.0*(S1*(-S3)+C1*C2*C3)
ZZ(3,4)=1.39*(C1*C2*C3*(-S4)-S1*S3*(-S4))

ZZ(4,5)=1.39*(C1*S2*C4-S1*C3*S4-C1*C2*S3*S4)
ZZ(4,1)=1.39*(C1*S2*C4+S1*C3*S4+C1*C2*S3*S4)
ZZ(4,2)=1.39*(S1*C3*S4+S1*(S2)*S3*S4)
ZZ(4,3)=1.39*(S1*(S3)*C4+S1*S2*C3*S4)
ZZ(4,4)=1.39*(S1*S2*(-S4)-S1*C3*C4-C1*C2*S3*C4)

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C
PX(1,5)=0.0
PX(1,1)=0.0
PX(1,2)=0.0
PX(1,3)=0.0
PX(1,4)=0.0
C
PX(2,5)=-S2*C4+C2*S3*S4
PX(2,1)=0.0
PX(2,2)=-C2*C4-S2*S3*S4
PX(2,3)=C2*C3*S4
PX(2,4)=-S2*(-S4)+C2*S3*C4
C
PX(3,5)=S2*C3*S4
PX(3,1)=0.0
PX(3,2)=C2*C3*S4
PX(3,3)=S2*(-S3)*S4
PX(3,4)=S2*C3*C4
C
PX(4,5)=S2*S3*C4-C2*S4
PX(4,1)=0.0
PX(4,2)=C2*S3*C4+S2*S4
PX(4,3)=S2*C3*C4
PX(4,4)=S2*S3*(-S4)-C2*C4
C
PY(1,5)=C1*S2*C4-S1*C3*S4-C1*C2*S3*S4
PY(1,1)=-S1*S2*C4-C1*C3*S4+S1*C2*S3*S4
PY(1,2)=C1*C2*C4-C1*(-S1)*S3*S4
PY(1,3)=-S1*(-S3)*S4-C1*C2*C3*S4
PY(1,4)=C1*S2*(-S4)-S1*C3*C4-C1*C2*S3*C4
C
PY(2,5)=S1*C2*C4+S1*S2*S3*S4
PY(2,1)=C1*C2*C4+C1*S2*S3*S4
PY(2,2)=S1*(-S2)*C4-S1*C2*S3*S4
PY(2,3)=S1*S2*C3*S4
PY(2,4)=S1*C2*(-S4)+S1*S2*S3*C4
C
PY(3,5)=-S1*C2*C3*S4-C1*S3*S4
PY(3,1)=-C1*C2*C3*S4-S1*S3*S4
PY(3,2)=-S1*(-S2)*C3*S4
PY(3,3)=-S1*C2*(-S3)*S4-C1*C3*S4
PY(3,4)=-S1*C2*C3*C4-C1*S3*C4
C
PY(4,5)=C1*C3*C4-S1*C2*S3*C4-S1*S2*S4
PY(4,1)=-S1*C3*C4-C1*C2*S3*C4-C1*S2*S4
PY(4,2)=-S1*(-S2)*S3*C4-S1*C2*S4
PY(4,3)=C1*(-S3)*C4-S1*C2*C3*C4
PY(4,4)=C1*C3*(-S4)-S1*C2*S3*(-S4)-S1*S2*C4
C
DO 200 I=1,4
DO 201 J=1,5
PP(I,J)=PX(I,J)*SS+PY(I,J)
201 CONTINUE
200 CONTINUE
TSS(1)=THS1-THS01
TSS(2)=THS2-THS02
TSS(3)=THS3-THS03
TSS(4)=THS4-THS04
TSS(5)=1.0
C
DO 50 I=1,4
DO 51 J=1,5
X(I)=XX(I,J)*TSS(J)
Y(I)=YY(I,J)*TSS(J)
Z(I)=ZZ(I,J)*TSS(J)
51 CONTINUE
50 CONTINUE

```

66-10000-1
 66-10000-1
 66-10000-1

```

CST1=COS(THS1)*COS(THS2)+SIN(THS1)*SIN(THS2)*COS(THS3)
CST2=SIN(THS1)*SIN(THS2)*COS(THS3)+COS(THS1)*SIN(THS2)*SIN(THS3)
1 *SIN(THS4)-SIN(THS1)*COS(THS2)*SIN(THS3)
1 *SIN(THS4)
PS=SS*CST1+CST2

```

```
DP=-PS
```

```

DEN= -X(2)*(Y(1)*Z(3)*P(4)+Y(3)*Z(4)*P(1)+Y(4)*Z(1)*P(3))
1 -Y(4)*Z(3)*P(1)-Y(3)*Z(1)*P(4)-Y(1)*Z(4)*P(2)
1 +X(3)*(Y(1)*Z(2)*P(4)+Y(2)*Z(4)*P(1)+Y(4)*Z(1)*P(2))
1 -Y(4)*Z(2)*P(1)-Y(2)*Z(1)*P(4)-Y(1)*Z(4)*P(3)
1 -X(4)*(Y(1)*Z(2)*P(3)+Y(2)*Z(3)*P(1)+Y(3)*Z(1)*P(2))
1 -Y(3)*Z(2)*P(1)-Y(2)*Z(1)*P(3)-Y(1)*Z(3)*P(2)

```

```

RNU1= DX*(Y(2)*Z(3)*P(4)+Y(3)*Z(4)*P(2)+Y(4)*Z(2)*P(3))
1 -Y(4)*Z(3)*P(2)-Y(3)*Z(2)*P(4)-Y(2)*Z(4)*P(1)
1 -DY*(X(2)*Z(3)*P(4)+X(3)*Z(4)*P(2)+X(4)*Z(2)*P(3))
1 -X(4)*Z(3)*P(2)-X(3)*Z(2)*P(4)-X(2)*Z(4)*P(1)
1 +BZ*(X(2)*Y(3)*P(4)+X(3)*Y(4)*P(2)+X(4)*Y(2)*P(3))
1 -X(4)*Y(3)*P(2)-X(3)*Y(2)*P(4)-X(2)*Y(4)*P(1)
1 -BP*(X(2)*Y(3)*Z(4)+X(3)*Y(4)*Z(2)+X(4)*Y(2)*Z(3))
1 -X(4)*Y(3)*Z(2)-X(3)*Y(2)*Z(4)-X(2)*Y(4)*Z(1)

```

```

RNU2= -DX*(Y(1)*Z(3)*P(4)+Y(3)*Z(4)*P(1)+Y(4)*Z(1)*P(3))
1 -Y(4)*Z(3)*P(1)-Y(3)*Z(1)*P(4)-Y(1)*Z(4)*P(2)
1 +DY*(X(1)*Z(3)*P(4)+X(3)*Z(4)*P(1)+X(4)*Z(1)*P(2))
1 -X(4)*Z(3)*P(1)-X(3)*Z(1)*P(4)-X(1)*Z(4)*P(2)
1 -EZ*(X(1)*Y(3)*P(4)+X(3)*Y(4)*P(1)+X(4)*Y(1)*P(2))
1 -X(4)*Y(3)*P(1)-X(3)*Y(1)*P(4)-X(1)*Y(4)*P(2)
1 +DP*(X(1)*Y(3)*Z(4)+X(3)*Y(4)*Z(1)+X(4)*Y(1)*Z(2))
1 -X(4)*Y(3)*Z(1)-X(3)*Y(1)*Z(4)-X(1)*Y(4)*Z(2)

```

```

RNU3= +DZ*(Y(1)*Z(2)*P(4)+Y(2)*Z(4)*P(1)+Y(4)*Z(1)*P(2))
1 -Y(4)*Z(2)*P(1)-Y(2)*Z(1)*P(4)-Y(1)*Z(4)*P(3)
1 -DY*(X(1)*Z(2)*P(4)+X(2)*Z(4)*P(1)+X(4)*Z(1)*P(2))
1 -X(4)*Z(2)*P(1)-X(2)*Z(1)*P(4)-X(1)*Z(4)*P(3)
1 +BZ*(X(1)*Y(2)*P(4)+Y(2)*Y(4)*P(1)+X(4)*Y(1)*P(2))
1 -X(4)*Y(2)*P(1)-X(2)*Y(1)*P(4)-X(1)*Y(4)*P(2)
1 -DP*(X(1)*Y(2)*Z(4)+X(2)*Y(4)*Z(1)+X(4)*Y(1)*Z(2))
1 -X(4)*Y(2)*Z(1)-X(2)*Y(1)*Z(4)-X(1)*Y(4)*Z(2)

```

```

RNU4= -DX*(Y(1)*Z(2)*P(3)+Y(2)*Z(3)*P(1)+Y(3)*Z(1)*P(2))
1 -Y(3)*Z(2)*P(1)-Y(2)*Z(1)*P(3)-Y(1)*Z(3)*P(2)
1 +DY*(X(1)*Z(2)*P(3)+X(2)*Z(3)*P(1)+X(3)*Z(1)*P(2))
1 -X(3)*Z(2)*P(1)-X(2)*Z(1)*P(3)-X(1)*Z(3)*P(2)
1 -BZ*(X(1)*Y(2)*P(3)+X(2)*Y(3)*P(1)+X(3)*Y(1)*P(2))
1 -X(3)*Y(2)*P(1)-X(2)*Y(1)*P(3)-X(1)*Y(3)*P(2)
1 +DP*(X(1)*Y(2)*Z(3)+X(2)*Y(3)*Z(1)+X(3)*Y(1)*Z(2))
1 -X(3)*Y(2)*Z(1)-X(2)*Y(1)*Z(3)-X(1)*Y(3)*Z(2)

```

```

DTH1=RNU1/DEN
DTH2=RNU2/DEN
DTH3=RNU3/DEN
DTH4=RNU4/DEN

```

```

T5=THS5
T6=THS6

```

```

THS1=THS1+I*TH1
THS2=THS2+I*TH2
THS3=THS3+I*TH3
THS4=THS4+I*TH4

```

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0
100
200
300
400
500
600
700
800
900
0

```

THS5=ATAN2((-SIN(THS1)*COS(THS2)+COS(THS1)*SIN(THS2))
1 *COS(THS2)+SIN(THS2)*COS(THS4))
1 +COS(THS1)*SIN(THS2)+SIN(THS1)*COS(THS2)
1 (COS(THS1)*COS(THS2)+COS(THS1)*SIN(THS2)
1 *SIN(THS3))

```

```

THS6=ATAN2((-COS(THS1)*SIN(THS2)+COS(THS1)
1 +SIN(THS1)*COS(THS2)+SIN(THS1)*COS(THS4)
1 *COS(THS2)*SIN(THS3)+SIN(THS1)*
1 ((COS(THS1)*COS(THS2)+COS(THS1)*SIN(THS2)
1 *SIN(THS3))-SIN(THS1)*COS(THS2)+COS(THS1)
1 +COS(THS1)*COS(THS2)+SIN(THS1)*COS(THS4)
1 *COS(THS2)+SIN(THS1)*SIN(THS3))

```

```

BTH5=THS5-75
BTH6=THS6-75

```

```

IBTH1=-SIN(BTH1)*180.0/3.1416)
IBTH2=-SIN(BTH2)*180.0/3.1416)
IBTH3=-SIN(BTH3)*180.0/3.1416)
IBTH4=-SIN(BTH4)*180.0/3.1416)
IBTH5=-SIN(BTH5)*180.0/3.1416)
IBTH6=-SIN(BTH6)*180.0/3.1416)

```

```

TYPE 4, IBTH1, IBTH2, IBTH3, IBTH4, IBTH5, IBTH6

```

```

TYPE 4, 'BY I RUN?'
ACCEPT 4, 1
IF(1.NE.1) GO TO 20

```

```

IF(1.NE.1) GO TO 510
CALL HANDLE
N=1000
FN=1000.0
THS1=0.0
THS2=0.0
THS3=0.0
THS4=0.0
THS5=0.0
THS6=0.0

```

```

THX50(1)=THS1(1)
THX50(2)=THS1(2)
THX50(3)=THS1(3)
THX50(4)=THS1(4)
THX50(5)=THS1(5)
THX50(6)=THS1(6)
THX50(7)=THS1(7)

```

```

THX50(1)=THS4
THX50(2)=THS5-THS1(1)*.315-THS1(2)*.32
THX50(3)=THS5+THS1(1)*.315-THS1(2)*.32
THX50(4)=THS1
THX50(5)=THS1+THS3
THX50(7)=THS2

```

```

IF(1.NE.20) GO TO 520

```

```

C
    THX(1)=THX1
    THX(2)=THX2(3)
    THX(3)=THX(4)
    THX(4)=THX(5)
    THX(5)=THX(6)
    THX(6)=THX(7)-THX(8)
    THX(7)=THX(8)

C
0400 CONTINUE
C
DO 251 I=2,7
AD(I)=THX(50(I))-THX(51(I))
251 CONTINUE

C
I=1
88 CONTINUE
DO 302 J=2,7

C
    THX(50(J))=THX(51(J)+(AD(J)/RN)*FLOAT(I))
    302 CONTINUE
    CALL ANBGL0
    CALL ADOT50(4.17, IDATA)
    I=I+1
    IF (I.GT.7) GO TO 301
    GO TO 88
301 CONTINUE
GO TO 10
END
SUBROUTINE ANBGL0
COMMON THX(7), THX(8), THX(20), THX(20), THX(20), THX(20)
COMMON IDATA(14)
DIMENSION COEF(7), ICONST(7)
DATA COEF /0.000000000, 0.00140, 0.000000000, -0.00177,
1 -0.00047, -0.00079, 0.00000/
DATA ICONST /0.0, 100, -100, 0.0, 0.0/

C
    CONVERT ANGLE READINGS INTO RADIAN

CALL ANBGL1(9, IDATA)
DO 10 I=1,7
THX(51(I))=FLOAT ICONST(I) * COEF(I)
THX(52(I))=FLOAT IDATA(I) * ICONST(I) * COEF(I)
10 CONTINUE
RETURN
ENTRY ANBGL0
CONVERT ANGLE RADIAN INTO OUTPUT FORM
DO 20 I=1,7
IDATA(I)=I*THX(51(I)) * COEF(I) + ICONST(I) * THX(52(I))
IDATA(I+7)=I*THX(52(I)) * COEF(I) + ICONST(I) * THX(51(I))
20 CONTINUE

DO 77 J=1,14
IF (IDATA(J).GT.32767) IDATA(J)=32768
77 CONTINUE

C
RETURN
END

```



```

C
AA=VI(1)
BB=VI(2)
VI(1)=BB
VI(2)=AA
AA=VI(3)
BB=VI(4)
VI(3)=BB
VI(4)=AA
AA=VI(5)
BB=VI(6)
VI(5)=BB
VI(6)=AA

```

```

C
DO 150 I=1,6
IVI(I)=I*INT(VI(I))
150 CONTINUE
TYPE *,IVI(1),IVI(2),IVI(3),IVI(4),
1 IVI(5),IVI(6)

```

```

C
THET=0 IN DEG
C1=-30.0*PI/180
C2=-10.0*PI/180-CC2
C3=10.0*PI/180+90.0
C4=-10.0*PI/180-CC4
C5=30.0*PI/180-CC5
C6=-10.0*PI/180

```

```

C
100 -TYPE *,MEASURE
ACCEPT *,1
IF(1) GO TO 30 TO 500
CALL AT(30,0.5,10)

```

```

C
DO 250 I=1,6
VI(I)=CVC*PI/180*IDT(I)
250 CONTINUE

```

```

C
AA=VI(1)
BB=VI(2)
VI(1)=BB
VI(2)=AA
AA=VI(3)
BB=VI(4)
VI(3)=BB
VI(4)=AA
AA=VI(5)
BB=VI(6)
VI(5)=BB
VI(6)=AA

```

```

C
THD(1)=-20.0*VI(1)-C1
THD(2)=-20.0*VI(2)-C2
THD(3)=20.0*VI(3)-C3
THD(4)=-20.0*VI(4)-C4
THD(5)=20.0*VI(5)-C5
THD(6)=-20.0*VI(6)-C6

```

```

C
DO 355 I=1,6
ITHD(I)=INT(THD(I))
355 CONTINUE
TYPE *,ITHD(1),ITHD(2),ITHD(3),ITHD(4),
1 ITHD(5),ITHD(6)

```

```

C
DO 450 I=1,6
THD(I)=(3.14159/180.0)*THD(I)
450 CONTINUE

```

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```

0      IF (THR(1).EQ.0.0) GO TO 270
C
C      S(1)=SQRT((TAN(THR(1)))**2+(TAN(THR(2)))**2)
C      TH1=D=S(2)
C      S(2)=ATAN(1.0/S(1))
C
C      S(3)=(TAN(THR(2)))/SIN(THR(1))
C
C      TH2=D=S(4)
C      S(4)=-ATAN(S(3))
270    GO TO 390
C      S(4)=(3.14159/2.0)-THR(2)
C      IF (THR(2).GT.0.0) S(4)= 3.14159/2.0
C      IF (THR(2).LT.0.0) S(4)=-3.14159/2.0
C      IF (THR(2).EQ.0.0) GO TO 900
290    CONTINUE
C      I=S(5)
C      S(5)=DA*CGS(S(2))+DB*SIN(S(2)+THR(4))
C
C      X=DA*CS(S(4))
C      Y=DA*FS(S(4))
C      Z=DA*TS(S(2))
C      I      -(DB*DCOS(S(2)+THR(4))+DC)
C
C      A=(3.14159/2.0)-(S(4)-THR(6))
C
C      TYPE *,X,Y,Z,S/
C      TYPE *,A,1,1,1
C
C      X=KX10.0
C      Y=KY10.0
C      Z=KZ10.0
C
C      IX=ININT(X)
C      IY=ININT(Y)
C      IZ=ININT(Z)
C      IA=ININT(A*130.0/5.14159)
C
C      TYPE *,IX,IY,IZ,IA
C
300    GO TO 100
C      CONTINUE
C      STOP
C      END

```

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PROGRAM TTT

C
COMMON /N1/ THX(1:7),THY(1:7),THZ(1:7),TH(1:7)
COMMON /N2/ THS(1:6),YS(1:6),ZS(1:6),YD(1:6),ZD(1:6)
COMMON /N3/ THX(2),XN(1),ZN(1),YD(1),ZD(1),YD(1)
COMMON /N4/ IDATA(14)
COMMON /N5/ IN,LINE,YES,ZPE,AYS,INY,IVY,IVZ,IT,IN
COMMON /N6/ XMTT,YMTT,ZMTT,IF

C
C
C
C
DIMENSION AD(7)

CALL ANINIT

CALL SOUT(24,0)
CALL IOUT(26,0)
TYPE * 'COMPUTER CONTROL ?'
ACCEPT * I
IF(I.NE.1) GO TO 900
CALL SINS(14,20,1DATA)
CALL ACUTS0(4,17,1DATA)

C
C
C
C
TYPE * 'NO. OF DIV/SPEED'
ACCEPT * I
IN=I(24)

C
C
C
C
TYPE * 'NEED ORIGIN SET ?'
ACCEPT * I
IF(I.NE.1) GO TO 500

C
C
C
C
TYPE * 'START ?'
ACCEPT * I
IF(I.NE.1) GO TO 900

CALL SUBI

C
C
C
C
C
C
THS(1)=THXSI(5)
THS(2)=THXSI(7)
THS(3)=THXSI(6)-THS(1)
THS(4)=THXSI(1)
THS(5)=(THXSI(4)+THXSI(3))/2.0+0.27*THS(3)
THS(6)=(THXSI(4)-THXSI(3))/1.55

C
C
C
C
C
C
THM(1)=THYMI(5)
THM(2)=THYMI(7)
THM(3)=T-XMI(6)-THM(1)
THM(4)=THYMI(1)
THM(5)=(THYMI(4)+THYMI(3))/2.0+0.27*THM(3)
THM(6)=(THYMI(4)-THYMI(3))/1.55

C
C
C
C
TYPE * 'PRESENT THS(I)'

C
C
C
C
C
C
ITHS1=INT(57.296*THS(1))
ITHS2=INT(57.296*THS(2))
ITHS3=INT(57.296*THS(3))
ITHS4=INT(57.296*THS(4))
ITHS5=INT(57.296*THS(5))
ITHS6=INT(57.296*THS(6))

C
C
C
C
TYPE * 'I1-S1, ITHS2, ITHS3, ITHS4, ITHS5, ITHS6'

CALL SUBS1

C
C
C
C
TYPE * 'FEED BY, DY, DZ, DS ?'
ACCEPT * I
IF(I.NE.1) GO TO 900

```

C      TMS9  A  004  004  004  004
C      000000  000000  000000  000000
C
C      XSD=XSD-00
C      YSD=YSD-00
C
C      ZSD=ZSD-00
C      SSD=SSD-00
C
C      IF(I.EQ.1) GO TO 250
C
C      TYPE 8, 'PRESENT XHTT, YHTT, ZHTT'
C      TYPE 8, XHTT, YHTT, ZHTT
C
C      TYPE 8, 'NEED NEW XHTT, YHTT, ZHTT ?'
C      ACCEPT 8, I
C      IF(I.NE.1) GO TO 200
C
C      TYPE 8, 'NEW XHTT, YHTT, ZHTT'
C      ACCEPT 8, XHTT, YHTT, ZHTT
C
C      XSD=XSD+XHTT
C      YSD=YSD+YHTT
C      ZSD=ZSD+ZHTT
C
C      IXS=I*INT(XS)
C      IYS=I*INT(YS)
C      IZS=I*INT(ZS)
C
C      TYPE 8, 'I=IXS, IYS, IZS, FROM SAY'
C      TYPE 8, IXS, IYS, IZS
C
C      TYPE 8, 'NEED INITIAL SET FOR SUBR ?'
C      ACCEPT 8, I
C      IF(I.NE.1) GO TO 220
C      I=1
C      CALL SUBPR
C      GO TO 180
C
C      I=2
C      CALL SUBPR
C
C      IXNE=INT(XS/NE)
C      IYNE=INT(YS/NE)
C      IZNE=INT(ZS/NE)
C
C      TYPE 8, 'IXNE, IYNE, IZNE, FROM NE'
C      TYPE 8, IXNE, IYNE, IZNE
C
C      TYPE 8, 'MOVE ?'
C      ACCEPT 8, I
C      IF(I.NE.1) GO TO 230
C
C      XSD=XNE
C      YSD=YNE
C      ZSD=ZNE
C      SSD=SS
C
C      TL1=TMS(1)
C      TL2=TMS(2)
C      TL3=TMS(3)
C      TL4=TMS(4)
C      TL5=TMS(5)
C      TL6=TMS(6)

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```

C      CALL      SUB52
C
IT1=ININT((THS(1)-TL1)*57.296)
IT2=ININT((THS(2)-TL2)*57.296)
IT3=ININT((THS(3)-TL3)*57.296)
IT4=ININT((THS(4)-TL4)*57.296)
IT5=ININT((THS(5)-TL5)*57.296)
IT6=ININT((THS(6)-TL6)*57.296)
C
TYPE *,IT1,IT2,IT3,IT4,IT5,IT6
C
GO TO 600
C
500 THS(1)=0.0
    THS(2)=0.0
    THS(3)=0.0
    THS(4)=0.0
    THS(5)=0.0
    THS(6)=0.0
C
600 TYPE *, 'MAY I RUN ?'
    ACCEPT *,I
    IF(I.NE.1) GO TO 900
C
    THXSO(1)=0.0
    THXNO(1)=0.0
C
    DO 300 J=2,7
    THXNO(J)=THXSI(J)
    CONTINUE
C
    THXSO(2)=THS(4)
    THXSO(3)=THS(5)-THS(6)*0.315-THS(3)*0.27
    THXSO(4)=THS(5)+THS(6)*0.305-THS(3)*0.27
    THXSO(5)=THS(1)
    THXSO(6)=THS(4)+THS(3)
    THXSO(7)=THS(2)
C
TYPE *, 'POINT 1'
C
DO 251 I=2,7
AD(I)=THXSO(I)-THXSI(I)
CONTINUE
I=1
C
TYPE *, 'POINT 2'
C
CONTINUE
DO 302 J=2,7
THXSO(J)=THXSI(J)+AD(J),END=FLOAT(I)
CONTINUE
C
CALL      SUBO
C
CALL      ADUTSO(4,17,1DATA)
I=I+1
IF(I.GT.N) GO TO 301
GO TO 38
C
TYPE *, 'POINT 3'
C
301 CONTINUE
TYPE *, 'POINT 4'
C
700 CONTINUE

```

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```

PROGRAM HICCN
C
COMMON THXSI(7), THXHI(7), THYSO(7), THYHO(7)
COMMON THS(6), AS, YS, ZS, SS, XSD, YSD, ZSD, SSD
COMMON THM(6), IM, TM, ZM, SM, XMD, YMD, ZMD, SMD
COMMON IDATA(14)
COMMON IM, YME, YMS, ZME, ZMS, IX, IY, IZ, IT, IN
COMMON XMTT, YMTT, ZMTT, IF

C
C
C THXSO(1)=0.0
C THXHO(1)=0.0
C
C CALL ANINIT
C
C TYPE *, 'KEEP PRESENT POSITION ?'
C ACCEPT *, I
C IF (I.NE.1) GO TO 900
C
C CALL AINSQ(16, 29, IDATA)
C CALL AOUTSQ(4, 17, IDATA)
C
C TYPE *, 'NEED TO SET A & B ?'
C ACCEPT *, I
C IF (I.NE.1) GO TO 140
C
C TYPE *, 'A(=0.7), B(=0.5)?'
C ACCEPT *, A, B
C A1=1.0-A
C
C 140 TYPE *, 'HEA INITIAL SET?'
C ACCEPT *, I
C IF (I.NE.1) GO TO 130
C
C IM=1
C CALL SUBME
C
C 130 TYPE *, 'MODE WITHOUT TABLE?'
C ACCEPT *, I
C IF (I.NE.1) GO TO 900
C
C MODE WITHOUT TABLE
C
C 90 T1=SECMS(0.0)
C 100 T3=SECMS(0.0)
C
C CALL SUBI
C
C THS(1)=THYSI(5)
C THS(2)=THYSI(7)
C THS(3)=THYSI(6) - THS(1)
C THS(4)=THYSI(8)
C
C CALL SUBS1
C
C THM(1)=THYMI(5)
C THM(2)=THYMI(7)
C THM(3)=THYMI(6) - THM(1)
C THM(4)=THYMI(8)
C
C CALL SUBM1
C
C XSD=AVAR*W1*AS
C YSD=AVAR*W1*YS
C ZSD=AVAR*W1*ZS

```

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```
YND=A*YS+A1*YD  
YMD=A*YS+A1*YD  
ZND=A*ZS+A1*ZD  
SND=A*SS+A1*SD
```

```
YSD=XSD+B*(XS-XS2)  
YSD=YSD+B*(YS-YSD)  
ZSD=ZSD+B*(ZS-ZSD)  
SSD=SSD+B*(SS-SS2)
```

```
XMD=XMD+B*(XM-XM2)  
YMD=YMD+B*(YM-YM2)  
ZMD=ZMD+B*(ZM-ZM2)  
SMD=SMD+B*(SM-SM2)
```

```
CALL SUBS2  
CALL SUBM2
```

```
THSI6=(THSI(4)-THSI(3))/1.05-THSI(6)  
THMI6=(THMI(4)-THMI(3))/1.05-THMI(6)  
THSO6=A*THMI6+A1*THSI6+THS(6)  
THMO6=A*THSI6+A1*THMI6+THM(6)
```

```
THSO6=THSO6+B*(THSI6-THSI(6))  
THMO6=THMO6+B*(THMI6-THMI(6))
```

```
THXS(2)=THS(4)  
THXS(3)=THS(5)-THSO6*0.825-THS(3)*0.27  
THXS(4)=THS(5)-THSO6*0.825-THS(3)*0.27  
THXS(5)=THS(1)  
THXS(6)=THS(1)+THS(3)  
THXS(7)=THS(2)
```

```
THXM(2)=THM(4)  
THXM(3)=THM(5)-THMO6*0.825-THM(3)*0.27  
THXM(4)=THM(5)-THMO6*0.825-THM(3)*0.27  
THXM(5)=THM(1)  
THXM(6)=THM(1)+THM(3)  
THXM(7)=THM(2)
```

```
CALL SUBO  
CALL ADUTSQ(4,17,DATA)
```

```
XS2=XS1  
YS2=YS1  
ZS2=ZS1  
SS2=SS1
```

```
XS1=XS  
YS1=YS  
ZS1=ZS  
SS1=SS
```

```
XM2=XM1  
YM2=YM1  
ZM2=ZM1  
SM2=SM1
```

```
XM1=XM  
YM1=YM  
ZM1=ZM  
SM1=SM
```

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```

C      THSI61=THSI61
C      THMI62=THMI62
C
C      THSI61=THSI6
C      THMI61=THMI6
C
C 170  T4=SECNDS(T3)
      IT4=AINT(T4*30.0)
      IF(IT4.LT.1) GO TO 100
C
C      T2=SECNDS(T1)
      IT2=ININT(T2)
C
C      IF(IT2.LT.60) GO TO 100
C
C      TYPE *, 'MODE WITHOUT TABLE OR WITH TABLE'
      ACCEPT *, I
      IF(I.EQ.1) GO TO 90
C
C      TYPE *, 'MODE WITH TABLE'
      MODE WITH TABLE
C
C      TYPE *, 'COINCIDENCE OF TWO ORIGINS ?'
      ACCEPT *, I
      IF(I.NE.1) GO TO 190
C
C      TYPE *, 'XMITT0.0, YBTT0.0, ZNTT0.0'
      ACCEPT *, XMTT, YBTT, ZNTT
C
C 180  CONTINUE
C
C      TYPE *, 'XS,YS,ZS,SS'
      IXS=ININT(XS)
      IYS=ININT(YS)
      IZS=ININT(ZS)
      ISS=ININT(SS)
      TYPE *, IXS, IYS, IZS, ISS
C
C      TYPE *, 'XM,YM,ZM,SM'
      IXM=ININT(XM)
      IYM=ININT(YM)
      IZM=ININT(ZM)
      ISM=ININT(SM)
      TYPE *, IXM, IYM, IZM, ISM
C
C      TYPE *, 'XME,YME,ZME,AME'
      IXME=ININT(XME)
      IYME=ININT(YME)
      IZME=ININT(ZME)
      IAME=ININT(AME)
      TYPE *, IXME, IYME, IZME, IAME
C
C 205  TYPE *, 'TABLE SPEED ?'
      ACCEPT *, I
      IF(I.NE.1) GO TO 210
C
C      TYPE *, 'IUX,IUY,IUZ,IT,IN'
      ACCEPT *, IUX, IUY, IUZ, IT, IN
C
C 210  TYPE *, 'TABLE GO?'
      ACCEPT *, I
      IF(I.NE.1) GO TO 205
C

```

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```

      THM=IM
      IN=0
C
      CALL MOVE(IUX,IUY,IUZ)
C
      X1=0.0
      Y1=0.0
      Z1=0.0
C
      X2=0.0
      Y2=0.0
      Z2=0.0
C
      III=0
310  T6=SECNDS(0.0)
C
      CALL MOVE(IUX,IUY,IUZ)
320  T5=SECNDS(0.0)
C
      CALL SUBC
C
      THS(1)=THXSI(5)
      THS(2)=THXSI(7)
      THS(3)=THXSI(8)-THS(1)
      THS(4)=THXSI(2)
C
      CALL SUBS1
C
      THM(1)=THXSI(5)
      THM(2)=THXSI(7)
      THM(3)=THXSI(8)-THM(1)
      THM(4)=THXSI(2)
C
      CALL SUBM1
C
      XSE=XS-X2
      YSE=YS-Y2
      ZSE=ZS-Z2
C
      IM=2
C
      CALL SUBME
C
C***** IUX----REAL SPEED
C*****
C
      XSD=A*XM+A1*YSE+X
      YSD=A*YM+A1*YSE+Y
      ZSD=A*ZM+A1*ZSE+Z
      SSD=A*SM+A1*SS
C
      XMD=A*YSE+A1*Y
      YMD=A*XSE+A1*X
      ZMD=A*ZSE+A1*Z
      SMD=A*SS+A1*SM
C
      III=III+1
C
      IF(III.GT.0) GO TO 710
C
      XSE1=XSE
      YSE1=YSE
      ZSE1=ZSE
      SS1=SS
C
      XM2=XM
      YM2=YM
      ZM2=ZM
      SM2=SM

```

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```

C
XSE1=XSE
YSE1=YSO
ZSE1=ZSE
SSI=SS

C
XM1=XM
YM1=YM
ZM1=ZM
SM1=SM

C
710 CONTINUE
C
XSD=XSD+P*(XSE-XSD)
YSD=YSD+P*(YSE-YSD)
ZSD=ZSD+P*(ZSE-ZSD)
SSD=SSD+P*(SSI-SSD)

C
XND=XND+P*(XM1-XND)
YND=YND+P*(YM1-YND)
ZND=ZND+P*(ZM1-ZND)

C
CALL SUB30
CALL SUB32

C
THSD=THSD+P*(THS1-THSD)
THSDC=THSDC+P*(THS1C-THSDC)
THSC=THSC+P*(THS1-THSC)
THSCC=THSCC+P*(THS1C-THSCC)

C
THSD=THSD+P*(THSDC-THSD)
THSDC=THSDC+P*(THSD-THSDC)

C
THXSD=THXSD+P*(THXSDC-THXSD)
THXSDC=THXSDC+P*(THXSD-THXSDC)
THYSD=THYSD+P*(THYSDC-THYSD)
THYSDC=THYSDC+P*(THYSD-THYSDC)
THZSD=THZSD+P*(THZSDC-THZSD)
THZSDC=THZSDC+P*(THZSD-THZSDC)
THSSD=THSSD+P*(THSSDC-THSSD)
THSSDC=THSSDC+P*(THSSD-THSSDC)

C
THXSD=THXSD+P*(THXSDC-THXSD)
THYSD=THYSD+P*(THYSDC-THYSD)
THZSD=THZSD+P*(THZSDC-THZSD)
THSSD=THSSD+P*(THSSDC-THSSD)

C
CALL SUB30
CALL SUB32

C
THS1=
THS1C=
THS1=
THS1C=
THS1=
THS1C=

C
THS1=
THS1C=
THS1=
THS1C=
THS1=
THS1C=

```

Table 1

Table 2

Table 3

Table 4

Table 5

Table 6

Table 7

Table 8

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END

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