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DEVELOPMENT OF A MULTIPURPOSE HAND CONTROLLER FOR JEMRMS

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ABSTRACT

A prototype multipurpose hand controller for the JEMRMS (Japanese Experiment Module Remote Manipulator System) has been developed. The hand controller (H/C) is an orthogonal type, with six degrees of freedom (DOF) and small size. The orthogonal type H/C is very simple for coordinate transformations and can easily control any type of manipulators. In fact, the JEMRMS is planned to have two manipulators controlled by a common H/C at this stage. The H/C was able to be used as a rate control joystick and a force-reflection master arm, using an experimental 6 DOF manipulator. Good maneuverability was confirmed in the verification test. The orthogonal type H/C is suitable for use as a common H/C for the two manipulators of the JEMRMS.

INTRODUCTION

The JEM (Japanese Experiment Module) consists of a pressurized module, an experiment logistics module, an exposed facility and a remote manipulator system (RMS). The JEMRMS has two manipulators, as shown in Figure 1 (Reference 1, 2). One is a large main arm (LMA) which is about 10 meters long, with 6 DOF for handling heavy payloads. The other is a small fine arm (SFA), which is about 2 meters long with 6 DOF and a gripper for carrying out sophisticated operations. It is attached to the LMA end effector. The two manipulators, LMA and SFA, are controlled by a single operator in the pressurized module.

Conventionally, the remote manipulators for unstructured work in hostile environments, such as space and nuclear power facilities, are manually controlled by a human operator. There are two main control methods. One is joystick rate control, such as used in the shuttle remote manipulator system (SRMS). The other is master-slave control, with a replica of the slave arm as the master arm. As master-slave control is often used in the nuclear field, sophisticated operations can be carried out easier than when using joystick control. However, the same number of master arms are needed as slave arms, because the master arm and the slave arm configurations are identical. On the other hand, joystick control is very simple.

The two control methods are desirable to be used appropriately, according to the required tasks for the manipulators. In space, the operation compartment is small and each equipment must be compact and lightweight. Consequently, a common hand controller for the two arms of the JEMRMS is needed.

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H/C DESIGN CONCEPT

The H/C equipped in a space station must be small size, lightweight and designed ergonomically as a man-machine interface. Furthermore, an ideal H/C can be used not only as a joystick but also as a master arm for any type of slave arm .

Thus, a 6 DOF orthogonal type H/C with force reflection was developed. It can be used as a common master arm for the JEMRMS. As the configuration of the LMA and the SFA is an articulated type and that of the H/C is an orthogonal type, it composes the master-slave manipulator system with different configurations (Reference 3, 4). The orthogonal type is very simple for coordinate transformations between the coordinate system of the master arm and that of the slave arm. It can easily control any type of slave arm merely by changing the coordinate transformation.

MECHANISM

The prototype H/C is about 35 x 35 x 35 cm in size, has a 15 x 15 x 15 cm motion area and is 15 kg in weight including the mechanical dead weight compensation system, which is not needed in space use. The configuration is shown in Figure 2.

The roll, pitch and yaw axes for the wrist joint are designed to cross at a center point of the grip handle. The 3 DOF for the translational axes are mechanically separated against the 3 DOF for the rotational axes. The drive units are commonly designed for the rotational axes and for the translational axes, respectively. Therefore, it becomes easier to control than any other structure in the H/C. The translational axes are driven by ballscrews, with an 8-mm lead. The three intersecting axes are driven by gears with a low gear ratio 1:4. Thus, the friction is very small for mechanical backdrivability and maneuverability.

A force or torque sensor using strain gauges is mounted in each joint. The gripper is controlled by a switch on the top of the grip handle. The optical sensor on the grip handle detects the operator's hand. When the operator removes his hand from the handle, the slave arm is servo held in position quickly.

The dead weight for the Z axis is compensated for by a constant force spring. Dead weights for the rotational axes are compensated for by a counterweight and a counterbalanced arrangement of drive units.

EXPERIMENTAL SYSTEM

The H/C was studied using a 1 meter long articulated type slave arm with 6 DOF and a gripper in place of the LMA and the SFA. The system configurations and specifications are shown in Figure 3, Figure 4 and Table 1. The specifications are not described for space use. The experimental slave arm has three intersecting rotational axes with a differential mechanism for easy control.

FUNCTIONS

The LMA and the SFA control methods are not always the same due to differences in structure, size and role. Control methods and auxiliary functions are required to control these two arms, using a common H/C. The investigated functions are shown in Table 2. The H/C has three control modes, a position mode, a rate mode and a hybrid mode.

In the position mode, the system becomes a bilateral master-slave manipulator with force reflection. This control mode is used for dexterous manipulation by the SFA.

In the rate mode, the velocity of the slave arm end point is controlled proportional to the H/C displacement or force applied by the operator. This control mode is used for the LMA in long distance movement, such as joystick control with return to origin.

As the H/C has a small motion area compared to that for the SFA, the operator can change the position of the H/C origin or the motion ratio between the H/C and the SFA to use the SFA motion area effectively. The SFA is held in position when the H/C origin changes. The motion area coverage is shown in Figure 5.

In the hybrid mode, the translation is controlled by the rate mode and the rotation is controlled by the position mode. This mode is useful to operate the SFA without changing the H/C origin or the motion ratio.

The position and rotation for the H/C correspond to those for the slave arm with coordinate transformations. The transformation point for the position is changeable at any point, so that the rotation is determined for that point. To test the function, the point can be changed from the wrist joint to the grasping center point and the slave arm end point. For the wrist joint, the slave arm movement is very intuitive for the operator because of good spatial correspondence. For other points such as the grasping center or the end point, the slave arm configuration changes and the movement is not intuitive, but the operator can easily move the slave arm around a working point. When only the pitch axis for the H/C is moved, the slave arm configurations for the two cases are shown in Figure 6. The dotted line shows the configuration at the end of the movement.

These functions were able to be changed by keyboard operation in this experiment.

CONTROL

The position mode is bilateral master-slave control with a position servo loop and a force serve loop. The control block diagram is shown in Figure 7.

Both the H/C and the slave arm have a force sensor, a position sensor and a dc-servomotor mounted in each joint. The slave arm motors are driven by the rate control amplifiers and the H/C motors are driven by the current control amplifiers.

The joint coordinate system for the H/C and that for the slave arm are different, and servo control is accomplished in the Cartesian coordinate system for the H/C. The slave arm position, rate and force are transformed between the joint coordinate system and the Cartesian coordinate system. The dotted line in Figure 7 shows this coordinate transformation.

In the position servo loop, the position error between the H/C and the slave arm in the Cartesian coordinate system is transformed into the joint velocity for the slave arm. The transformation is expressed as:

$$\dot{\theta} = Js^{-1}\dot{\chi} \quad (1)$$

where:
$\dot{\theta}$ represents the joint angle vector, Js^{-1} is an inverse Jacobian matrix for the slave arm, and $\dot{\chi}$ is the Cartesian velocity vector.

This transformation is the same as that used for resolved motion rate control (RMRC). And the position of the slave arm in the Cartesian coordinate system is obtained by a homogeneous transformation matrix (Ts).

In the force servo loop, the slave arm joint torque, in which the dead weight is compensated for, is transformed into the force and torque in the Cartesian coordinate system. The transformation is expressed as:

$$f = (Js^{-1})^T\tau \quad (2)$$

where:
f represents the Cartesian force and torque vector, $(Js^{-1})^T$ is the transpose Js^{-1} matrix, and τ is the joint torque vector.

The force and torque error in the Cartesian coordinate system is fed back to the H/C. The torque in any part of the slave arm can be reflected, owing to the torque sensors mounted in each joint. In this control, the translational axes are force servocontrolled, but the rotational axes are controlled by only the slave arm force because of the low friction.

To change the transformation point, only exchange Js^{-1} for $Js^{-1}Jtp^{-1}$ in above equations. Jtp^{-1} is an inverse Jacobian matrix for the transformation between the slave arm wrist joint and the transformation point.

The rate mode is RMRC, which is used partially in the position mode, and it is easy to change from the position mode to the rate mode and the hybrid mode. The end point velocity for the slave arm is proportional to the H/C displacement or force applied by the operator, and the H/C is servo held in position at the origin. The two rate modes, displacement-use and force-use rate modes, can be easily realized by both H/C sensors. The input from the H/C is controlled with an insensitive range so that the slave arm cannot move by noises automatically.

Other types of slave arm can be easily controlled with the same H/C, by changing the coordinate transformation for the slave arm.

CONTROL SYSTEM

The H/C system is controlled by a 16-bit multi-CPU system (Intel 8086 and 8087) via Multibus interface, with a 10 millisecond sampling rate. The main calculation items are coordinate transformations, force feedback bilateral servo control, and slave arm dead weight compensation. To reduce the calculation time, an inverse

Jacobian matrix is induced by a computer algebra system REDUCE in advance, and a table look-up method for the trigonometrical function is employed. The main tasks for each CPU are as follows.

CPU1: system management and man-machine interface
CPU2: slave arm servo control
CPU3: H/C servo control
CPU4: inverse Jacobian calculation and dead weight compensation

BASIC EXPERIMENT

FUNCTIONAL TESTS

Functional tests were carried out using an experimental slave arm. The slave arm was able to be controlled by the H/C in the three control modes. The slave arm motion area was used effectively by the auxiliary functions.

In the two rate modes, force feedback was able to be realized in the displacement-use rate mode but not in the force-use rate mode. The slave arm movement when using force was smoother than when using displacement, because the inertia and friction for the translational axes of the H/C were not sufficiently compensated for. But, force feedback was effective in preventing the slave arm from an overload. Better rate mode selection requires more study and experiments, with the system improvement.

The hybrid mode was more useful than the rate mode, because the experimental slave arm was not as long as the LMA and it seemed to be difficult for the operator to control the six axes rates simultaneously by a H/C.

The most important function of the H/C system in the position mode is to feed back the force and to control the slave arm. As a result, an operator can feel the force acting on the slave arm correctly, and can move the slave arm freely.

Thus, the H/C was tested for the force reflection from the slave arm to the H/C, and the position trace accuracy using a geometrical pattern.

FORCE REFLECTION TEST

The slave arm was locked by brakes and the H/C was locked by stoppers mechanically. The force of the load cell acting on the slave arm and the generated force of the H/C force sensor were measured. The results are shown in Figure 8. Though the force hysteresis (dotted line) was large in PD control due to friction loss, a linear force relationship between the H/C and the slave arm was obtained in PID control, according to the force reflection ratio. However, the integral compensation in PID control was limited, because the H/C inertia effect was larger in operation, as the friction was smaller. The operation force for the H/C was less than 500 g in normal operation.

POSITION ACCURACY TEST

The operator watched a geometrical pattern directly in front of the slave arm, and traced the pattern with the slave arm holding a dry ink pen using the H/C. The trajectories for the slave arm and the H/C are shown in Figure 9.

The H/C trajectory is the output from the Y, Z position sensor in the X-Y plotter. The motion ratio between the H/C and the slave arm was 1:2. Both trajectories corresponded even for detailed motions. The distortion seen in the H/C trajectory is due to the backlash from the wrist joint of the slave arm to the pen tip.

In this test, the working time when using the position mode was faster than when using the hybrid mode more than two times.

The position and the force between the H/C and the slave arm were found to be correctly transformed, with coordinate transformations from these data.

PERFORMANCE TESTS

Verification tests were carried out to investigate the work ability for the H/C system, such as inserting a peg into a hole and screwing a bolt. The two tasks needed force feeling. The force reflection ratio was less than 50 percent for stable operation. The operator watched the work situation directly in the following tests. The slave arm was controlled by the rate mode or the position mode with a large motion ratio, to approach the working place.

INSERTING A PEG INTO A HOLE

The H/C system was able to insert a peg (20 mm diameter) into a hole with 15μm clearance, for both horizontal and 45 degree inclined directions. The average working time was 10 seconds in the horizontal direction and 15 seconds in the inclined direction after short exercises. An experimental scene is shown in Figure 10. In such a fine task, a 1:1 motion ratio allowed better control for the slave arm than a 1:2 motion ratio.

SCREWING A BOLT

The H/C system was able to screw a bolt whose head design was large enough to grasp easily, standing in a vertical direction. The experimental data are shown in Figure 11. In this work, when the transformation point was selected at the grasping center (Figure 11b), the work was able to be carried out smoothly without vibration, and was easier than being selected at the wrist joint (Figure 11a). Only the yaw axis for the H/C could be controlled at the grasping center. On the other hand, the yaw axis and the Y translational axis had to be cooperatively controlled at the wrist joint. Changing the transformation point is effective, to allow moving the slave arm around a point.

CONCLUSIONS

A prototype multipurpose H/C with force reflection was developed. A basic study to control the JEM's LMA and SFA was carried out using a 6 DOF experimental slave arm. The verification test results showed that this orthogonal type H/C is suitable for use as a common H/C for the LMA and the SFA of the JEMRMS and can control them by selecting the control mode. Even when the controlled slave arm configuration is changed, this H/C can easily control it by changing the coordinate transformation.

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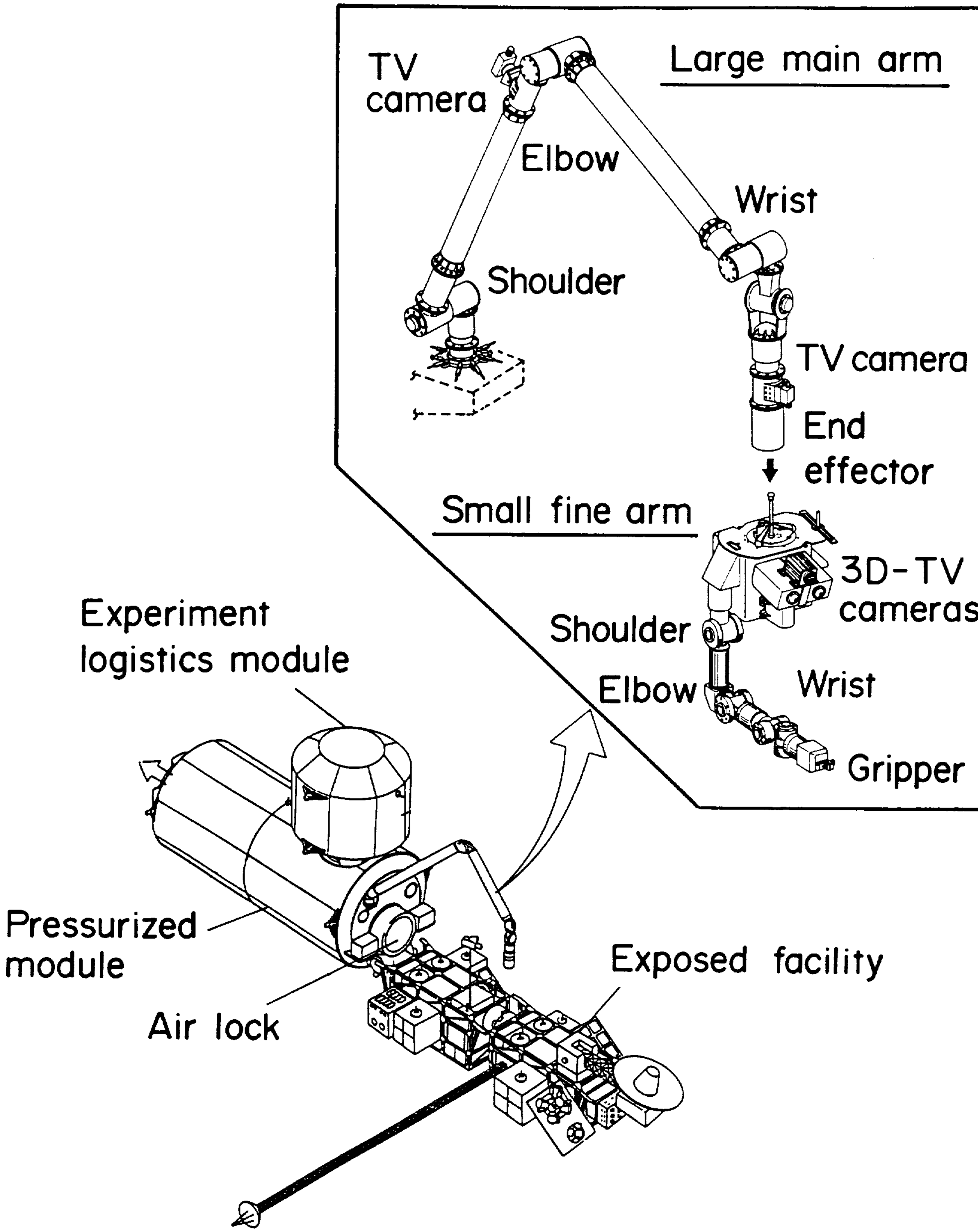

Figure 1. JEMRMS configuration (Initial)

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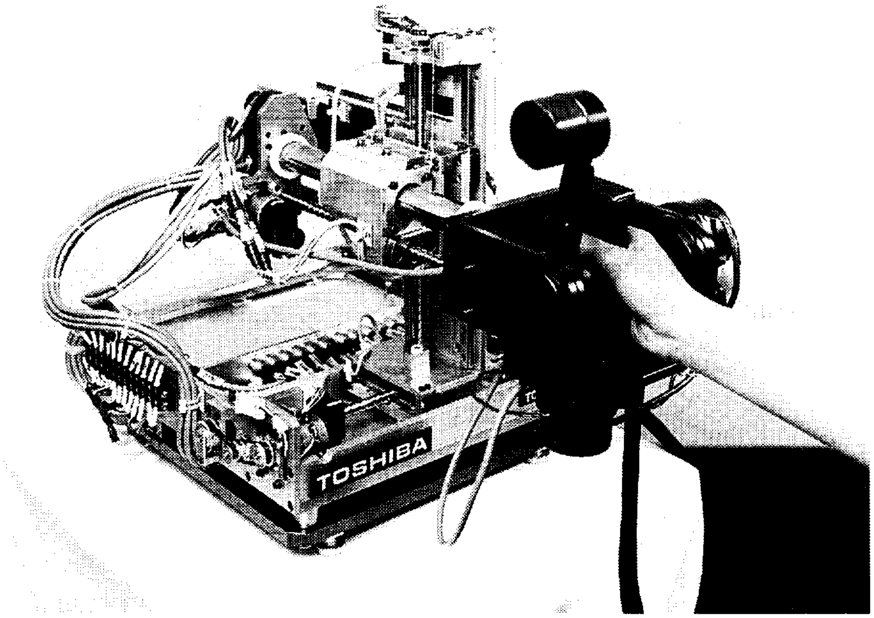

Figure 2. Multipurpose H/C prototype

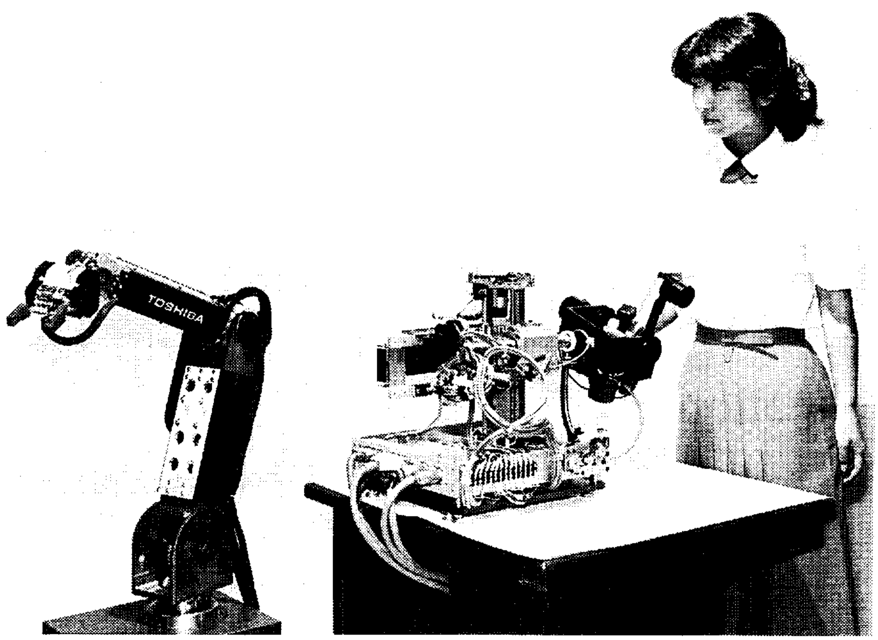

Figure 3. Experimental system

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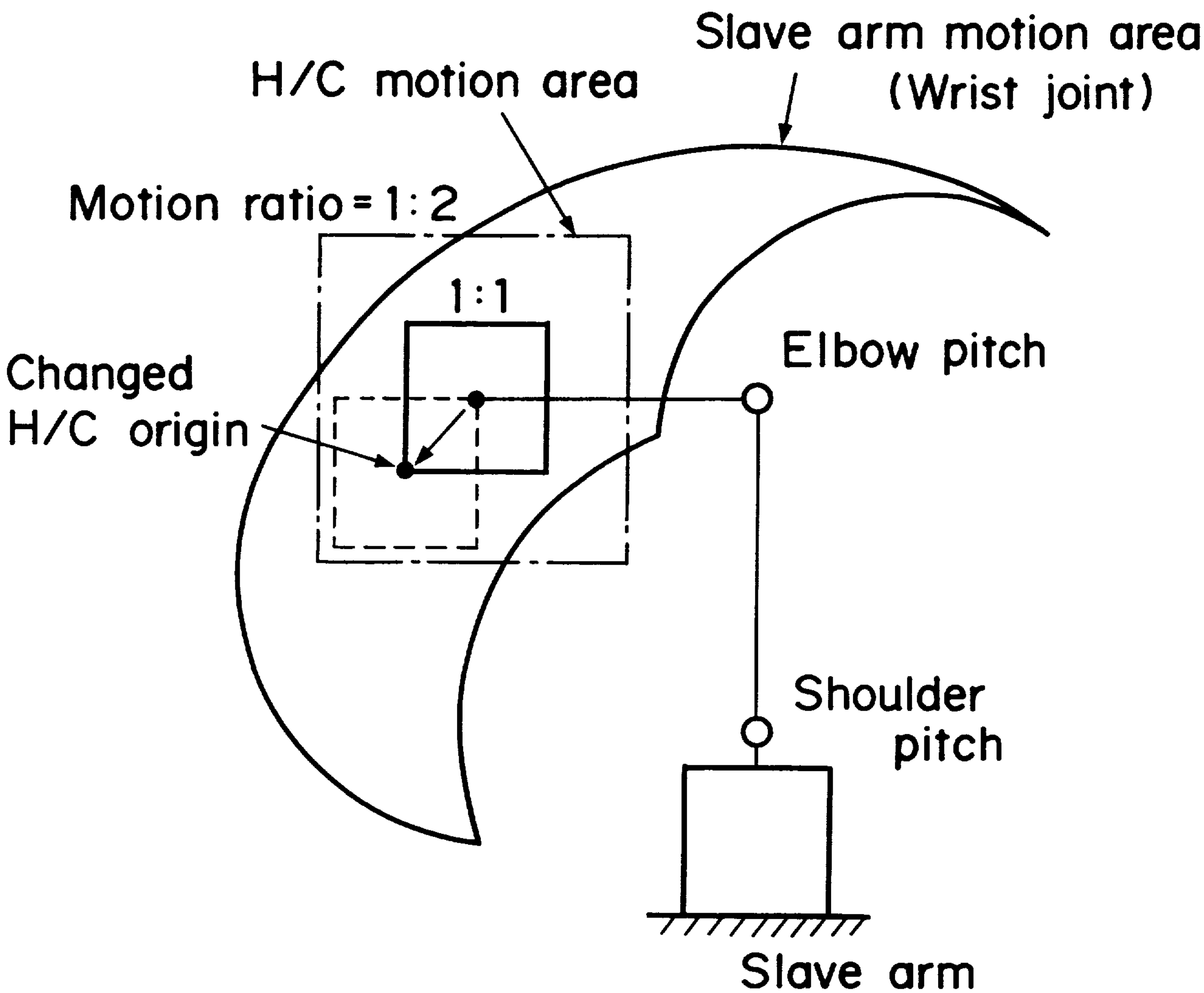

Figure 5. Motion area Coverage (Motion ratio/Origin change)

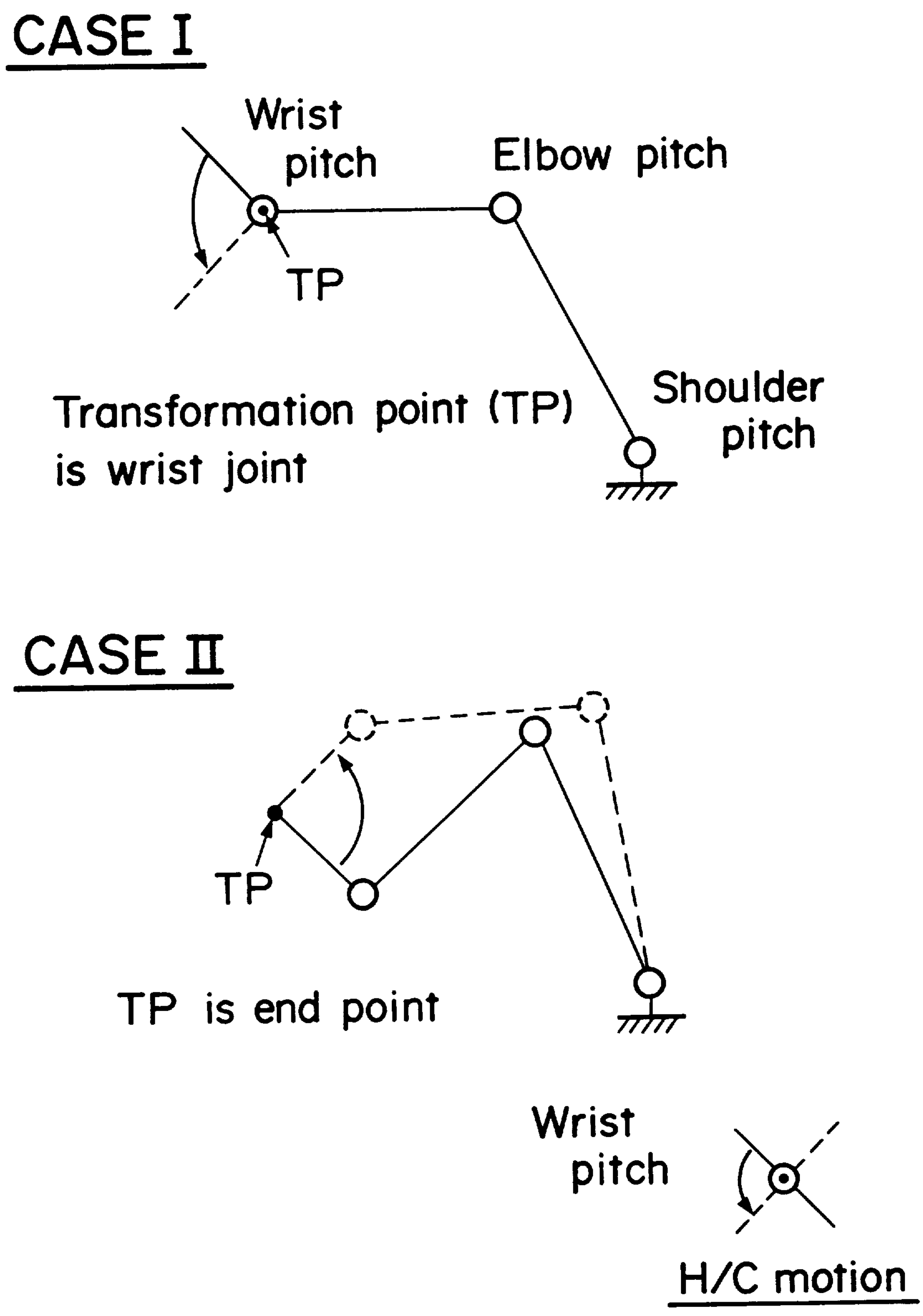

Figure 6. Differences in slave arm configuration

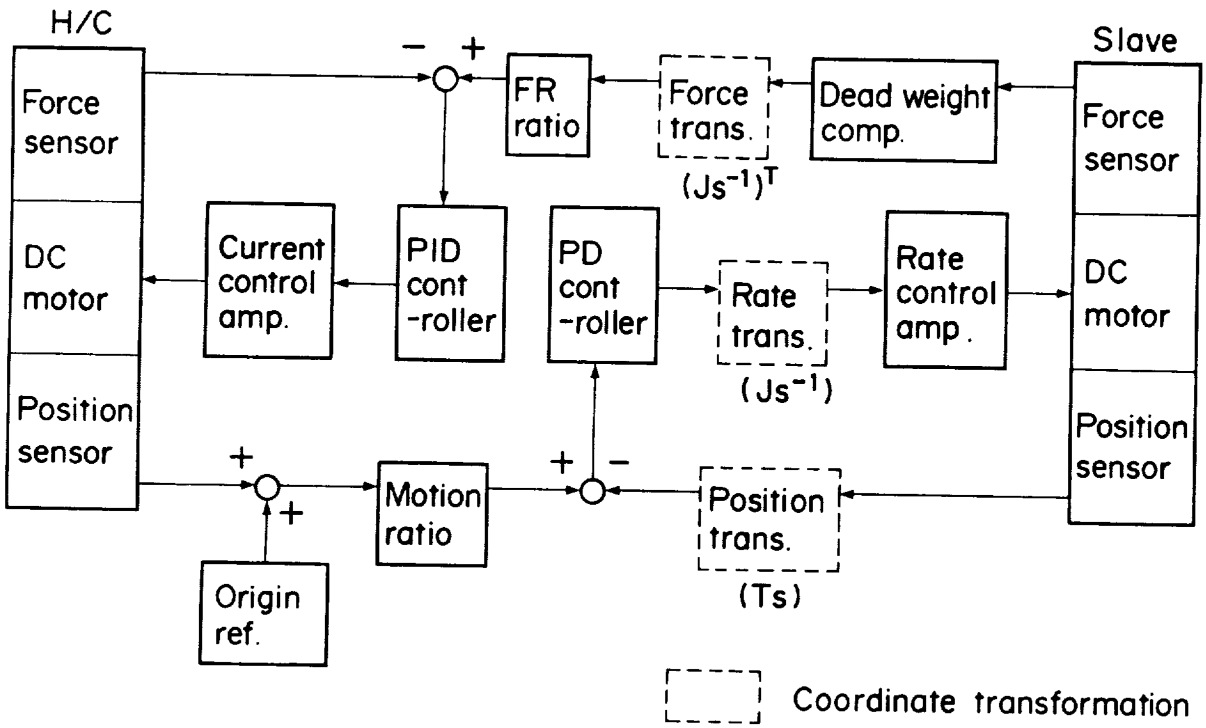

Figure 7. Control block diagram (Position mode)

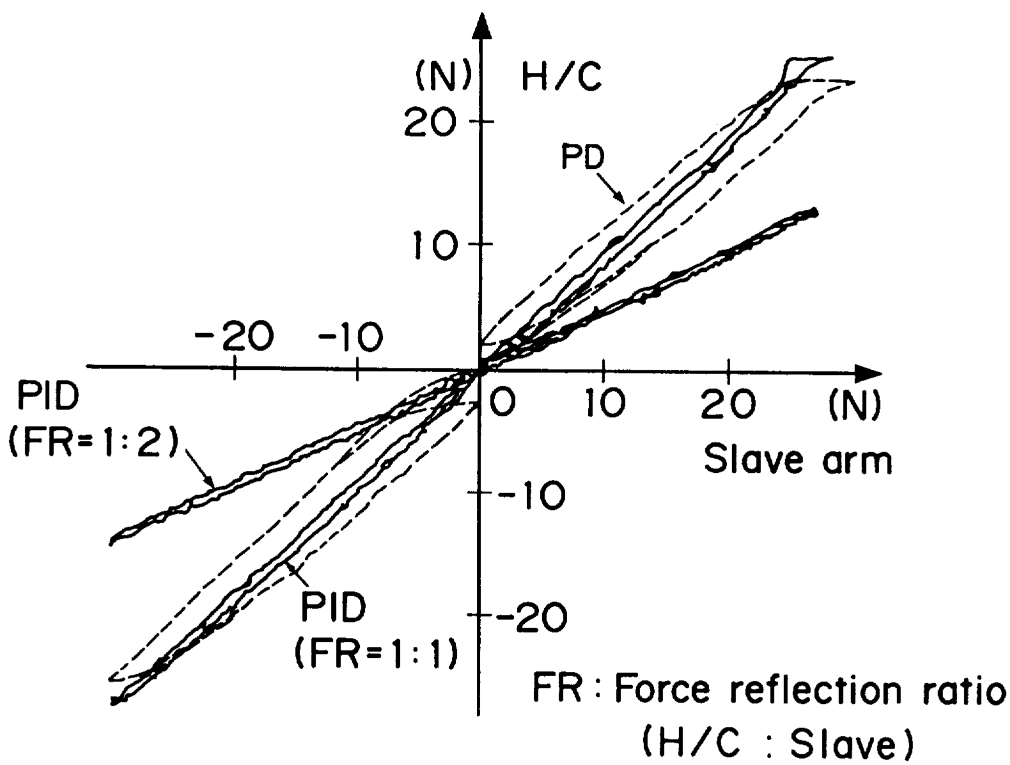

Figure 8. Force reflection test

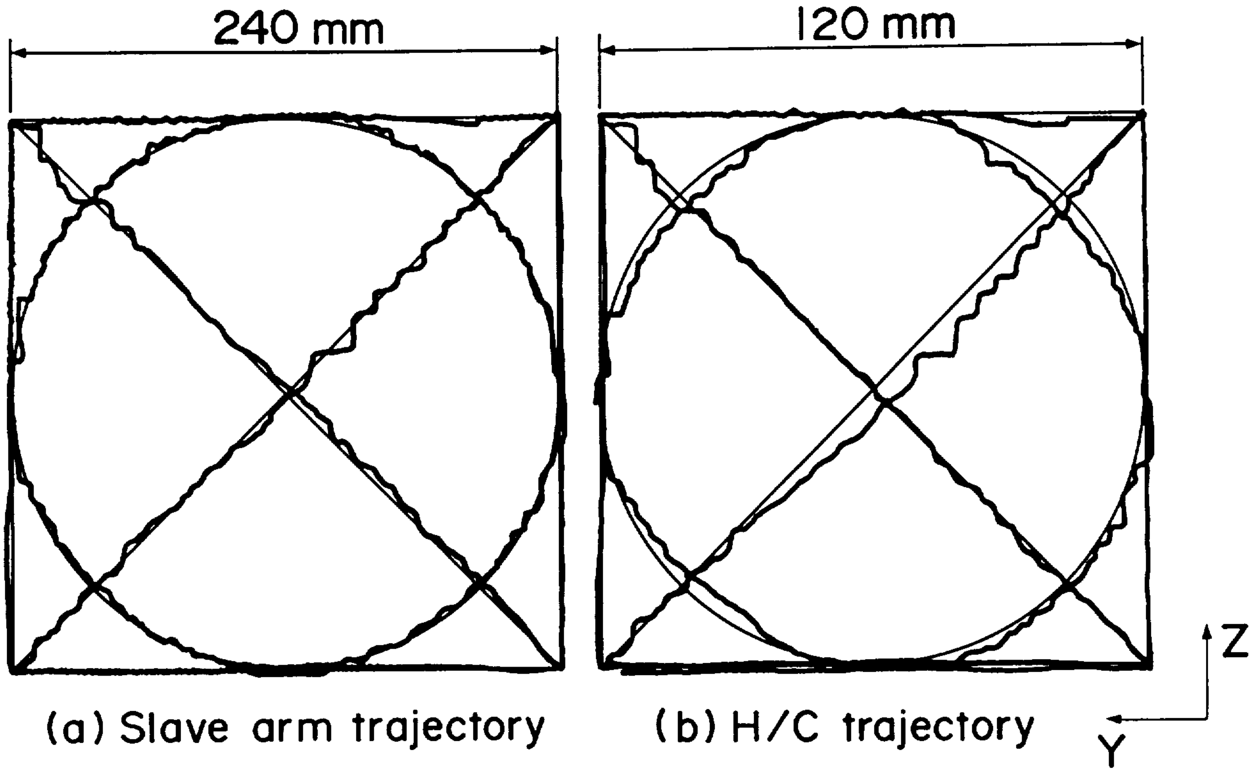

Figure 9. Position accuracy test in pattern trace

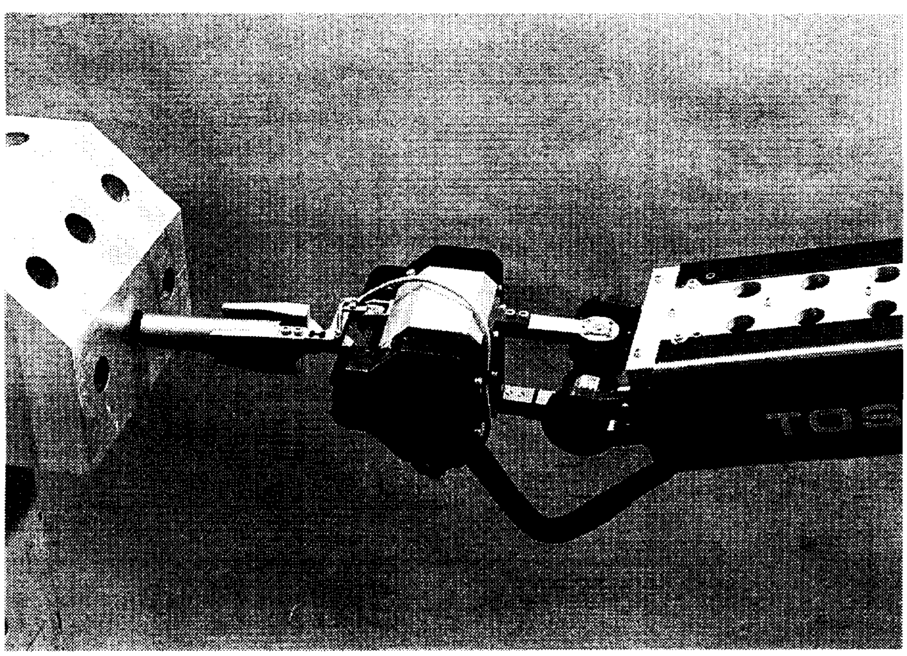

Figure 10. Peg-in-hole test

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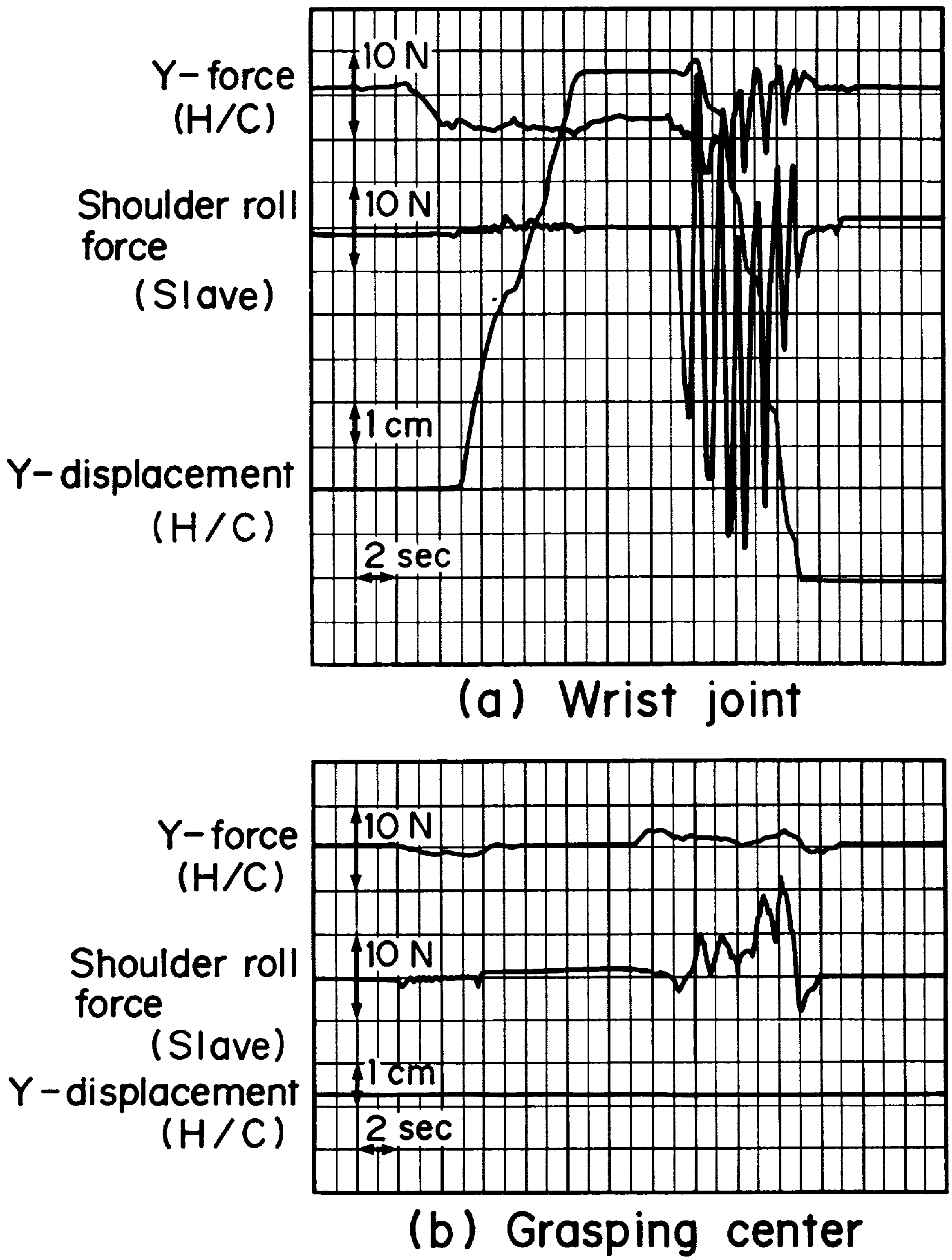

Figure 11. Change in transformation point (Screwing a bolt)