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THE CONSTRUCTION OF MAN-MACHINE INTERFACE FOR REMOTE CONTROL ROBOT

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ABSTRACT

Of the functions of the man-machine interface of the remote control robot, those functions that are especially related to safety are described in this report. Based on the assumption that the human operator inevitably makes mistakes when issuing commands to the robot, two types of interlocks are proposed for the remote control robot system. The robot system is equipped with a fundamental, main-interlock for safety monitoring on the robot side and with a supplementary, quasi-interlock for exceptional tasks that cannot be covered by the main-interlock. A manipulator system approach is taken to add to the reliability of the quasi-interlock. The quasi-interlock scheme that does not impair the safety of the human operator when he makes mistakes is developed for the pneumatic manipulator that can control the compliant motion over a wide range of conditions.

1. Introduction

In recent years, the rapid progress of robotics has accelerated the mechanization and automation of construction jobs to increase productivity and safety at construction sites. The robotization of construction tasks is an extension of the automation of construction machinery and is the same as the introduction of industrial robots at factories in this respect. Constrained by a variety of working environments and conditions, few construction tasks can be automated by using standardized industrial robots and employing methods that are extensions of conventional automated machinery. Robotization in the manufacturing industries has advanced from the field of materials handling to that of assembly where highly sophisticated techniques are required. In the construction industry, however, the speed of this progress is slow and many of the sophisticated and complicated construction tasks still depend on the abilities and skills of human workers. A remote control robot that moves autonomously in a well-maintained place but is operated directly by the human operator according to his knowledge, judgment and skill in a place where the job content is not clear is thus suited for use at the construction site.

As construction machinery increases in complexity and output, many new hazards are occurring and accidents that arise from mistakes of operators tend to increase in scale and seriousness. Remote control manipulators will encounter this contradiction if they are made more difficult to operate to no purpose.

When the operator operates the remote control robot, the mistakes the operator and computer may make in issuing commands to the robot cannot be completely prevented. Since the command information also involves ambiguity, the man-machine interface of the remote control robot must be provided with fool-proof interlock functions. An interlock system that includes command units and sensors and helps to perform tasks safely is studied here. The validity of the interlock system is verified by using a pneumatic manipulator that is equipped with the characteristics of an adaptive robot and operated by ambiguous commands.

2. Relationship Between Human Operator and Remote Control Robot

2.1 Operation of Robot by Operator

A small-sized shovel or crane operated using a remote control box can be regarded as a simple remote control robot. Their mechanisms, however, limit the use of these machines to simple tasks. For the operator must operate too many buttons or joysticks to cause the machine to perform complicated tasks.

The human operator uses the robot to replace or augment some of his functions. In this sense, a cooperative master-slave system is desirable that emulates the actions of the operator. This type of robot is a manual manipulator that has a mechanism resembling a human arm. It allows the operator to display his skill, works in a natural way because the master arm conforms to the motion characteristics of the operator, and is expected to lessen the fatigue of the operator and to reduce the number of operation mistakes by the operator.

When the operator remotely controls a robot of the manual manipulator type, the motion of the robot entirely depends on the action of the operator. Since human commands are not always correct, such a man-machine interface must be constructed that assures safety even if the command information is erroneous or ambiguous.

2.2 Work Spaces of Human Operator and Robot

When a robot is used in a construction job, the work space of the robot is not often fixed. Where there is a possibility that the human operator and robot may be present together in an area, interlocks must be used to assure the safety of the operator. The work spaces of the human operator and robot are defined to clarify the interlock construction conditions required.

The work space in the construction job is divided into the human work space, robot work space and common work space. The robot work space is subdivided into the robot fixed space, main-interlock space and quasi-interlock space. The joint work space is that portion of the human work space that overlaps the main-interlock space or quasi-interlock space of the robot. These work spaces are configured as shown in Fig. 1. The respective spaces are defined below.

(1) Robot work space R: The entire space where the robot moves and performs the assigned task.

Explanation: The work space of the robot consists of the robot fixed space RS, main-interlock space IP and quasi-interlock space IQ, as expressed by

$$RS \cup IP \cup IQ \supset R \qquad (1)$$

(2) Robot fixed space RS: The space that the robot occupies and where no humans are obviously present or the space where humans are not allowed to

work.

Explanation: This space protected against the entry of humans by fence etc., need not be especially monitored for the presence or absence of the humans.

(3) Human work space H: The space where the humans are allowed to work.

Explanation: In this space, the human operator or other workers may work outside the reach of the robot arm or may enter into a position that the robot arm can reach, as expressed by

$$H \supset (A \cup B) \qquad (2)$$

(4) Interlock space I: Of the robot work space, the spare where safety is monitored by means of an interlock.

Explanation: Human workers may be exposed to the hazard of the robot arm where the human work space overlaps the robot work space. This space calls for safety monitoring by some type of interlock. The interlock space generally consists of the main-interlock space IP and quasi-interlock space IQ, as expressed by

$$I = IP \cup IQ \qquad (3)$$

(5) Main-interlock space IP: Of the robot work space, the space where safety is monitored by a main-interlock (as discussed in detail later).

Explanation: Whether or not humans are present in this space is monitored by the main-interlock to assure safety. Since safety monitoring is performed over a wider area than the human work space, the following relation holds:

$$IP \supset A \qquad (4)$$

(6) Quasi-interlock space IQ: Of the robot work space, the space where safety is monitored by a quasi-interlock (as discussed in detail later).

Explanation: This space is supplementary to the main-interlock space. Namely, the quasi-interlock space is especially provided to cope with the case in which the mechanism of the robot makes it impossible to confirm the absence of humans and the case in which there is a very low frequency of the need to confirm the absence of humans. A human interlock must be constructed for this space. Namely, the operator must constantly monitor to see that other humans do not collide with the robot. Since safety monitoring is performed over a wider area in reality, the following relation holds:

$$IQ \supset B \qquad (5)$$

These definitions specify that in all of the spaces where the humans work exposed to the hazard of the robot arm, safety must be monitored by the main-interlock or quasi-interlock. That is,

$$(R \cap H) \subset (IP \cup IQ) \qquad (6)$$

3. Construction of Interlock in Man-Machine System

3.1 Basic Construction of Interlock

The robot is not permitted to start before the safe condition that there are no humans in the two interlock spaces described above is detected and transmitted as positive logic. A means that satisfies this requirement is termed a "means of the safety confirmation type."[1] The construction of an interlock that realizes this means is shown in Fig. 2. It is evident from Fig. 2 that when the safe condition is transmitted as positive logic, harm is not done to the humans even if an operation command is erroneously issued. The confirmation means and AND gate in the block diagram, however, must have such an asymmetrical error rate[2] that the output logic value goes 0 (to stop the machine) in the event of failure.

Conversely, the method whereby the hazardous condition of human entry is detected and transmitted to stop the robot is designed to detect the hazardous condition as positive logic and is called a "means of the hazard detection type." A NOT element (logic inversion) is inserted between the confirmation means and AND gate in Fig. 2, in order to provide a means of the hazard detection type with a function equivalent to that shown in Fig. 2. The confirmation means (referred to as a detection means here) must be given such a characteristic as to output a logic 1 in the event of failure. This characteristic implies that the detection means must continue to have energy output even after its failure. It is not realistic to design a detection means with this characteristic.

Therefore, an interlock to assure safety must be the means of the safety confirmation type shown in Fig. 2, and the construction of a confirmation means that gives an operation permit is specified.

3.2 Construction of Interlock in Positive Interlock Space

A human proximity sensor is commonly used for the robot to confirm the absence of humans in the robot work space. The human proximity sensor must be constructed to produce a logic 1 and permit the robot to work as long as it confirms the absence of humans and operates normally. Namely, the sensor itself has a NOT structure to detect and transmit the NOT information signifying the absence of humans. An interlock that includes a confirmation means having the characteristic of this sensor is defined as a main-interlock. Let Ia a operation command, f be an operation output and $\overline{H}$ be the absence of humans in the joint work space. Then, the construction of the main-interlock is as shown in Fig. 3. The operation output f is given by

$$f = Ia \wedge (\overline{H} \wedge Sa^*) \wedge Ga^* \qquad (7)$$

where Sa^* is the normal operating state of the sensor S and Ga^* is the normal operating state of the AND gate G (the sensor and AND gate both produce a logic 1 when they are normal and a logic 0 when they are not normal). If the absence of humans or $\overline{H}$ is confirmed, an error in the operation command Ia is permitted. (Unless this construction is adopted, no mistake is allowed in the operation command for fear of resultant hazard.) The main-interlock can be also termed a purposive safety interlock because it actively detects the safe condition and creates purposive safety[3] (a condition in which the assigned task is carried out after confirmation of safety).

A photoelectric switch of the transmission type is an example of fail-safe human proximity sensor that detects safety or absence of humans as positive logic. This type of sensor has a NOT structure itself. The photoelectric switch of the transmission type outputs a logic 1 or proves the absence of humans as long as the light beam projected by the transmitter is received by the receiver and outputs a logic 0 when the light beam is interrupted by a human worker. It does not deliver a logic 1 when either the transmitter or receiver fails to operate. General types of human proximity sensors are not of fail-safe construction. A shield beam sensor[4], fail-safe safety mat[5], and fail-safe pulse radar sensor[6] have been developed as fail-safe sensors. A fail-safe AND gate[7] is already available on the market.

3.3 Construction of Interlock in Quasi-interlock Space

Ideally, a confirmation means to be used in the interlock must be of fail-safe construction. If such a means is not available, a specially assigned watchman takes its place. The watchman must constantly see to it that there are no human workers in the common work space and must continue to issue a signal representing the confirmation of safety; for instance, he must continue to keep a pushbutton pressed. This is to assure the shutdown of the machine when he leaves his place. The sensor and AND gate in Fig. 2 correspond to the human eye and brain, respectively. Since humans have no fail-safe characteristics, a human interlock does not satisfy the construction requirements of the main-interlock and only has a form analogous to that of the main-interlock to some degree. This human interlock is defined as the quasi-interlock.

It imposes heavy mental and physical loads on the watchman for him to constantly pay attention to safety and continue to confirm safety. These loads can be somewhat lessened by a method that detects the approach of humans and shut downs the machine in emergency. This method, called monitoring of the hazard detection type, is likely to result in an accident due to a human error. As long as safety monitoring depends on humans, there is a limit to the degree of safety that can be accomplished by this method.

Another quasi-interlock in the form of hardware is provided to construct duplicated quasi-interlocks as shown in Fig. 4. In this case, safety monitoring is performed by the operator who operates the robot. In Fig. 4, the eyes of the operator are denoted by Sh^* and the AND gates (hardware) of the robot are represented by G_1^* and G_2^*. In the construction of Fig. 4, the high-rigidity action requirement Ia that involves the highest hazard can be satisfied only according to the expression of will C and confirmation by the operator W. When confirmation by the operator W is not enough, however, the robot can carry out low-rigidity action alone. The block diagram of Fig. 4 signifies: "When an unexpected event occurs, the robot is switched to perform action of lower rigidity, so that no harm or damage is done to the human or surrounding equipment." The potential hazard of the robot can be suppressed to a large extent if the robot is made rigid only when it exerts force and performs the assigned task and is made flexible in other cases. If the AND gates G_1^* and G_2^* in Fig. 4 are fail-safe AND gates, an error is permitted only in the input W to G_1. Since the human operator has a clear will to work when he exerts force, however, the input W can be regarded as the willingness of the operator to cause the robot to exert force. In other words, the interlocks of Fig. 4 are extremely adapted to the characteristics of humans.

Realization of the interlocks shown in Fig. 4 requires a robot that can be changed in rigidity (or compliance). The robot may be an essentially rigid robot that is made compliant through control or an essentially compliant robot that is made rigid through control. The former type of robot is equivalent to an electric or hydraulic robot and cannot be adapted to the interlocks of Fig. 4 because its compliant condition (called virtual compliance) is obtained only when it is controlled normally. The latter type of robot does not apply a large force to a human worker when it contacts the human worker if it is designed to move to the high compliance of air in the event of failure.

The present work built the interlock model of Fig. 4, using an pneumatic manual manipulator, the compliance of which can be adjusted from outside, and verified the validity of the interlocks.

4. Man-Machine Interface in Pneumatic Manipulating System

4.1 Construction of Pneumatic Manipulator

In the manipulator used in the present work, two Mckibben artificial rubber muscles are used antagonistically as an actuator, the pneumatic pressure supplied to each muscle is adjusted, and an angle control system based on angle sensor feedback is built for four axes. The overall construction of the pneumatic manipulator is shown in Fig. 5. The pneumatic pressure control system controls two direct-operated flow control valves of the ball poppet type[8] in unison and forms a pressure feedback loop. The valves feature a supply pressure of 0.4 MPa (gage) and maximum flow rate of 0.4 m^3/min. Since they are normally closed, they can hold the manipulator in the event of electric power failure. It is confirmed that the pneumatic pressure control system has high-accuracy static characteristics through high-gain control. The construction of the drive system[9] (for one axis) is shown in Fig. 6.

The angle compliance $\Delta\theta/\Delta F$ of the manipulating system can be approximated by

$$\Delta\theta/\Delta F = 1/(A \cdot Gv \cdot G \cdot Hp) \qquad (8)$$

where is displacement in each joint axis; F is the force generated; A is the effective cross-sectional area of the artificial muscle (characteristic value); Gv is the voltage-pressure conversion gain of the pneumatic pressure control system; G is the voltage gain of the electric circuit; and Hp is the angle-voltage conversion gain of the angle sensor. This equation indicates that the compliance of the manipulator can be changed by changing the gain G. In this respect, the manipulator may be called a manipulator of the variable loop gain type. Its compliance is basically different from the compliance of a high-rigidity manipulator that virtually creates flexibility.

4.2 Transmission of Commands to Manipulator and Control of Manipulator

This manipulating system comprises a master-slave arrangement. Generally, a bilateral control system that has a mechanism to feed back force as sensor information to the master is adopted for a master-salve manipulator. The force sensed when the manipulator touches an object is sent to the operator and the master-slave manipulator is not desinged to avoid contact with objects. The bilateral control system thus does not assure freedom from hazards as long as a high-rigidity manipulator is used.

A compliant manipulator, on the other hand, is essentially flexible and assures safety when it contacts other objects. Operator training can thus focus on operating techniques rather than on safety. Since the operator operates the manipulator with his visual sense, positional errors are particularly large. These positional errors are considered to be accommodated by the flexibility of the manipulator, however. As force reflections need not be fed back to the master, the manipulating system can be constructed as a unilateral control system. The work relationship between the master and slave manipulators under the unilateral control system is shown in Fig. 7.

High accuracy is not required of the master command unit (Ia in Fig. 4) when a pneumatic manipulator is used. For this reason, a simple angle sensor was developed that uses extensible conductive rubber and can be attached to the elbow joint of the operator. The construction of the elbow angle sensor is shown in Fig. 8.

A grip force sensor is used as a compliance command method whereby conscious action of the operator, involving safety confirmation, is extracted as motion of low load. This device has a pressure sensor made of extensible conductive rubber attached to one end of a hollow rubber ovoid. The general view of the grip force sensor[10] is shown in Photo. 1. The hollow rubber ovoid is open at the other end and the operator must consciously close this end with the thumb to increase the rigidity of the manipulator. This action is represented by C in Fig. 4. The action of safety confirmation W is not provided as a function because it is assumed that a high-rigidity operation command cannot be issued unless safety is confirmed. Therefore, the device Ia also performs the function of W.

The compliance of the manipulator is adjusted by changing the voltage gain G of the angle control system according to the signal of the grip force sensor. When the gain G is extremely small, however, the angle control characteristic deteriorates. To prevent this situation, the lower threshold of grip force is established. Unless the hollow rubber ovoid is gripped with a force larger than the lower threshold, the voltage gain G is zero and the manipulator remains relaxed. The upper threshold of grip force is established for ease of operation. When the hollow rubber ovoid is gripped with a force larger than the upper threshold, the voltage gain G is saturated. The threshold settings are illustrated in Fig. 9. An experiment being run is shown in Photo. 2. Figure 10 shows the measured values of the elbow angle compliance characteristic as converted into corresponding values of rubber ovoid pressure. A hysteresis of 4.4×10^{-4} rad/Nm occurred. This degree of hysteresis is considered to fall within limits permitted in view of the ambiguity of the human operator and the positional error of the manipulator.

4.3 Evaluation of Interlock System

With the interlock system built as regards compliance, active information required for safety confirmation is produced by the operator himself. This means that the interlock system is that of the safety confirmation type. The threshold levels that constitute the interlock conditions comprise digital levels for confirmation of the operator's will or his closing of one end of a hollow rubber ovoid with the thumb and analog levels in the form of the voltage gain G of an angle control system. The threshold levels are thus extremely useful in assuring safety. It is difficult for the operator to issue two commands at a time to the robot through different routes as shown in Fig. 4. Since the operator uses sensors made of rubber to issue the two commands, however, he can know directly if the commands are positively sent to the robot.

In the interlock system, any deviation between the actual position of a work object and the target position command issued by the operator is accommodated in a high-compliance condition and a command that erroneously causes high-rigidity control is taken care of by conscious safety confirmation by the operator. When the operator operates a high-rigidity manipulator, he must constantly strain himself to confirm safety. Since this system allows the operator to make mistakes, it is expected to lessen the metal and physical fatigue of the operator for safety control and to improve his operating efficiency.

5. Conclusions

Since the operation of a remote control robot is entirely left to the discretion of a human operator, a man-machine interface system must be constructed with full attention paid to operation mistakes and ambiguous commands of the operator. There are limits to operator education, maintenance control and safety control in assuring human safety. Safety design must be made based on the design concept of human superiority. In other words, the functions must be allocated between the human operator and robot according to the conditions of use, and the man-machine system must be provided with necessary interlocks, all based on human superiority.

The man-machine interface system is basically constructed according to a fail-safe approach on the robot side and a fool-proof approach on the human side. The notion that the machine is certain to fail and the human operator is certain to err lies at the basis of this construction. It has been discussed above that where the aforementioned two approaches are difficult to accomplish as in construction jobs, the use of an adaptive robot allows the construction of an interface system that conforms to the characteristics of the human operator and is effective in assuring the safety of the operator. The possibility that tasks can be safely performed with the aid of the interface system has been also demonstrated.

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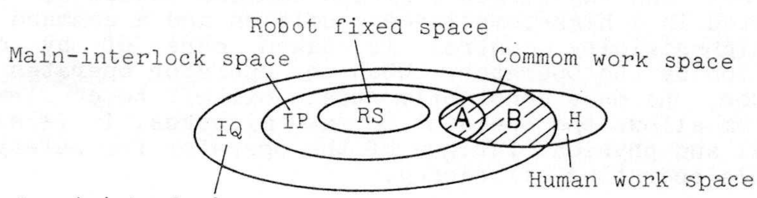

Fig. 1. Definitions of human and robot work spaces.

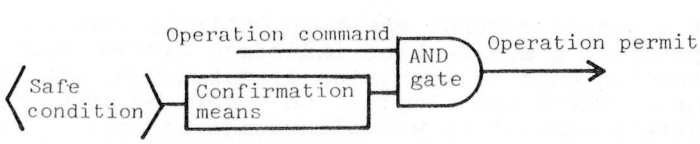

Fig. 2. Basic construction of interlock.

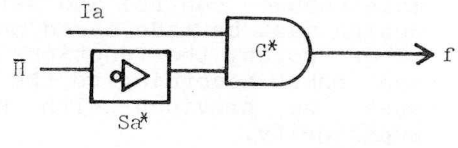

Fig. 3. Construction of main-interlock.

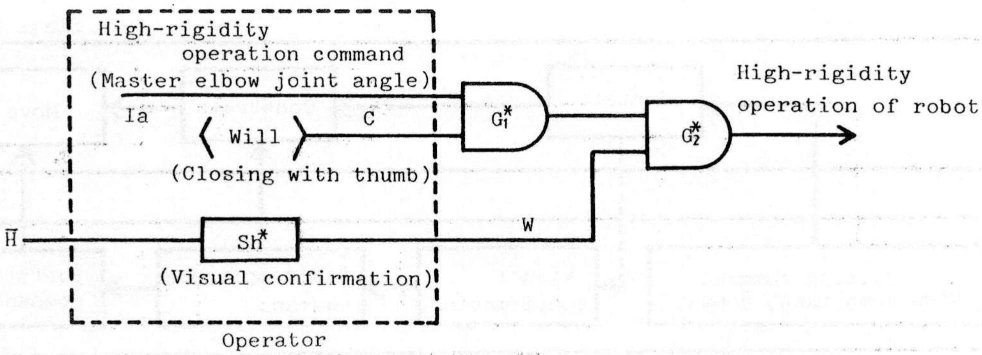

Fig. 4. Construction of duplicated quasi-interlocks.

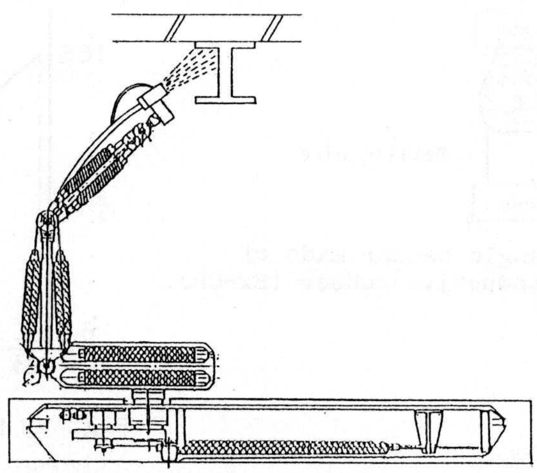

Fig. 5. Construction of pneumatic manipulator.

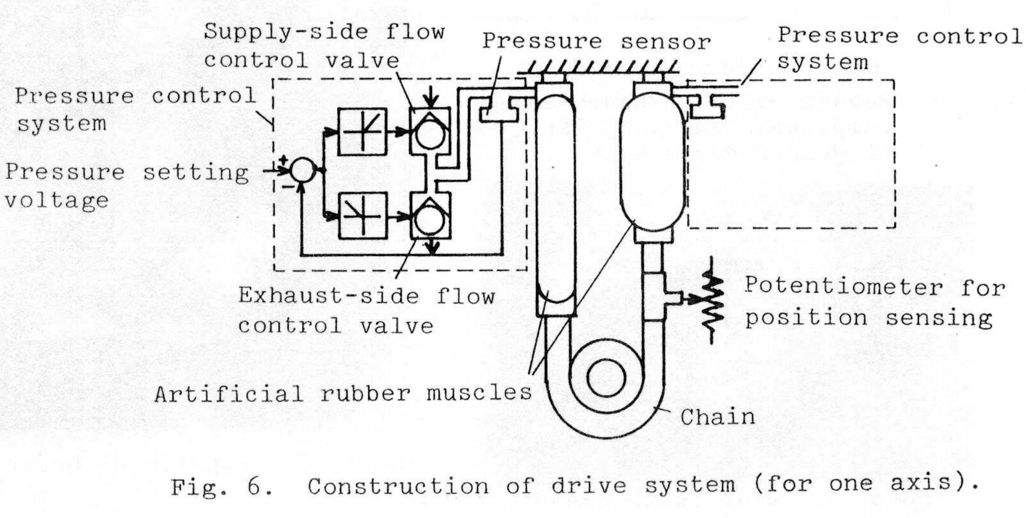

Fig. 6. Construction of drive system (for one axis).

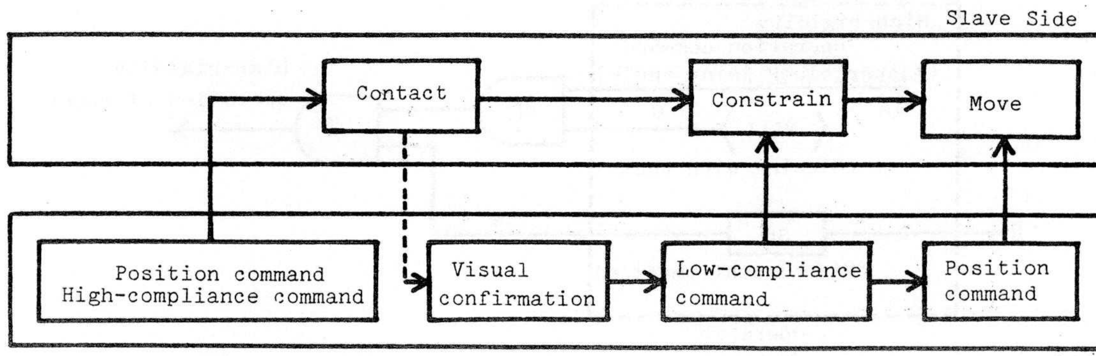

Fig. 7. Work relationship between master and slave.

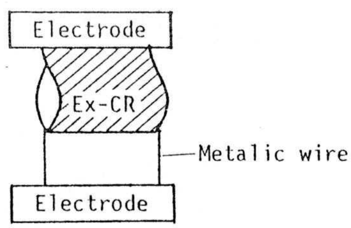

Fig. 8. Elbow angle sensor made of extensible conductive rubber (Ex-CR).

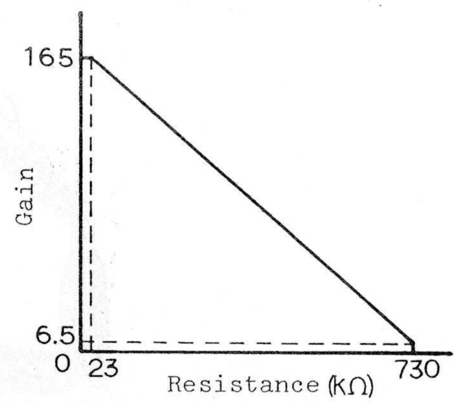

Fig. 9. Resistance-gain characteristic of extensible conductive rubber (Ex-CR).

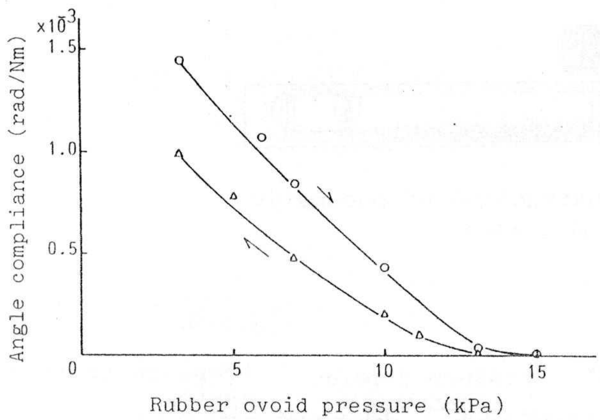

Fig. 10. Rubber ovoid pressure-angle compliance characteristic of grip force sensor

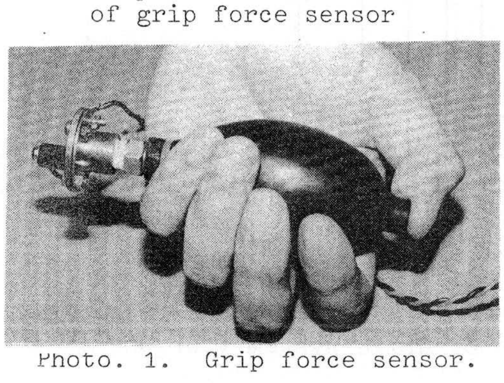

Photo. 1. Grip force sensor.

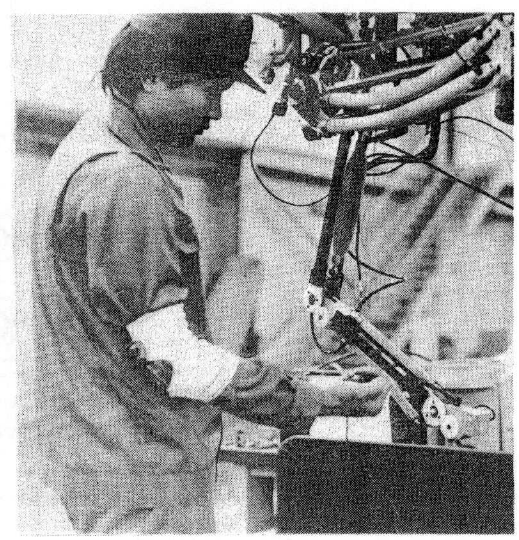

Photo. 2. Experiment being run.