Memoirs of the Faculty of Engineering, Nagoya University
Vol. 27, No. 2. (1975)

# SENSORS AND SYSTEMS OF AN INDUSTRIAL ROBOT

MINORU UEDA, KAZUHIDE IWATA, TOSHIO SHIMIZU
and ITSUO SAKAI

*(Department of Electrical Engineering)*

(Received December 1, 1975)

## 1. Introduction

In the ancient days human beings did work only by their arms and legs. In these several hundred years many types of machines were developed and they helped human work. These machines have two important purposes, one of them is the stronger power than human bodies and the other is the better repeating accuracy. At first these machines helped human workers and increased human abilities. But the development of automatic machines in the recent years made possibility of substitution of machines instead of human labors.

In addition, shortage of skillful labors and a rise of labor cost compel us to research on the method of labor saving. Simultaneously the development of electronics and computer technique have been very remarkable and plucked up our courage to develop more exquisite automatic machines which can work in place of human workers.

Nearly forty or fifty years ago there were many robots in comical pictures for children. Those robots had very strong arms, legs and a superior brain, and could run very fast, jump very high and struggle against their enemies. They did entirely like a great human being. They were products of children's dream. Now the robot is not a dream but a real machine which we can use in many production lines.

In the modern scientific research field it seems to us that there are two different types of robots. One of them is very near to the robot in the children's dream. But this is not a dream now, but a realizable one. Such a robot has a brain, consists of a large computer (artificial intelligence), eyes, consists of TV cameras, ears, hands and legs. He can run, walk, work, see, hear and recognize matters and circumference, and understand human language. Research on these type of robots is very important for the many fields of human life, especially for the space science and for the exploitation of sea bottom. But such a robot is so expensive that we can not use in the most production lines in the modern industries.

In the production lines in the modern industries there are many human labors working in very dull and repetitive works. The developing of many automatic machines in these several ten years has made such tendency that the precise and accurate works have been done by automatic machines and the remaining works for human labors are uninteresting ones such as cleaning, dusting, carrying or lubrication.

Generally there are three kinds of works in the industries. They are making, assembling and handling. Automatic machines are mostly used for making, but in the field of assembling and handling still more handworks of human labors can not be left out. In assembling and handling there are many cases in which the very precise and fine sensation of human fingers is required. The human hands and fingers can grasp and carry matters of several kilograms of weight but can sense a difference of several grams on the surface of the fingers. Moreover, the human fingers can know the surface smoothness, hardness and the shape of the object. The industrial robot which works in place of human labor in the assembling and handling processes or saves human labors from dull uninteresting works must have abilities of sensations of weight, shape, surface smoothness and hardness. There are many researchers on pattern recognition with TV cameras and great computers, and they are succeeding in some extent now. But it seems not to be able to useful in many production lines in the near future by reason of cost and speed of computation. Working speed of human hands and fingers seems to be less than automatic machines in repetitive works, but it is unexpectedly fast in delicate and puzzling works.

## 2. Definition of an Industrial Robot

As mentioned above, an industrial robot differs from the high intelligent robot. At the present, there are many — more than 100 — makers of industrial robots in the world, and very many robots are working in production lines. Most of these robots have not artificial intelligence. But they work in place of human workers in the field of handling and assembling.

These industrial robots without artificial intelligence resemble very much to automatic machines. Automatic machines can work instead of skillful human labors in the field of repetitive works. Especially "numerically controlled machines" have been developed in these ten years. These NC machines have computers and have abilities to remember long machining programmes. In the machining programmes there can be tool changing programmes and work pieces can be made by cutting, drilling, scraping or screwing.

These programmes of NC machines are very dexterous and the finishing is very precise. In a manner of speaking this NC machine can be called an industrial robot. But these NC machines are very difficult in making and changing the programmes. Usually the drawing of the object matters is designed on a sheet of paper. To make a programme of machining from the design on a paper is very difficult and there are many researches on the method of making programme from the design. Moreover, whether the programme is correct or not can not be tested without the actual machining.

Industrial robots working in the production lines, for assembling or handling, must be able to work for various different works, which are changed every week or every day. For this purpose the programme of the robot must be easily changed. Then we do not include NC machines in industrial robots.

Simplisity of programming is one of the most important points for the machine which is called an industrial robot. In the international symposia in these several years ('72 Chicago, '73 Zürich and '74 Tokyo) the definition of industrial robots was discussed and there had been various opinions. Finally it had been made clear that there could be in existence various type or grade of artificial intelligence in industrial robots: the simplest one had only a simple memory of sequence and the highest class had the highest intelligence, but one point which is common to the most of the machines, called industrial robots, is easily programmable and easily reprogrammable. In conclusion of these discussion they came to an agreement that a programmable machine can be called an industrial robot.

## 3. Construction of an Industrial Robot

### 3. 1. *General Construction*

General construction of a robot is shown in Fig. 1. In this figure the part "hand" is not necessary a hand but may be a leg or another moving part, generally called working ends. An "eye" is also not always an eye, but may be ear or tactile sensing units, generally called sensor. There are many types of sensor such as tactile, optical, magnetic, pneumatic, mechanical or fluidic. "Brain" is one of the most important parts of an industrial robot. This part must have an ability of memory of sequence and positions. If the brain is an ideal one and resembles to a human brain, such as a dream robot in a childbook, there is no necessity of "monitor" and "input" in the figure. But an industrial robot saving human labors also requires some human controls.

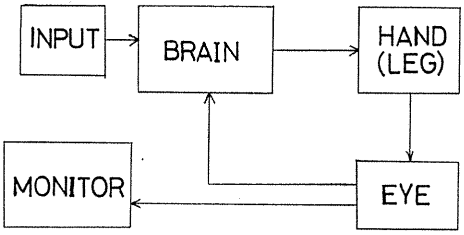


Fig. 1. General construction of an industrial robot.

The fact that the industrial robot for labor saving requires human control seems in some meaning curious. But usually many industrial robots are used in one production line, and the number of human workers who control or check the robots are very less than the case of the production line without robots.

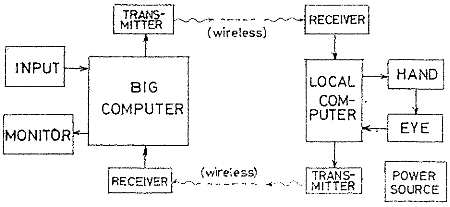


Fig. 2. General construction of a robot for space research or sea bottom exploitation.

There are some industrial robots which have no feed back loop as shown in Fig. 1. They have no sensing unit. For example, the robot, whose working end is driven by a pulse motor, may be operated by one directional flow of information from the brain to the working end. This type of robot is rather simple and cheap, and it would be better to be called an "automatic machine". But we may also call an industrial robot when this machine is easily programmable.

In order to call a robot, I hope, there must be a feed back loop including some sensing units and it must some judging abilities for various unexpected situations. From the other standpoint we can say that the accuracy of an industrial robot can be very increased by a feed back loop. Let us consider by an example of playing with toy building blocks. A child, three years old, can build a toy gate with blocks, namely, the gate is completed by placing one block upon two standing blocks. If we let a robot to do same playing, when the positions of the first two blocks are very correct the third block will be safely placed upon the first two blocks by the high positioning accuracy of the robot. But when the positions of the bigining blocks vary by an unexpected reason the robot will fail to complete the gate as the third block is placed at the unchanged position according to lack of a feed back loop.

Another example, let us consider the case of threading a needle. The positioning accuracy of a human arm and hand is not so good. If a man shuts his eyes and moves his hand to appointed position, there will de several cm of positioning error. However the man can thread into a minute hole of a needle. It can not be done without visual feed back system.

### 3. 2. *Kinds of Feed Back System*

One of the simplest feed back systems will be a limit switch or a mechanical stopper. Mechanical stopper, sometimes used in pneumatic control system, has very high accuracy of positioning, and the position can be easily changed in order to engage in another handling work. But only one or two mechanical stoppers can be fitted on one axis of motion, so the robot with mechanical stoppers can not engage in handling including many steps of motion. Limit switches also can not give many stopping positions. But there are contactless limit switches such as magnetic or optical devices, and they can be operated by signals of a central computer. So we can set many such limit switches on one axis of motion, and we can make a programme that different switches operate in each steps of a sequence.

One of the most convenient methods of continuous feed back system for positioning will be potentiometers. Usually two potentiometers are connected to make a bridge, and the difference of the outputs of two potentiometers is amplified and sent to driving unit of the arm. One potentiometer for feed back of position is, of course, fitted on the arm or the arm driving unit, and the other potentiometer for instruction of position must be fitted on the control board. One potentiometer can instruct one position of one axis. So there must be three potentiometers for one position. When an operation of a robot includes 10 steps, there must be 30 potentiometers on the control board.

Most developed and accurate system will be the numerical control system. In this system a pulse generator fitted on the arm makes pulse series according to the motion of the arm. The position is appointed by the number of pulses set in a counter, and the arm is stopped when the number of pulses feeded back from the pulse generator becomes equal to the set number in the counter.

### 3. 3. *Control System of An Industrial Robot*

There are two different systems in the control method of an industrial robot. One of them is an analogue system and the other is a digital system. The main device of an analogue control system is variable rheostats, *i. e.* potentiometers. The motor of the working end is driven by the amplified output of the bridge, which is constructed from the commanding potentiometer and the feeding back potentiometer, in order to decrease the unbalance of the bridge. So the driving force of the motor is nearly proportional to the difference between the two potentiometers. And then the velocity of the working end gradually decreases when it approaches to the ordered position, and it stops smoothly at the position. But, the accuracy of a potentiometer can not be so good, say 1% to 0.5%, that the positioning accuracy in a range of 1 m of stroke can be 10 to 5 mm as far as possible.

In a digital control system the main actor is a pulse transducer fitted on the moving unit and a pulse counter in the control box. The motor is driven by nearly constant power unless the content of the pulse counter is coincident to the destinated number of pulses. The most precise pulse transducer can generate 500 to 1000 pulses per revolution, and the accuracy of positioning with these pulse transducers can arrive to 0.01 mm theoretically. But there is another difficulty in such a whole digital control system. The driving force of the motor does not vary when the working end approaches the destination, the stopping point may differ from the destination by the inertia of the carring matter.

The memory of a sequence and positions is more convenient with digital signals than analogue signals. The most of modern industrial robots are controlled by a mini- or micro-computer, and the input or the output is digital. So the most suitable control system can be said to be a combination of digital and analogue systems. That is the digital memory and analogue driving system. In this combination system there must be a good A-D and D-A converters. Especially A-D converter which can treat analogue quantity with the accuracy of 1/10000, *i. e.* 14 to 15 bits of digital quantity, is one of the most difficult points for such a combination system. So we can say that the quality of control of an industrial robot in the near future will be decided by the quality of an A-D converter.

### *3. 4. Power Source*

As the power source electric motors, hydraulic motors and pneumatic motors can be used. Power control or torque control is the easiest in an electric motor. Especially a DC motor is easily controlled by the armature current. The demerit of an electric motor is low power or torque in proportion of its size and the maximum limit of torque is not so large in proportion of its normal torque. Sometimes in handling process the speed of an industrial robot is too slow and can not work instead of a human labor. The higher the accuracy, the slower is the speed. To increase working speed of handling the large starting torque is required.

A DC shunt motor can be easily controlled by the field current. But when the motor has to be accerelated the field current must be decreased. Decreased field current causes decrease of magnetic flux and the torque. So the better method to control DC shunt motor is by the supply voltage of armatur. Then a DC series motor is better than a DC shunt motor for a handling machine. Torque of a series motor is increased when the supplied DC voltage is increased for accerelation.

An AC induction motor is very cheap and very convenient but is not so good for control system. But recently many thyrister circuits to control induction motors have been developed. One of the most convenient method of speed control of induction motors is the thyrister-cycloconverter method. Cycloconverter can generate variable frequency directly converted from the commercial frequency.

Hydraulic motor is stronger than the other power systems and the unit is smaller than the other. Hydraulic cylinders can generate very strong power and very quick motion, and moreover can stop at arbitrary position without any brake unit. So the hydraulic system is very desirable for the robot, but the robot must have a compresser and a pressure tank. Sometimes noise of these equipment and leakage of oil in clean production lines can become new point of problem.

Pneumatic power source is very convenient and very clean. But by the pneumatic cylinder the positioning can be only at the end of the cylinder, so we must arrange another positioning devices for stopping in the midway of the cylinder.

## 4. PTP and CP Robot

### *4. 1. Point-to-point robot*

Point-to-point (PTP) robots are the most general machines in the process of handling and assembling. In the each step of a sequence co-ordinates of the three axes are remembered and the arm of the robot is ordered to move to position to position. The path and the velocity between the positions are decided by the differences of the co-ordinates. In the handling process the position is very important and such a PTP robot is very convenient. The other important point of such a PTP robot is that the teaching is very easy. And when any point in one sequence is not correct, reteaching or correction of this point (address) is also easy.

Universal type PTP robot has the merit such as: his hand can go to any point in the range of the movement and according to number of freedoms his fingers can be set in any direction, and moreover the programme can be very easily changeable. For example in the befornoon the robot is used for a handling work and in the afternoon he can work for press operation or another handling work. The kind of work is also easily changed by changing finger or gripper.

Another merit of an universal PTP robot is that it can do simultaneously two or more different works by sitting between two different production lines.

### *4. 2. Coutinuous Path Robot*

For spray painting, for example, PTP robots can not work so satisfactory. There must be a memory of spraying path and the speed of motion, and of course the motion of the robot must be along the path. Then there must be a continuous path type control. In this type of control the motion of the arm must be continuously remembered in a magnetic tape and the positioning must be done by potentiometers. It is an analogue control method and then the accuracy of positioning is not so good, but in spray painting very high accuracy of positioning is not required.

The most difficult point of the CP type robot is difficulty of teaching. And whether the taught programme is good or not can be decided only by actual spray painting work with the taught memory tape. If the teacher hesitates during the teaching, all the process are remembered and in the actual spraying the robot will hesitate at the same point. And when the taught programme is not correct at any point, the correction of this point is impossible. So the teacher must be very skillful labor on robot teaching. Robots should be used for labor saving or saving of skillful labor, the CP robot requires another skillful labor.

### *4. 3. Co-Ordinates*

There are two fundamental co-ordinate systems for an industrial robot. They

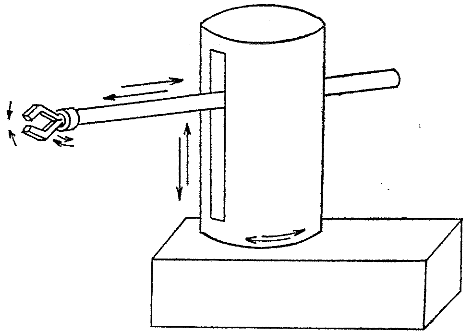


Fig. 3. Cylindrical co-ordinates

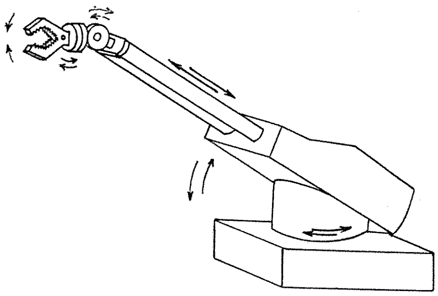


Fig. 4. Spherical co-ordinates

are cylindrical co-ordinates and spherical co-ordinates. In the case of cylindrical co-ordinates the arm can move horizontally in and out. This is one merit of this system. In production lines there are many horizontal straight moving such as push in or pull out a pin or block from or into some construction. In this case spherical co-ordinates are rather unadequate so far as the positioning is point-to-point system. But in the case of cylindrical co-ordinates there must be a strong vertical construction to guide the arm movement of upward and downward.

In the case of spherical co-ordinates the driving motors and driving systems of main three axes are gathered in the fundamental base of the body, so the construction of the body is rather easier than the cylindrical co-ordinates.

### *4. 4. Number of Freedoms*

For positioning there must be three fundamental freedoms, *i. e.* X, Y and Z irrespective of type of co-ordinates, cylindrical or spherical. But for handling matters there must be the other several freedoms, which are grasping motion, rotation of fingers and inclination of hand or gripper. Six freedoms seem to be sufficient for an ordinary industrial robot, but in general we can say the robot will be better to have one or two more freedoms than the necessary minimum number of freedoms. The excess number of freedoms can simplify the programme of some complicated handling work.

Let us consider the case that an industrial robot engages in such a work, that a metal rod must be inserted in a metal hole as shown in Fig. 5. In this case the hand of the robot grasping the rod must move horizontally straight to the left or right. Only by the cylindrical co-ordinates it is impossible. The robot must come to the correct front position of the hole, and the wrist of the robot must rotate 90 degrees. In the case of Fig. 5 the robot rotates to the right and the wrist of the robot must be held in same direction.

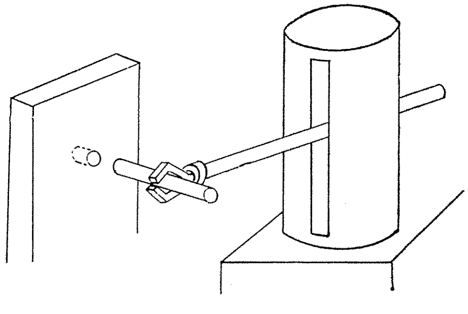


Fig. 5. A rod is inserted into a hole by a robot.

Generally the hand of robots must have at least three freedoms in addition to the motion of grasping and open. Namely, rotation arround the arm axis, lateral moving and bending of the wrist. The more the freedoms, the more simple is the programme in complicated handling works.

The least necessary number of freedoms is 6, they are the fundamental 3, X Y Z, and excess 3, movement of hand or fingers. But generally 7 to 8 freedoms are hoped to simplify the programme.

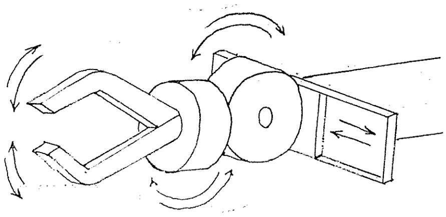


Fig. 6. Freedoms of a hand

## 5. Fundamental Construction of a Digital Robot

### 5. 1. *Simplest Model of a Digital Robot*

Construction of the simplest and the most fundamental robot with a digital control system is shown in Fig. 7. In this figure only one axis is shown. Of course a robot has at least 3 axes of freedoms of motion and other 3 or 4 freedoms in the motion of the fingers.

The control center corresponding to the brain in Fig. 1 includes a preset counter, ring counter (address counter), grasping and rotation command signal generators. Input of the programme is given in a control board shown in Fig. 8. Driving system consists of a servo-amplifier, a hydraulic servo-motor with an electric servo-valve, a brake actuator and a magnetic brake. Feed back system includes a pulse transducer, generating 10 pulses per 1 mm of the stroke, and the pulses are sent to the preset counter.

In the preset counter there are adequate number of preset counter circuits according to the number of steps of handling work. In the case of the number of steps is 10, 10 counter circuits are set. These counter circuits are preset according to the stroke differences of each steps by a pin-board or mechanical counters. In the preset counter there are two output terminals, one is "zero" terminal which produces a pulse when the content of the preset counter becomes zero, and the other is "sub-zero" terminal which produces a pulse when the content of the preset counter decreases and becomes equal to a settled number, between 200 and 500. The output of the "sub-zero" terminal is used for retardation of speed when the arm approaches its destination.

Power source is a hydraulic servo-motor which is controlled by an electric servo-valve, and the speed of the arm in one axis is variable between 0 and 500 mm/sec., corresponding to the input voltage of the servo-amplifier between 0 and 5 V (positive or negative). This input voltage to control the speed in each steps of motion is set by dials in the control board.

Method of operation of this robot is as follows. At first an operator sets the dials or mechanical counters of each steps of motion and the speed between every step. Grasping or opening motions and/or rotation of the gripper are also ordered on the control board.

Then the operator pushes the button of "automatic operation" after pushing the

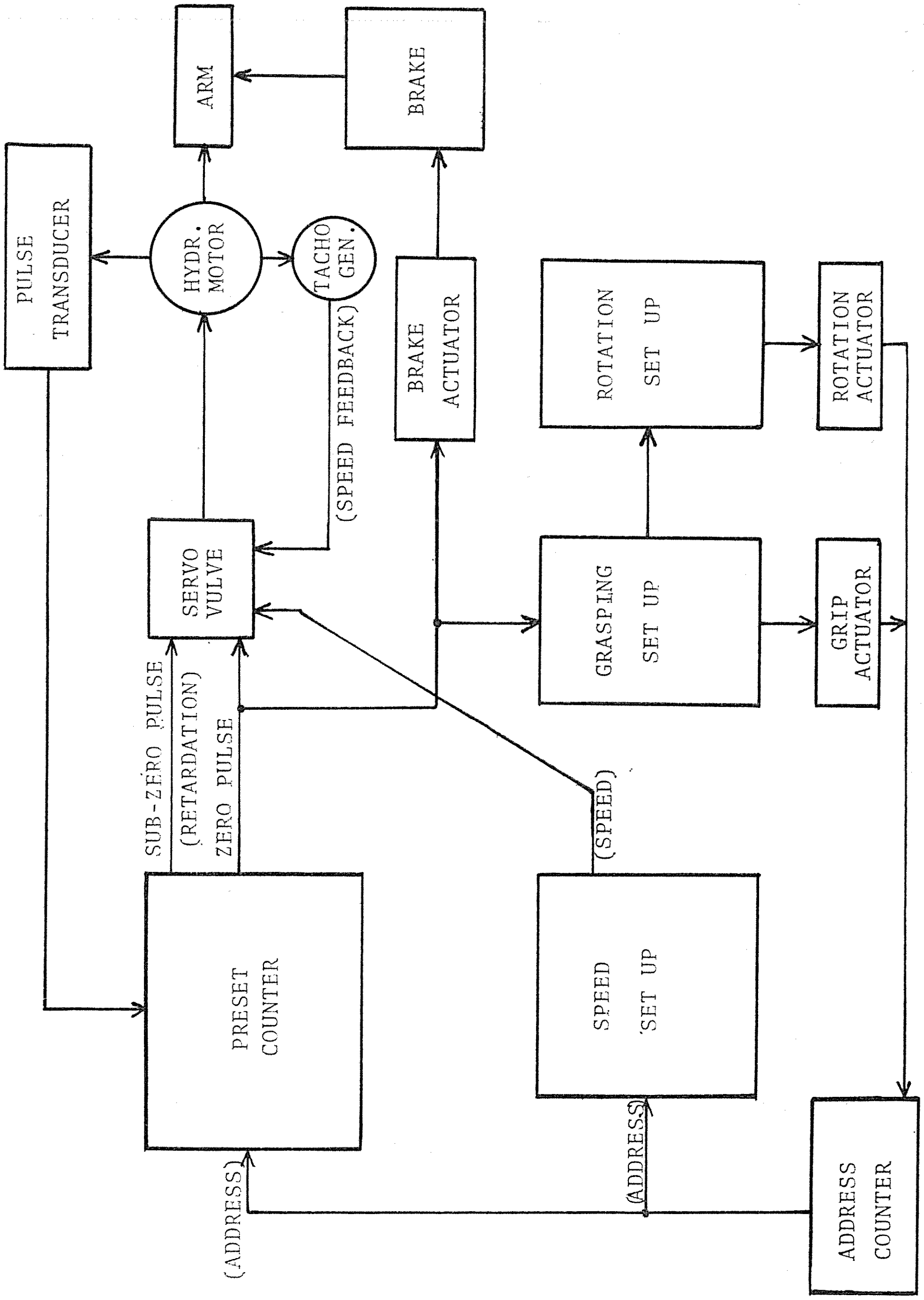


Fig. 7. Simplest digital robot. (only one axis is shown)

"reset button". Then the hand of the robot starts to move and goes to the first ordered position.

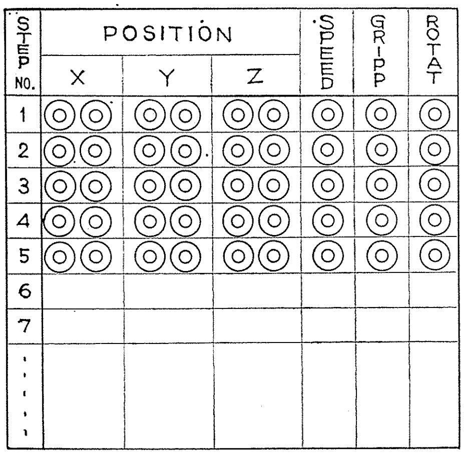


Fig. 8. Control board of a robot shown in Fig. 7.

In this model the electronic circuits are rather simple and the teaching operation is very clear. Here, a skillful operator is not necessary.

The pulse transducer sends pulses to the preset counter, and when the difference between the sent pulses and the preset number becomes equal to the "sub-zero" number, the preset counter generates a pulse which is sent to the servo-valve and used for retardation signal. When the difference becomes equal to zero the preset counter generates a brake signal. Then after the motion of grasping or opening of the fingers and rotation of the gripper the address counter (ring counter) changes the preset counter circuit to the next one. Then the arm starts to go to the next point.

### *5. 2. Retardation Circuit*

There is one problem in the retardation process. Let us consider the retardation process when the "sub-zero" number is set at 400 pulses, for example. The retardation circuit has a C-R circuit which produces a relaxation curve of invariable time constant when the "sub-zero" pulse comes here. According to the speed of handling motion this time constant may be in the range of 0.1 to 1 sec., and then the C-R circuit consists of the capacity of the order of 1 $\mu F$ and the resistance of

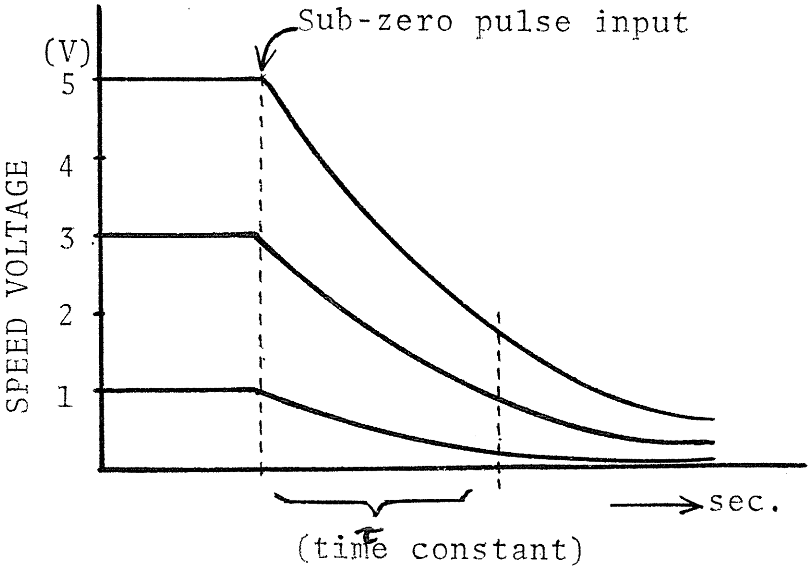


Fig. 9. Retardation curves against time abscissa.

the order of $1\,M\Omega$. 400 pulses mean 40 mm of the stroke, and the speed before "sub-zero" pulse is settled in the control dial. In Fig. 9 retardation curves against time abscissa in the case of 5, 3 and 1 volts of the initial speed (nearly corresponds to 500, 300 and 100 mm/sec.). Since three curves have same time constant, the time interval that the speed of the arm sufficiently decreases so far as it can be stopped smoothly by the brake is nearly same. Fig. 10 shows the same curves against the abscissa of length. When the initial speed corresponds to 5 V, the necessary time to transit 40 mm is so short that the speed at the braking point is yet very fast and the arm must be suddenly stopped. This causes increasing of positioning error. In the contrary, when the initial speed corresponds to 1 V, the necessary time to transit 40 mm is so longer than the time constant of C-R circuit that the speed of the arm before the destination is very slow. This causes elongation of working time in spite of the high positioning accuracy. When the initial speed is moderate (3 V for example) the arm stops very smoothly and the accuracy is also high.

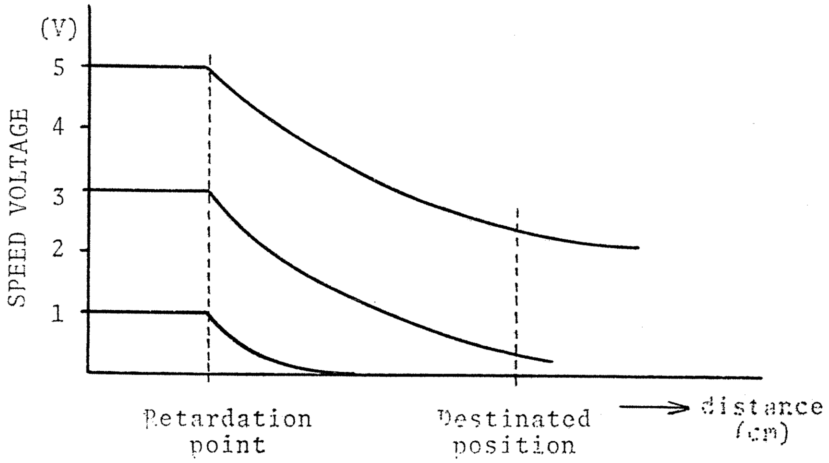


Fig. 10. Retardation curves against length abscissa.

We have developed a new circuit to improve the above mentioned difficulties. This circuit can generate a retardation voltage curve of variable time constant which is decided by the initial voltage before the "sub-zero" pulse. The block diagram of this circuit is shown in Fig. 11, and the whole circuit is shown in Fig. 12. The input voltage, between $-5\,V$ and $+5\,V$, goes into the sign discrimination circuit at first and it is changed to a positive same voltage when the input is negative. Positive voltage from 0 to 5 V is divided into five steps, 0—0. 6, 0. 7—1. 1, 1. 2—2. 0, 2. 1—3. 0 and 3. 1—5. 0 V. The relaxation circuit has one condenser of $2\,\mu F$ and five different discharge resistances, they are 38, 70, 150, 350 and 900 $k\Omega$, which are selected automatically by the input voltage. Then the time constant is selected automatically in five values, *i. e.* 0. 076, 0. 14, 0. 30, 0. 70 and 1.80 sec. The absolute value of the input voltage is sent to a height discrimination circuit and the output of this circuit commands the connection of necessary discharge resistance to the condenser. Adequately selected C-R circuit generates a necessary relaxation curve

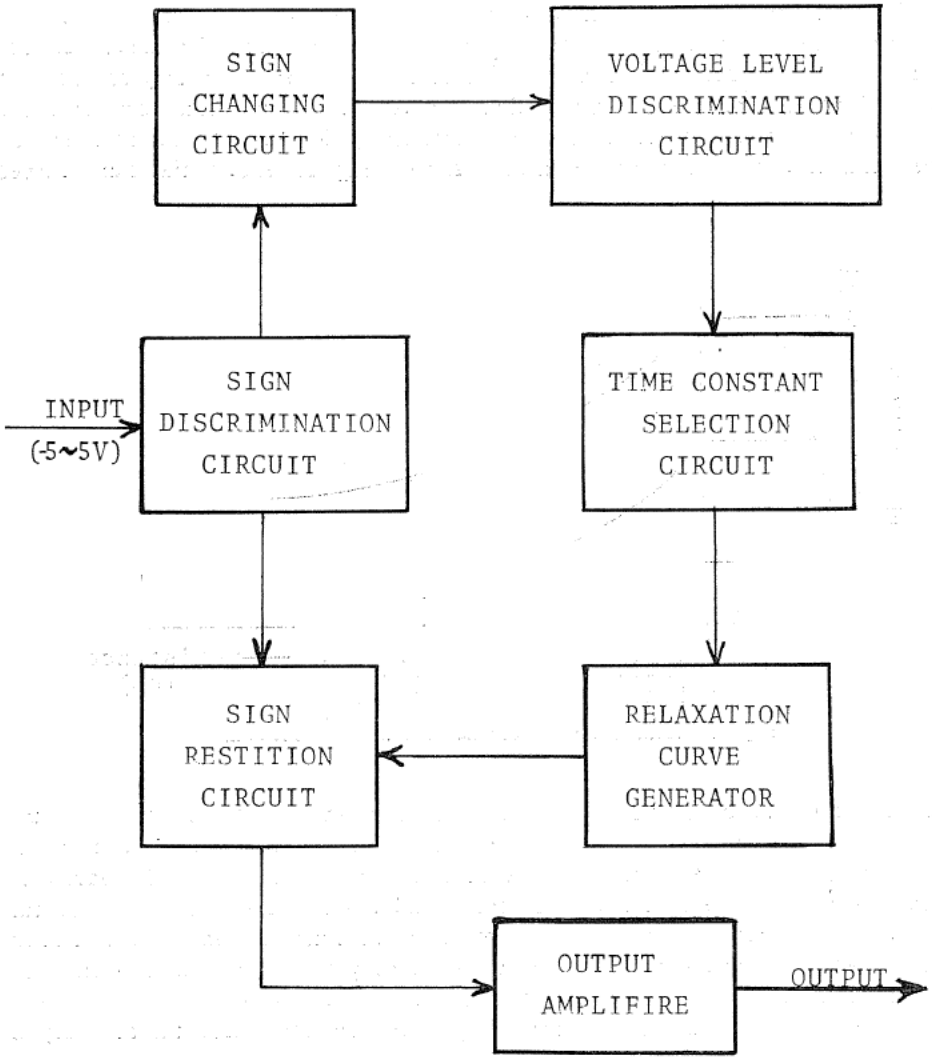


Fig. 11. Block diagram of variable time constant retardation curve generator.

when the "sub-zero" pulse comes here. Here generated relaxation curve is of course positive sign and it must be changed to negative sign if the initial input voltage has been negative. The output amplifier is controlled by the output of the sign discrimination circuit and the last output is sent to the servo-valve with the same sign of the initial voltage of speed. In Fig. 12 there is some complicated circuit made of diodes at the first gate of the input. This is a compensation circuit for the voltage drop in transistors. The input voltage varies from $-5$ V to $+5$ V continuously, so the base-emitter potential drop of the order of 0.6V makes unsensible region. With the compensation circuit this new retardation circuit has no unsensible region between $-5$ V and $+5$ V. Fig. 13 shows the experimental results of the new retardation circuit. Since this is shown in time abscissa the end points of each

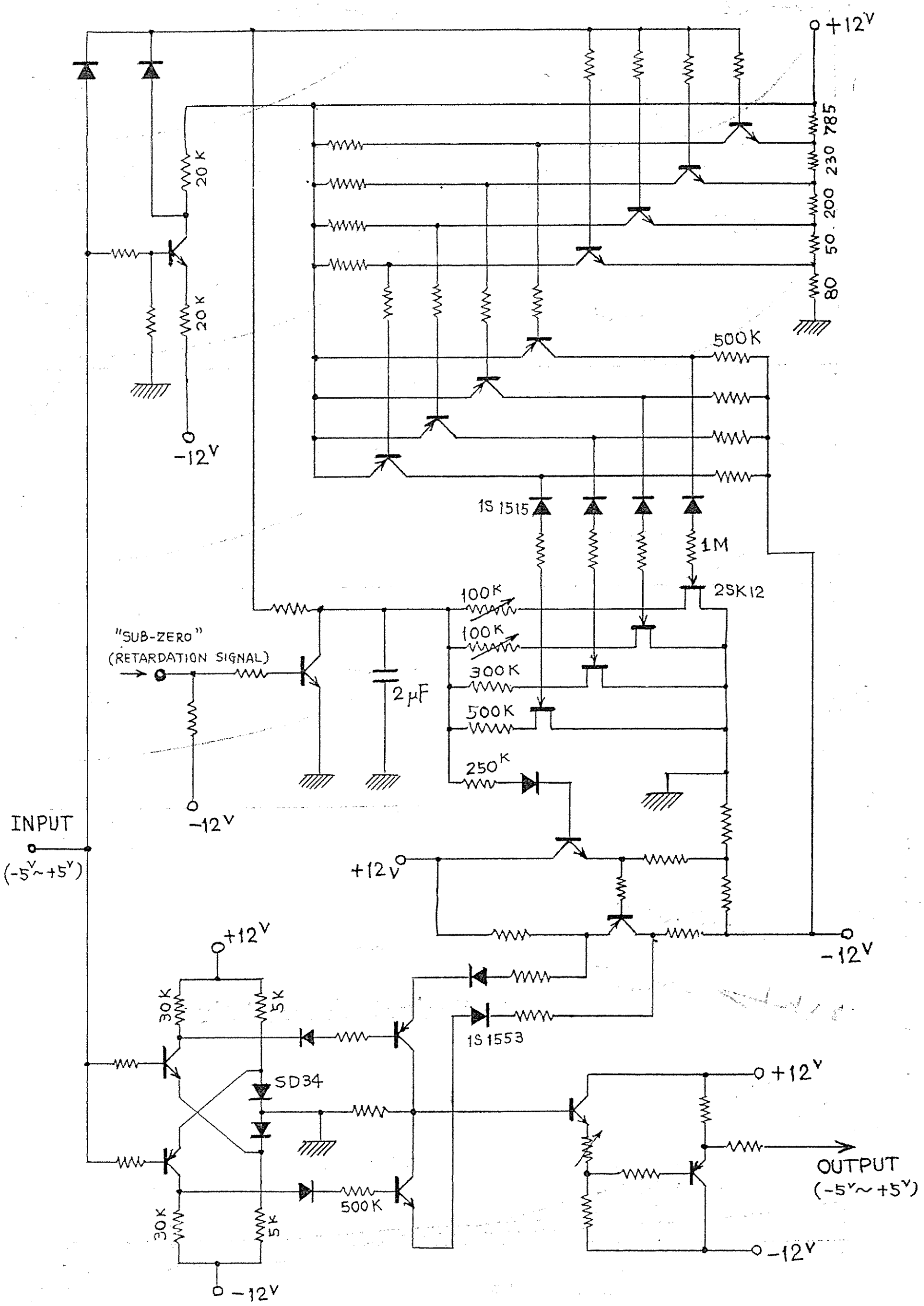


Fig. 12. New retardation circuit.

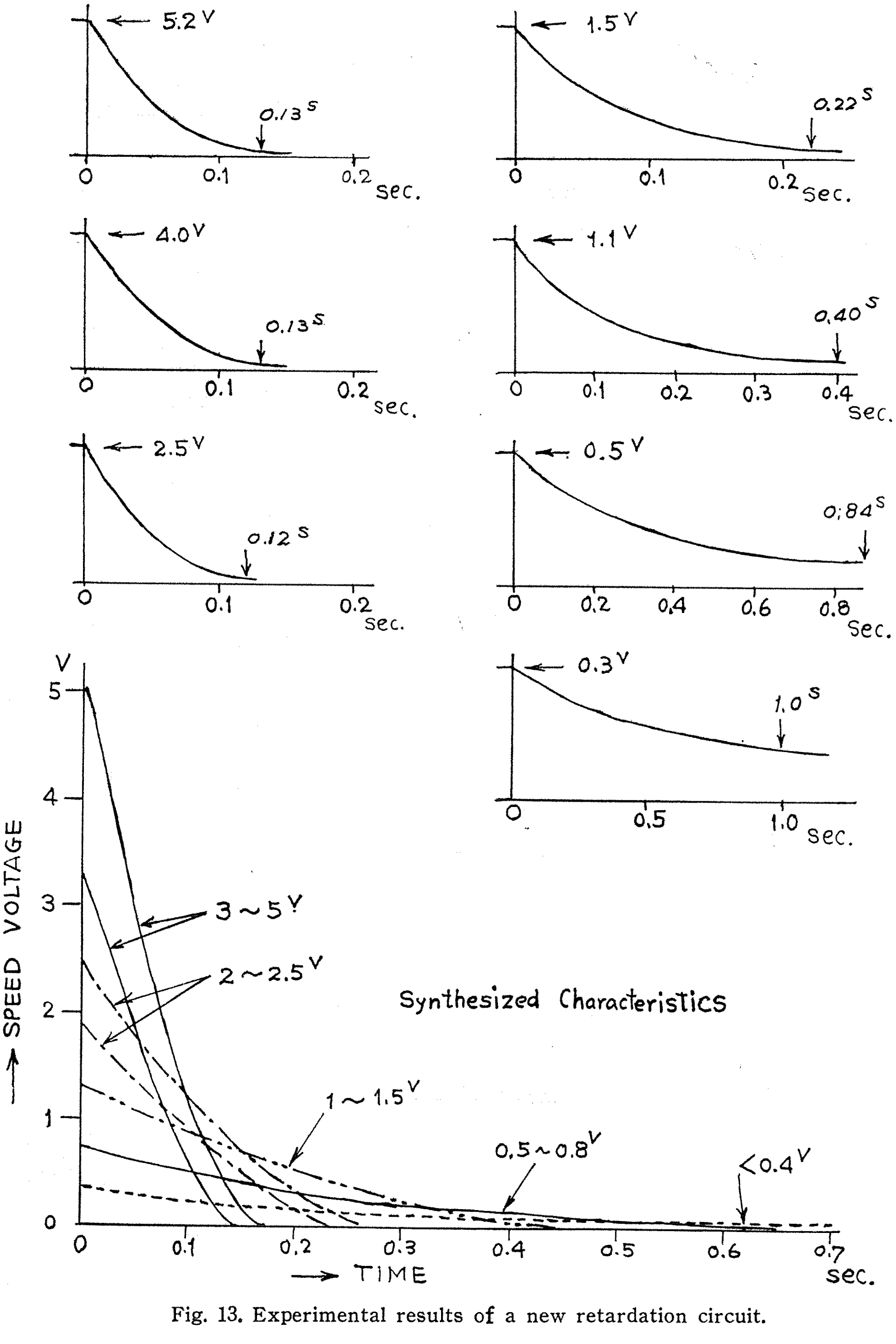


Fig. 13. Experimental results of a new retardation circuit.

curves are very different each other, but if they are shown in the abscissa of length the end points of each curves are very near to the destination. The practical experiment of a robot with this retardation circuit showed very good results, its arm stopped very smoothly and the positioning accuracy was very high — the error was smaller than 0.3 mm.

### *5. 3. Higher Class Robot System with a Memory Drum*

The industrial robot which is controlled by a pin board, dial counters or an electronic preset counter can do only 10 to 20 steps of motion. There is a stepping programmer, or called sequence drum, shown in Fig. 14. A cylindrical drum divided into four domains, each corresponds to X, Y, Z and U axes, has 30 to 40 slots corresponding to steps of motion. X, Y and Z are used for three fundamental freedoms and U axis is used for the other excess freedoms. This cylinder rotates step by step, and small plugs inlaid in the slots make contacts of small relays installed near the cylinder. The small plugs can be moved along the slots manually. Since the small relays are connected to each potentiometers, the positions of the small plugs indicate destinating positions of the steps. This equipment is one of the most convenient memory equipments, for the size is not so big and the capacity is large in proportion of size. The merit of such a equipment is entirely mechanical and the contents of memories can not be broken by electric noises or mistreatments. But the maximum capacity of memories will be 40, and can not be increased to several hundred or thousand.

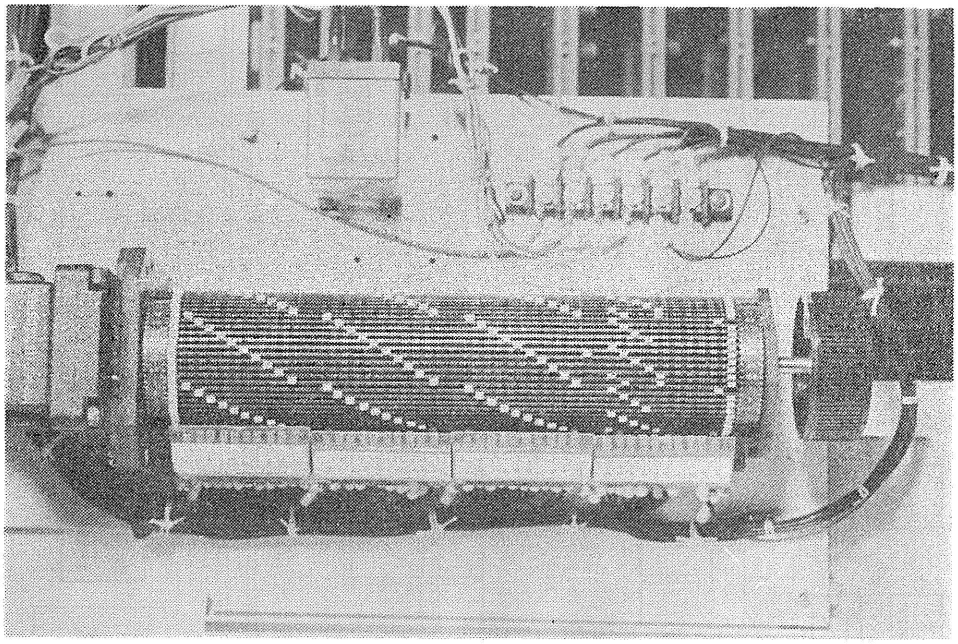


Fig. 14. Stepping programmer.

One of the highest memory capacity can be available by a magnetic memory drum. A small magnetic drum suitable to industrial robots has the capacity of $10^5$

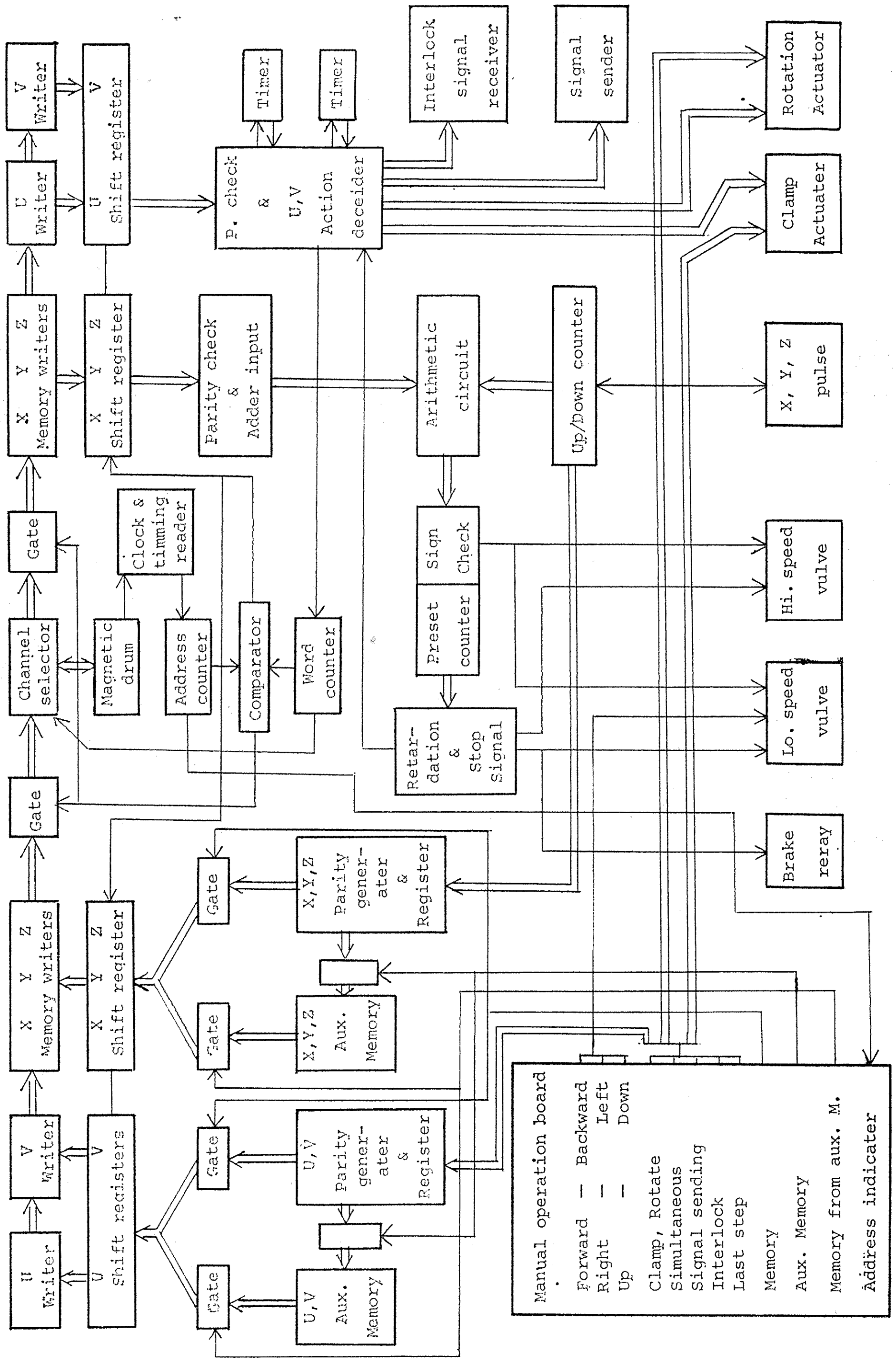


Fig. 15. Block diagram of a robot with a magnetic memory drum.

bits in 30 trucks. If we use 16 bits for one word or one numerical cord, 64 bits are used for one address (step of motion) using 4 axes. Then we can have 1500 addresses, *i. e.* 1500 different positions. Fig. 15 shows the block diagramme of such a high class industrial robot which was designed in our laboratory. The stroke of the arm is 1000 mm in X (forward) and Z (upward) axes, and 360 deg. in Y axis. This robot is whole digitally controlled and in each axes pulse transducers are fitted, generating 10,000 pulses in each full stroke. This means in X and Z axes 10 pulses per 1 mm, and in Y axis nearly 30 pulses per $1^0$. Number of pulses up to 10,000 can be written by 14 bits in binary cord, and excess one bit is used for parity check. In U axis commands of grasping motion of the gripper, rotation of the gripper and simultaneous motion of the arm and the gripper rotation are written. V axis is used for some interlock signals between this robot and the other machines at which the handled object is loaded or unloaded. Commands written in U and V axes are written in 3 to 5 bits binary cords. So every five axis uses 16 bits and one address uses 80 bits.

Power source is a hydraulic system and each axes have two speed hydraulic motors. The gripper is also driven by hydraulic power and can handle up to 15 kg. The maximum speed of Z and X axes is 750 mm/sec.

At first this robot is taught the programme by manual control. During manually driven, the pulse transducer (in Z axis for example) sends pulses to a binary counter with the sign of upward (add) or downward (substract). At any position if the teacher pushes the memory button after the commands of grasping, rotation and/or interlock, the contents of the binary counter and the automatically added parity check cord are sent to a writing amplifier and are written in the first address in the magnetic memory drum. Of course the cords of the U and V axes commands are written simultaneously.

Then the teacher repeats the same treatment at the next position, the address counter is added by 1, and the position and U or V axis motion are written in the next address in the drum. Such teaching process can be done up to 1250 different positions. At the last step of the programme the teacher must push the "last" button, by this cord the robot stops or returns to the first step.

After all programme has been taught, the robot can do automatic running by the button of "auto". The reading amplifier reads the contents of the first address in the magnetic drum and sends the numerical cords corresponding to the first destinated position to the arithmetic circuit. In the arithmetic circuit the difference between the destinated and the present position is calculated, and the result is sent to a preset counter and a sign discrimination circuit. Then the direction of motion is decided and the hydraulic motor starts in higher speed until the output of the arithmetic circuit becomes less than the previously set quantity. The preset counter gives a retardation signal and stop signal according to the output of the arithmetic circuit. After the arm stops at the destinated position the cords in U and V axes are sent to each actuators of auxiliary motion. When the motion in the first address ends, the addsess counter is added by 1 and then the reading amplifier reads the next address. The same processes are repeated until the "last" cord is read.

The merit of the here explained type robot is the simplicity of teaching. The robot controlled by a preset counter, mentioned in the previous section, must be taught by a dial counter of each axis. Therefore, the operator must measure the given position in a space with the length of each axis. This operation can not be precisely done for a freely given point. But in this robot the operator may not know the co-ordinates or distance up to the appointed position, he may lead the arm by manual control button to the point.

### *5. 4. Excellence of Our Robot*

The distinctive points of this robot, which was designed in our laboratory, are sub-memory circuit and the address indicater. The sub-memory circuit consists of electronic logic circuits (flip-flop) and can hold memories of one position and UV axes cords at this position during the whole teaching process. This can be used for the case of the same position is commanded many times in one programme. For example, many number of objects are packed in a box which is carried next by next after the all objects in a box are removed. When we use a robot let to pick up these objects from the box and put on the a fixed position of a belt conveyer, we must teach alternatively many different positions in the box and the fixed position on the conveyer. In the ordinary robot without the sub-memory circuit we must teach the same fixed position many times. In this robot there is the sub-memory circuit and we can store the fixed position on the conveyer in the sub-memory circuit, then we can transmit the contents of the sub-memory circuit to the magnetic memory drum by a "memory from sub-memory" button. So we can teach whole programme with the different positions in the box and only with a button of "memory from sub-memory". Of course a simplification of such a programme can be made by a improvement of the address counter. Namely, the cord of the fixed position is stored in a special address, and the address counter can be made to command the address that the robot must read. In this system the capacity of the magnetic drum can be used for more steps than our system, but the construction of address counter becomes a little complicated.

Another new point of our robot is the address indicater. This indicates the address number during the manual driving and the automatic running. Still more we can call out a desired address by manually setting of address number. This can be used in the case of correction of one position in a long programme. If there is no such system, when one position in a long programme must be corrected we must begin the automatic running from the first address until the address reaches to the desired step. In our robot the correction of any address is very fast and easy, *i. e.*, we set the desired number of address and manually operate the robot to the correct position and then push the memory button, the content of this address is corrected.

## 6. Sensors for an Industrial Robot

In section 3 we explained several kind of feed back systems. The mechanical stoppers, limit switches and pulse transducers are sensors for feeding back the position of the arm. But these sensors are fitted for the purpose of detection whether the position of the arm is correctly equal or not equal to the taught (appointed) position. These sensors can not judge whether the previously taught position is the most adequate position or not. Even if the position is correctly equal to the taught position, whether the object exists there or not can not be known. We hope to explain here on the sensing method of judging.

### *6. 1. Necessitive Sensors for an Industrial Robot*

Industrial robot such as explained in the previous section the accuracy of the positioning or repeating accuracy can be reached 0.1 mm theoretically in the electronic circuit. And these robots can do any desired sequence as taught by an operator. The sequence can be easily changed every month, every week or every day. And the accuracy and ability are superior to the human labor. So such a robot seems to be excellent machine for labor saving. Labor saving is one of the most important problem in the modern production line and in the near future it will be greater and greater importance. Especially human labors have to be removed from hazardous or unfavourable environments, such as high temperature molten metal work or handling of radioactive materials or poisonous materials.

The robots introduced in the market now are unable to be in place of human labor, for they can not make decision affecting their performance. For example, an industrial robot transferring manufactured objects to some position cannot judge whether the objects remain or not, and whether they are placed in the correct position or not.

In the modern industries the production works are divided into three fields, *i. e.* making, assembling and handling, as mentioned in the introduction. Making is automated in very wide range now, but assembling and handling are very difficult to be automated. The reason for this is that assembling and handling, especially assembling, need very fine sensing ability of human labors.

The industrial robot in the near future must be used more in the field of assembling than in making. Therefore the robots in the near future must have some artificial sensing ability so that they may be used satisfactory in various application.

For artificial sensors the visual and tactile sensors may be considered. Of course another types of sensor — magnetic, fluidic or sonic sensors — can be used, but a visual sensor will be excellent one and a tactile sensor will be the simplest and cheapest one. So we developed at first some kinds of tactile sensors. With the tactile sensors installation and treatment are comparatively easy.

### *6. 2. Touch Sensor*

Industrial robots in the market have hands made of metal which are driven by hydraulic or pneumatic motors. Most of their hands are controlled by on-off valves or switches. So the fingers can be opened or closed. If there are sensors which can know the moment the finger touches the object the hand can be stopped when the finger touches the object, then the hand of an industrial robot, even if it is made of metal, can grasp weak and fragile objects without crashing.

As a touch sensor a pressure sensing semi-conductor can be used. Fig. 16 shows this device.

### *6. 3. Detection of Slippage*

Fingers of the most industrial robots are made of metal and the grasping force is given by pneumatic or hydraulic equipment, so they can grasp metal works but cannot grasp a fragile object such as a paper box or a egg. Let us consider on picking up and transferring various objects by a same artificial fingers. It is very difficult to design an industrial robot capable to grasp both hard, heavy objects and fragile objects. The hand made of soft material required for grasping a paper box fails properly to grasp hard and heavy metal objects. However, it will be not

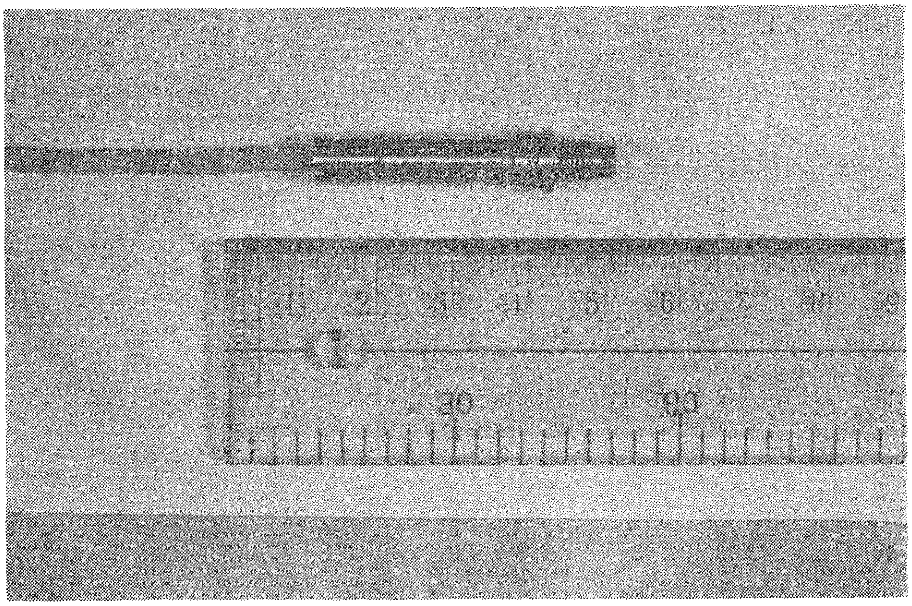


Fig. 16. Semi-conductor pressure sensor.

hopeless that we let a robot finger made of metal to grasp all objects of various materials, from iron to paper.

Human fingers can know the moment of touching on the object and simultaneously know hardness of the object, and when the fingers hold up the object in very little height they know the weight and they can grasp it in necessary force. This can be done by the ability of the fine sensation of slippage. Human fingers can detect the moment at which an object begins to slip skillfully. If we give a robot an ability of sensation of slippage the robot will be able to grasp an object with the least and necessary force whenever the object is hard and heavy or soft and light. Since it is impossible to detect the moment just before the grasped object begins to slip, let us consider the moment just after it begins to slip. At this moment relative displacement is produced between an object and the fingers. If this displacement can be detected and the grasping force can be augmented to stop slippage as quickly as possible, an object may be grasped with a necessary minimum force. The programme of the above mentioned method is shown in Fig. 17.

### *6. 4. Tactile Slip Sensor*

(1) Piezo-electric device

This is same to the detection of a surface roughness of the object as an oscillation and its principle is analogous to that of a record player. Our experimental device is shown in Fig. 18, and is made of rochelle salt crystal supported by a rubber damper which eliminates noise during operation and a sapphire needle attached to the point detects surface roughness on the object. Fig. 19 shows the prototype device which is made of a crystal type receiver obtainable in the market. Fig. 20 shows a example of the oscillographs produced when the grasped object

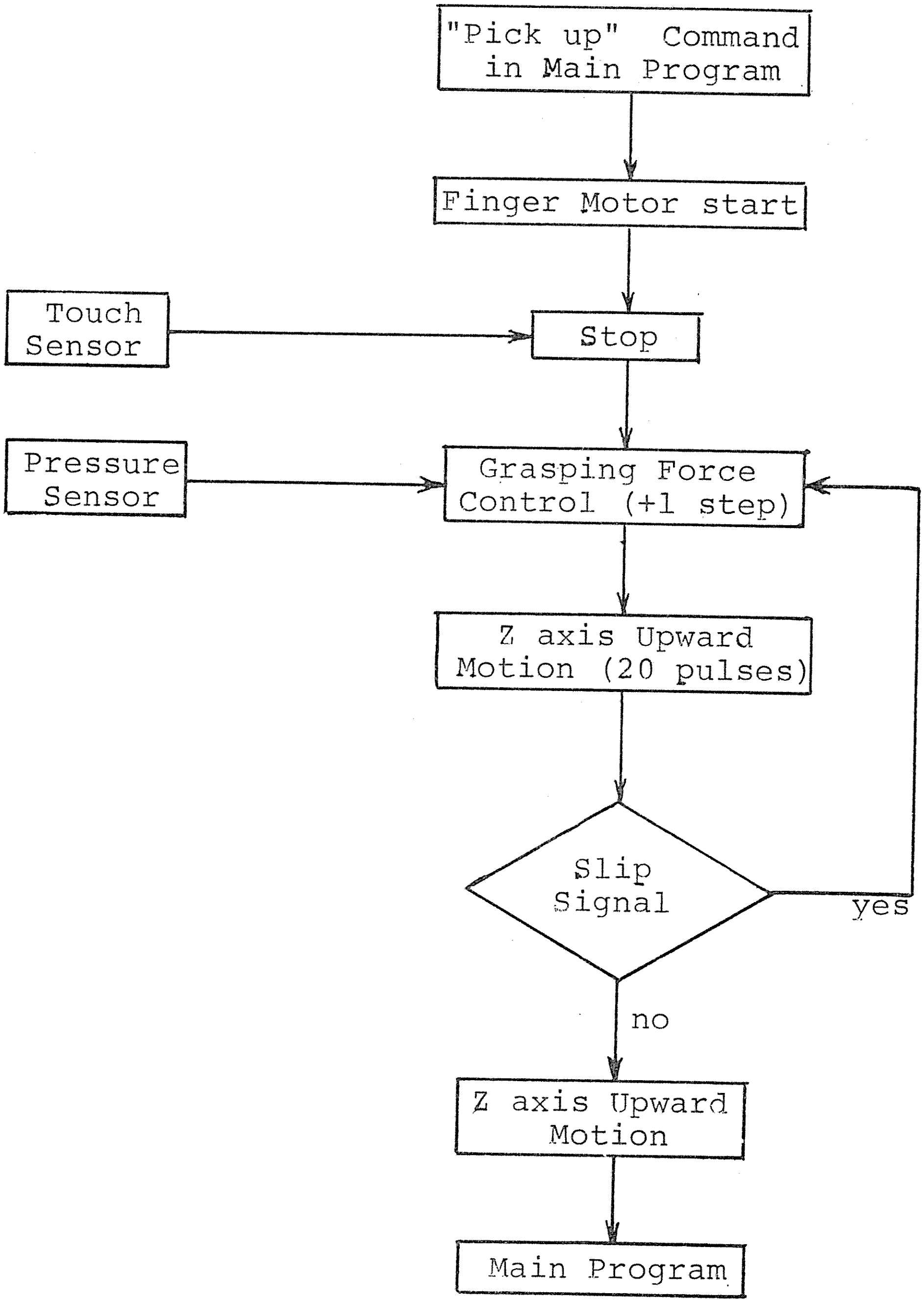


Fig. 17. Program of "Pick up" motion.

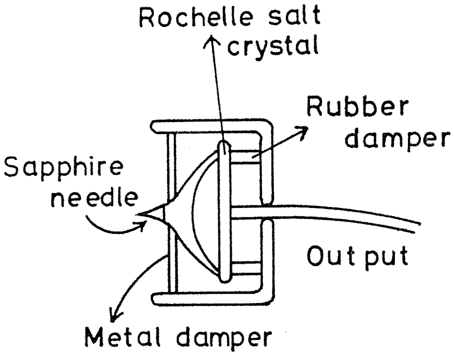


Fig. 18. An outline of a slip detection device using a crystal receiver.

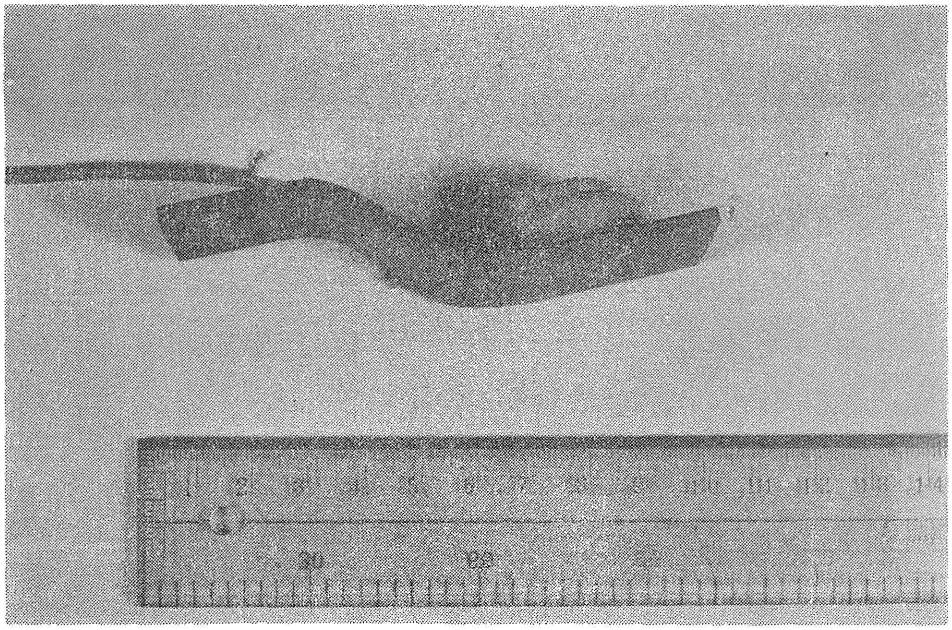
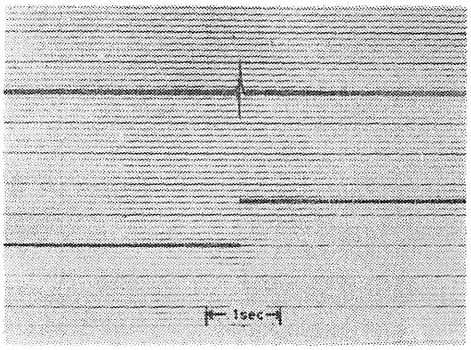


Fig. 19. Hand with a crystal slip sensor

Fig. 20. Oscillograph of output of crystal slip sensor.
Uupper trace: output voltage of the device shown in FIG 19.
Lower trace: output voltage of flip-flop triggered by a slip signal.



begins to slip.

It is apparent from the figures that the slip sensitivity of this device is very good and the slip signal can be distinctly distinguished from noises. Therefore, it seems that the device are ready for practical application. Since the non wave-shaped slip signal waveforms are dependent on the surface roughness of a object and the sharpness of the needle attached to the point. One application of these devices may be the surface inspection of manufactured matters.

(2) Electromagnetic device

This is shown in Fig. 21. In substitution of a sapphire needle of the piezo-electric device a steel ball of 0.5 mm diameter and the main part of the device is in an oil room to augment strength and to eliminate noises. Fig. 22 shows the photograph of the finger with such a electromagnetic device in our laboratory. Fig. 23 shows a sample oscillogram showing when a grasped object begins to slip.

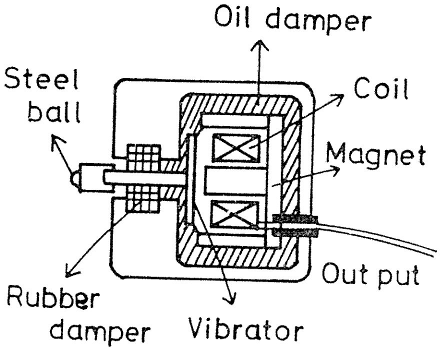


Fig. 21. An outline of a slip detection device using an electro-magnetic receiver.

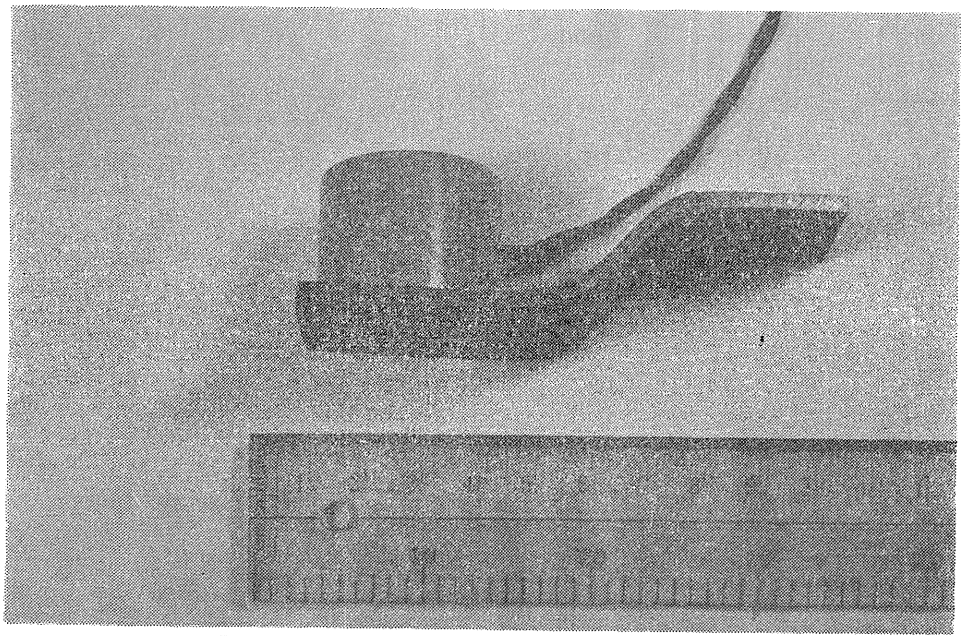


Fig. 22. Finger with a elctromagnetic slip sensor.

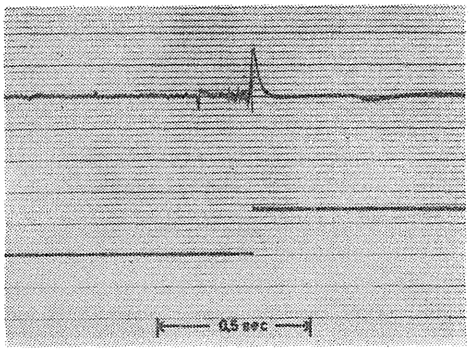


Fig. 23. Output of a electromagnetic slip sensor.
Upper trace : output voltage of the device shown in FIG. 21.
Lower trace : output voltage of flip-flop triggered by a slip signal.

(3) Roller type devices

This method is the detection of a rolling displacement by a roller covered by an elastic body with a large coefficient of friction so that it rolls with the object. Various A-D converter in the market may be applied to this method. For example, Fig. 24 illustrates the use of a magnetic type A-D converter and Fig. 25 demonstrates a photo-electric type A-D converter. These methods have the advantage of being able to detect a slip signal without afraid of mis-touching the object, however, the disadvantage are that only one direction of a slip can be detected and the size of the device is larger than the piezo-electric device.

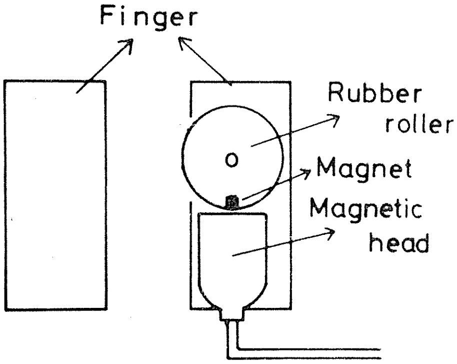


Fig. 24. Roller type slip detection device using a magnetic A-D converter.

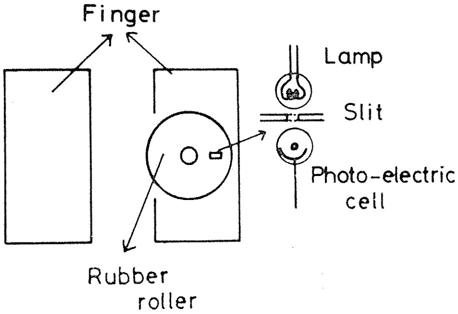


Fig. 25. Roller type slip detection device using a photo-electric A-D converter.

(4) Another sensors

Pressure sensor is also can be used to detect a slip of an object. In Fig. 26 there is a pressure sensor (semi-conductor) and a needle put in the elastic body (silicone rubber). The needle makes a change of pressure at the slip and causes a vibration of pressure sensor output larger than the operational noise.

The oscillogram in Fig. 27 shows the resulting slip signal wave-form and the flip-flop triggered output voltage when the arm is controlled to move up and down with the device in Fig. 26. Obviously a slip signal is clearly distinguished from noises.

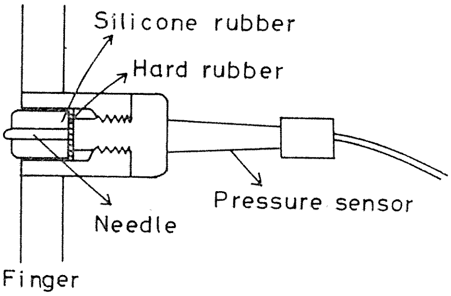


Fig. 26. Pressure sensor and a needle.

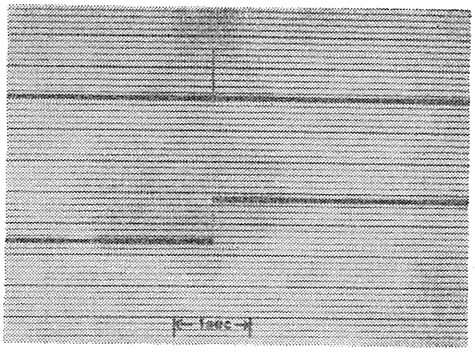


Fig. 27. Slip signal wave form.
Upper trace: output voltage of the device shown in FIG. 26.
Lower trace: output voltage of flip-flop triggered by a slip signal.

## 7. Grasping Force Control

### 7. 1. *Steps of Grasping Force*

The fingers of a robot in our laboratory, force of which must be controlled, is driven by a separate excited DC motor and the grasping force is controlled by the armature current.

In this experiment the armature current of the motor is controlled in seven steps corresponding to seven steps of grasping force as shown in Fig. 28. Seven comparators are corresponding to the grasping force levels and threshold values are set at a higher level than noise at each grasping force levels. When the output of a pressure sensor is higher than a particular threshold

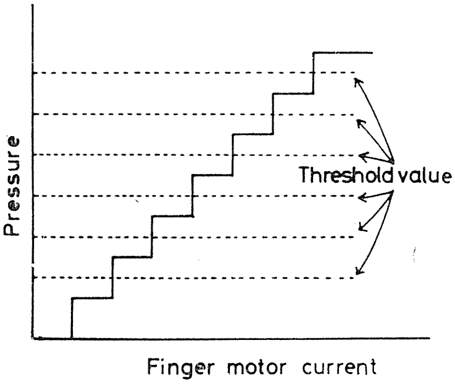


Fig. 28. Seven steps of grasping force.

value, the grasping force is increased one step by the motor. The block diagram of the force control is shown in Fig. 29.

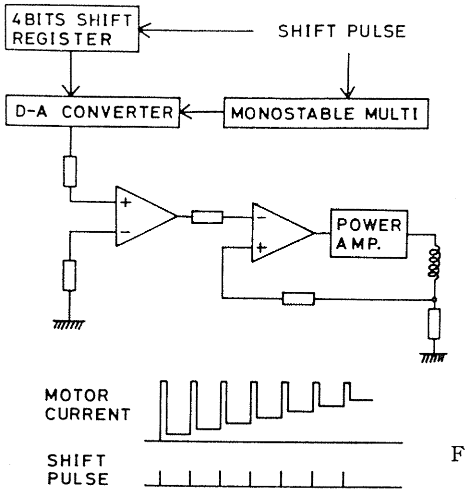


Fig. 29. Block diagram of grasping force control.

## 7. 2. *Experimental Result of Force Control*

Fig. 30 shows the experimental results of force control by the electromagnetic type sensor. It is clear in the figure that the finger motor (lower trace) is controlled by the slip signal (upper trace) and an object is grasped with the

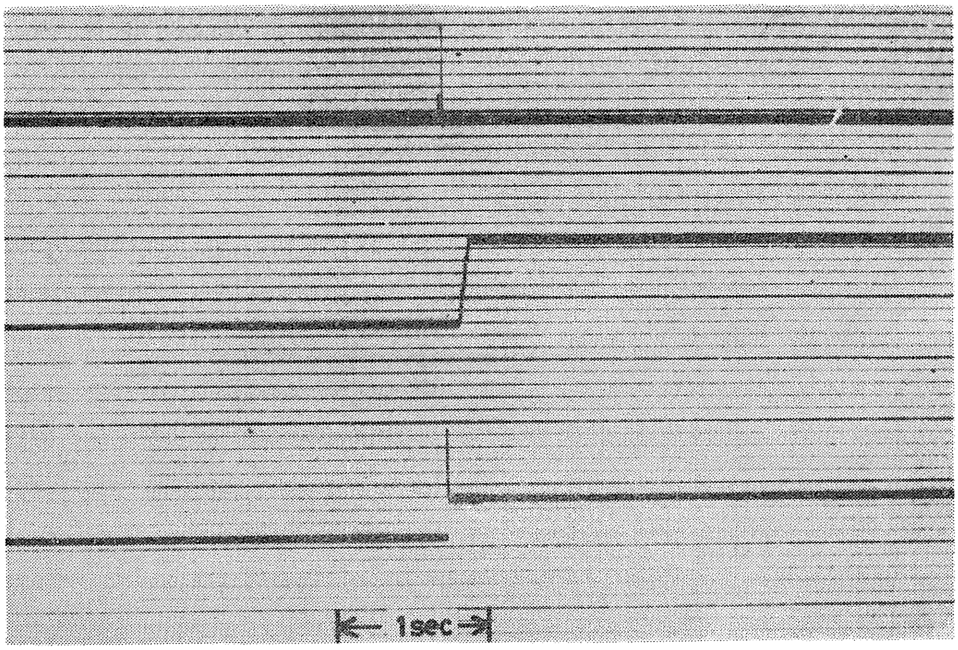


Fig. 30. Experimental results of grasping force control with a electromagnetic sensor.
Upper trace : output voltage of the device shown in FIG. 21.
Middle trace : output voltage of pressure sensor.
Lower trace : finger motor voltage.

necessary minimum grasping force (midtrace). Fig. 31 shows the experimental results of using the pressure sensor and a roller type slip detection device which was conducted with the same requirement as the above. It is apparent from the figure that the finger motor is controlled to argument the grasping force by one step when the output voltage of the pressure sensor (upper trace) is above the threshold value shown by the dotted line.

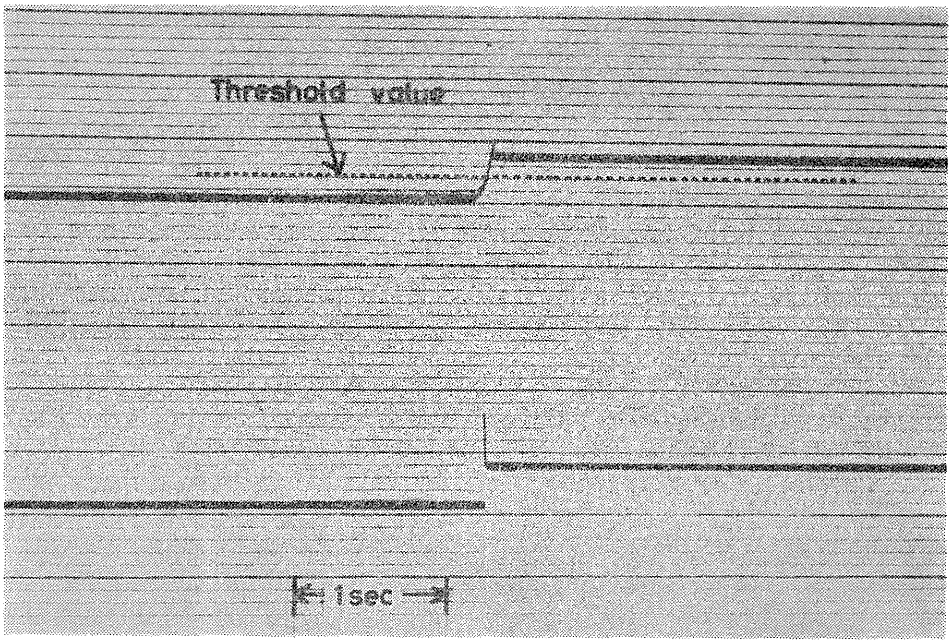


Fig. 31. Experimental result of force control with a roller type sensor.
Upper trace: output voltage of pressure sensor.
Lower trace: finger motor voltage.

By the above mentioned method we made advanced material handling to be possible by a simple sub-programme without increasing the work of the central computer as much as the intelligent robot does.

## 8. Weight Sensing System

### *8. 1. Necessity of Weight Sensing*

Slip sensor explained in § 6 has a needle or small ball point to touch on the surface of the object. If the object is a box or cubic shape the needle of the slip sensor can relatively easily touch the surface of the object. But the object is a ball or a cylinder the needle can hardly touch the surface.

The next difficulty is as follows. The dynamic frictional coefficient is smaller than the static frictional coefficient. Then after the object begins to slip, the frictional force between the object and the fingers more or less decreases and the object goes down with rather high speed. So there is afraid of that the increase of grasping force can not be in time to prevent the object from dropping, because of the time of computation.

Eventually, an entirely different method must be developed. This method must be such that the grasping force is increased just before the object begins to slip. And the slip sensor can not be used in this purpose.

We have developed an entirely new method to determine the weight of the object.

### *8. 2. Weight Sensing Unit*

When a hand of a robot holds an object, obviously the weight of the object is added to the weight of the arm at the end of it, and causes some excess stress in the arm. So if the arm is set in horizontal direction and the length of the arm is constant, the weight of the object can be known by measuring of strain occured on the arm at the fixed point. Strain can be easily measured by strain gauges fitted on the surface of the arm.

In our experiment we used strain gauges fitted on the surface of the arm at the midpoint of the length at first, and afterwards fitted on the finger. Fig. 32 shows the photograph of the robot which has strain gauges on the arm. The arm of this robot can move up and down and rotate arround the perpendicular axis, but can not vary its length. This robot is specially made for the purpose of measuring weight of the object. Of course with the ordinally robot which can vary the arm length, the measuring of the weight of the object can be done so long as the

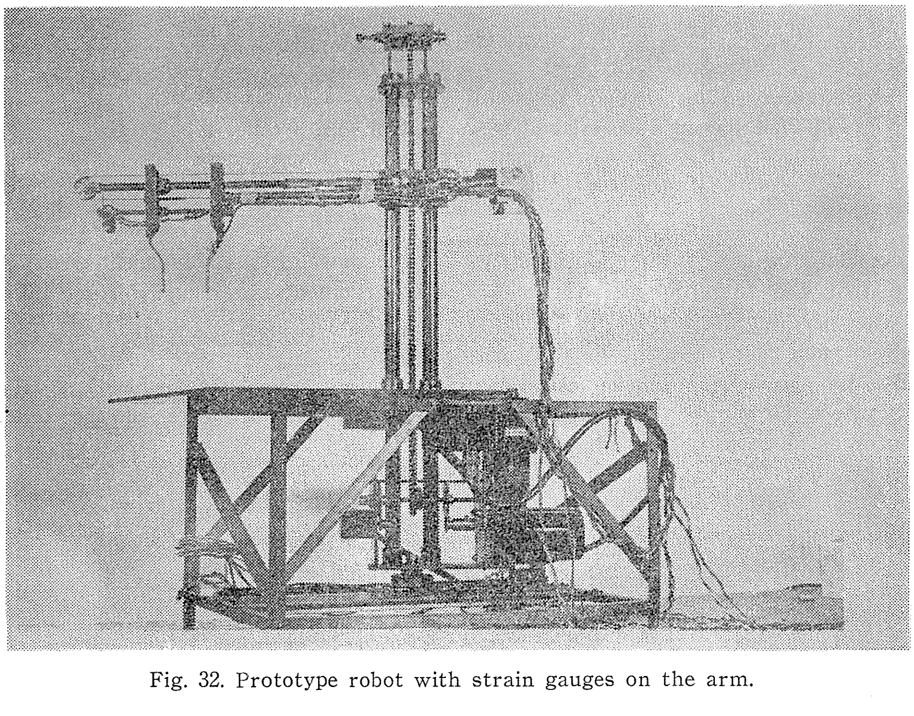


Fig. 32. Prototype robot with strain gauges on the arm.

measuring position is fixed. When the strain gauges are fitted on the surface of the finger, the weight of the object can be measured at whatever position the arm is.

### *8. 3. Force Control System by the Weight Sensing*

(1) Block diagram of the control circuit

Fig. 33 shows the block diagram of grasping force control by the weight sensing system. Fig. 34 shows the relation between the weight of an object, friction between the surface of the object and the fingers, and the grasping force. When the fingers can hold up the object the weight of the object becomes to be a stress of the arm. And when the fingers can not hold the object the stress in the arm is equal to the frictional force between the object and the inner surface of the fingers.

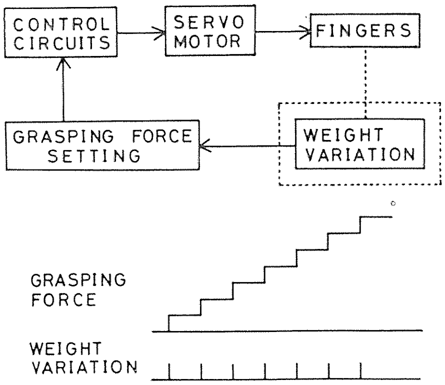


Fig. 33. Block diagram of grasping force control by weight sensing.

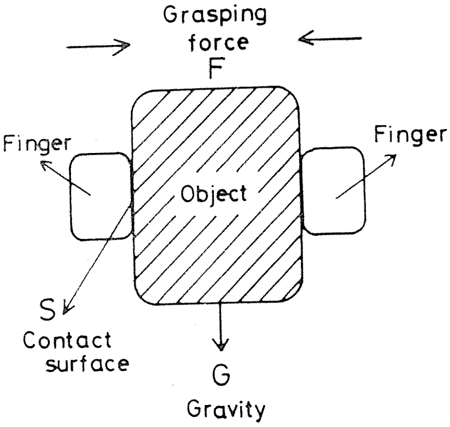


Fig. 34. Relation between weight and frictional force.

At the "pick up" command in the main programme of the robot operation the finger motor starts to move. The current of the armature of the DC motor is set to be the first step. The armature current is divided in several steps. Then the fingers touch the object and the motor current is kept on the same value, so the fingers grasp the object at the first step of grasping force. In the sub-programme of picking up, shown in Fig. 35, there is a command of "move upward 20 pulses". According to this command Z axis motor moves upward 2 mm. If the fingers succeeded to hold the object, then the variation of weight on the arm occurs. So if the weight variation does not occur the finger motor current increases to the next step and the Z axis motor moves again upward 20 pulses (2 mm). This operation is repeated until the weight variation of the arm occurs. This operation is shown simply in Fig. 35.

(2) Experimental results of picking up motion

Fig. 36 shows the relation between the grasping force and the armature current of the finger motor, measured with the metal cylinder on which strain gauges are fitted, shown in Fig. 37.

Experimental results of the pick up operation are shown in Fig. 38. Oscillogram No. 1 is the weight variation, No. 3 is the finger motor current. The current

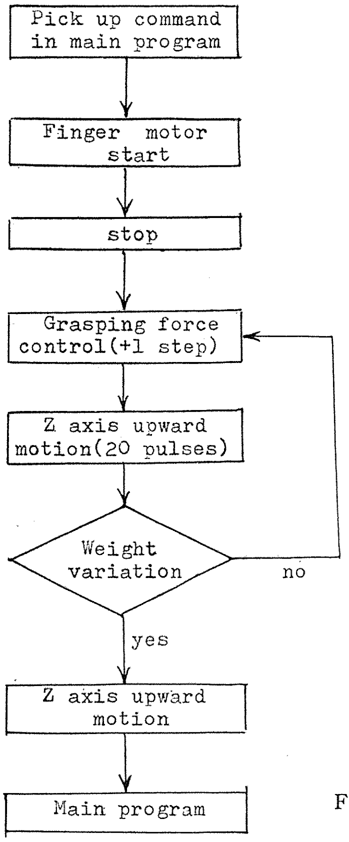


Fig. 35. Flow chart of "pick up" motion.

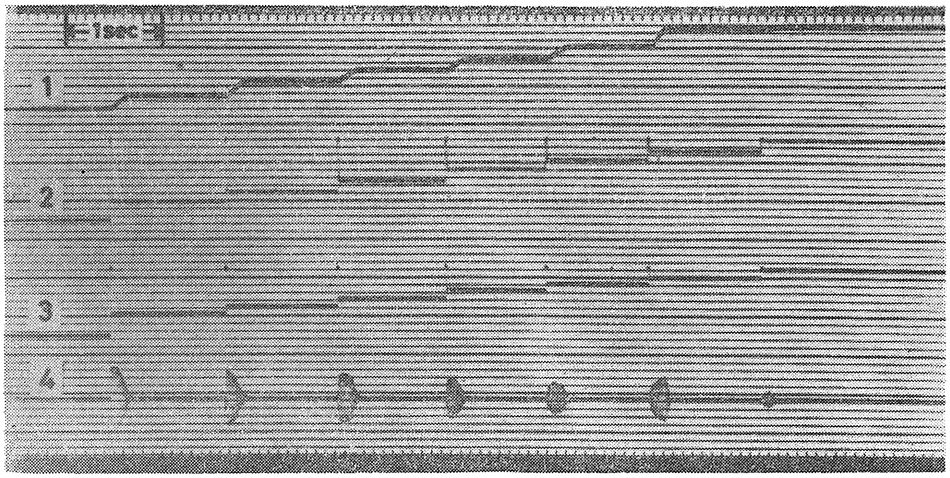


Fig. 36. Relation between grasping force and armature current measured by a test cylinder.

1. Grasping force.
2. Input voltage of the servo-amplifier.
3. Finger motor current.
4. Frequency tacho-generator voltage of the finger motor.

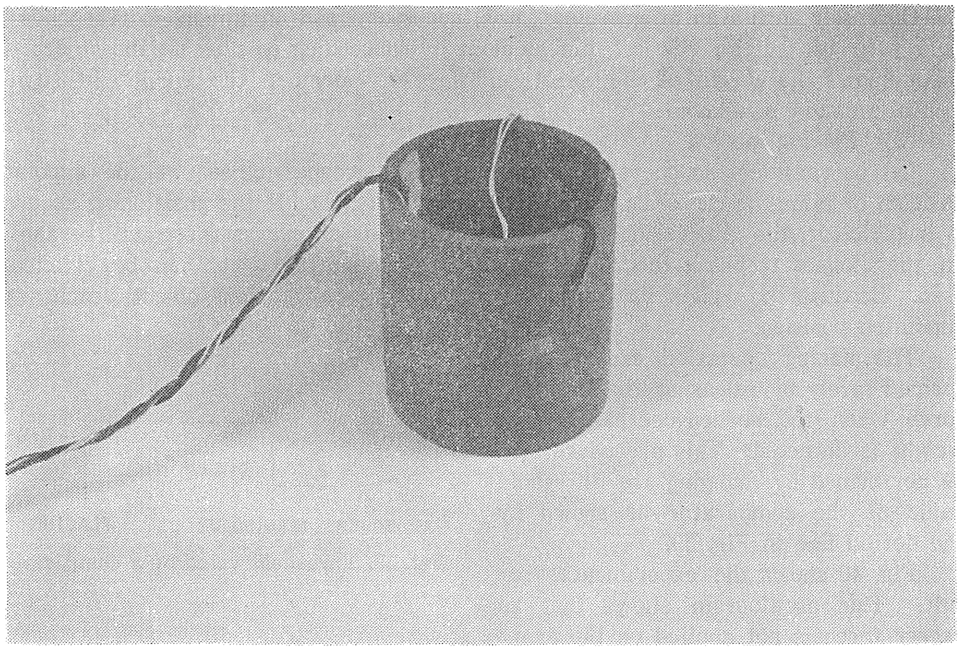


Fig. 37. Test cylinder with strain gauges.

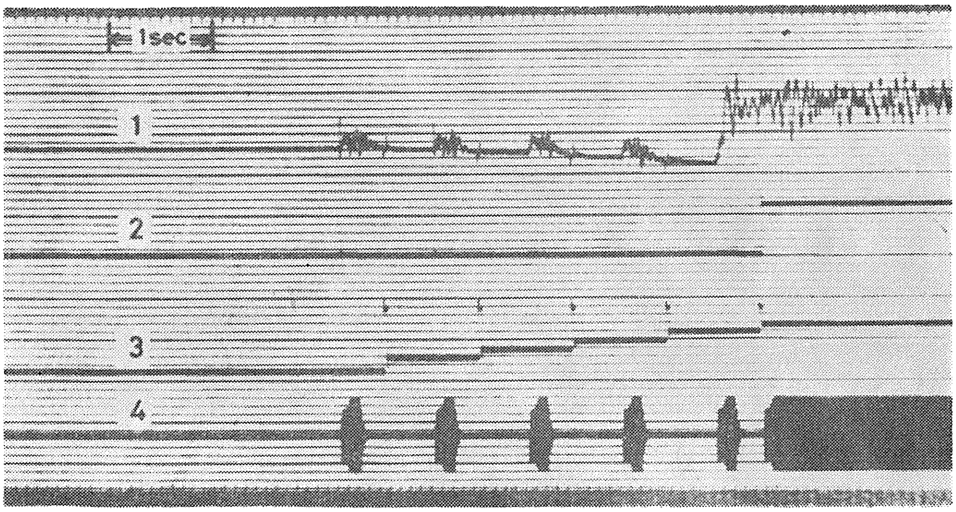


Fig. 38. Experiment of pick up operation.
1. Weight.
2. Comparator ($T_1$).
3. Finger motor current.
4. Up-down motion motor voltage.

increases clearly step by step, but weight variation does not appear until the 5th step. The output of the comparator appears at the 5th step and Z axis motor is driven after the 5 th step.

Obviously each step of grasping force, necessary and minimum, corresponds to each step of weight. So at the moment of succeeding to pick up the object this robot knows the weight of the object, and he can remember the weight in supplemental memory equipment.

(3) Placing motion

Let us consider the operation of placing the grasped object at the appointed position or piling up the grasped object on another object. If the positioning accuracy is insufficient, the grasped object will be crushed or an excess force will be applied on the fingers to break them. In this case the weight variation can be efficiently used. Because the weight decreases suddenly when the grasped object reaches the appointed position.

The placing operation can be performed safely by releasing the grasping force when the sudden decrease of the weight is detected. This procedure may be performed by changing the threshold value of the comparator as shown by the dotted line in Fig. 39.

Fig. 40 shows the experimental result. This oscillogram shows that an excess force is not applied on the arm.

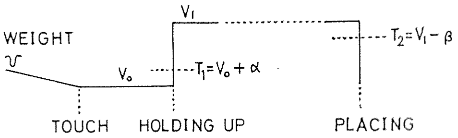


Fig. 39. Threshold value of a comparator.

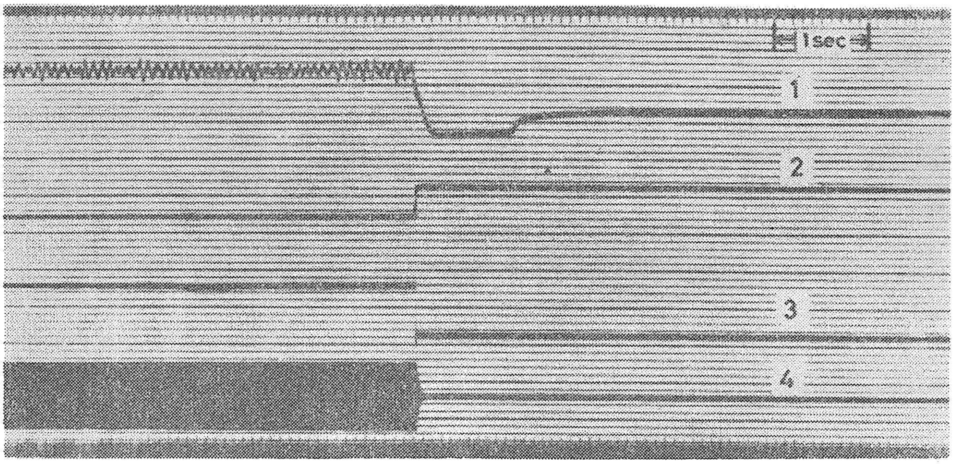


Fig. 40. Experimental result of placing operation.

1. Weight.
2. Comparator ($T_2$).
3. Finger motor current.
4. Up-down motion motor voltage.

(4) Threshold value

As we discussed above, two threshold values $T_1$ and $T_2$ are used for detecting the weight variation. A block diagram of setting these values is given in Fig. 41. In this figure the voltage $V_0$ is an initial value and the voltage difference $V_1-V_0$ shows the weight of an object. The threshold value $T_1=V_0+\alpha$ is used for holding up operation and $T_2 = V_1 - \beta$ is used for placing operation. $\alpha$ and $\beta$ have to be determined experimentally with respect to the operational noise and gain of a *DC* amplifier for strain gauges.

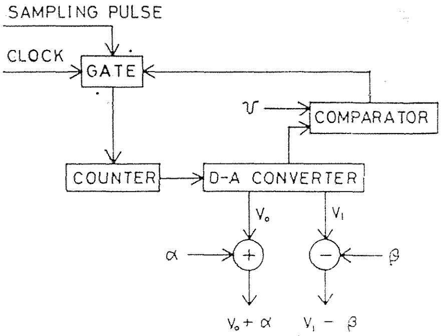


Fig. 41. Threshold setting diagram.

## *8. 4. Grasping Force Control when the Weight of the Grasped Object Increases*

(1) The meaning

Now, let us consider the grasping force control problem in case of holding a glass cup and pouring water into it. As the weight of water poured into the glass cup increases the weight of the glass cup obviously, then the grasping force determined at the holding up operation becomes insufficient to hold it and the glass cup begins to drop. With respect to the grasping control in this case, the slip sensors, mentioned in the former section, can not be used. Here the robot has to know insufficiency of the grasping force just before dropping of the object. So we developed a new control system which can increase grasping force at the moment just before the grasped object begins to slip.

(2) Theoretical analysis

The physical meaning of the procedure which determines the grasping force by checking up whether the weight can be measured or not is as follows:

When the grasping force is divided into n steps as shown in Fig. 42 and a glass cup can be held up barely with the grasping force $j \cdot f$ at the $j$ th step, where $f$ means the elemental force of the steps. Then we have the next equation of friction.

$$w = \mu_s \cdot j \cdot f \qquad (1)$$

where, $w$: weight of the glass cup

$\mu_s$: static coefficient of friction.

This grasping force is the minimum necessary force to hold the glass cup, so this is not sufficient to hold safely when the arm moves to another position. In our experiment the grasping force is increased to the next step before up-motion of Z axis starts. This means, the grasping force is equal to $(j+1) \cdot f$. Then we have the following equation during the glass cup being held by the hand.

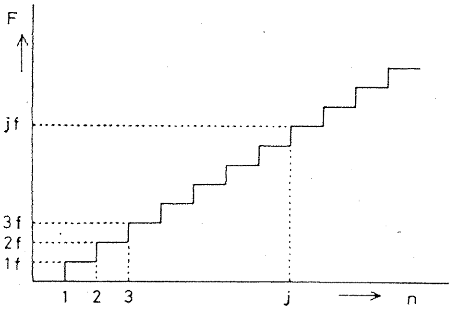


Fig. 42. Number of steps of grasping force.

$$w<\mu_s(j+1)f \tag{2}$$

When the arm arrived the appointed position and water is poured into the glass cup, equation (2) becomes following equation so far as the glass cup does not begin to drop.

$$w+x\leqq\mu_s(j+1)f \tag{3}$$

where, $x$: weight of water poured into the glass.

If inequality of the above equation is valid, the hand safely holds the glass, but when the equal sign is valid, the grasping force is the limit to hold the glass and the force must be increased. We get the following equation by substituting the equation (1) into (3);

$$x=\mu_s\cdot f=\frac{w}{j} \tag{4}$$

Therefore, the grasping force must be increased to the next step when the weight of water poured into the glass cup becomes equal to the weight of the glass divided by the grasping force step number. And this is the moment just before the grasped object begins to slip. It has been made clear that we can control the grasping force just before dropping.

(3) Block diagram

A block diagram describing the procedure above mentioned is given in Fig. 43. This threshold voltage $V_c$ is presented by the following equation;

$$V_c=V_0\left(1+\frac{m}{j}\right),\quad 1\leqq m\leqq n-j \tag{5}$$

(4) Experimental result

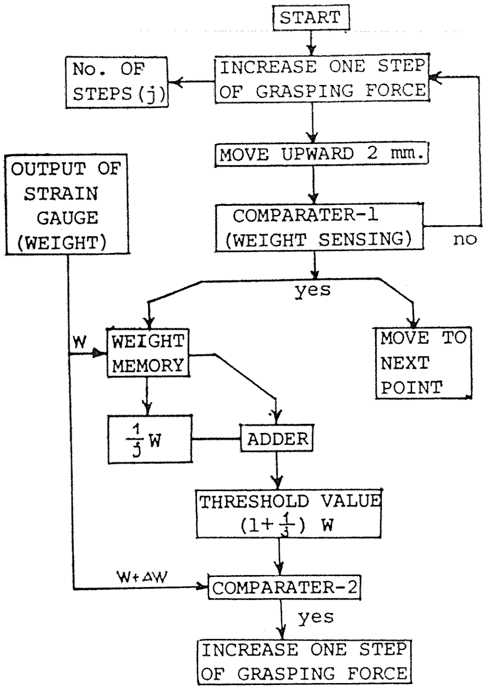
Fig. 44 shows the result of our experiment which was defined by the requirement of holding a glass cup and pouring water into it. It is apparent from this oscillogram that the finger motor is controlled to increase the grasping force by one step at the moment just before the glass cup begins to slip.

### *8. 5. Improved Weight Sensing System*

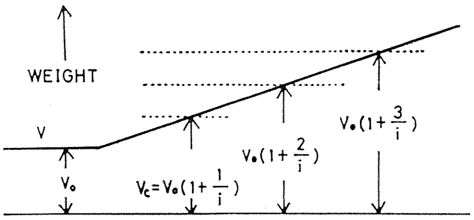
In the previous section the weight sensing system has been explained. In that system as seen in the block diagram of the system shown in Fig. 35, there is upward motion of 20 pulses of Z axis motor, until the weight variation is detected. And the experiment has been carried with a glass cup. But it has been made clear, afterwards, that the sub-programme shown in Fig. 35 has succeeded when the material of the object is made of metal or glass, and has not succeeded when the material of the object is covered by PVC tape. Fig. 45 shows the result when the cup is covered by PVC tape, and obviously from the figure the robot has failed to know the correct weight of the object.

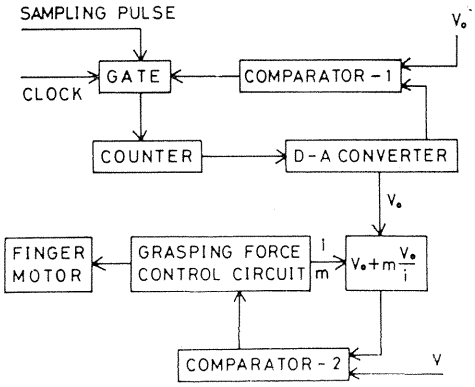
The reason will be, we think, as follows:

The friction between the PVC-covered cup and the fingers of the robot is so large and the PVC tape has a little adheasive character, that some fraction of the weight of the cup is transmitted onto the fingers even if the finger could not hold up the cup. Then on the output of the strain gauges fitted on the arm there is very little change when the fingers could hold up the cup. And the robot hardly judges whether the object is held up or not.



(a) Flow chart





(b) Block diagram

Fig. 43. Diagram of grasping force increasing when water is poured into a glass cup.

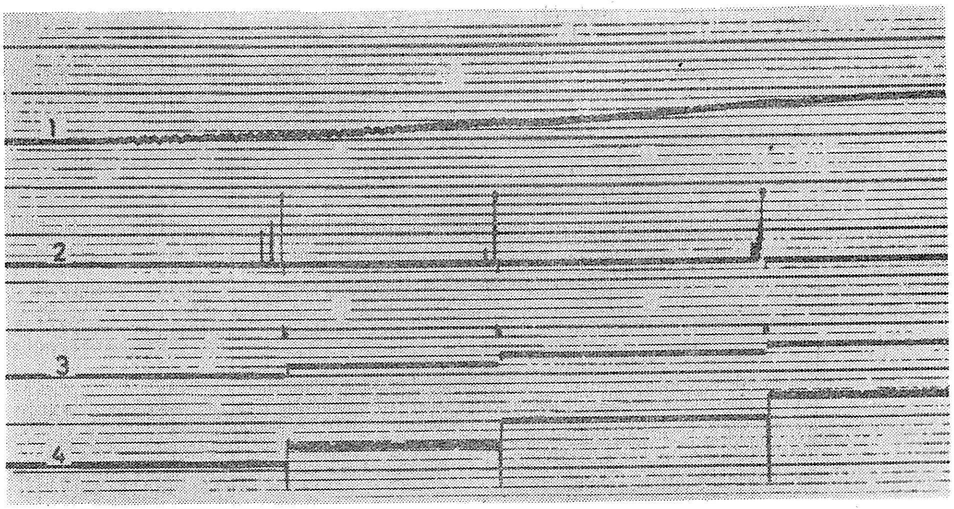


Fig. 44. Experimental result of grasping force increase just before the glass cup begins to drop.

Water poured into the glass cup held by a robot

1. Weight.
2. Signal to increase grasping force.
3. Grasping force.
4. Threshold value.

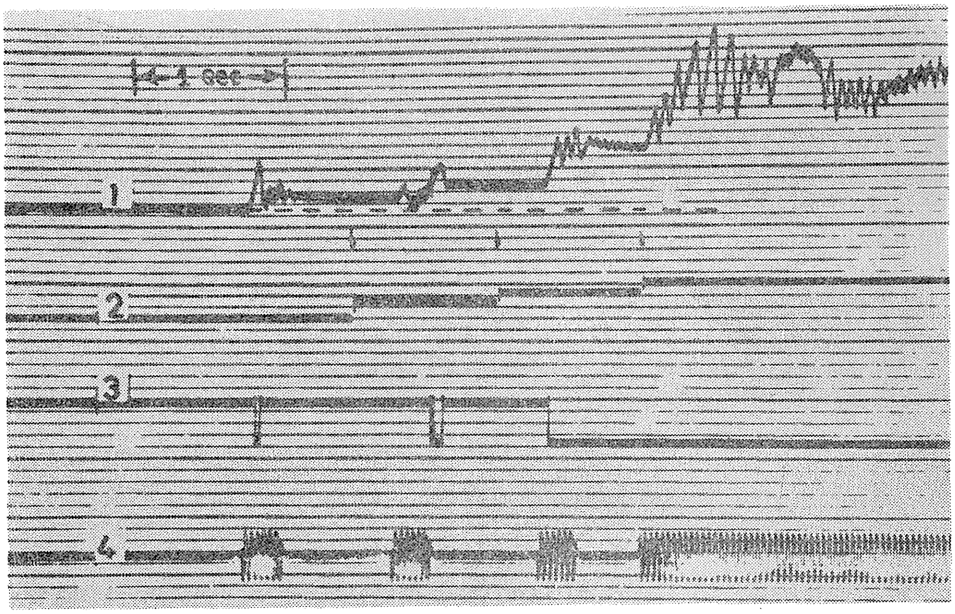


Fig. 45. Weight sensing motion with a PVC covered glass.

Holding up of PVC-covered cup

1. Output of the strain gauge.
2. Grasping force.
3. Output of comparater.
4. Motion of upward-motor.

From this result we tried to make a new system, in which after the every step of the little upward motion of the arm the less downward motion of the arm was inserted. The block diagram is shown in Fig 46 and the experimental result is shown in Fig. 47. In these figures the output of the weight sensor becomes negative when the fingers can not hold up the cup. This is the result of the downward motion of the arm. And the fingers succeed to hold up the object at minimum and necessary force. Clearly this system can be applied even if the material of the object is metal or glass.

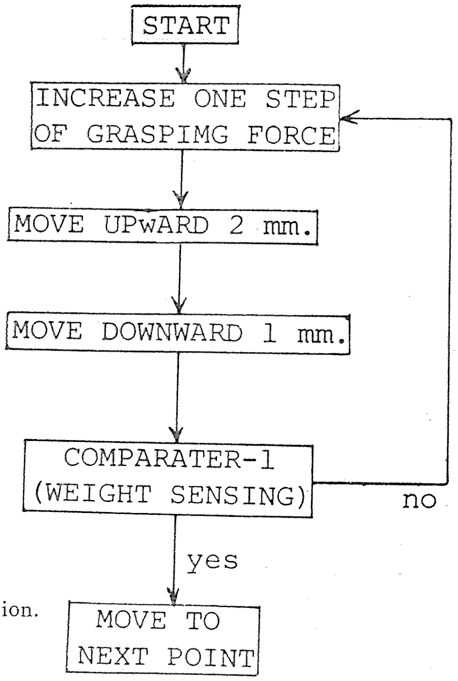
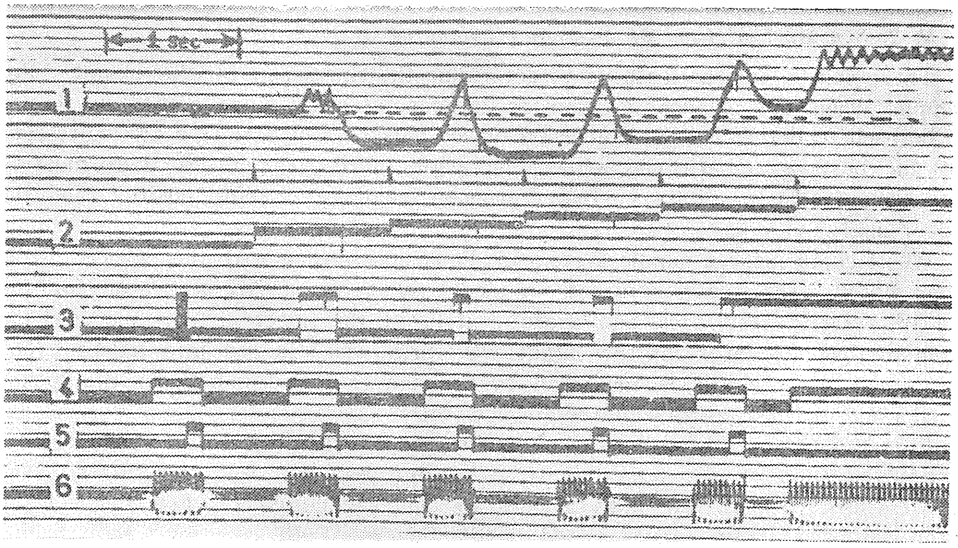


Fig. 46. Diagram of improved pick up motion.
Improved weight sensing system



Eig. 47. Experimental result of Fig. 46.
Holding up of PVC-covered cup by the improved system

1. Weight.
2. Grasping force.
3. Output of comparater.
4. Output of servo-amplifier.
5. Signal of downward motion.
6. Motion of Up-Down-motor.

## 9. Dimension Sensing System

### *9. 1. Necessity of Dimension Sensing*

In this section we like to discuss on the simplest dimension sensing system. Human fingers know the dimension of the object without measuring tool when they grasp it. It is very important fact to do some handling works in production lines. So we think the industrial robots must have an ability of dimension sensing. But the system for this purpose must be the simplest one.

Of course there are many researches on pattern recognition and some of them have get good success. Most of these researches on the pattern recognition use TV cameras and big computers. For the industrial robot the pattern recognition is very important ability to judge whether the object is correct one or not. But in the most production lines in the modern industries the possibility of handling unknown various objects is not so big. The handling objects are fixed model and the robot is required to judge whether the object is in the correct position or direction. For example a robot is handling some boxes which have three different length of the edges, when the box comes to the appointed position, the robot which must pick up this box and put it on the another place for the next treatment must know whether the direction of the box is correct or not. In this case the robot can know the direction of the box by measuring the dimension between the fingers when the fingers grasp it. So the robot can have an ability of judging without a big computer. This method is very useful for an industrial robot in production lines.

### *9. 2. Simplest Method of Dimension Sensing*

There can be various methods to determine the dimension of the object. For example, when the gripper is a pincer like one the angle between the two fingers can be used to determine the dimension of the object. But here is a difficulty such that the position of grasping affect the angle of the gripper. So there must be some computation to get the correct dimension from the grasping position and the gripper angle.

We tried to make a simple system of dimension sensing with the motion of the finger motor. The finger motor of our model robot has a AC generator for the sake of velocity feed back and speed control of the finger motor. We used the output of this alternator and the output waveform was changed into pulses. The dimension of the object is measured by the number of pulses between the opened position and grasped position of the fingers.

15 pulses are generated in every 1 mm stroke of the finger. At the widemost spreaded position of the finger there is a limit switch. And the finger has a contact sensor to know the both fingers to contact the object. For the contact sensor we used strain gauges fitted on the fingers. Pulse counting circuit begins to count the output pulses of the alternator when the limit switch is opened and ends to count when the output of the contact sensor is detected.

The result of experiment is shown in Fig. 48. The curve shows the accuracy of dimension measuring is nearly 1 mm. We can not say that this accuracy is very good. In the field of modern industrial robots the accuracy of movement is required to be better than 0.1 mm. It is true that when a robot sets a small screw into a female screw the moving accuracy or dimension measuring accuracy must be better

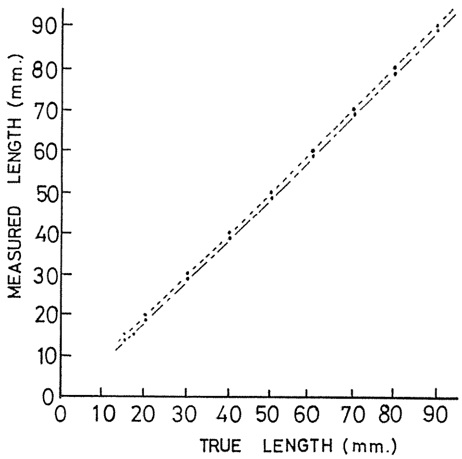


Fig. 48. Experimental result of dimension sensing.

than 0.1 to 0.05 mm. But in the most case of handling some work pieces the accuracy needs not such a value.

In the above mentioned dimension sensing system the additional parts are only strain gauges on the fingers and a pulse counting unit. By such a simple system the robot can have an ability to know the dimension of the objects and by using a selection system the robot can handle the correct work pieces only.

## 10. Distance Sensing System with a Laser Beam

### (1) Necessity of a visual sensor

Let us consider the case that an industrial robot engages in spray painting or welding on a surface of a curved plate as shown in Fig. 49. In this case it is

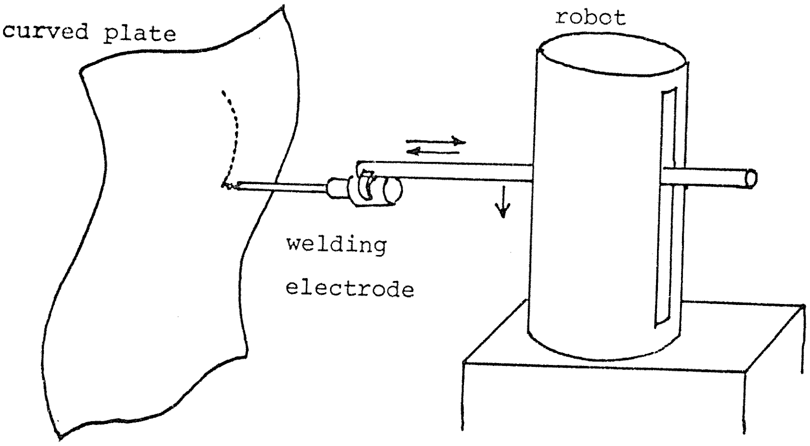


Fig. 49. Welding on a curved surface.

desirable that the hand of an industrial robot keeps up a constant distance up to the surface of the plate. Fig. 49 is an example, where the arm of the robot here can move up and down and the plate moves horizontally. Since the plate is not flat, the hand of the robot must be driven automatically forward and backward to keep up the distance.

This operation, of course, can be by a tactile sensor. Fig. 50 shows an example using a tactile sensor which consists of a sensing rod and a differential transformer. The sensing rod can be moved before and behind by the position of the plate and the variation of the length of the sensing rod is detected by a differential transformer. The installed position (vertical position in Fig. 50) of the sensing rod can not be same to the position of the welding electrode, there must be some computation to control the arm. Assuming the vertical position of the rod is under the welding electrode and the vertical motion of the arm is downward, the arm length must be controlled to keep the value which is detected such time interval ago that the position difference is divided by the vertical speed of the arm.

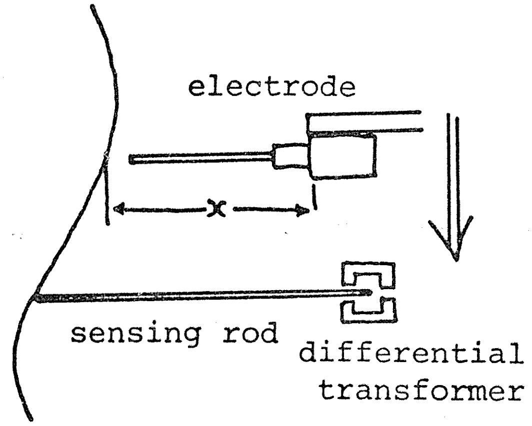


Fig. 50. Example of a tactile sensor for Fig. 49.

Experimentally, however, the motion of the sensing rod of 30 to 40 cm long is very difficult to move in and out smoothly and may be more or less bent by the frictional force of the plate surface. Then even if the sensitivity of the differential transformer is very high, there will be large error in detection of distance.

And there will be the case that contact on the surface of the object can not be allowed. Including these cases visual sensor seems to be the most suitable one. But the visual sensor used here is not a TV camera. This is not a problem of the pattern recognition, but the dimension sensing.

(2) Principle of a optical dimension sensing method

Fig. 51 shows the principle of detection of distance with an optical equipment. Condensed light flux from the light source is projected onto a rotating mirror, and the mirror is rotated by a 4-pole synchronous motor. So the incident light flux is reflected on the mirror, and emitted to the object surface. The vertical angle of emission at the moment of illumination emits diverged light from the

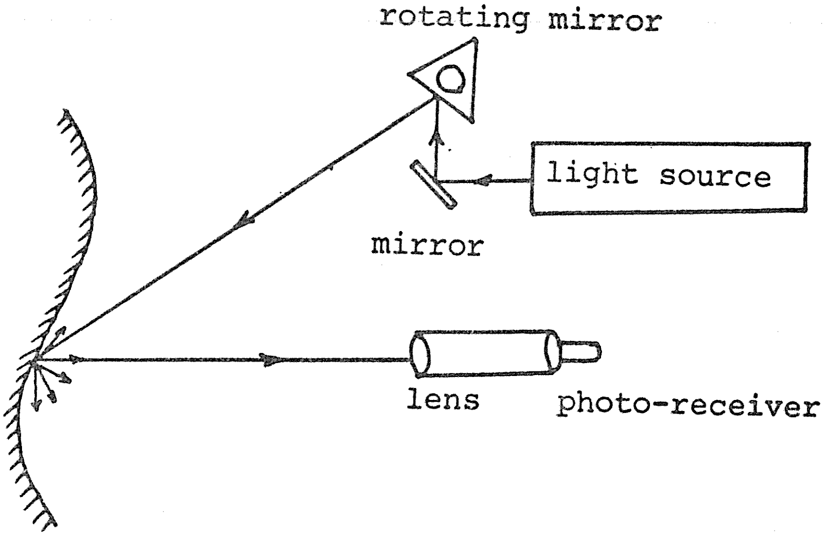


Fig. 51. Principle of optical distance sensing.

illuminated point. At a fixed position aloof from the mirror by an adequate length there is a light receiver (photo-transistor) in fixed direction. Of course the light receiver has an adequate lens system to catch only one point on the object surface. Since the triangled mirror does synchronized rotation with the source frequency, the light receiver receives light pulses three times in two cycles of the frequency. And the phase of the light pulses is entirely corresponds to the waveform of the source.

Meanwhile, a pulse generator makes a timing pulse series of high frequency which is synchronized at the moment of zero point voltage wave. This pulse series is counted until the light pulse is received. Counted number of timing pulses corresponds to the angle of the mirror at the moment that the light flux collides upon the correct front of the photo-receiver. Then the distance up to the object surface can be quickly determined by the pulse number.

The base length of the measurement, that is the vertical distance between the mirror and the receiver, affects the accuracy of measurement. The longer the base length, the higher is the accuracy. But too long base length causes decreasing quantity of received light flux.

### (3) Application of laser beam

In the above mentioned optical system there are some difficulties such as the difficulty of light condensing system and a sensitivity of the light receiving equipment. Moreover, if the operation with this system is carried in a light room the light source must be chopped by a special frequency in order the received light can be distinguished from the other light. But the received light is also pulsive, then the chopping frequency must be very high that at least several chopped pulses included in the received pulse duration. In this purpose a Xenon flash lamp can be used.

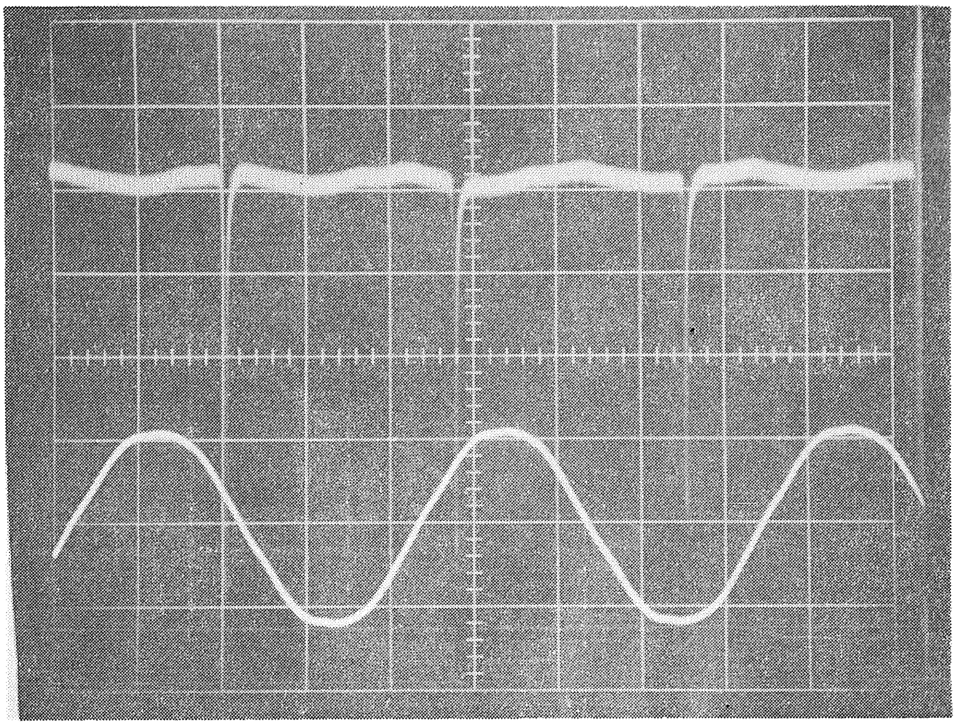
The limit of the condensing lens system of strong white light may be able to make a focus of several mm in diameter. When the base length is several cm and distance of several ten cm is to be measured, the difference of a few mm corresponds to the error of distance larger than 2-3 cm.

The laser beam is very suitable in this case. A small size He-Ne gas laser beam generator can emit strong beam nallower than 1 mm of diameter, and the power density is very great. So the received light pulse can be distinguished from the surrounding light. Moreover the wave mode and the wave length of laser beam are strictly fixed, so it can be also distinguished by this wave mode or wave length when the strength of the received light is weak and can not be distinguished by the strength.

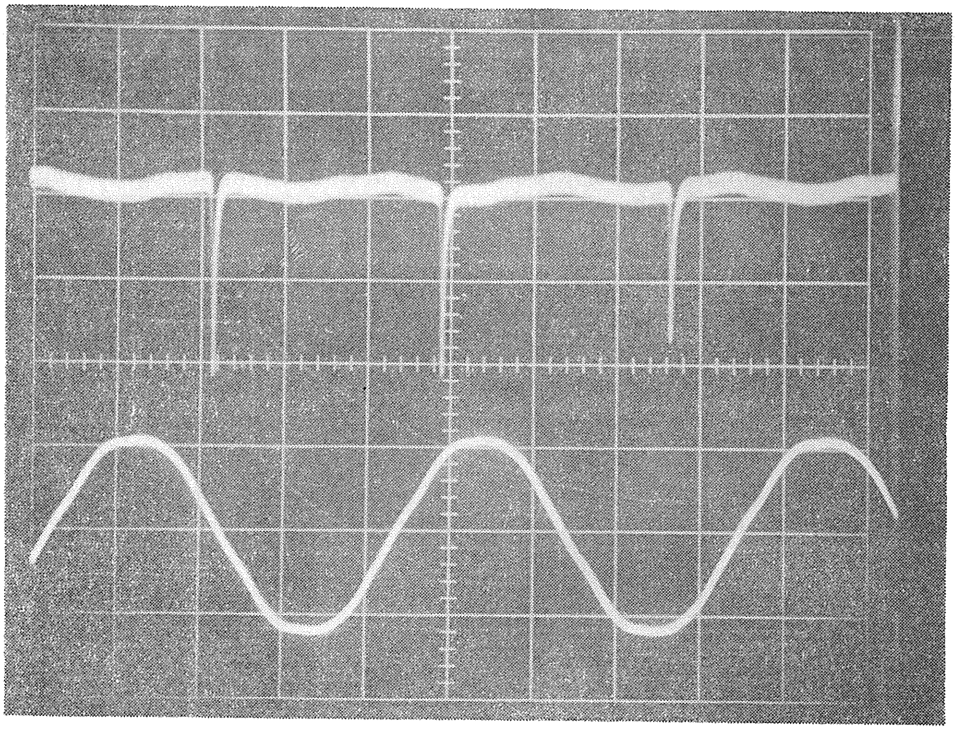
(4) Experimental results

Fig. 52 (a) to (c) show the light pulses received by the photo-transistor. The thick base line shows the light noise of the circumference, since this experiment was carried in a light room in the daytime. However the received pulses are clearly distinguished from the surrounding light noise. Distance up to the object surface was 20 cm in 52 (a), 30 cm in 52 (b) and 40 cm in 52 (c). The position of the received light pulses in the photographs clearly varies with the distance up to the object. Sinusoidal wave is given for the comparison of the phase of pulses in three photographs. The timing pulse series of 100 kHz can not be shown in pulsive shape in these photographs.

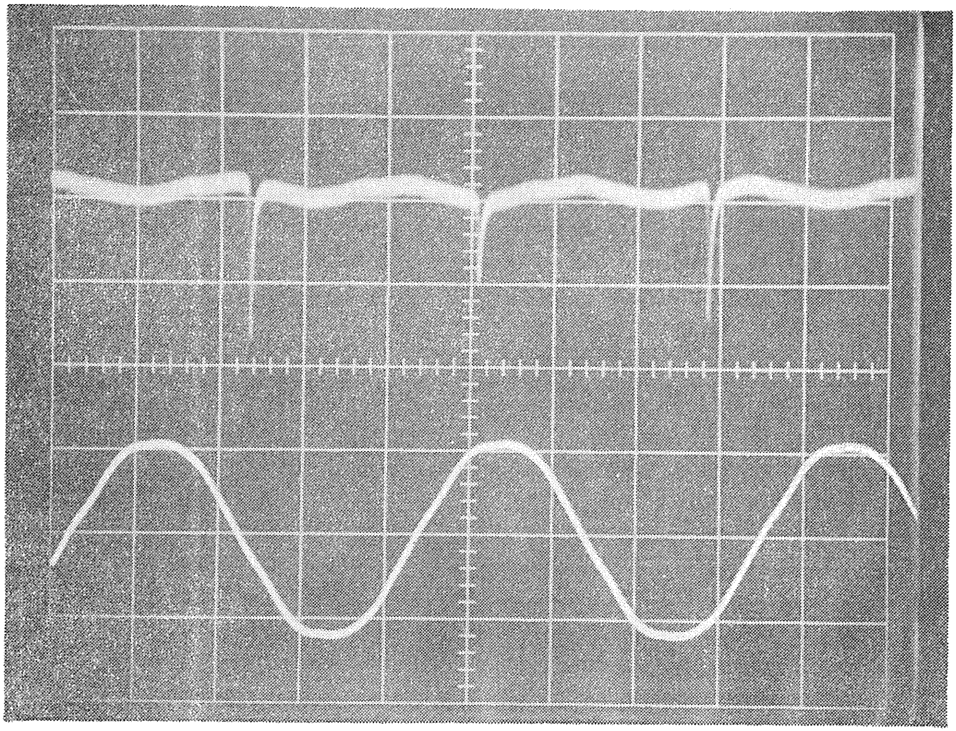
The pulse of received light is differentiated, then the crossing point of the differentiated curve and the base line gives the moment of peak of the light value.



(a)



(b)

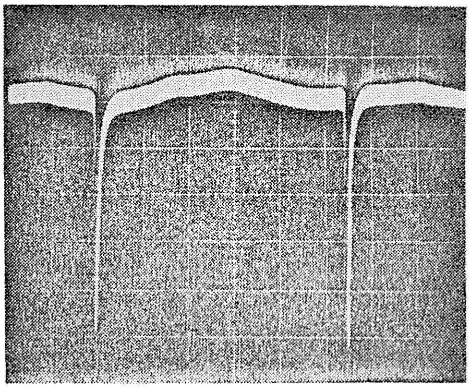


(c)

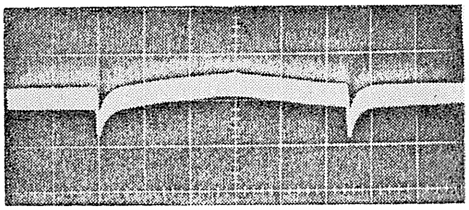
Fig. 52. Received laser light pulses with various distances.

The counting of timing pulses ends at the peak point. From a simple calculation it is clear that one interval of the timing pulses corresponds to 0.216° (=13′) of angle difference of the mirror. When the measured distance is 40 cm, the theoretical accuracy of distance with this angle difference is 3.2 mm by the base length of 10 cm, and 1.9 mm by 20 cm base.

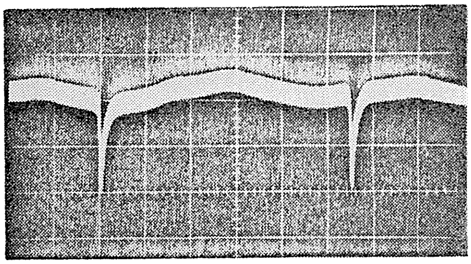
The strength of received light can be seen in Fig. 53 (a) to (d). The object was white paper in (a), brown paper in (b), rough aluminium in (c) and black paper in (d). Clearly a white paper gives the best diverged reflexion. It is to be noticed that a "black body" does not reflect light in any direction, and a dark gray body also cannot give sufficient diverged reflexion of the laser beam. In other hand, an optical flat surface (mirror) also does not emit any diverged light but only a normal reflexion, and then the light receiver fitted in the fixed direction can not receive the light flux.



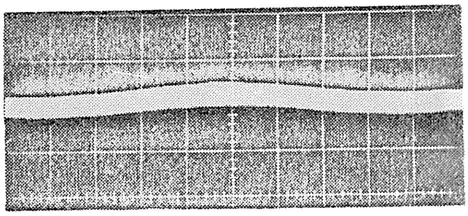
(a) White paper



(c) Rough aluminium



(b) Brown paper



(d) Black paper

Fig. 53. Received laser light pulses with various materials.

This dimension sensing system, here explained, cannot be used when an object surface is made of glass, finely polished metal or deep black material.

## 11. Conclusion

An industrial robot is one of the most hopeful machines in the near future for saving human labors, saving cost and growth of productivity in industries. Of course the price of an industrial robot working in place of human labor must be cheaper than a human labor taking into consideration the number of shifts and the life of the robot. Inevitably the industrial robot can not be a high intelligent robot with a big computer.

On the other hand, industrial robots in the market now are rather near to programmable automatic machines. They have not sensing abilities as human labors and then cannot be placed instead of human workers.

We have developed various methods to solve the above mentioned problems. Our researches are on the methods of giving sensing abilities to an industrial robot without lot of expence. Tactile sensors, strain gauges or laser beam sensors are very cheap sensors and the treatment of these outputs is not so complicated.

It has been made clear that with these rather cheap sensors and sensing systems the industrial robots will become very useful machines for labor saving. From our researches the industrial robot can have abilities of weight sensing, dimension sensing and distance sensing.

However the most important problem in the production lines will be automation of assembling works. In the assembling works there are many screwing works. Suppose we let an industrial robot to do screwing of diameter of 3 mm for example. When a human hand does screwing the 3 mm screw, very fine sensation of human fingers can recognize the inclination of the screw or pressure inuniformity when the male screw reaches the entrance of the female screw. This sensation is very delicate and very difficult for an industrial robot. Very difficult but not impossible. This problem must be solved in 2 or 3 years. We hope many researchers come to the field of industrial robots. This field can not be developed only by electric or electronic engineers but by mechanical, system, metallurgy and optical engineers.

This research has been made by supports of scientific research budget of the ministry of education and there has been co-operation of Nagoya Kiko Co. Ltd..