# DEVELOPMENT OF AN INTERIOR FINISH WORK ROBOT

Sumio Fukuda, Masayuki Takasu, Sigeyuki Kojima
Mechatronics Research Office
Tokyu Construction Co., Ltd.
1-16-14, Shibuya, Shibuya-ku,
Tokyo, 150, JAPAN

## ABSTRACT

Installation of ceiling finish boards, which involves the handling of heavy gypsum boards performed on scaffolds, is a laborious and dangerous work.

An interior finish work robot capable of installing gypsum boards automatically was developed in 1989 to relieve workers of such a dangerous, hard work.

The developed interior finish work robot installs sub-ceiling boards to double-layered ceilings. The tasks the robot performs are to hold, lift, position and screw gypsum boards onto light-weight steel frames, while traveling along the base line.

This paper describes the functions of this robot and results of experiments conducted at several construction sites.

## 1 INTRODUCTION

Development efforts to robotize construction work are active today. Several methods for a more advanced and comprehensive automated construction technology have already been proposed and are being implemented.

In 1989, our company began to work on the development of "interior finish work robot" which was to automate the installation of ceiling boards. After completing the main body of the robot in December 1989, we proceeded to make auxiliary equipment for the robot, while conducting operation tests. Several modifications were made to the robot during this period, and the machine was completed in April 1990 as a fully automatic ceiling board installation robot. The robot is now in operation.

In this paper, details of the interior finish work robot, as well as operating conditions used and results of operation tests, are reported. In addition, prospects of this type of robot are discussed based on experience with this fully automatic robot.

## 2 CURRENT METHOD OF CEILING BOARD INSTALLATION

Prior to the development of the robot, a series of surveys on current installation work were conducted at several construction sites.

Robotization of the installation of ceiling boards (backing gypsum boards) was considered to be easy because (1) procedure had been standardized, (2) it could be done indoors, and (3) floors (slabs) had been made smooth and flat enough for a robot to move around on before the installation of ceiling boards.

Traditionally, installation of ceiling boards (1,820mm × 910mm) has been performed on unstable footing, such as trestles and steel scaffolds, where boards were manually held up overhead, positioned and fixed with screws. This work is one of the most painstaking manual works forcing unnatural postures. The work may be performed by a team of two workers, but usually it is done individually.

A ceiling board positioned by the worker is manually supported and pushed against an LGS (light-gauge steel) frame until a minimum number of screws needed to hold the board are put on. Then, the manual support for the board is removed, and all screws to fix the board are tightened. The height of footing is adjusted to the height of each worker so that ceiling boards can be easily supported (Photo 1).

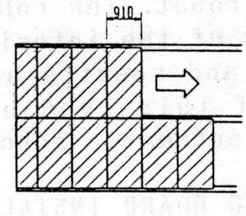
Furthermore, a ceiling board is usually large, and the power driver must be pushed against the ceiling with a force of 10Kgf or more while the board is fixed with screws. Forcing an unstable, unnatural posture, this is a very demanding work.

## 3 PURPOSE OF DEVELOPMENT

The purpose of the development was to improve the productivity of the installation of interior ceiling boards (supplying, positioning and screwing boards, and moving to a next location), reduce manpower requirement, and assure safety through automation.

(1) Objects to be Handled
- Ceiling board
  Thickness: 9mm-15mm
  Dimensions: 1,820mm × 910mm
- Steel frames (JIS A 6517) are to be used.
- Standard size boards without opening are to be used.

(2) Working Conditions
- Height of ceiling: 2.1m-3.0m
- Work area: any area in which standard size boards can be installed. (The perimeter zone of the ceiling and the vicinities of columns are not included.)
- Flatness of floor: ± 5mm/m or less
- Floors are to be free of any obstacle.
- Straightness of LGS frame: ± 5mm or less (double furring strip)
- Flatness of LGS frame: ± 5mm or less
- Installation patterns:



(3) Key Point in Development

Currently, the worker manually install a board with as many as 30 to 40 screws, aiming at assumed locations of LGS frames behind the board, while supporting the positioned board with a hand and the head. LGS frames, however, have openings or reinforcements, and often are not positioned in parallel. Because of this, even skilled workers often misplace screws.

The most important technical consideration in the development of the robot, therefore, was the full automation of the screwing of ceiling boards, aimed at preventing misplacement and inconsistent pitches of screws for an improved quality of board installation.

## 4 BASIC SPECIFICATIONS

### 4.1 Basic Experiment

Prior to the definition of basic specifications for the detail design of the robot, the following experiment was conducted on gypsum boards and LGS frames:

(1) Confirmation of the Performance of Proximity Sensors

Purpose: When ceiling boards are screwed on, the locations of their backings need to be detected. The performance (effective distance, hysteresis, etc.) of different types of sensors for this purpose was tested. (See Fig.1)

Result: Three types of high-frequency sensors were tested to take measurements of Sn (distance between the LGS frame and the sensor), a (distance between the center of the LGS frame and the sensing point) and b(distance between the center of the LGS frame and the return point).

Results of the test are shown in Fig.2.

As shown, Type-1 detected nothing at smaller distances (Sn). Type-2 and Type-3 showed similar behavior, but Type-3 whose performance was more stable in the range of Sn in which actual sensing was to be performed (12mm-20mm) was adopted.

(2) Coefficient of Friction Between Ceiling Boards and Light-Gauge Steel Frames

Purpose: Since ceiling boards are moved horizontally while being pushed up against LGS frames on the ceiling surface, friction between the ceiling board and the LGS frame was investigated to determine the force (W)required to push the board against the LGS frame and the force requirementfor the actuator to move the board in the X and Y directions.

Result: As shown in Fig. 3, LGS frames (single bars and double bars), like ones used in actual ceiling work, were prepared, and hooks were attached to the ends of the board to be positioned. Load applied to the board was increased by stages while tensile forces required to pull the board in X and Y directions were measured. The coefficients of friction thus obtained, $\mu_X=0.53$ and $\mu_Y=0.61$, were used as a basis for determiningpushing force and moving force (X and Y directions) requirements.

### 4.2 Basic Specifications

Other tests concerning several items and surveys on the performance of components were conducted, and basic specifications of the robot were defined accordingly.

## 5 CONFIGURATION AND MOTION SEQUENCE OF INTERIOR FINISH WORK ROBOT

### 5.1 Configuration

(a) Carriage: 4-wheel, motor-driven; with steering function, auxiliary wheels and auto leveling function

(b) Hydraulic unit: power source for leveling jack and lifting arm cylinders

Table 1. SPECIFICATIONS

| | | | |
|---|---|---|---|
| 1 | Dimension | 4 | Positioning device |
| | L × W × H (mm)<br>·main body : 1,600 800 1,800<br>·boards carrier: 1,600 780 1,100 | | ·X-axis slide table: 950 mm stroke<br>·Y-axis slide table: 100 mm stroke<br>·Z-axis lifting arm: 2,100~3,000 mm from floor height |
| 2 | Weight | 5 | Screwing device |
| | ·main body : 900 Kg<br>·boards carrier : 300 Kg<br>·loadage of boards: 400 Kg | | ·driver : electric driver 2 set<br>·loading screws number: above 2,000 pieces<br>·detector of L.G.S. : proximity sensor |
| 3 | Travelling device | 6 | Supply source |
| | ·travelling speed : 6 m/min.(100 mm/sec.)<br>·travelling accuracy: within ±20mm from base line<br>·steering control : 4-wheel steering | | ·A.C. 200 V (3Φ) 6 KVA |

(c) Compressor: power source for screw feeders and for vacuums of suction pads
(d) Control panel: programmable controllers, motor drivers, etc.
(e) Lifting arm: telescopic slide (with a built-in hydraulic cylinder)
(f) X-axis slide table: ball screw feed, 950mm stroke
(g) Y-axis slide table: ball screw feed, 100mm stroke
(h) Screw feeder: a device to supply screws to the screw driver
(i) Screw driver: motor driven; with a cylinder for a vertical (z-axis) slide and a proximity sensor for the detection of light-gauge steel frames
(j) Handling table: guide rollers for the positioning of ceiling boards, suction pads, board supply rollers, position sensor, screw driver feeder
(k) Board carrier: connects to the robot's main body, loads ceiling boards and supplies them to the robot; slide cylinders, feed rollers, lifting mechanism
(l) Power supply: cable reel
(See Fig. 4.)

## 5.2 Motion Sequence

(1) Loads ceiling boards onto the board carrier.
(2) Moves the robot to the starting position (first row).
(3) Installs boards in the first row (reference row) in the step and manual modes.
(4) Installs the first board (reference board) in a next row in the step mode.
(5) Perform automatic installing operation.
(6) Moves to a next row.
(7) Repeats (4) through (6) above.
(8) Completes operation.

Fig. 5 shows a flowchart for the above motion sequence.

*Note that since the robot positions boards by moving them in X and Y directions, the boards in the first row and the first board in each row are installed in the step and manual modes, and the remaining boards are automatically installed on the basis of the positions of these reference boards. (See Fig.6)

## 6 BASIC FUNCTIONS

### (a) Board Supplying Method

Ceiling boards are stacked on the carrier. When the robot is at the home position, the uppermost board is feed out horizontally by two claw aircylinders and motorized rollers. The next board is lifted by the thickness of one board by microjacks set up under the board. Boards are loaded onto the carrier manually and are elevated by a lifter at the lowerpart of the carrier up to the feeding level.

(b) Positioning Method

As mentioned earlier, a board is positioned by pushing it in the X and Y directions. When a board is slid in the Y direction, it sometimes interferes with a double furring strip near an adjacent board already installed and thus cannot be pushed forward. Therefore, the sliding process in the Y direction is divided into two stages, (4) and (6), as shown in Fig. 7, and when a board is slid, a part of the board on the installed board's side is lowered with a suction pad to let the board clear the interfering double furring strip.

(c) Screwing Method

In screwing boards, the locations of LGS frames behind the boards were determined with a high-frequency oscillation type, proximity sensor provided on the tip of the screw driver. Distances between the proximity sensor and the LGS frame vary under the influence of changes in the level of the floor on which the robot travels and the level of the ceiling surface, resulting in variation in the detected locations of LGS frames to be screwed on. For this reason, modifications were made to always push up a board with two sets of spring and pressure plate, and maintain the distance between the proximity sensor and the LGS frame for reliable screwing.

(In Fig. 8, $d_2$ remains constant even when $d_1$ changes.)

Depending on the condition of operation, distance $d_2$ can be changed by adjusting the pressure plates. The distance the screw driver moves after an LGS frame has been detected by the proximity sensor can be preset through a timer in an increment of one-hundredth of a second.

As shown in Fig. 9, the screwing sequence is such that after the first row is screwed with right and left drivers, the X table moves forward the handling table, by a screwing pitch input from the operation panel, for screwing operation in the second row. This sequence is repeated until all screws for the board are put in. Input screwing pitches can be set in an increment of one millimeter.

(d) Traveling Method

Originally, LGS frames (double furring strips) along the ceiling surface were to be used as datums for the adjustment of robot movement during automatic operation. Because of some problems, such as the interruption of double furring strips around openings, alternatives were considered.

As a result, an alternative method was adopted. In the method, metal tape (or piano wire or similar material) was to be laid on the floor so that proximity sensors provided on the front wheels controlled the steering of the robot.

The traveling distance of a single step (910mm) was controlled by measuring the rotation of the rear wheels through rotary encoders.

## 7 FEATURES OF THE INTERIOR FINISH WORK ROBOT

- The entire process of supplying, positioning and screwing ceiling boards and moving to next locations is repeated automatically.
- Proximity sensors detect LGS frames behind ceiling boards in order to perform reliable screwing operation.
- Parameters, such as the number of boards to be installed continuously, height of ceiling, and screwing pitches, can be set, depending on operating conditions, simply by inputting from the control panel.
- Following the datum lines laid on the floor, the robot travels on the floor, correcting its path.
- The robot eliminates the need for scaffolds throughout the floor, making for improved safety and efficiency.

## 8 SCOPE OF WORK

The interior finish work robot is intended to automate a conventional, single set of work. From the stage of planning, coexistence with traditional manual work had been considered in order to define its scope of work clearly.

As explained in Section 3, the use of the robot is limited to the installation of standard size boards to the extent that it does not interfere with other structural elements.

Generally speaking, out of a ceiling area of 600m² or more, where the use of the robot is considered to have favorable effect, about 70% can be covered by the robot. The remaining 30% will have to be done manually. About 15% of the total area represents areas where measurement or cutting around columns or along the perimeter needs to be carried out.

## 9 INSTALLING CAPABILITY AND MANPOWER REQUIREMENT

The time required for each step of automatic operation is shown below. Operation continues until all of a preset number of boards or all boards stacked on the board carrier have been installed.

| | | |
|---|---|---|
| 1) Supplying and holding boards (by suction) | : | 11 sec. |
| 2) Lifting up and pushing boards | : | 19 |
| 3) Positioning (X and Y directions) | : | 26 |
| 4) Screwing | : | 118* |
| 5) Returning to home position | : | 24 |
| 6) Moving to a next position | : | 9 |
| 7) Leveling | : | 10 |
| Total | | 217 sec. |

(*It is assumed that 5×7 = 35 screws per board are put in. Screwing pitches (number of screws) are to be input from the operation panel.)

The above means that the installation of a board including its loading onto the carrier takes four minutes.

If the net operation time is assumed to be seven hours per day, the installing capability of the robot is about 170m²/day. If the robot's daily installing capability of 170m² is assumed to be 70% of the area of the ceiling surface, the area that needs to be covered manually is

72m$^2$/day.

A field survey showed that manual installing capability is 93.9m$^2$/worker for standard size boards and 39.1m$^2$/worker for non-standard size boards (based on seven hours per day working time, of which 70% is spent for board installation, and 30% for the relocation and setup of scaffolds, and the handling of materials). This is summarized as follows:

Table 2. Area and installing capability

| working division | | execution area | execution capacity | manning |
|---|---|---|---|---|
| install by robot | | 170 m$^2$ (70%) | 170 m$^2$/unit | 0.7 men |
| install by manpower | regular size | 36 m$^2$ (15%) | 93.9m$^2$/man | 0.38men |
| | cutting size | 36 m$^2$ (15%) | 39.1m$^2$/man | 0.92men |
| total | | 242 m$^2$ (100%) | | 2 men |

That is, the total area of ceiling board installation by use of the interior finish work robot is about 240m$^2$/day. The configuration of a set of robot installation system is as follows:

- Worker : 2 persons
- Robot : 1 unit

(where 0.7 person is to work on the initial positioning for board installation, and the loading of boards onto the carrier).

## 10 PROBLEMS CONCERNING OPERATION

The interior finish work robot has already been run at more than ten construction sites.

During the periods of these operations, several problems concerning the robot's functionality and operating conditions were encountered:

(1) When double furring strips, on which board ends were screwed, were interrupted by openings, such as those for lighting equipment and access holes, the sensor is likely to regard them as abnormal locations, causing the robot to stop on completion of positioning.

(2) Burrs protruding from the ceiling surface on which ceiling boards were installed prevented the boards from being slid along the LGS frame surfaceduring positioning.

(3) When two furring strips were close to each other, the proximity sensor to locate screwing points misinterpreted it as a single strip.

The above problems, however, can be solved by, for example, changing layouts so that double furring strips and openings do not meet during robotized operation.

(4) Inconsistent accuracies of screws used resulted in unsuccessful feeding of screws to the screw driver. Currently, only limited manufacturers and types of screws are used.

(5) When a board was screwed, if the detected position of a double bar deviated from its specified position, the robot came to a halt. This problem can be solved by correcting the position of the double bar in advance.

(6) Since boards were positioned by pushing them against LGS frames and sliding them along, they needed to be pulled away from the ceiling surface temporarily if there was any obstacle protruding from the ceiling surface,such as hanging bolts for lighting equipment and sprinkler heads.

(7) This robot installs ceiling boards while moving straight ahead. Therefore, if a floor is small and has many columns, the number of boards in a row in which continuous automatic operation is possible inevitably becomes small, and work efficiency falls because of frequent changeovers to next rows. On floors where ceiling boards are installed not in a manner shown in Fig. 10 (a), but in a crosswise manner, as shown in Fig. 10 (b), work efficiency greatly decreases.

If robots are to be introduced, therefore, it is necessary to establish such operating conditions, during the planning stage, that enable efficient operation.

## 11 Conclusion

The interior finish work robot has been completed as a robot that can perform automatic operation, while permitting conventional manual work.

The bulky structure of the current machine, however, imposes restrictions on horizontal movement by its traveling system and vertical movement by its lifting system. Hence, the robot makes for efficiency only when the total area of the floor is large enough (600m² or more), and the areas of parts of the floor where automatic operation is possible are large enough.

With this in mind, the authors are working on the design of a manipulator that maximizes the capability of this fully automatic robot, is light enough and can be disassembled for easy handling and high operability even at smaller sites.

Currently, types of boards applicable to the robot are limited to gypsum boards used as ceiling backers. The authors will continue modifications of the robot, including the development of new material, to increase the types of boards, such as decorative boards, whose installation can be robotized. The application of the robot to wall boards will be considered, too.

The authors intend to carry on their study on the improvement of environmental conditions, including the above-mentioned operating conditions, in order to achieve higher work efficiency. It is the authors' sincere hope that the development of this robot will serve as an element technology for future construction automation.

In closing, the authors would like to express their appreciation to all those who provided invaluable assistance concerning experimentation.

## REFERENCES

1) Architectural Institute of Japan. Proceedings of the Sixth Symposium on Organization and Management of Building Construction, 1990
2) Architectural Institute of Japan. Proceedings of the Fourth Symposium on Construction Robotics, July 1990

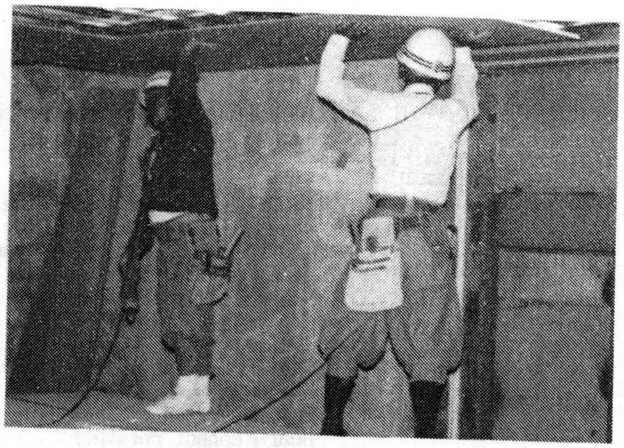


Photo.1. Current method

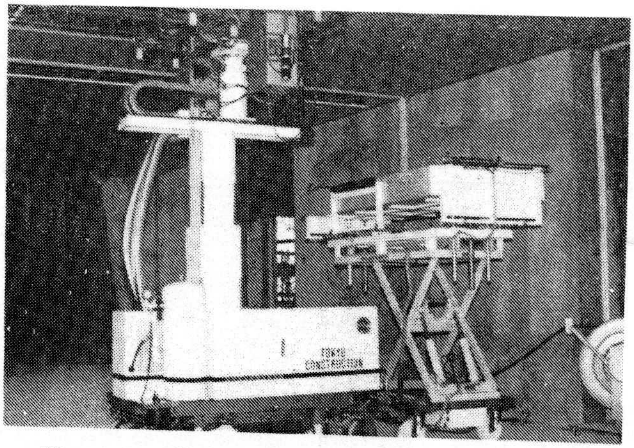
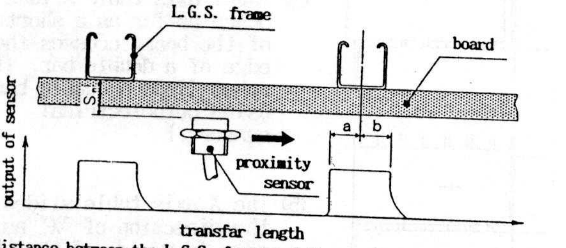
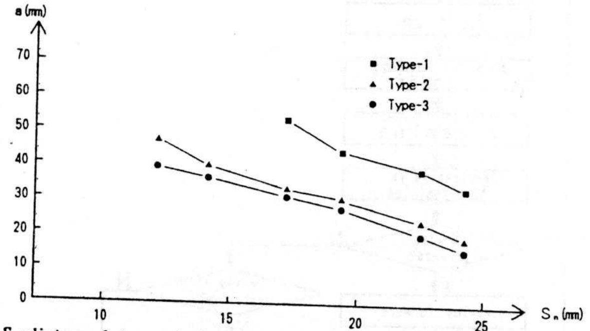


Photo.2. Interior finish work robot



$S_n$:distance between the L.G.S. frame and the sensing point
a:distance between the center of the L.G.S. frame and the sensing point
b:distance between the center of the L.G.S. frame and the return point

Fig.1. Ditection of L.G.S. by proximity sensor



$S_n$:distance between the L.G.S. frame and the sensing point
a:distance between the center of the L.G.S. frame and the sensing point

Fig.2. Result of detectoin by proximity sensor

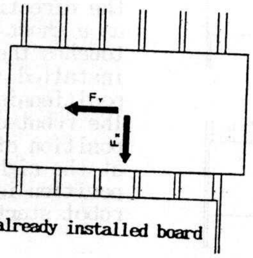


Fig.3. Sliding direction of board

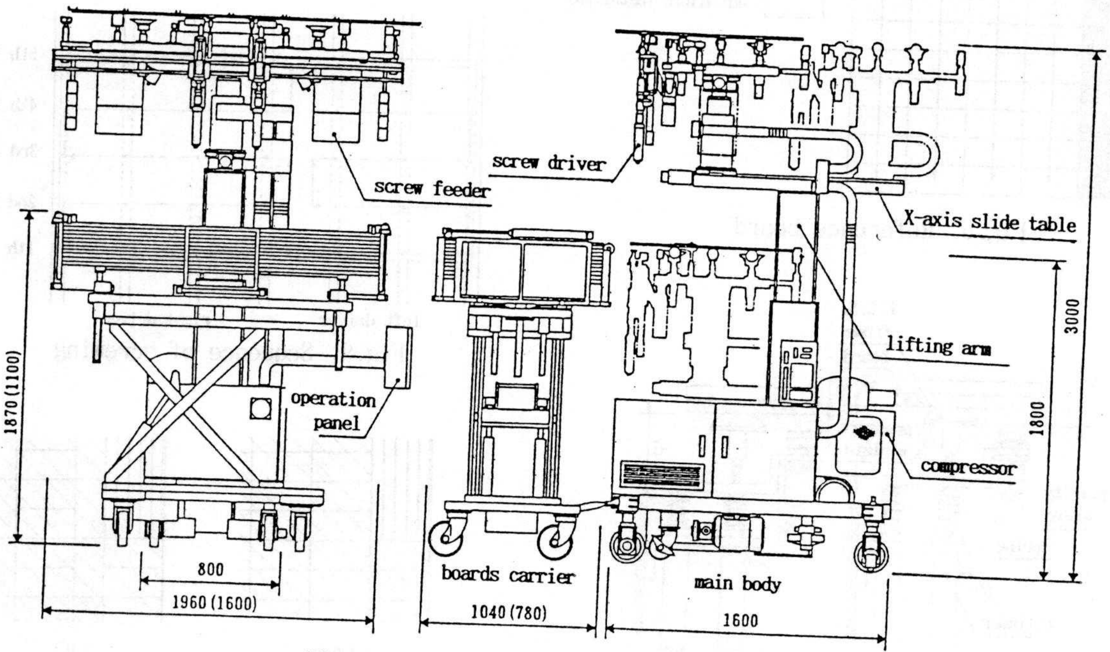


Fig.4. Dimentions and designation

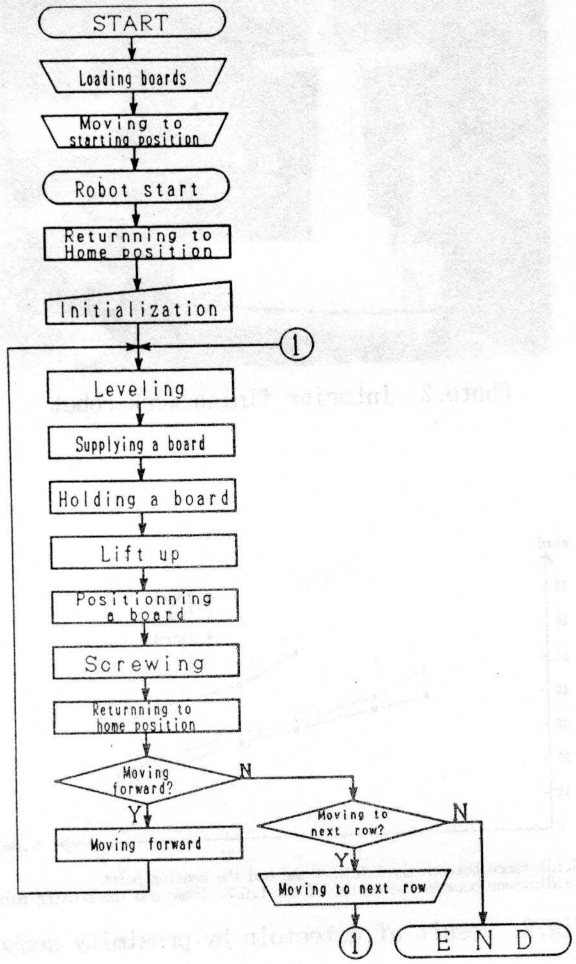


Fig.5. Flowchart

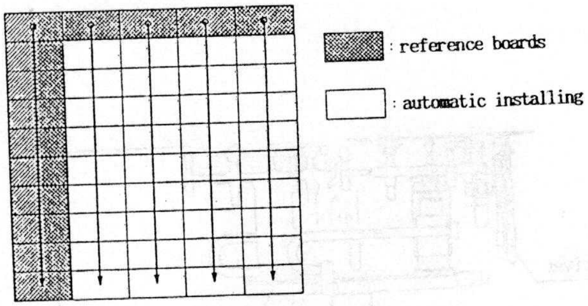


Fig.6. Reference board

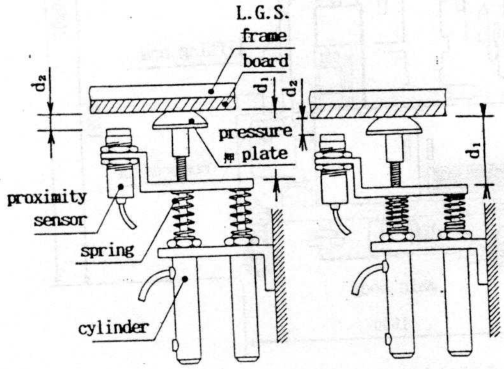
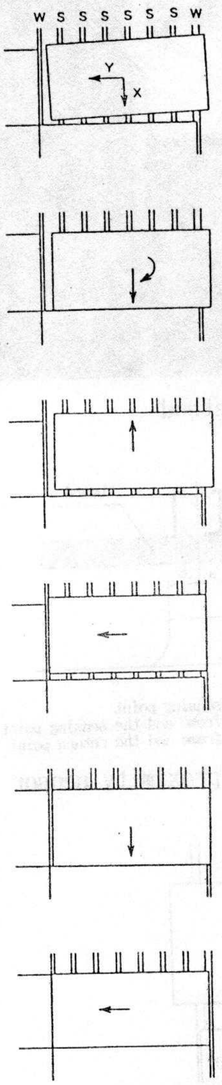


Fig.8. Setting form of proximity sensor



① The situation that the board touches L.G.S. frame.

② The X-axis table slides the board as far as a long side of the board touches the one already installed. (The board can rotate freely.)

③ The X-axis table slides the board as much as 20mm in the direction of "-X". (The board cannot rotate.)

④ The Y-axis table slides the board as far as a short side of the board crosses the edge of a double bar. (The robot finds a double bar by using optoelectrical sensors.)

⑤ The X-axis table slides in the direction of "X" as far as a long side of the board touches the one already installed.

⑥ The Y-axis table slides in the direction of "Y" as far as a short side of the board touches the one already installed. (The end of the positionning.)
The robot detects the position of the double bar at the right side. If the position is correct, the robot starts screwing.

Fig.7. Sequence of board positionning

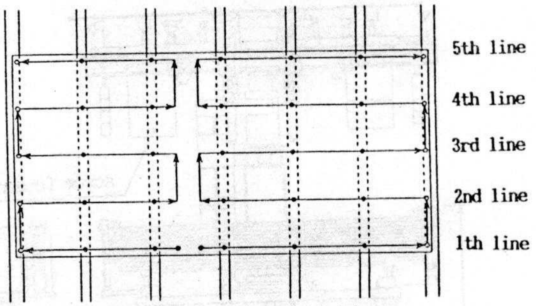


Fig.9. Sequence of screwing

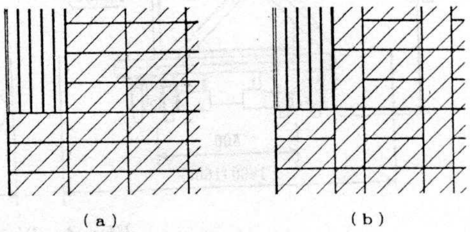


Fig.10. Layout of boards