The 5th International Symposium on Robotics in Construction June 6-8, 1988 Tokyo, Japan

Development of the Horizontal Distributor for Concrete Placing

Hayao AOYAGI, Yasushi SHIBATA

TAKENAKA CORPORATION
Technical Research Laboratory
5-14, 2-chome, Minamisuna, Koto-ku
Tokyo 136, JAPAN

ABSTRACT

The concrete placing method using a pump equipped with pipes and an end-hose has been used extensively. But placing concrete is still, in general, one of the most labor intensive in construction.

The Horizontal Concrete Distributor has solved diverse problems involved in moving the end-hose and relocating pipes.

This robot mechanizes feed hose-nozzle relocation to improve the working environment as well as to save lavor in concrete placing works. The robot is a large manual manipulator with an overall length of 20 meters and four horizontally bendable articulations.

The operating system of the robot is intelligent and sufficiently flexible to respond to any command given by the operator regarding direction of movement. The direction of movement of the nozzle can be input by a single universal lever. When the input is made, the computer determines the shape of the robot so that the nozzle can avoid obstacles such as columns in the vicinity, and the system controls the movement with 4 actuators.

The development of both the automatic nozzle positioner and automatic obstacle avoidance system has greatly improved the safety and the operability of the Horizontal Concrete Distributor, while contributing toward largely improving concrete placing works.

1. Introduction

It is recognized that the production system of the construction industry has been slower to become automated and also is more difficult to automate than those of manufacturing industries.

Concrete placing work is one of the important items of construction work. It is performed with the manual labor of a number of workers. In particular, works at the nozzle tip including moving the nozzled end-hose and resetting pipes are very tough and dirty. Moving the heavy nozzled end-hose around also involves structural quality problems in the way of disturbing created reinforcing bars.

Thus, it is strongly desired to improve and automate concreting work for the purpose of improving the working environment and the quality of structures.

The Horizontal Concrete Distributor (HCD) has been developed to improve and automate concrete distributing work. The HCD is a multiarticulated robot 20 m long, weighing about 3.8 t with horizontal and 2 vertical joints.

The development of the HCD started in 1981 and a practical model started concreting in 1983. The new machines have since been concreted about 120,000 m³ at more than 20 sites. After 1985, to improve operability, automatic nozzle positioning and automatic obstacle avoiding systems were developed.

This report deals with the purposes of development, and outlines the practical model and the automated system.

2. Purposes of development

The development was intended to establish a better method for placing concrete by solving difficulties in the pumping method currently in wide use. Particular stress was laid on liberating workers from hard and dirty work and on improving the working environments and the quality of structures.

3. Basic concept

Concrete placing using a pump includes moving the end-hose around and resetting the pipes. This involves the following problems (Fig.1).

1) Moving the nozzled end-hose around more frequently is more likely to disturb erected reinforcing bars. This is because the hose is too heavy for manual work.
2) The working environment is very bad: work is very hard and workers are subjected to concrete spatters.
3) The working procedures are difficult to standardize. They also involve overly complicated manual work.

Thus, the requirements of development were set as shown in Table 1. Basically, as shown in Fig. 2, new concrete placing works was designed to distribute concrete to any point without touching erected reinforcing bars using horizontal beams equipped with pipes.

4. Practical model

The HCD is a manual manipulator having 4 joints (degrees of freedom) on the horizontal plane and 2 vertical joints. The location and the position of the nozzle are freely selectable, permitting the nozzle to be brought into a narrow space, achieving high operating rate.

The HCD consists of 4 beams, pipes, control panels, a hydraulic drive unit and a base. Table 2 shows its specifications and Fig. 3 and 4 provide its schematic diagram and moving functions respectively.

To reduce weight, the beam has a box structure made of high-tension steel. Joint bearings are made of resin and a hydraulic motor is used for beam moving. Each beam joint is located about 20 cm off the beam center so that the beams can be folded up compactly and conveniently for transport.

The end-hose at the head has 2 links for inclination. This is to avoid obstacles such as equipment piping and bars rising from the floor. The beam at the head is also equipped with a captire winder for the high-frequency vibrator which is helpful in saving labor during compacting work.

The calculations show that the beam system sags about 25 cm at its tip under its own weight. To reduce this drooping, the joints are so designed that each beam is set at an upward angle of about 1.5 degrees.

The pipes, including the end-hose, are 125 mm in diameter, permitting lower slump concrete (about 8 - 15 cm) than conventional to be applied. The joints are hollow at the center through which concrete tubing is passed. This design enables the concrete tube to be removed from the beam, providing ease of maintenance. The tubing has elbows at 7 points and it has been proved that losses in concrete feed pressure are within a range, in terms of distance, about 1.3 times the tubing length (23 m).

The control panels include manual and automatic types. The manual control panel has 4 levers for joint actuators. Beams can be moved by tilting these levers. There is also a switch for inclining the end-hose at the head. The automatic control panel has a universal lever for commanding the moving direction of the nozzle.

The base is designed to be adaptable to machine inclination adjustment and differing column sizes.

Measures taken for the safety of the workers with the HCD are as follows:

1) Strip touch sensors (operating pressure 500 gf) are fitted on the bottom side end of the third and fourth beams. If any of them is touched by a worker, the beam is stopped immediately (Fig. 5).
2) The moving rates of beams are controlled to 0.6 - 0.7 m/sec so that the workers can avoid beams moving at any joints.
3) When a beam is moving, the red lamp at the joint flashes and the buzzer sounds to warn the workers.

5. Concrete placing by manual control

For the order of concrete placing, it is generally recommended to start with walls and columns and then proceed to beams and floors. However, this order is not always followed conventionally because of frequent moving around of the end-hose and resetting of pipes and physical difficulties.

Originally, the HCD could only be operated manually. In manual control, the nozzle is moved by operating the 4 levers. It was expected that this moving required some skill of the operator. So,a survey was made to see how the HCD was operated by manual control.

As a result, it was found that where there were relatively few obstacles beams were moved very smoothly (Photo 1). The trace of nozzle movement showed that concrete placing started with walls and columns (Photo 2) and proceeded to beams and floors very finely over the full area (Photo 3). Each displacement of the nozzle during concrete placing averaged about 60 cm. This shows that the nozzle can be moved more finely by the HCD than by the conventional end-hose handled by the worker.

However, it is a great psychologically burden on the operator to move the nozzle and avoid obstacles such as columns and walls under manual control. Furthermore, it is difficult, with some shapes of beams, to operate the 4 levers. This raised strong demand for the development of an operating system designed to avoid obstacles such as columns automatically.

6. Automatic system

Under manual control, it was difficult to position the nozzle and operate the beams to avoid obstacles such as columns and walls. Thus, to improve operability, a system was needed to automatically position the nozzle and avoiding obstacles.

6.1 Basic planning

The system for automatic nozzle positioning and automatic obstacle avoidance was designed as a one-lever type that is easy to operate, and is highly flexible so that alterations in the order of concrete placing are allowed. The common method of preliminarily simulating the route of concrete placing is not the answer to actual working situations today where various jobs are combined together. The one lever system is a command system which enables the operator to move the nozzle in a desired direction by tilting the lever in the same direction. Given a command, the computer operates a beam shape for avoiding obstacles on the route the nozzle is moving and control the joint actuators accordingly (Fig. 6).

In addition to the 4 horizontal joints, the HCD has 2 vertical joints for inclining the end-hose at the head, while this system controls the 4 horizontal joints directly related to positioning and obstacle avoidance.

6.2 Recognition of obstacles

Two systems can be used to detect obstacles: One using external sensors such as ultrasonic, proximity and color and the other using internal sensors which check the situation of the machine itself with such devices as encoders with an obstacle map stored in the system.

The external-sensor system is excellent and widely applied in robots. However, where beams move in a bent position on a horizontal plane as in HCD, it is necessary to distinguish the beams from obstacles, which is a very complicated process. On the other hand, the internal-sensor system which has obstacle maps is easier to use provided that the shape of the beam system can be recognized accurately.

The present automatic system employs the internal-sensor system.

6.3 Structure of system

The system consists of an input section for moving directions, an arithmetic section for shapes, a control section for actuators and a data file for obstacles (Fig. 7). When the moving direction of the nozzle is input by a single universal lever, the moving direction input section outputs a signal for the moving direction to the arithmetic section for shapes. The arithmetic section for shapes simulates the shape of the beam on the route of the moving nozzle and outputs the operating data including displacements and moving rates of the joints to the actuator control. In accordance with the results of operation at the arithmetic section for shapes, the actuator control synchronously controls the 4 axes in a manner similar to continuous path control so that the nozzle moves along the prescribed route. The obstacle data file has data on the locations, sizes, etc. of obstacles such as columns and walls in the work area, which are memorized by the shape arithmetic section at the start of the system's operation.

(1) Moving direction input section

There are two methods for inputting moving directions with one lever using a stationary or moving coordinate system (Fig. 8).

With the stationary coordinate system which uses the datum lines of the building as its reference, the lever-input direction consistently agrees with the moving direction of the nozzle, irrespective of the position of the head beam. This input method is suitable if the operator gives commands down near the nozzle outside the cabin of the HCD or at a remote place. With the moving coordinate system which uses the position of the head beam as a reference point, the moving direction of the nozzle, with the same input position of the lever is varied depending on the position of the head beam. This method is suitable where operator stays in the HCD cabin when giving commands.

(2) Shape determining section

Since there are 4 degrees of freedom, no beam shape can be determined univocally simply by specifying the location of the nozzle. Thus, an algorithm which meets several requirements was developed for shape determination. The requirements are: the movement of the entire beam must be smaller than that of the nozzle, the beams must be able to avoid obstacles smoothly (Fig. 9). Beam shape simulation is performed at each step (about 20 cm) along the desired course of the moving nozzle. Simulation starts with the algorithm mentioned above which operates a beam shape with no obstacles taken into consideration. Then, the block for obstacles in which the beams are located is extracted and it is checked whether or not the beams will hit the obstacles (Fig. 10). If it is judged that they will, the beam shape is modified by finely moving specific joints of the HCD and a check is performed again likewise. When a beam shape which will avoid obstacles is determined, the displacements and directions of the joints etc. are operated.

(3) Actuator control section

The control section consists of an axis control, an oil flow control, normal/reverse rotation switching control, and a sensor unit for location and speed control, and absolute location detection (Fig. 11). In order for the nozzle to move along the desired course in accordance with the results of the operation at the shape determining section, feedback sensors including angle detectors and a 16 bit control computer are combined into a servo-system to control the displacements and moving rates of the actuators.

The axis control is consistently designed to hold 2 sets of commands (results of simulation) to smoothly control speed variations. In addition, during axial control, the operator can stop the beams at the current point by cancelling control.

(4) Obstacle data file

An interactive input system using a personal computer together with working drawing was developed on the assumption that the preparation of the obstacle data file performed by site personnel.

Although obstacles to be avoided may have various shapes, the system handles 3 categories: circles, rectangles and segments. Columns, etc. are treated as circles or rectangles and walls and large obstacles as segments. Input data for obstacles treated as circles and rectangles are safety factors of dimensions by operating with real dimensions, overall dimensions and X-Y dimensions from the intersection of the center lines. Input data for obstacles treated as segments are the coordinates for both ends of segments moved to the safe side.

The obstacles in the work area are preliminarily basketed in suitably sized blocks, each within one block without extending over two.

7. Performance check for automatic system

There are two aspects to the performance of the system: software and hardware. For the software performance, various simulations were made to check beam shape determination and obstacle avoidance. The system's performance including hardware aspects was checked with an actual model. The actual model used for this purpose was 18 m long, weighing 4.5 ton and was driven by a hydraulic motor.

Such factors as nozzle/joint positioning accuracy depend on the mechanical properties of each model. On the other hand, they affect the safety factors of obstacle dimensions during the operation of shapes. If the control accuracy is low, for example, obstacle dimensions must be treated as being larger than the actual dimensions, resulting in a disadvantage to the HCD, which fails to show its full performance.

Positioning accuracy was judged by the level of the deviation of the actual location from the arithmetic reference point. The positioning accuracy of the nozzle after one motion with reference to the starting point was within ± 10 cm. The nozzle positioning accuracy after a series of movements on the reference of the starting point was controlled to within about ± 20 cm (Fig. 12).

Synchronous control of the actuators is essential for the beams of the HCD to avoid obstacles as simulated. Should the axes fail to move during one step of beam movement from one shape to another, no operation for obstacle avoidance by simulation would be ensured. When the axes are moved synchronously in accordance with the results of simulations at several 10 cm intervals on the course of the nozzle, the nozzle draws on almost straight trace. Deviations of nozzle traces from straight lines were varied depending on the shapes of beams, but generally measured about 7 cm or less. This shows that the 4 axes are controlled synchronously, proving that obstacles can be avoided in accordance with the results of simulation.

Repetitive nozzle positioning accuracy was determined by nozzle movement under a command for continuous round travel on the sides of a square, each about 2 m long. The results of the measurements showed that in movement in the same direction, deviations were limited to ± 10 cm. When the moving direction was changed, deviations increased because of mechanical factors such as gear backlashes, but the original locus was resumed in the course of additional movements in the order of several tens of centimeters.

Among mechanical properties gear backlashes affect synchronous control and the insensitive range of the hydraulic system with respect to very small oil flow affects positioning accuracy etc. To prevent additive errors, this system has feedback sensors mounted on the joints.

A comparison of operability between manual and automatic systems revealed that in the manual mode, the nozzle moved in a trial-and-error fashion, which was not observed in the automatic mode. This shows that skill savings, and also time savings, were achieved in operation (Fig. 13).

The above confirmation proves that the system has sufficient control accuracy to avoid obstacles automatically and meet requirements for nozzle movement during actual concrete placing.

8. Concrete placing by automatic system

The automatic system was mounted on a practical model 20 m long and weighing 3.8 ton for use in actual concrete placing.

The work site was the 7th to 10th floors of an office building as shown in Table 3. The amounts of concrete placed daily were about 270 m^3 on the 7th through 9th floors and about 340 m^3 on the 10th floor. Manual mode operations were only used on the 7th floor and both the manual and automatic modes were used on the 8th through 10th floors.

Nozzle movements of the HCD during concrete placing are provided in Fig. 14.

The automatic system was used in blocks which contained many obstacles leaving small work spaces and making nozzle movement difficult. the manual system was used on beams and floors which contained, fewer obstacles, permitting easy nozzle movement, and on interior of obstacles which could not be reached by the automatic system.

Thus it was found that at the work sites surveyed, the manual and automatic systems were used selectively where they are most suitable.

9. Conclusion

The HCD was developed to improve and automate the work environment for concrete placing. It has been widely applied, finding a place at concrete placing sites, though very slowly. The development of the automatic nozzle positioning and obstacle avoidance system aimed at skill saving and higher safety during operation proved very effective in improving the performance of the Horizontal Concrete Distributor.

We express our sincere thanks to those concerned who offered valuable suggestions and assistance in the development of the new system.

Reference

H. AOYAGI, et al: Development of the Horizontal Distributor by Concrete Placing vol 1 Vol 5., 1983 - 1987
Presented at a meeting of The Architectural Institute of Japan.

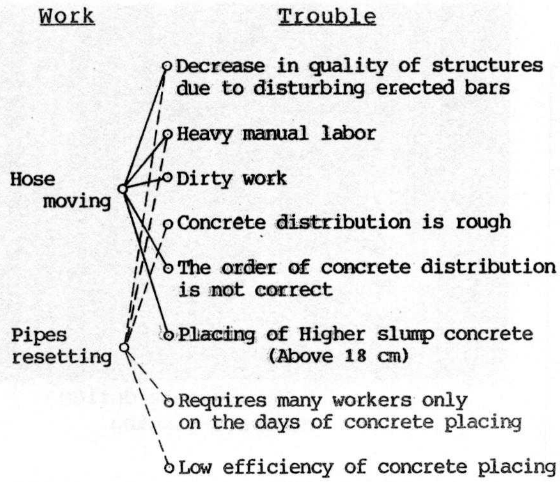


Fig. 1 Difficulties in pumped concrete placing

Table 1 Requirements

Quality	No disturbance of created bars
	Fine distribution of concrete
	No ill effects on forms
	Hard concrete must be used (Slump 8 - 15 cm)
Cost saving	
	Fewer workers
Higher efficiency	Liberation from heavy,dirty work
	Less work required for carrying tools
	Effective use of pump cart capacity
Universality	Ease of detaching and movement
	No need for special operator

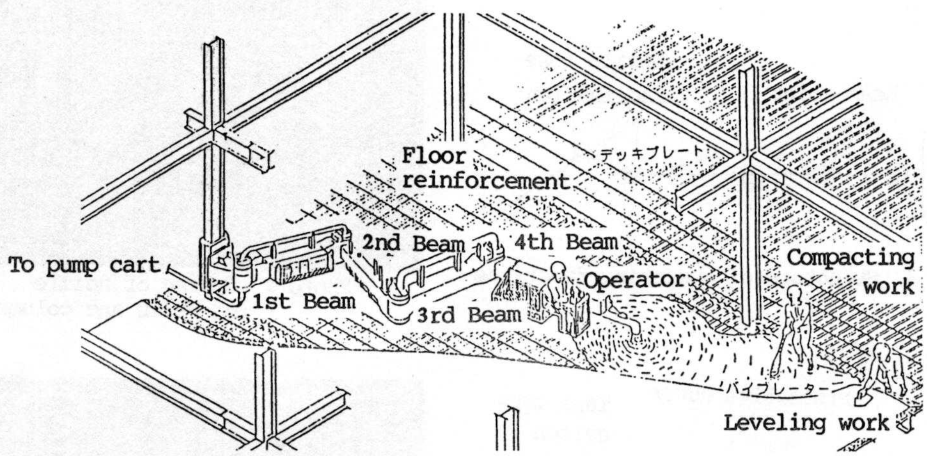


Fig. 2 Basic concept

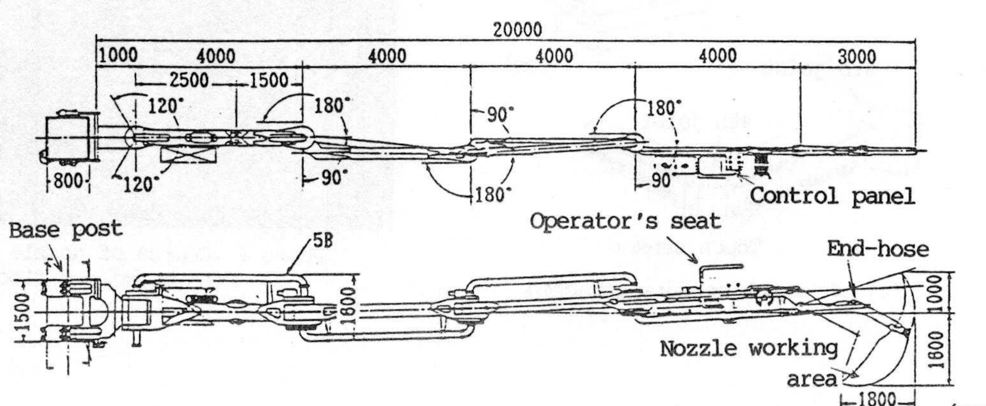


Fig. 3 General structure of practical model

Table 2 Specification of the HCD

Total length	20 m (beams: 4 m,7 m)
Weight	3,500 kg/800 kg
Hose gage	125 mmϕ
Joint drive	Hydraulic motor
Operation	Manual : 4 levers Automatic : 1 lever
Sensor	Touch sensor Rotary encoder
Power unit	5.5 Kw, 3-ph 200 V
Working area	about 1,000 m²

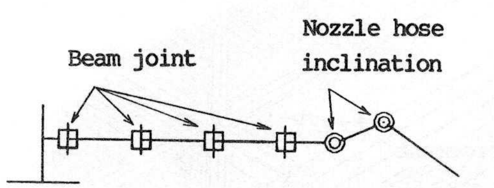


Fig. 4 Structure of operating functions

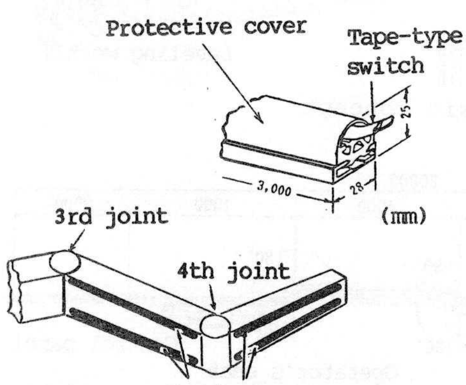


Fig. 5 Touch sensors attached

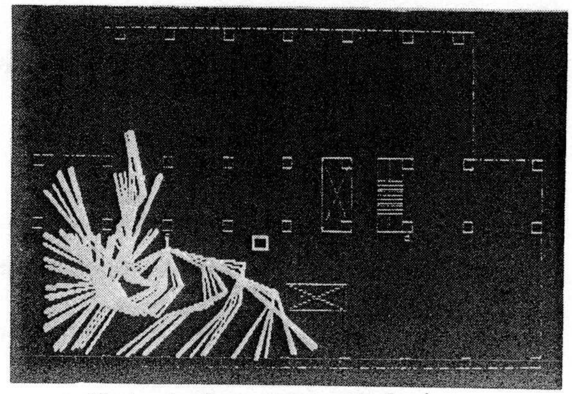


Photo 1 Beam movement during concrete placing

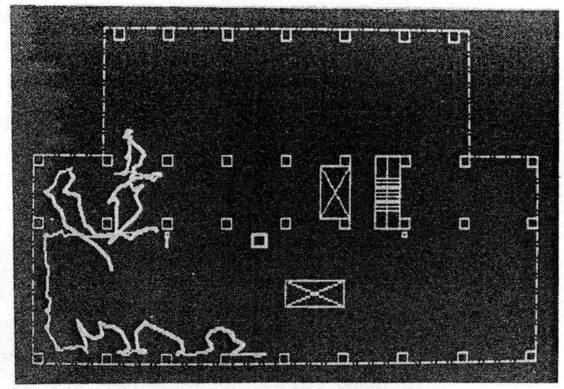


Photo 2 Course of nozzle (on walls and columns)

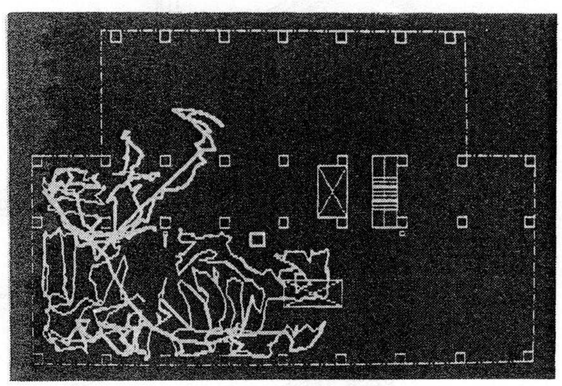


Photo 3 Course of nozzle (on beams and floor)

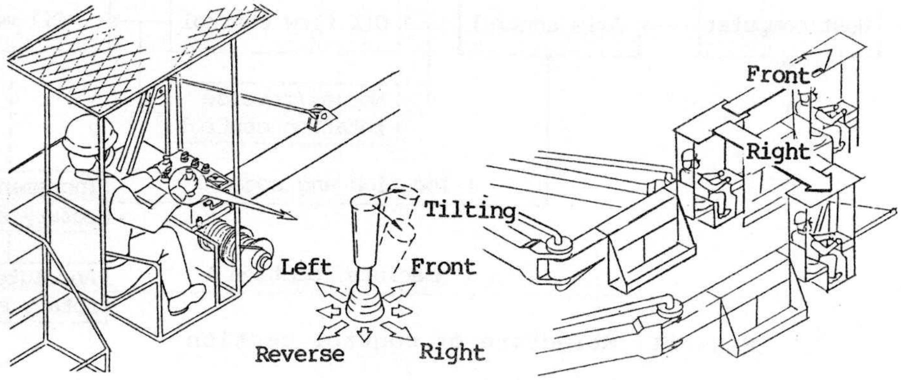


Fig. 6 Basic concept of operating system

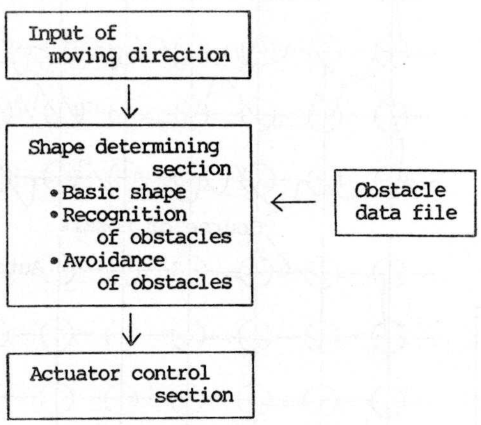


Fig. 7 Structure of system

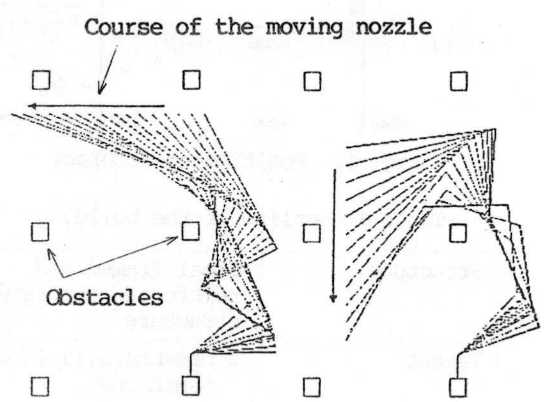
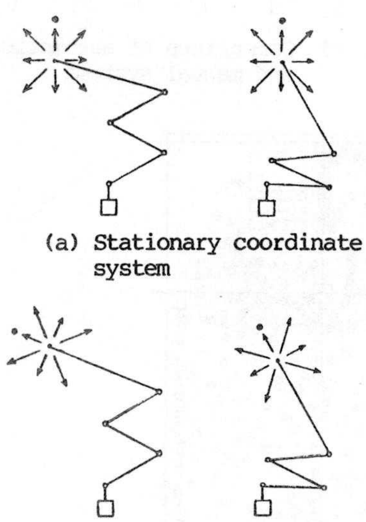


Fig. 9 Beam shape determination



(a) Stationary coordinate system

(b) Mobile coordinate system

Fig. 8 Input mode for moving direction

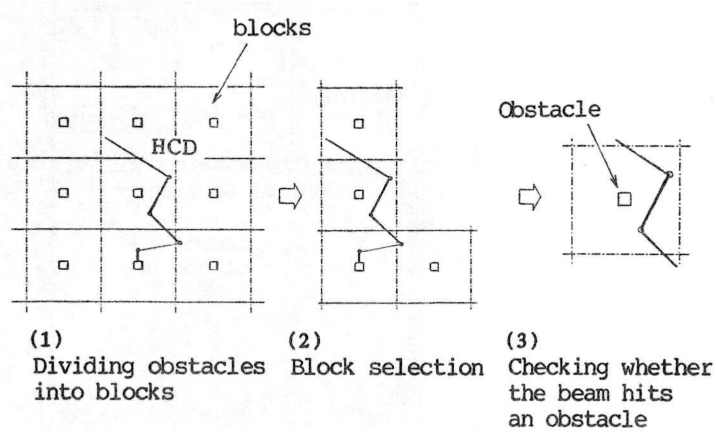


Fig. 10 Check of hitting obstacles

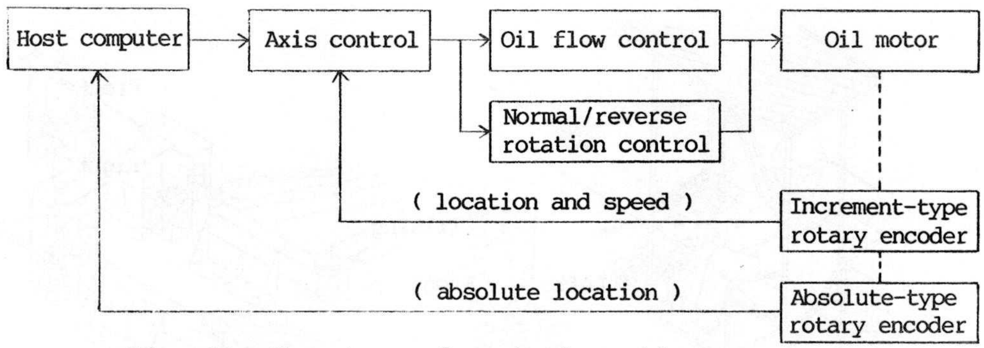


Fig. 11 Structure of control section

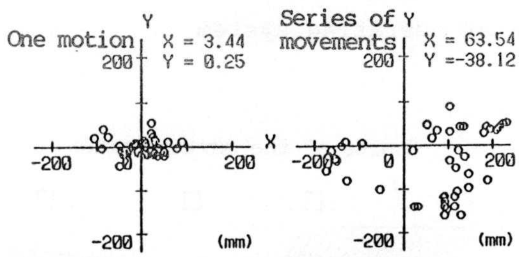


Fig. 12 Positioning accuracy

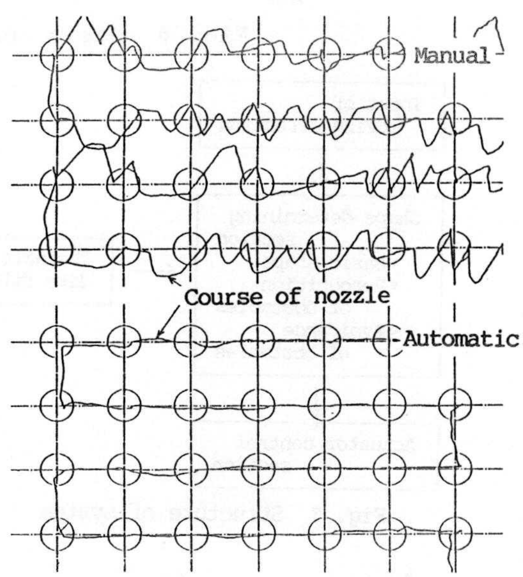


Fig. 13 Comparison of automatic and manual systems

Table 3 Outline of the building

Structure	Steel framed and reinforced concrete structure
Extent	2 basements,13 floors penthouse
Building area	2,540 m²
Total floor area	21,740 m²
Principal use	Office, hotel, stores

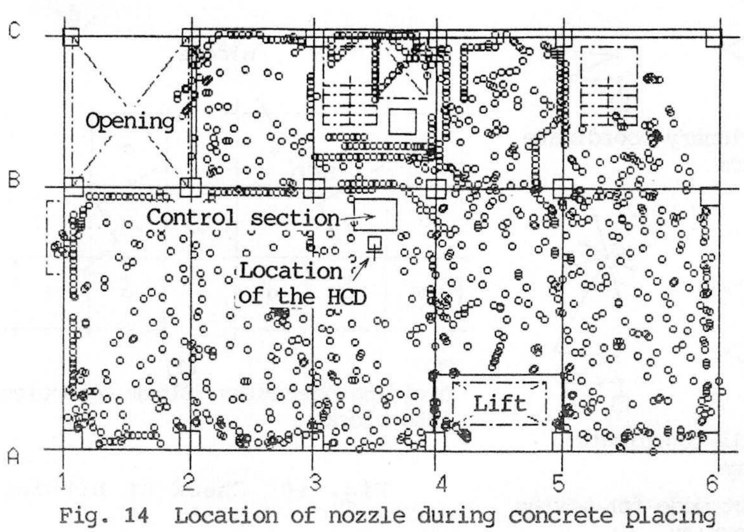


Fig. 14 Location of nozzle during concrete placing