Rationalization of Asphalt Paving Work Using Robot Asphalt Paver: Image-Processing, Fuzzy-Controlled Paver

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A robot paver equipped with image processing system and fuzzy computer controls was developed, resulting in labor savings, reduction of skilled labor and hard manual work, and rationalization of asphalt paving work. Because the paving conditions in Japan change frequently, considerable labor is necessary for paving operations, such as control of paving thickness and width, asphalt mix feeding, and steering operations. This demands a heavy work load and a high level of skill of operators and screedmen; it also affects the work load of subsequent manual operations, such as shoveling and raking. To solve these problems, a robot asphalt paver was developed. By analyzing construction work factors, this total system paver automates, preprocesses material transport, and postprocesses manual operations (such as shoveling and raking). The features of new automatic functions applied to the robot paver are (a) automatic feeding of asphalt mix to the working equipment, (b) automatic control of the paving thickness, (c) automatic screed extension control, (d) automatic steering control, and (e) semi-automation of asphalt-mix receiving process.

The general trend of skilled and experienced workers aging and leaving the workforce, young workers dropping off from the construction industry, and the rapid aging of the workforce continues in Japan. Although road paving work is called mechanical work, the paver has to be operated by two to three skilled operators, and this working system has remained unchanged until today. Also, about seven to eight workers, including rakers, shovelmen, and a supervisor, are usually arranged around the paver. Paving work is still a labor-intensive operation depending on manual workers and skilled operators. Japan’s paving industry has various aspects of work-related problems, and it still strongly depends on manual labor and skilled operators.

To solve these problems, the authors have jointly developed a one-man robot asphalt paver with the aim of labor savings and lowering of the level of skill required by the operator. The robot asphalt paver is a total system that automates the preprocesses (material transport), the self processes (asphalt paving), and the post processes (manual operations such as shoveling and raking).

DEVELOPMENT TARGETS

Analysis of Existing Work Processes

The current construction practice with a conventional paver was analyzed to determine the development targets.

- Analysis of current paving work processes. The functions of the conventional paver, operators, screedmen, and workers were analyzed using industrial engineering (IE) techniques and videotaping the paving conditions.
- Performance survey of the paver and finish. Paving work was conducted only by operators and screedmen, and the effect on the operations of the operators and screedmen and on the finish were surveyed.
- Investigation of the operational functions of the paver.

Operators and screedmen were surveyed regarding the operations under various working conditions, and the level of difficulty of machine operations was investigated.

Current Construction Practice

The following problems were identified quantitatively from the results of the analyses:

- The steering and asphalt mix feeding operations account for a large percentage of the work. These two difficult operations are performed simultaneously by the operators and require a high level of skill.
- Transverse movements of the screedman to control and adjust the screed extension are frequent, and the workload is heavy.
- To ensure a satisfactory level of finishing accuracy, the work heavily depends on rakemen and screedmen for manual labor in the postprocesses.
- The overall work efficiency decreases during the docking of the paver with the dump truck to receive the asphalt mix.
- Irregular work (manual work) occurs at the beginning and the end of the paving work (tapering to the existing road), resulting in a peak work load for the workers.

Functions

From the problems in the current construction, irregular work is a problem that cannot be avoided during construction, but others are problems related to functions of the conventional paver. Therefore,
these points were taken up as targets for development, and five elements of automation were selected as the functions to be developed, namely: (a) automatic feeding of asphalt mix, (b) automatic control of paving thickness, (c) automatic extension of the screed, (d) automation of steering operation, and (e) semi-automated receiving of asphalt mix.

**DEVELOPED CONTROL SYSTEM**

The automatic functions of each equipment developed are given below.

**Automatic Ultrasonic Type Feeder for Asphalt Mix**

Figure 1 shows the automatic feeding system for asphalt mix. The automatic ultrasonic type feeder (proportional control system) is fitted with ultrasonic sensors at four locations, as shown in Figure 1. The speeds of the left and right bar feeders and screw and the rotation of the extension screw are controlled by the computer to obtain uniform feed of material over the entire screed width. If the feed quantity of the asphalt mix is inadequate, an alarm rings and the motion stops.

**Automatic Control System for Paving Thickness**

The automatic control system for paving thickness consists of the automatic system for indicating paving thickness and the automatic system for adjusting paving thickness. Figure 2 shows the automatic control system for paving thickness.

**Automatic System for Indicating Paving Thickness**

This system consists of two ultrasonic sensors fitted on the left and right sides of the leveling arm; inclination sensors; travel distance sensors; and a computer that records, processes images, and displays data. It measures the paving thickness automatically all the time and displays the values on the monitor by the driver's seat. The control mode can be selected from the thickness priority control mode based on the height above the subgrade level, and the level priority control mode based on the height above the structure.

Figure 3 shows the algorithm for measurements of paving thickness. The paving thickness $T$ at point $B$, when the robot paver travels a distance $M$ from Condition 1 to Condition 2 is:

$$T = H_2' + \delta - M \tan \theta' - H_0$$

Condition 1—Measures and calculates the difference in subgrade levels, $\delta$, $B$, and $C$. Since

$$H_1 + \delta = H_2 + M \tan \theta$$

$$\delta = H_2 - H_1 + M \tan \theta$$

is calculated.

**FIGURE 1** Automatic feeding system for asphalt mix.
FIGURE 2 Automatic control system for paving thickness.

FIGURE 3 Paving thickness measurement.
Condition 2—If the paver travels a distance \( M \) only between \( B \) and \( C \),

\[ H_2' + \delta = H_0 + T + M \tan \theta' \]

The paving thickness is calculated as:

\[ T = H_2' + \delta - M \tan \theta' - H_0 \]

Automatic Adjusting System for Paving Thickness

This system consists of the side level control device and paving thickness priority control device. The data of the first and second height sensors, the inclination sensors, the travel distance sensors, and the side level sensors are processed by the computer; the pivot cylinder is activated; and the paving thickness is controlled. Figure 4 shows the control block diagram.

Image Processing System Used in Automatic Screed Extension and Automatic Steering Control Systems

Automatic extension screed and steering control systems were developed considering relevancy with the control system and the following points:

- To aim for labor savings by using existing structures, lines, and chalk lines as references, and to eliminate the need for new reference settings;
- To use the same sensor for sensing all objects that can be used as references; and
- To use common sensors for automatic screed extension control and automation of steering, thereby minimizing the number of sensors.

Based on the conditions mentioned above, a sensor that uses laser beams and a CCD camera (hereafter called “road-eye”) was developed. The road-eye detects the edge when there is a level difference in the reference line. For flat reference lines, such as chalk lines, only the CCD camera is used, which detects the reference line by bright and dark binary values of the image.

Figure 5 is an example of using a curb stone as the reference line. A laser slit beam is projected from the front side of the curb stone. The CCD camera captures the image, and the computer processes the image. In this image, the edge of the curb stone can be detected because the laser slit beam is at a different level.

Automatic Extension Control Device for Screed Using Image Processing

Figure 6 shows only the screed part of the robot asphalt paver and its motion with time. Sensors are installed at two locations: the front
end (Sensor A) and the rear end (Sensor B) of the screed end plate. Both sensors are controlled so that they are always inside (paving side) of the reference line; this is to prevent collision when the reference line is a structure and to prevent the spilling of material outside the reference line when other materials are used as reference lines. Figure 7 shows the block diagram of the control system.

### Automatic Steering Control System Using Image Processing

The sensor used to measure the azimuth angle deviation of the robot asphalt paver is the road-eye. The sensing position is behind the swiveling shaft center of the vehicle body, and the road-eye moves opposite to the steering direction at the start of the steering operation. The steering angle must be changed according to the displacement of the line of travel from the reference line. Under these conditions, fuzzy control was used because framing of control rules by numerical functions was considered difficult.

Figure 8 represents the fuzzy control input/output unit. Fuzzy deduction is performed using three types of input data in fuzzy control, and the steering angle is determined. The two fundamental rules for fuzzy control are

- **Variable value travel control.** This rule defines the approach of the screed end plate toward the reference line. The robot paver travels along the reference line according to this rule. In Figure 9, when the distance between the front Sensor A of the screed end plate and the reference line is taken as X1, and the distance between the rear Sensor B and the reference line is taken as X2, steering control is performed according to this rule such that the deviation in both X1 and X2 is 0.

- **Parallel travel control.** This rule ensures that the screed end plate is parallel to the reference line. This rule is effective and contributes to attaining a good finish of the paving surface and in suppressing overshoot. In Figure 9, steering control is performed so that X1 equals X2.

Computer simulation was performed for determining fuzzy rules and creating membership functions. The effects of the control rules were verified and then applied to the robot asphalt paver.

By applying computer simulation travel, it was possible to reduce the time needed to create rules and membership functions, and to minimize the risks of malfunctions; debugging of actual machine; and disturbances, such as tire slips, that hinder the creation of rules and membership functions.

Figure 10 is an example of the computer simulation screen, showing the locus of travel during automatic steering when the sensor on the right side of the vehicle was brought in line with the curb stone (dotted line), and the vehicle was steered from a straight line course to a right curve.
Semi-Automated Dump Truck Guidance

A large indicator panel was installed in the robot asphalt paver by the driver's seat. The indicator panel has two modes: the docking mode with the dump truck and the material feeding mode. The modes are switched automatically. During the docking mode, the distance remaining to the stop position is displayed on the indicator panel by the distance sensor. When the stop position is reached, "STOP" is displayed on the panel. The robot paver operator can dis-
play the lateral displacement on the indicating panel by pressing a button. If a person or an object comes between the dump truck and the robot paver at this time, an alarm rings. During the material feeding mode, instructions for dump-up, dump-down, and release can be displayed by pressing a button.

**OUTLINE DRAWING OF THE ROBOT PAVER**

Figure 11 shows the outline drawing of the robot paver. The robot paver has the following features:

- Total weight of 13,000 kg,
- Overall length of 6,700 mm,
- Overall width of 2,499 mm, and
- Engine power of 66 Kw/2,000 rpm.

**ON-SITE WORK**

Actual field trials were conducted on National Highway 45 to test the adaptability of the robot paver for on-site work, evaluate developed functions, and verify the degree of rationalization of the work.

There were curvatures of 120 m and 200 m, and the width of the road varied from 6.5 to 7.0 m at the test site. The mix used was recycled, gap-graded dense asphalt concrete, which in recent years is used in the surface layer for repair work in cold regions with heavy snowfalls.

**Working Method**

The cut-and-cover method generally used in conventional repair work in Japan was used as the working method. Because the trial work was to be carried out similar to that of repair work, one-half of the road was kept open for traffic while work was performed on the other half of the road. The work was carried out in accordance with the common specifications of the Ministry of Construction. Construction control standards for ordinary work were followed also.

**Arrangement of Workers**

Figure 12 shows the arrangement of workers for the paving work. Because the work involved repairs, the arrangement of workers around the robot paver was similar to that used in conventional work, and the possibilities for cutting down various manual operations and reducing heavy manual labor during the operation of the robot paver were investigated.

**Items Investigated and Descriptions**

Table 1 provides the investigation methods and descriptions of the robot functions.
Results

For evaluating the performance of the paving, paving thickness, surface smoothness, cross-section profiles, accuracy of the paved ends, and conditions of the paved surface were evaluated. Figures 13 and 14 show part of the results. The thickness of the paved layer is controlled so that the difference between the values indicated on the monitor and the actual values is within ±3 mm.

The accuracy of the paving ends is controlled to ±5 mm with respect to the reference line. It was confirmed from the field trial that satisfactory control accuracy could be obtained. During the processing of the end parts of the construction joints by the center side, automatic screed extension and feeding of the asphalt mix were satisfactory, and finished shapes also satisfied the required quality without using auxiliary workers. Possibilities of reducing the number of auxiliary workers were also confirmed. A satisfactory paved surface was obtained during the winter time in spite of the heating effect of the screed and asphalt mix. The surface smoothness and density satisfied the construction control standards, and there was no problem in paving quality.

A survey of the workers after the work was completed confirmed that the work load of the workers was cut down drastically, despite the fact five auxiliary workers performed the work.

CONCLUSION

The authors have verified labor savings, reduction in skilled labor and hard labor, and effective rationalization of work from the results of the field trials of the robot asphalt paver. The authors will improve the robot paver to adapt more effectively to the site conditions and work toward its perfection so that it becomes a commercially viable product.

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<td>Confirmation of feasible range of automatic control work</td>
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FIGURE 14 Automatic screed extension accuracy.

REFERENCES


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