Next Generation Construction Production System: On Automated Construction Machinery

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ABSTRACT: Kajima Corp. has been pushing forward the research and development of the next generation construction production system named A⁴CSEL® (Quad-ACSEL: Automated/Autonomous/Advanced/Accelerated Construction system for Safety, Efficiency, and Liability) focusing on automation of construction machines for the dealing with "lack of labor, shortage of expert", "the low construction productivity", "the numerousness of work-related accident and the construction work in the disaster or danger area" that are urgent problems in the construction business in Japan. In this paper, we report on the implementation situation of applying the next-generation construction system constituted of two types of automatic construction machineries in the dam construction. As the result of applying the actual construction, we were able to demonstrate the following:
• It was possible to operate two automatic vibration rollers simultaneously by one worker.
• Running accuracy of the automatic vibration roller during compaction work was within ± 10cm.
• It was possible to spread RCD(Roller Compacted Dam) concrete with an error of about ± 10cm compared to the set shape using the automatic spreading system.

INTRODUCTION

In view of the aging and shortage of skilled workers, continuous decrease in total number of construction workers, and further reductions in budget for construction projects, it is essential to improve the productivity at construction sites; in other words, to execute construction work with fewer workers without loss of quality. Radical countermeasures to reduce work-related accidents are also highly desired. These have been important issues in the construction industry for a long time. In response, we are developing a next-generation construction production system...
focusing on automation technologies for construction machines. Figure 1 illustrates the concept of A^4CSEL®
(Quad-ACSEL: Automated/Autonomous/Advanced /Accelerated Construction system for Safety, Efficiency, and Liability). The features of this construction production system are: development of automatic construction machines based on general-purpose construction machines, not on dedicated machines such as construction robots; accumulation of data on driving operation by skilled workers as the basis for performing automatic operation; and realization of safe and efficient construction where relatively few workers operate many machines; more specifically, where workers prepare a flexible work plan according to the conditions while automatic construction machines perform routine work. These features are outlined below.

1. Development of autonomous type automatic construction machines

Information-oriented construction systems utilizing ICT are being actively introduced mainly in large-scale construction and dam construction. Examples related to construction machines include: “3D-MG” or “3D-MC” construction technology that checks the design data at the position of a specific construction machine measured using GPS and enables unskilled operators to execute construction work with high precision, for example, by issuing an instruction to a bulldozer regarding the blade height or by automatically controlling the height; and the “filling and compaction control system” control technology that evaluates the work quality based on area data and number of compactions obtained from the travel trajectory of a vibration roller and submits the information to an operator. Streamlining and increased efficiency using these technologies have been reported.

We are developing construction machine automation technology to overcome the decrease in skilled workers and total number of workers as well as to improve safety at construction sites based on the above technologies for maintaining or improving the construction efficiency, but with as few workers as possible. The construction work handled by A^4CSEL® is earthwork using heavy equipment, typical examples of which are dam body construction and large-scale land development as shown in Figure 2. To realize the concept shown in Figure 1, it is necessary to automate many types of construction machines, which we are developing in turn.

As the first stage, we recently developed an automatic compaction system and an automatic spreading system in which automation equipment and measurement control equipment are retrofitted onto general-purpose vibration rollers and bulldozers. Here,
we outline the automatic construction system developed and the results of its test application at a roller-compacted dam (RCD).

![Image](image.png)

FIG. 2. Target construction example of A'CSEL

2. Automatic compaction system

(1) Outline of development

As the first step to realizing an automatic construction system for compaction, a general-purpose vibration roller was automated. An automatic vibration roller operated by control commands based on measurement data was created through remodeling in which measuring equipment and automation equipment (described later) as well as a PC for measurement control was retrofitted onto a general-purpose vibration roller. A system that performs the following automatic operation was realized: The operator, who prepares a plan and issues instructions to the automatic vibration roller, wirelessly transmits work instructions, e.g., the scope of construction and work specifications set up on a tablet PC. The PC for measurement control on the automatic vibration roller then sets a travel path automatically.

When introducing this system at a construction site, we focused on safety measures because this was the first case of introducing an unattended machine at a general construction site. This is an automatic operating system with functions for handling construction situations where the workers, this machine and other machines come and go in a complex manner. For example, this system always measures the shape of the roadbed ahead and at the rear of the machine. If there is any irregularity exceeding a certain level, the system recognizes it as an obstacle and stops the machine. If the obstacle is removed, the machine resumes operation. To enable a single worker to operate multiple machines simultaneously in parallel for improving work efficiency, work instructions can be issued from one tablet PC to multiple vibration rollers.

(2) Automation equipment

An outline of the equipment to automate a vibration roller is described. Figure 3
shows an automated 11 ton vibration roller (SD451, Sakai Heavy Industries, Ltd.).

![FIG. 3. Vibration roller](image)

**a. Retrofitted automation equipment**

As retrofitted automation equipment to automate a general-purpose vibration roller, motor-driven self-steering equipment was developed and installed on an existing handle so that the steering could be automatically controlled by the control PC. For switching between forward and backward movement and on-off switching, we adopted a control method connecting a switching circuit to the existing electronic circuit (Figure 4).

**b. Measuring sensors**

Various sensors were installed on the machine (Figure 5).
- Machine position measurement: RTK-GPS
- Machine direction measurement: GPS declinometer
- Machine inclination (roll and pitch angles): gyro compass
- Articulate angle (relative angle between front roller and cabin)

![FIG. 4. Retrofitted automation equipment](image)

![FIG. 5. Measuring sensors](image)

**c. Work instruction interface**
Work instructions for an automatic vibration roller are issued using a tablet PC. Figure 6 shows a screen when a work instruction is issued. The touch panel of the tablet makes it easy to issue instructions for specific work, such as the scope of construction, number of compactions, traveling speed, lap width and length limit till completion for changing lanes, as well as commands for work start.

![Work instruction interface / Example of the work instructions on the PC screen](image)

**FIG. 6. Work instruction interface / Example of the work instructions on the PC screen**

(3) Application to RCD construction

To verify its practicality, the system was applied to the compacting work of RCD concrete for constructing the dam body at the Gokayama Dam in Fukuoka Prefecture. In the construction, a single worker could operate two automatic vibration rollers simultaneously (Figure 7), which demonstrated the feasibility of operating multiple construction machines by fewer workers.

In addition, the quality of automatic construction was evaluated based on the deviation of the travel trajectory of a vibration roller during compaction (consolidation) from the target trajectory. Figure 8 shows the travel trajectory during compaction indicated by a solid line. For straight-ahead travel, compaction is carried out with the line \( y = 0 \) as the target trajectory. For changing lanes, the machine travels with the chain line as the target, and then begins compaction work with the line \( y = 0 \) as the target. The area surrounded by dotted lines shows the error range of \( \pm 10 \text{ cm} \) around the line \( y = 0 \). It can be seen that the error during compaction is always within \( \pm 10 \text{ cm} \) in both cases.

![Situation of simultaneous construction](image)

**FIG. 7. Situation of simultaneous construction**
3. Automatic spreading system for bulldozers
(1) Outline of development

As with the case of vibration rollers, we began to automate a bulldozer as the preliminary step to establishing an automatic construction system. We did this by retrofitting various sensors, a control PC and communication equipment onto a Komatsu D61-PXi bulldozer (machine mass: 18.9 t, overall length: 5.5 m, overall width: 3.9 m, height: 3.2 m) shown in Figure 9. Unlike vibration rollers, bulldozers are used in various types of work including excavation, dozing and spreading. As the first stage in this development we focused on spreading, which constitutes a large part of the work in dam construction and large-scale land development. We aimed to achieve fully automatic soil spreading by automatically controlling the bulldozer’s travel and its blade operation so that it followed the planned travel path and blade operation determined in advance according to the work conditions and based on several examined work patterns.

This system was developed jointly with Komatsu Ltd.
(2) Automation system  

a. Retrofitted automation equipment  
A PC for measurement control was retrofitted onto a bulldozer. The PC communicates with the controller on the bulldozer via a dedicated interface based on the signals from measuring sensors, etc. (described later) in order to control the travel and steering of the bulldozer and its blade operation. The PC sends control commands to the bulldozer, and at the same time, it acquires information on the bulldozer including the travel speed and the manipulated variables of various levers and the blade. The PC is also used to record the manipulation data of skilled operators, which is utilized as the basic control rules of this system, and to replicate the operator’s manipulation based on the data.

b. Measuring sensors  
Various sensors were installed on the bulldozer to measure the following variables:
- Machine position measurement: RTK-GPS
- Machine direction measurement: GPS declinometer
- Machine inclination (roll and pitch angles): gyro compass

Figure 10 shows components of the automation system.

![FIG. 10. Components of automation system](image)


c. Travel control algorithm  
As an example of the travel control rules, the procedure for following the path set for the bulldozer’s travel is described. The algorithm used to follow the path is shown in Figure 11. A target azimuth angle is determined so that the bulldozer reaches the target path after traveling a predefined distance, $L_1$, based on the relative positional relationship between the bulldozer and the path. The steering variables used to follow the target path are calculated based on the position error relative to the target path, $d$, ...
and the angular error relative to the target angle, $\theta$. The aim of this method is to avoid a rapid change in direction and to ensure that the bulldozer reaches and follows the target path without disturbing the road surface with its blade. Because the travel speed, the manipulated variables of the blade, etc. during automatic travel can be set in detail, complex operation according to the work conditions is realized. Figure 12 shows the results of an experiment to evaluate tracking performance along a target path using an actual machine. Travel data of skilled workers during construction work was measured, and automatic tracking travel was executed using the data as the target. Although the shape of the ground differed between the operator’s travel and the automatic travel, it was demonstrated that tracking within an error range of about ±10 to 20 cm could be achieved.

Figure 12 shows the results of an experiment to evaluate tracking performance along a target path using an actual machine. Travel data of skilled workers during construction work was measured, and automatic tracking travel was executed using the data as the target. Although the shape of the ground differed between the operator’s travel and the automatic travel, it was demonstrated that tracking within an error range of about ±10 to 20 cm could be achieved.

![Figure 11. Path following algorithm](image1)

![Figure 12. Example of tracking performance](image2)

(3) Test construction in land development

To verify the performance of this system, test construction was implemented at an actual land development site. We carried out spreading according to a predefined travel path and blade operation using soil of about 20 m$^2$ (diameter: 5 m, height: 3 m) unloaded from a dump truck. The results showed that fully automatic spreading can be performed to meet the predefined specifications (width: 8 m, thickness: 3 m) (Figure 13).
(4) Test application in RCD body construction

This system was tested at an RCD construction site to verify its practicality. Spreading and shaping of RCD concrete was carried out using an automated bulldozer for dam body construction at the Gokayama Dam in Fukuoka Prefecture. Figure 14 shows a scene of this automatic operation. Figure 15 shows an example of the differences between the target path (dotted line) and actual travel path (solid line) of the bulldozer during automatic spreading and shaping. The shaded area in the figure corresponds to the time when the height and horizontal angle of the blade are controlled for shaping of a mound. Figure 10 shows that differences between the target path and actual travel path occur when the bulldozer passes a position with considerable unevenness, such as traveling over discharged concrete, during times other than mound shaping. During mound

FIG. 13. Result of automatic spreading test at earthwork site

FIG. 14. Automatic operation at dam construction site
shaping, however, tracking at a precision of about ±10 cm was achieved.

The rectangular mound shown in Figure 16 was constructed through comprehensive automatic spreading work achieved by combining the measurement control performance of this automatic bulldozer and information on the travel path and blade operation given to the bulldozer. This result demonstrated that automatic spreading of RCD concrete requiring complex operation could be realized with sufficient construction precision.

CONCLUSIONS

An automatic compaction system and an automatic spreading system were developed by retrofitting automation equipment and safety equipment onto a general-purpose vibration roller and a bulldozer, and by introducing a control algorithm developed based on the operation data of skilled workers. The performance and effectiveness of the system was confirmed through tests at actual construction
sites. We will continue to improve the performance and develop more sophisticated systems.

Meanwhile, for full-fledged diffusion of the described automation system at construction sites, it is necessary to examine construction procedures and methods suited to automated machines. Given the limitations to what general contractors can do in this respect, we believe that collaboration with ordering parties, consultants and subcontract companies is necessary, in parallel with the development of equipment and systems. Conducting such R&D and promoting this construction method will lead to innovative changes for the next generation at the construction stage, which accounts for a large part of the production activities in civil engineering, and problem-solving in industry. We intend to continue our efforts in this area.

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REFERENCES