A study on an Autonomous Crawler Carrier System with AI based Transportation Control

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Abstract – This paper proposes an autonomous crawler carrier system to improve productivity of earth and sand transportation work. In general, multiple crawler carriers on the transportation work repeatedly move on almost the same route between loading and unloading locations. There is a risk that the crawler carrier deviates from the transport path due to the driver's fatigue and reduced concentration since the transportation work is a monotonous and repetitive operation. The proposed system enables multiple crawler carriers to automatically move on the same route without collision using an artificial intelligence (AI) based control. There are four steps in the AI control flow. First, the driver performs the teaching operation while checking the route from the camera image. Then, teaching route data for an autonomous crawler carrier is created. Second, the AI on the personal computer selects several routes that can maintain safe crawler carrier positions for all routes of multiple carriers. Third, AI generates an efficient operation plan that minimizes the working cost and time from all positional relationships. Finally, when the operator presses the start switch on the control panel, AI controlled multiple crawler carriers move efficiently without collision. This smart control was introduced for the construction of earth and sand transportation in the Aso-Ohashi area, and efficient operation was confirmed.

Keywords –

Autonomous crawler carrier system; Artificial intelligence; Productivity improvement

1 Introduction

In recent years, information and communication technology (ICT) [1] has made great progress with the development of signal processing technology [2], computer technology [3], wireless communication technology [4], and so on. As a future society, "Society 5.0" has been proposed by the Cabinet Office, which is a Japanese administrative agency [5]. Although life has become more convenient in Japan with the progress of ICT, an aging society causes labor shortages and increasing energy consumption. Society 5.0 tries to incorporate robot technology [6], artificial intelligence (AI) technology [7, 8], etc. into society in order to solve such social issues. To realize Society 5.0 in Japan construction industry, a big project called "i-Construction" is underway to improve the productivity of the entire construction production system.

This i-Construction, which is managed by the Ministry of Land, Infrastructure, Transport and Tourism, includes the development of an unmanned system for construction machinery [9-11]. In the automatic control of this construction machine, the personal computer (PC) in the control device drives the crawler carrier instead of human operators. The application of the automatic control reduces the needs of skilled operators, solves the shortage of human resources, and can be expected to improve productivity.

In this paper, we noticed that the earth and sand transportation work is a monotonous repetitive work of reciprocating the route. This cyclical work causes physical and mental fatigue of the operator. Therefore, we are developing an automatic driving technology for crawler carriers to reduce accidents by operators during the transportation work using the AI technology [12].

The remainder of this paper is organized as follows. Section II introduces the details of automatic driving system in the earth and sand transportation field. In Section III, we explain the proposed autonomous crawler carrier system with AI based transportation control. Moreover, in Section IV, we verifies the effectiveness of our proposed scheme by the computer simulation. In addition, experimental results of Aso-Ohashi area are briefly explained in Section V. Finally, the conclusion and future works are presented in Section VI.

2 Automatic driving system in the soil and sand transportation field

2.1 System configuration

The automated driving system uses a network-compatible crawler carrier that enables human-less construction. Figure1 shows two crawler carriers which are used for transporting earth and sand. The specifications of this crawler carrier, which is manufactured by KATO WORKS, are as follows. It has a payload of 11,000 kg, a machine mass of 14.100 kg, a length of 6.05 m, a width of 2.84 m and a height of 2.91 m.

Figure 1. Two Crawler carriers for transporting earth and sand.

Figure 2 shows system configuration for the automated driving system. In this construction, the crawler carriers are controlled using the internet protocol (IP) network. The automatic driving system is composed of the following devices.

- Global Navigation Satellite System (GNSS) / IMU(Inertial Measurement Unit) device that measures the position information of the moved route, where this device includes GNSS reference station
- PC for automatic driving control (1 vehicle side, 1 remote control side)
- Vehicle camera to watch the surrounding conditions during remote control

IP addresses are assigned to these devices, and they can be controlled by packet transmissions using a wired local area network (LAN) system or a wireless LAN system. GNSS / IMU is a combined inertial measurement device for GNSS and IMU. In addition to the position information from the G

GNSS device, the position and direction of the vehicle can be combined with the IMU device to measure the position of the vehicle with high accuracy.

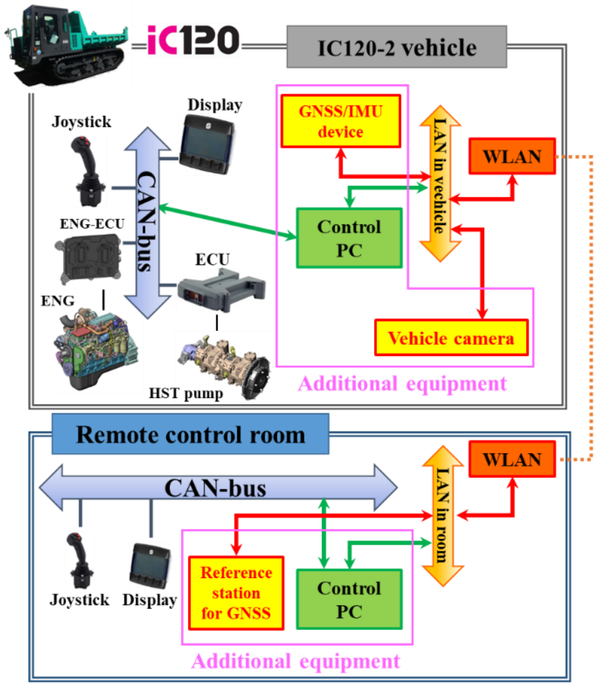


Figure 2. System configuration for the automated driving system where wireless communication is conducted between the remote control room and crawler carriers.

2.2 System control flow

Figure 3 shows a framework related to the important devices for teaching and automatic driving operations. In this figure, there are two modes, which are teaching mode and auto-driving mode. As shown in this figure, a remote and automatic operation panel including the PC is set in the remote control room which has monitors, PCs, and wireless communication devices. If the operator would like to control the crawler carrier, command signals are transmitted to the PC which is set in the crawler carrier via the WLAN packets. On the other hand, the crawler carrier's information is transmitted to the remote control room via the WLAN packets.

There are three flows: teaching operation, preparation of automatic driving, and automatic driving mode. These flows are explained as follows in detail.

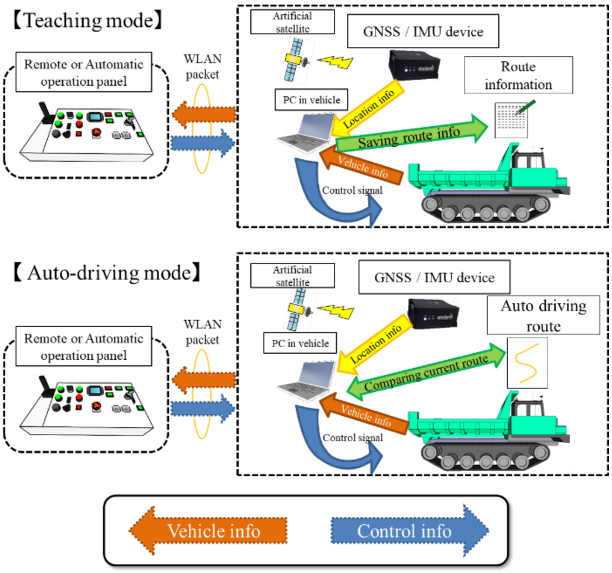


Figure 3. The framework related to the important devices for teaching and automatic driving operations.

2.2.1 Teaching operation

A start signal for the teaching operation is transmitted from the remote control room to the PC in the crawler carrier, and the operator moves it remotely. When the crawler carrier is running, the position and speed information from the GNSS / IMU device are stored in the in-vehicle PC as a teaching path. This information is used in the automatic driving mode.

2.2.2 Preparation of automatic driving

First, a control packet for switching the remote driving mode to the automatic driving mode is transmitted from the remote control room to the crawler carrier. Secondly, the control signal to start the automatic operation is transmitted. Third, the teaching data for the automatic driving is saved in the in-vehicle PC inside the crawler carrier. Thirdly, the teaching data for automatic driving is saved in the hard disk of the PC stored inside the crawler carrier.

2.2.3 Automatic driving mode

The in-vehicle PC automatically drives the crawler carrier while comparing the teaching data with the current position from the vehicle's GNSS / IMU device. In addition, the movement of the crawler carrier is automatically stopped when the teaching path and the current position greatly deviate from each other.

3 AI based automatic driving technique

3.1 Necessity of AI-based autonomous driving

In the automatic driving system described in the previous section, a stop operation by a worker in the remote control room is required in order to halt the crawler carrier during the automatic moving from the start point to the end point. Therefore, at least two operators are needed in the working field. One remotely controls the excavator and loads the crawler carrier with sand, and the other manages and watches the movement of the crawler carrier. If the number of autonomous crawler carriers increases, operation management by one worker becomes much difficult, and there is a possibility of collision among crawler carriers. In order to prevent collisions, a system that manages the operation of multiple crawler carriers on behalf of the worker is required. Therefore, in this paper, we propose an AI-based autonomous driving technique.

The developed AI-based automated driving technology does not require human operation management, and single worker can perform a series of operations from loading and unloading sediment. Figure 4 shows the configuration of the AI-controlled automatic driving system. As shown in this figure, the PC in the remote control room (PC-r) controls two remote and automatic operation panels via and two in-vehicle PCs (PC-v). The PC-r transmits the AI start signal to the PC-v via the operation panel. Moreover, the PC-r directly transmits the stop signal to the PC-v. On the other hand, the PC-v transmits the vehicle information to the PC-r via the operation panel, but it directly transmits the position information to the PC-r. There are two information flows among the control PC in the remote control room and two crawler carriers.

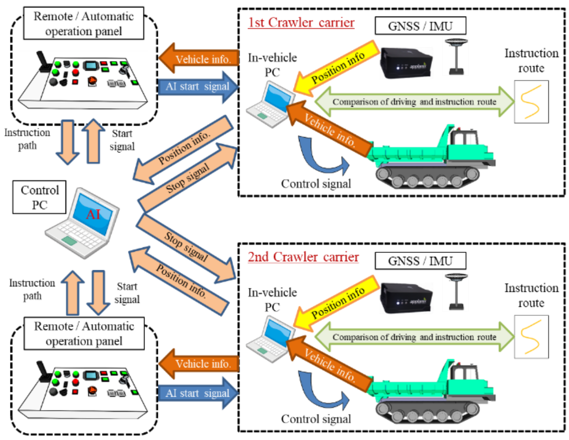
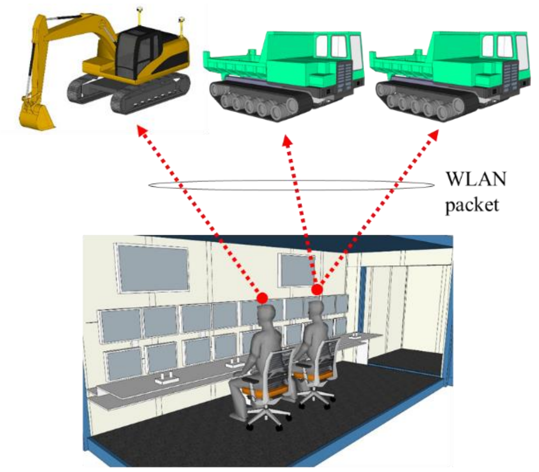
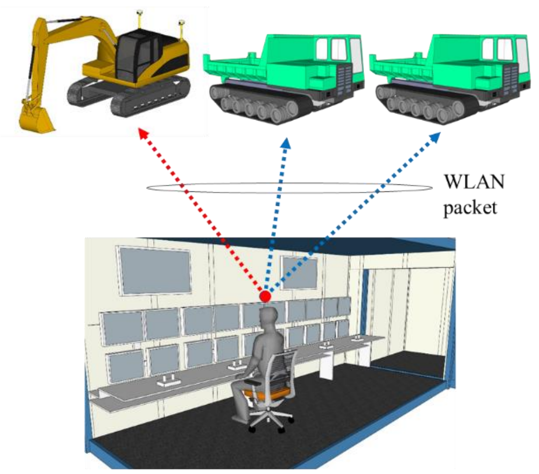


Figure 4. Configuration of the AI-controlled automatic driving system.



The number of construction machineries is three.
The number of operators is two.

(a) Before AI based remote control room



The number of construction machineries is three.
The number of operators is one.

(b) After AI based remote control room

Figure 5. Control of multiple vehicles by one operator.

Figure 5 shows the control of multiple vehicles by one operator. As shown in this figure, the number of operator is two, when the number of construction machineries is three before AI based remote control room. On the other hand, the number of operator is only one after the AI based remote control room. This means that our proposed system is one of the best solutions for the shortage of human resources in Japanese construction field.

3.2 AI control flow

Figure 6 shows our proposed AI control flow in which there are four steps: instruction, analysis, plan, and command. These steps are explained as follows.

- First, the operator remotely moves the crawler carrier, and the route information for teaching process is generated.
- Second, based on the obtained route data and crawler carrier size conditions, the AI on the PC-r finds safety positions between crawler carriers and positional relationships in possible. Then, several candidate routes that allow safe operation are selected.
- Third, the operation pattern that minimizes the cost and time is selected from the candidate routes in the previous step, considering the productivity of earth and sand transportation work. At this time, the start and end positions of the instruction route are also taken into consideration. For example, the unloading and loading operations are conducted in the start and end points. Optimal operation pattern of vehicles is calculated from the candidate routes and other conditions. The operation pattern satisfies spatial limitation to avoid interference between vehicles while minimizing expected time necessary to complete load and unload of sediment. In this phase, algorithms to solve multi agent path finding problem are used with original expansions to increase flexibility and efficiency [13].
- Finally, the PC-r remotely controls the two crawler carriers on the most efficient operation pattern. The GNSS position information from the each carrier is sent to the remote control room, and the start and stop of moving can be determined by the AI monitoring in constant. Moreover, the second and third processes are re-conducted in our proposed scheme if the variation of the environmental condition, for example a muddy road and an increase of loading time, changes the position relationship between two crawler carriers.

As a result, the number of operators for monitoring the crawler carriers can be reduced. When the number of vehicles is only one, the difference of driving efficiency between the automatic driving with and without the AI is none. However, in the case of more than two vehicles, the AI based automatic control considers the collision avoidance on the driving route. On the other hand, in the case of the automatic control without the AI, if a forward vehicle and a return vehicle meet on a narrow road, either one vehicle needs to return to the back wide road, which incident wastes operation time. Therefore, the AI control will enable efficient transportation in the construction field.

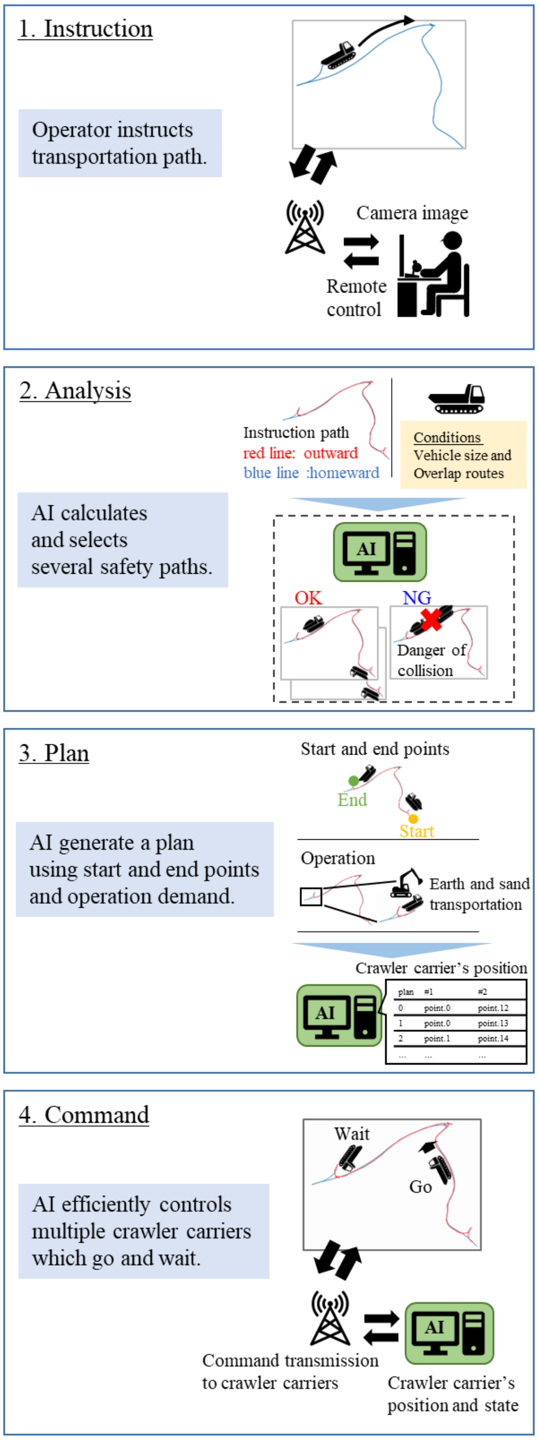


Figure 6. Configuration of the AI-controlled automatic driving system including instruction, analysis, plan, and command processes.

4 Computer simulation

4.1 Simulation parameters

Performances of our proposed AI-controlled automatic driving system are evaluated by the computer simulation. There are three fields in this simulation, where the first field is in the Aso-Ohashi area, the second and third fields are in Tsukuba area.

In this simulation, the sand loading time to the crawler carrier using the excavator was not considered. The maximum number of crawler carriers (maximum N_t) is two. In addition, the start point for moving the crawler carrier is the unloading point. There are two routes. One is an outbound route from the unloading point to the loading point. The other is a homeward route from the loading point to the unloading point. Overlap of forward and return routes is allowed. Even if there is no overlap between the forward and return paths, it is not possible to pass each other within 6 m. We set the waiting and separating points in the driving route. These points increase the driving efficiency and they are determined by the operator's empirical knowledge.

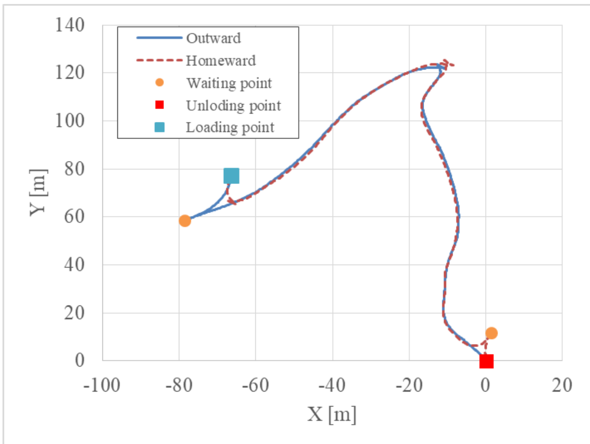


Figure 7. Driving route in the Aso-Ohashi operation area in which the number of waiting points is two.

Figure 7 shows driving route in the Aso-Ohashi operation area which size is 80m by 120m. There are two separating points. When one crawler carrier is in the loading point, the excavator loads its crawler carrier with earth and sand. The other crawler carrier waits until the loading work is completed at the waiting point which is near the loading point. Similarly, when one crawler carrier is unloaded, the other crawler carrier waits until the unloaded operation is completed at the waiting point which is near the unloading point.

Figure 8 shows driving route in the 1st Tsukuba area which is inside Technical research & Development institute on Kumagai Gumi. The area size is 40m by 30m. There are two waiting point.

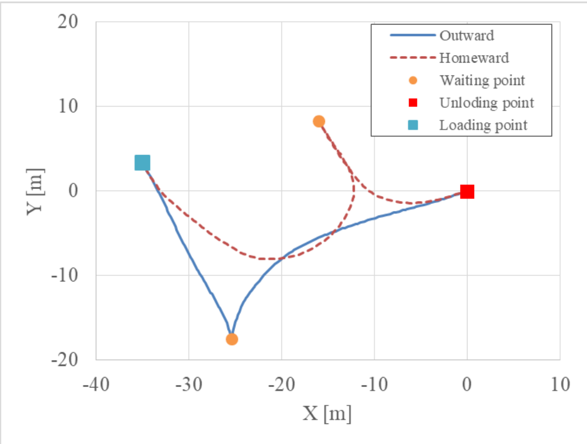


Figure 8. Driving route in the 1st Tsukuba area in which the number of waiting points is two.

Figure 9 shows driving route in the 2nd Tsukuba area which is inside Technical research & Development institute on Kumagai Gumi. The area size is 40m by 30m. There are two waiting points in order to increase work efficiency for more than two crawler carriers. Moreover, two separating points(SPs) are added to this filed. If there are no waiting points, either of crawler carriers frequently stops the movement on the outward and homeward path because the AI based control selects the extremely safe operation plan. Therefore, it is expected that two waiting points improve work efficiency in the case of N_t = 2.

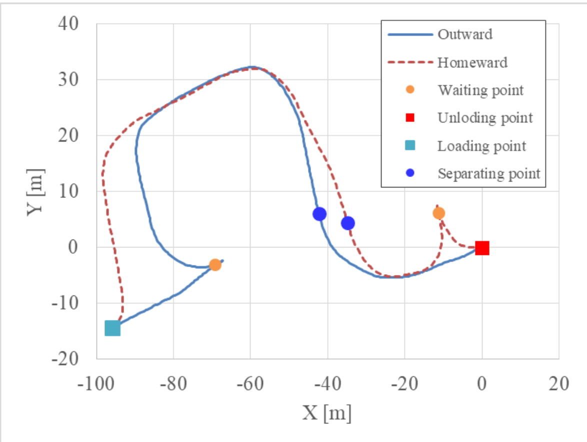


Figure 9. Driving route in the 2nd Tsukuba area in which there are two waiting points and two separating points in order to increase work efficiency for more than two crawler carriers.

4.2 Simulation results

Table 1 shows work efficiency in Aso-Ohashi and Tsukuba area in the simulation. As shown in this table, at first, work efficiencies for the case of N_t = 1 and N_t = 2 are 16.2 and 31.1 cycle/hour in the Aso-Ohashi area. In this area, work efficiency for the case of N_t = 2 is improved by 72% compared to the case of N_t = 1.

Secondly, work efficiencies for the case of N_t = 1 and N_t = 2 are 66.1 and 105 cycle/hour in the 1st Tsukuba area. In this area, work efficiency for the case of N_t = 2 is improved by 59% compared to the case of N_t = 1.

Thirdly, work efficiencies for the case of N_t = 1 and N_t = 2 are 24.5 and 42.2 cycle/hour in the 2nd Tsukuba area without two separating points. In this area, work efficiency for the case of N_t = 2 is improved by 72% compared to the case of N_t = 1. On the other hand, work efficiency for the case of N_t = 2 is 46.4 cycle/hour in the 2nd Tsukuba area with two separating points. Work efficiency for the case of N_t = 2 is improved by 89% compared to the case of N_t = 1.

By determining two separating points and planning the automatic driving routes, the unnecessary waiting time of the two crawler carriers due to the overlap of the outward and homeward routes is reduced. Efficiency ratio for the case of N_t = 2 with separating points is 17% higher than that for the case of N_t = 2 without waiting points. Therefore, if our proposed automated driving is applied in an area where the travel paths are complicated, it is important to provide some separating points when making the driving plan.

Table 1. Work efficiency in Aso-Ohashi and Tsukuba area in the simulation.

Area	Work efficiency [cycle/h]		Efficiency ratio
	1 vehicle	2 vehicles	
Aso-Ohashi	16.2	31.1	1.72
1st Tsukuba	66.1	105	1.59
2nd Tsukuba (w/o SP)	24.5	42.2	1.72
2nd Tsukuba (w/ SP)		46.4	1.89

5 Experimental results

In this section, experimental results of the construction in Aso-Ohashi area are briefly described.

Table 2 shows construction outline in this area. As shown in this table, verification period of this construction was in September 2018. The verification place was a collapse slope area at the top of the soil retaining embankment. One way distance was about 300m. Path width and maximum path gradient were about 5m and 20%. The path gradient was able to decrease the moving speed of crawler carrier. The number of construction machines was three including one excavator and two crawler carriers.

Table 2. Construction outline in Aso-Ohashi area.

Construction name	Slope countermeasure work in Aso-Ohashi area	
Verification period	September 2018	
Verification place	Collapse slope area at the top of the earth retaining embankment	
Path condition	Distance (one way)	about 300m
	Width	about 5m
	Gradient (maximum)	20%
Num. of construction machines	Excavator	1
	Crawler carrier	2

Figure 10. External remote control room in Aso-Ohashi area in which the number of operators is only one.

Figure 10 shows an external remote control room in Aso-Ohashi area. There were two remote control panels including the PC-r. Multiple monitors were set on the table in order to check movements of crawler carriers and their surrounding area. The excavator loaded earth and sand to the crawler carrier which was controlled by the AI when the operator remotely moved the excavator.

Figure 11 shows the snapshot of the verification in Aso-Ohashi area, which is a partial area of -80 to -60 m on the X axis and 55 to 80 m on the Y axis in Fig. 7. The crawler carrier (green) had waited at the waiting point while the earth and sand loading operation for the other carrier (magenta) had been conducted. After its operation was finished, the crawler carrier (magenta) with earth and sand went to the unloading point and the crawler carrier (green) approached the loading point as shown in Fig. 11. If the waiting point was not set on this path, the incident may happen where one of the crawler carriers turned back the way which it came from.

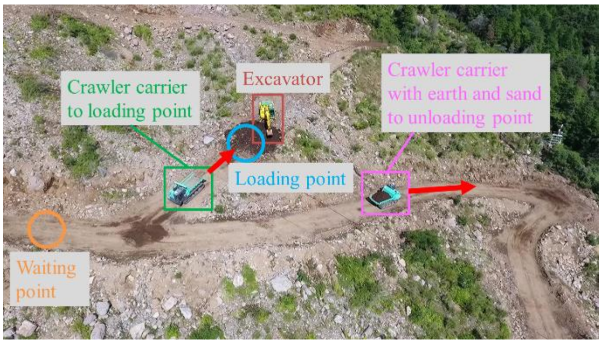


Figure 11.Snapshot of the verification in Aso-Ohashi area where one crawler carrier (magenta) moves to the unloading point and the other (green) moves to the loading point near the excavator.

Table 3 shows work efficiency in Aso-Ohashi and Tsukuba area in the simulation and real environment. As shown in this table, the simulation result is same as Table. 1. Work efficiencies for the case of N_t = 1 and N_t = 2 are 7.47 and 13.1 cycle/hour in the real field. In this case, work efficiency for the case of N_t = 2 is improved by 75% compared to the case of N_t = 1.

The results of work efficiency for the real environment are low compared to the simulation results, because time durations of earth and sand loading and discarding are not assumed in the simulation environment. In addition, we consider that the influence of mud and gradient in the real field can decrease the speed of crawler carriers. Moreover, the maximum speed of the crawler carrier is adopted in the simulation. On the other hand, the difference of efficiency ratio between the real and simulation environments is almost the same value. The simulation analysis enables us to search the semi-optimal waiting points and separating points in the driving route. Therefore, its analysis is important before the verification of our proposed scheme in the real environment.

Table 3. Work efficiency in Aso-Ohashi area in the simulation and real environments.

Area	Work efficiency [cycle/h]		Efficiency ratio
	1 vehicle	2 vehicles	
Aso-Ohashi (simulation)	16.2	31.1	1.72
Aso-Ohashi (real)	7.47	13.1	1.75

6 Conclusions

This paper proposes an autonomous crawler carrier system with the AI based transportation control. In the proposed scheme, the AI based operation management eliminates the need for the safety confirmation between two crawler carriers. Moreover, it reduces the number of operation monitoring workers, which means that the proposed system is one of the best solutions for the shortage of construction workers in Japan.

The AI makes the movement plan for crawler carriers in the earth and sand transportation. This plan is produced by the major flow consisting of instruction, analysis, plan, and command processes. In the simulation results, when two crawler carriers in the Aso-Ohashi area are automatically controlled by the AI, work efficiency improves 72% compared to the case of one crawler carrier. In addition, when the same AI controls the automatic driving in the 1st Tsukuba area, work efficiency improves 59% compared to the case of one crawler carrier. Moreover, work efficiency improves 72% compared to the case of one crawler carrier in the 2nd Tsukuba area which is larger than the 1st area when there are no separating points. On the other hand, work efficiency improves 89% compared to the case of one crawler carrier in the 2nd Tsukuba area with setting two separating points.

Moreover, results of efficiency ratio for real and simulation environments are almost the same value. Therefore, we aggressively use the simulation analysis before the verification of the AI based auto driving system in the real construction field.

As a future study, it is possible to further improve work efficiency of the earth and sand transportation by efficiently arranging the waiting and separating points in the driving routes. Furthermore, determination of waiting and separating points using AI control will be conducted.

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