Efforts to Unmanned Construction for Post-disaster Restoration and Reconstruction

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Abstract –

This paper presents largely severe natural disasters had happened in Japan, and efforts to unmanned construction until now. First, problems in responses to post-disaster restoration and reconstruction are reported. Secondly, are described demonstration of ultra-long-distance unmanned construction and the requirements for the deployment. Thirdly, this paper presents research and development on autonomous crawler carrier. Finally, concluding remarks and further works are reported. In addition, are proposed levels of promising applicability of robots in responses to post-disaster restoration and reconstruction.

Keywords –

Post-disaster, Unmanned construction system, Situational Awareness, Ultra-long-distance, Autonomous crawler carrier

1 Introduction

Japan is located in the Circum-Pacific Mobile Belt and Japanese archipelago, which are formed on the complex crusts. Accordingly, we are always facing and fearing natural disasters such as typhoons, unexpected strong and sudden tempest, and then deadly flash floods, earthquakes, volcanic activity, slope failures, landslides, avalanche of earth, fire of petrochemical complex, nuclear power station accident, and so on. Largely severe natural disasters have recently occurred in Japan are listed below.
(1) The 1995 Hanshin-Awaji Earthquake,
(2) The 2004 Mid Niigata Prefecture Earthquake,
(3) The 2011 off the Pacific coast of Tohoku Earthquake with the Fukushima daiichi nuclear power station accident,
(4) The 2016 Kumamoto Earthquakes, and

(5) The 2018 Hokkaido Eastern Iburi Earthquake.

Now, we need consider countermeasures against largely severe natural disasters. When facing dangerous situations in post-disaster restoration and reconstruction, in order to avoid any secondary disasters, we inevitably demand unmanned construction.

This paper reports efforts to unmanned construction for post-disaster restoration and reconstruction, which have been and are being discussed in the disaster and accident sub-committee, construction robot committee, JSCE in Japan. As for post-disaster restoration and reconstruction, this sub-committee plays a role in:
(1) Finding out applicability of unmanned construction system,
(2) Analysis of examples of the unmanned construction systems responded to natural disasters and accidents,
(3) Investigating advanced technology applicable to develop future unmanned construction systems,
(4) Guidance to put the future unmanned construction systems in practice,
(5) Informing the public widely of the achievements of these, and utilizing them to society, and
(6) Proposal of levels of promising applicability and objectives of research and development on construction robots.

The discussions in this sub-committee here will make it possible for researchers, engineers, and users to have a shared awareness of efficiency index and applicability level, performance to be the goal, state-of-the-art to be attained, and so forth, in responses to post-disaster restoration and reconstruction. Moreover, it will contribute to the research and development on robotics for post-disaster restoration and reconstruction.

This paper is organized as follows. First, this paper presents problems that we have to face when conducting unmanned construction. Secondly, this paper reports issues and future directions pertaining to ultra-long-distance remote-control unmanned construction system.

Thirdly, efforts to research and development on autonomous crawler carrier are described. Finally, are reported concluding remarks, further works, and proposal of the promising applicability in levels of responses to post-disaster restoration and reconstruction.

2 Problems

In response to post-disaster restoration and reconstruction, construction machines are often remotely controlled to remove earth and rocks at the steep slope on the left and at the ridge of steep cliff on the right as shown in Figure 1. As mentioned above, when facing dangerous situations, in order to avoid any secondary disasters, we inevitably demand unmanned construction system.

Figure 1. Works at the ridge of steep cliff and at the steep slope

Handling joysticks to operate construction machines, either directly or remotely, is an inherently eye-hand coordination task. The eye-hand coordination task means to control eye movements with hand movements, as processing the situational views to handle joysticks. Considering unmanned operation, however, the operators handle their joystick controllers to operate construction machines remotely in narrow field of views produced by camera-monitor system at the control room. Problems here include machine operability, difficulty in a task at hand, performances limited by bearings of operators in their behavioural frameworks, and continuous or intermittent mental workload on them. The continuous or intermittent mental workload might be caused by communication with latency, narrow field of view, different reference frames without realistic sensation, and so forth. Although, the operators have to make a decision instantaneously on do's and don'ts in their operations, it is sometimes difficult to ensure line-of-sight for location and movement direction of their machines, positions of and clearance from surroundings of the machine and the target. Then they have to mentally translation, rotation and scaling between different frames of references in Figure 2.

As shown in Figure 3, however,
(1) Just by images from on-board cameras, it is difficult

to grasp shape of work target,
(2) Just by images from fixed cameras, it is almost impossible to understand the whole of situations on site, and so,
(3) It is required to have functions to adjust coordinates of the entire of work site.
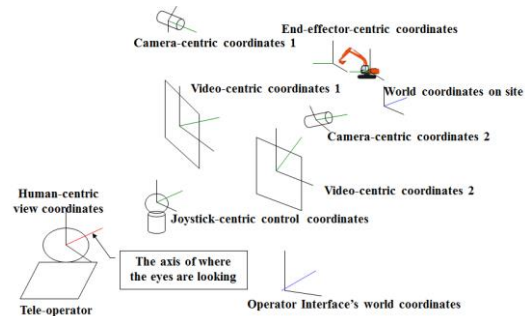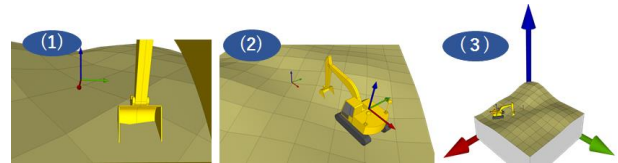

Figure 2. Different reference frames

Figure 3. Images from camera

Therefore, the unmanned construction requires that operators indispensably acquire extensive trainings and broad experiences on problem-solving skills pertaining to:
(1) Different viewpoint control,
(2) Spatial locations and positioning,
(3) Figuring out and completing the given task at a hand in real-time manner.
(4) Endurance of continuous or intermittent workload
(5) Scale ambiguity
(6) Rate of motion, and
(7) Loss of peripheral vision with retention of central vision, which is liable to result in a constricted circular tunnel-like field of vision.

The skilled operators are imperative for the unmanned construction operation. In Japan, however, there are very few skilled operators, and most of them are aged people.

Therefore, it is very important and significant to provide the operators with physical cues related to behaviour of construction machines, in order to compensate for their realistic sensations, which operators would feel when directly operating their machines, and to increase their consciously and situationally spatial awareness, which enable them to infer and understand the present and future surroundings of remotely controlled machines and watch oneself in their work space.

3 Ultra-long-distance Remote-control Unmanned Construction

When the 2011 off the Pacific coast of Tohoku Earthquake occurred, the Ministry of Land, Infrastructure, Transport and Tourism of Japan (hereafter called MLIT) conducted demonstration tests on ultra-long-distance remote-controlled operation of unmanned construction machines, in March of that year, at the foothills of Mt. Unzen. This demonstration tests aim to prepare for future large-scale volcanic disasters [1], [2]. Figure 4 shows Demonstration tests network. The experiment yard is shown in Figure 5, and the mobile relay station in Figure 6.
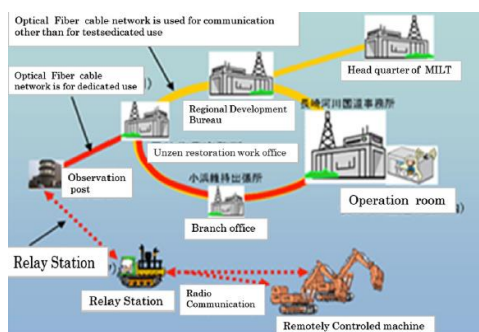

Figure 4. Demonstration tests network in ultra-long-distance remote-controlled operation of unmanned construction machines

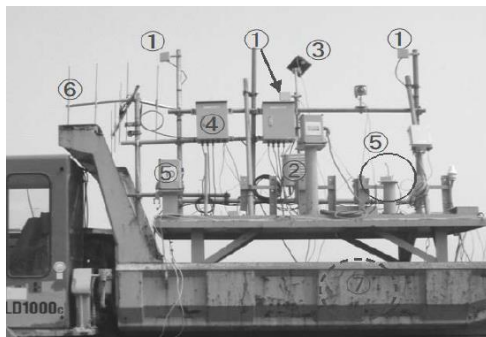
Figure 5. Experiment yard for demonstration tests

Figure 6. Mobile relay station for demonstration tests

The devices shown in Figure 6 are explained as follows:

① Directional patch antenna for wireless LAN (IEEE802.11),
② Wireless LAN (IEEE802.11) master unit 5GHZ,
③ 25GHZ low power radio device,
④ RS232C 422-LAN converter,
⑤ Specified low power radio station (429MHz),
⑥ Public broadband communication antenna, and
⑦ Public broadband communication device.

Communication latency, and image degradation in ultra-long-distance remote-control machines might make it difficult to figure out and complete the given task at a hand in real-time. And then it is easily conceivable to decrease the work efficiency. Moreover, the machines are highly liable to collide with each other.

The purposes of the demonstration tests are described below.
(1) Evaluation of capability (e.g., data-carrying capacity, latency) of various communication methods as follows:
    1) Long-distance communication (from control room to relay station on site), and
    2) Local communication on site.
(2) Analysis of operating environment and operator's bearings related to:
    1) Influence by communication latency, and image degradation,
    2) Maintenance of construction machines (refuelling, maintenance, etc.), and
    3) Operator's skill (operating envelope, proficiency, etc.).
(3) Comparison and verification experiments with respect to:
    1) Operator's proficiency (skilled, unskilled) and
    2) Operational envelope limited by image communication latency and degradation.

The demonstration tests used actual construction machines and an optical fibre cable network for the first time in Japan, and demonstrated the applicability of remote-control operation technologies to ultra-long-distance unmanned construction machines. The machines here were remotely operated from a remote-control room 30 km away. Are also demonstrated that the communication system, combined with wireless mesh LAN, simultaneously transmitted high-definition 1 Mbps images from 20 cameras. Then hydraulic excavators could be operated with a high degree of accuracy. In addition, are verified the transmission capabilities of alternative long-distance communication such as public broadband communications, long-distance wireless LANs, satellite communications, etc. in this demonstration tests.

3.1 Operator's Qualification

Operators with different level proficiency (e.g., skilled, unskilled) participate in this comparison

and verification experiments, which have been done in demonstration tests. These experiments conducted are outlined in the following subsections

3.1.1   Climbing Over a Large Bump

Each of the skilled and unskilled operators remotely controls a backhoe with 1.2 m^2 bucket for one-cycle of a series of the following operations as shown in Figure 5.
(1) Level down a fill with two meters in height and the inclined part 45 degrees, and
(2) Build a runway and climb the fill
Operators' hacks learned from the above operations are summarized below.
(1) It was observed that the unskilled operator's cycle time runs 1.9 times longer than the skilled operator's one.
(2) When not using a camera car, the difference between the two has spread to 2.3 times.
(3) On the other hand, in case of boarding operations, the unskilled operator's cycle time runs 1.8 times longer than the skilled operator's one
(4) Putting the cycle time of boarding operation equal to one, the unskilled operator took a work time to complete the task from 2.0 to 3.6 times of the one.

Figure 5. Climbing over a large bump

3.1.2   Travelling as Avoiding Obstacles

The three colored corns are installed in a 40 m interval of running path. In addition, three concrete blocks are placed at the running path. The backhoe zigzags between the three colored corns. The backhoe is planned to stop and scoops the three objects of concretes in the middle of running. The experiment shows the following results.
(1) The unskilled operator's cycle time runs 1.5 times longer than the skilled operator's one.
(2) In case of boarding operations, the unskilled operator's cycle time runs 1.7 times longer than the skilled operator's one.
(3) If image latency occurred, the difference between the two has decreased.

3.1.3   Pseud-refueling Operation

Aiming to unmanned maintenance, pseud-refueling works by remotely controlling a backhoe was conducted as shown in Figure 6 and Figure 7. It could be seen from this experiment that
(1) If and when camera images of the refueling hose and the refueling neck are intersecting perpendicularly, it becomes easier to position the refueling hose and to adjust its height direction, and
(2) Although it is required to improve the filler neck, the current method in this experiment could be more than enough put it in practice.
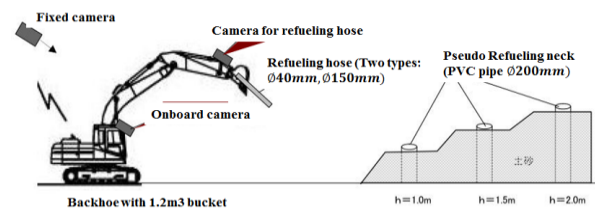

Figure 6. Image of pseud-refueling operation

Figure 7. Pseud-refueling scene

3.2   Operational Envelope Limited by Image Communication Latency and Degradation

Concerns about ultra-long-distance communication are latency and degradation of images, and presence or absence of camera cars. As arbitrarily changing conditions of images from monitors, the skilled operator has remotely operated a backhoe with a hydraulic breaker as shown in Figure 8.

Figure 8. Backhoe with a hydraulic breaker

This aims to confirm influences and operability of remote control to the following works.

(1) Travelling, grasping and placing boulders, and turning by the backhoe.

(2) Crushing boulders by the hydraulic breaker.

Accordingly, it was were confirmed that allowable delay time was less than 1.5 seconds in rough works and one second in precise works.

3.3 Lesson Learned from Demonstration

The lesson learned from these demonstration tests are outlined below.

3.3.1 Availability of Wireless LAN Method （IEEE802.11j）

The confirmed availabilities of wireless LAN method are listed below.

(1) Time delay of operational data with video communication via optical fiber network and wireless LAN is less than 1 second even if the communication distance is more than 80km.

(2) High resolution of six images per one channel of wireless LAN can be transmitted simultaneously and stably.

(3) The transmission delay long-distance wireless LAN is less than about 1 second. Communication intermittent might be occurred under the condition of the large amount of data transmission (e.g.,1.5 Mbps), that's why dropping frames of image data transmitted might happen. If the number of cameras is less, that is, volume of data transmitted is less, it might be available.

(4) The transmission amount of wireless LAN is large, but the communication sneak performance is poor.

(5) Image transmission capability

The wireless LAN is able to stably transmit 6 images per channel in case of quick changes (one image: 1.5~3.0 Mbps/30 fps), and 10 images per channel (one image: 1.0~1.5 Mbps/30 fps) in case of little changes.

3.3.2 Communication within Construction Site

In case of usage of wireless LAN and specified low power radio, it is limited to about 10 units of construction machines, in order to prevent communication interference. In this demonstration, both the image system signal and the operation system signal could be handled without hindrance. When using wireless LAN (IEEE802.11j) and specified low power radio, the each reaching distances was about 230 m. It might be promising to use low-latency type codec in wireless LAN method in future.

3.3.3 Possibility of Public Broadband Communication

The public broadband communication shows superior communication sneak performance with about 70 degrees at location where there are impenetrable hills, buildings and the like. According to narrowness of the bandwidth, image degradation, dropping frames of image, and so on, it is difficult to concurrently use image system signal. Boom or arm of backhoe might cut radio waves off sometimes. The communication sneak performance might be valid at a place with poor visibility.

3.3.4 Long-distance Communication Method

Allowable limit of transmission delay to operators is up to about 2 seconds. In ultra-long-distance communication method more than 30 km, the transmission delay is less than 0.8 seconds. When combining wireless LAN (one channel/IEEE802.11j) and optical fiber, transmission delay of operation data was less than 100 msec.

Although optical fiber communication is applicable to unmanned construction, it is necessary to carefully consider the usage environment and conditions.

3.3.5 Inmarsat Satellite Communication System

The transmission capacity is 64 kbps, and the 8-second delay occurred. If and when the usage is limited to emergency applications with fewer amount of data, it is likely that this system works well for control system.

3.3.6 Startup of Communication and Unmanned Construction Systems

To sum up the participants' opinions, it might take four days to arrange the orders and shipping pertaining to equipment such as remote-control room, relay stations, allocations of unmanned construction machines, and forth. Moreover, it might take one day to set up them, and moreover one day to take their test runs. Considering examination of new technologies, however, it shall take ten days to do so.

4 Efforts to Post-disaster Reconstruction at Aso Bridge District

4.1 Efforts Up till Now [3]

The 2016 Kumamoto Earthquakes are in a series of earthquakes, which are a foreshock earthquake observed at 21:26 on April 14, 2016 with a magnitude 6.5 at a depth of about 11 kilo meters, and then main shock earthquake with a magnitude 7.3 observed at 1:25 on April 16, 2016 with a magnitude 7.3 at a depth of about 12 kilo meters.

It was heavily damaged around the centre of Mashiki, where the earthquakes with a Japanese scale, that is seismic intensity of 7 (hereinafter called Shindo) occurred two times. Moreover, earthquakes with more than Shindo 1 were observed 4,481 times as of April 13,

2016, including seven earthquakes more than Shindo 6 lower.

After the earthquakes, 172 deformations of river embankments such as cracks and subsidence were confirmed in relatively larger river system under control of MLIT. Approaching the verge of rainy season, urgent restoration works were required without a moment's delay

MLIT has carried out urgent restoration works 24 hours a day on 11 relatively larger deformation points in 172 damaged points of river embankments, and worked it out and accomplished the restorations on May 9 before the rainy season in 2016. In addition, considering causes of the damages, methods of restoration and monitoring on the situation of restoration, full-scale restoration works have been done on 52 points required to restore and accomplished by the end of May before rainy season in 2017.

Slope failures and landslide by these earthquakes shredded major transportation routes and then it was transport impossible everywhere. These damages made it difficult to rescue and transport emergency supplies, and moreover to take measures for livelihood rehabilitation. Accordingly, MLIT had urgently restored roads within about 1 week after the disasters, which had been essential for lifesaving and indispensable to transport relief supplies.

The scale of the large-scale landslide at Aso bridge district run up about length 700 meters and about width 200 meters, and the sediment discharge was estimated about 500,000 cubic meters. Many crown cracks and terrace scarps occurred on the head of the landslide. Since the post failure ground surface was steep slope, there was a danger of further collapse caused by rainfall or aftershock.

Since it was the most important task to avoid any secondary disaster under the above circumstance, the latest unmanned construction technologies, which are leveraged the knowledge and results obtained from the demonstration tests as mentioned before, were introduced into the rehabilitation works, as monitoring and sensing movement of the post failure ground surface and the surrounding.

The works commenced on May, 2016. Firstly, as considering what kind of works are possible in the landslide area, building approaching path to the crown of the landslide started in order to construct retaining embankment.

Since sediment in the area destructed by landslide had high soil moisture content, it was forced to move forward to consolidate the surface and subbase of the approaching path as stirring and mixing soil amendment and additive in situ. Subsequently, a full-fledged construction of retaining embankment could commence in July of that year, where was utilized unmanned

construction system with multiplexing of connected devices with high-speed and wide-bandwidth data transmission as shown in Figure 9. This unmanned construction system made it possible to remotely operate up to 14 construction machines at the same time and to build retaining embankment. Moreover, this system enabled us to do rounding and remove large boulders at the crown of the landslide, and to remove soil at the post ground surface. Accordingly, urgent construction works could be completed to avoid secondary disaster.
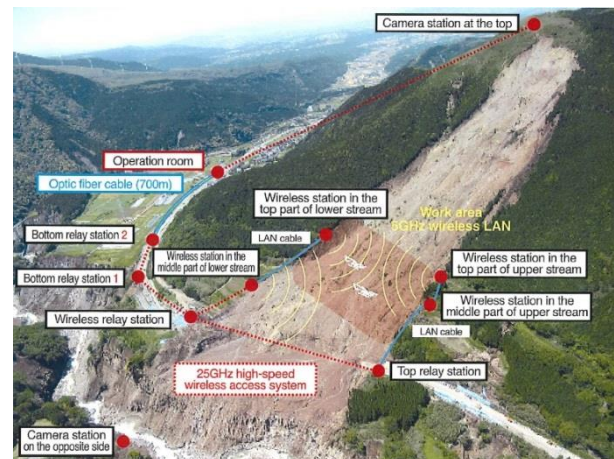

Figure 9. Bird's eye view of unmanned construction conducted at Aso bridge district

Because the danger of secondary disaster is reduced, currently, manned works have been and are being implemented to build permanent fix works such as protection net and inserting rebar.

5 Research and Development on Autonomous Crawler Carrier

5.1 Supposition and Purpose

To achieves a less burden on operators mentally, we have been and are doing research and development on autonomous crawler carrier utilized for material haulage. It is supposed that autonomous construction machines might cause new mental strain on operators, such that, as expecting nothing happens, waiting for something might happen. Then, it is worth providing operators with infographics pertaining to construction machine's behaviour. The infographics include figures, evaluation indexes and messages as to operability, safety and productivity. The infographics give operators opportunity to prognosticate something that might happen.

5.2 Experiments at the institute of technology

Experiments as to operability of a crawler carrier and driving performance of the autonomous crawler carrier developed were conducted at the institute of technology, Kumagaigumi, Co., Ltd. Objectives of the experiments are as follows:
(1) Comparison of operabilities between boarding operation and remote-control of a crawler carrier, and
(2) Confirmation of driving performance of the autonomous crawler carrier developed.

5.3 Field test on at Aso bridge district

The field test on autonomous operation of crawler carrier to haul soil removed at the mountainside was conducted. These crawler carrier was remotely controlled at loading and unloading spots and automatically run through the haulage road.

Examples of the infographics shows the following hazards latent in the haulage road:
(1) Many impacts and free-falls in Figure 10 show the surface of the haulage route is rough and uneven;
(2) Figure 11 shows sudden acceleration occurred uphill and rapid deceleration downhill and both sudden acceleration and rapid deceleration at the waypoint of turnaround, and
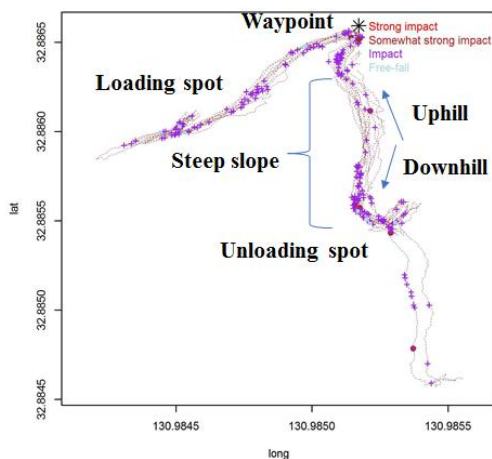(3) Attitude of machine body, however, was stable as shown in Figure 12.

Figure 10. Impact and free fall latent spots occurred in the haulage road

These infographics are visualizing the spatiotemporal behavior of the autonomous crawler carrier, and help the operators to prognosticate hazards. These infographics could enhance their spatial awareness, which would be able to provide the operators with the opportunities to reflect on their own bearings as facing their own works at hand, to reduce likely stress in remote-control operations of construction machines. Furthermore, it would be possible to take timely and quickly correct actions based on detailed visibility of appearances and motions of the autonomous crawler carrier in a whole unmanned construction process.
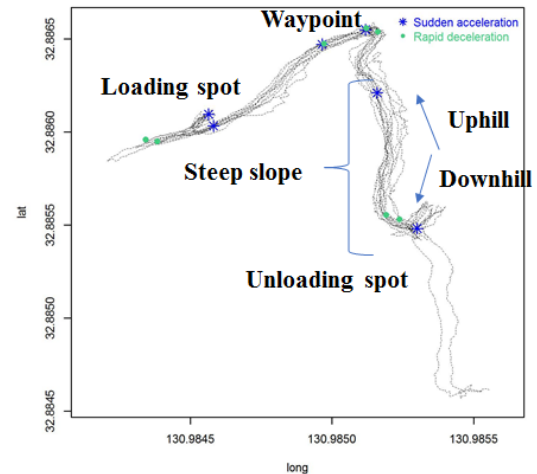

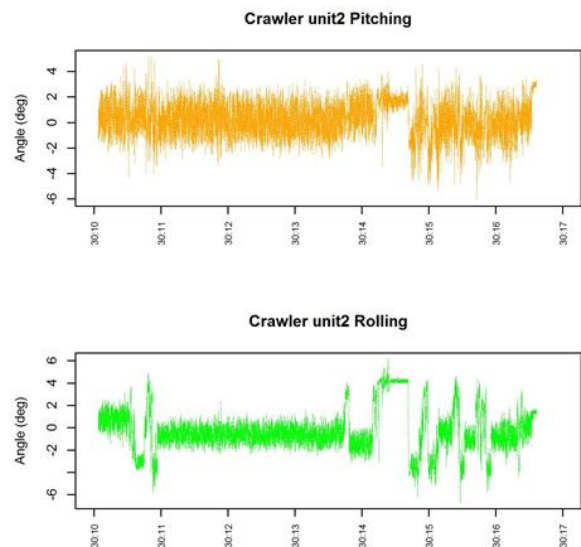Figure 11. Sudden acceleration and rapid deceleration spots occurred in the haulage road

Figure 12. Attitude of machine body

6 Remarks, Further Works and Proposal

This paper presents largely severe natural disasters happened in Japan until now, problems in responses to post-disaster restoration and reconstruction, demonstration tests of ultra-long-distance unmanned construction and the requirements for the deployment, the research and development on autonomous crawler carrier.

Considering the participants' opinions, tasks to be resolved for practical use are listed below.

(1) Unmanned refueling, lubricant oil supply, and machinery maintenance.

(2) Preventive maintenance techniques for inspection and maintenance.

(3) To ensure durability of on-board communication devices.

(4) Autonomous system adjustments such as setup of devices, change of IP address, and so on.

(5) Operator training system to develop skilled operators.

(6) To build communication system suitable for peculiarities of post-disaster restoration and reconstruction site.

(7) Procurement management of construction machines and devices suitable for unmanned construction.

Providing operators with perpendicularly intersecting images of objects, it will become easier to position the object and to adjust its height direction. More arbitrary viewpoints on the monitor, however, are liable to increase new mental workload to memorize and understand simultaneously. It is desirable to develop functions that enable operator to easily accommodate mentally translation, rotation and scaling between different frames of references.

Although automation of construction machines will decrease mental workload on operators, it will produce new mental workloads to carefully watch unexpected occurrences of unsafe events, and cooperative states of several autonomous machines. It is desirable to develop service planning and executing diagram and functions to control complement of remote-control machines, autonomous machines and computer devices operating together for construction.

In future, when unmanned construction system would be deployed in various kinds of remotely dexterous operation in close proximity to other, for examples, approaching to the target (e.g., inspection, repair, monitoring another one), positioning or repositioning dangerous materials, connecting an object with other, grasping and stacking sandbags or gabions, inserting nozzle into a fuel filler port for replenishment, and so on. Then, it is desirable to find the better way to control micro manipulation by remote-control operation.

Finally, following discussions on construction robots at the disaster and accident sub-committee, we propose the following levels of promising applicability of robots in responses to post-disaster restoration and reconstruction.

Level 1: It could be remotely controlled to monitor and investigate within disaster-stricken location.

Level 2: It could propel oneself within disaster-stricken location to complete simple works.

Level 3: It could propel oneself within disaster-stricken location and then remotely controlled to complete complex works. and

Level 4: In combination of autonomous and remote-control operations, it could smoothly complete sophisticate works.

Considering these levels, we are going to do research and development on the further tasks to be resolved.

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