Review:

Technology of Unmanned Construction System in Japan

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[Received May 1, 2014; accepted May 22, 2014]

This paper describes the application of Japan's most advanced unmanned construction technologies to disaster recovery operations. These technologies were originally R&D focused, but have continued to become increasingly sophisticated with invaluable real-world applications. This paper focuses on robotic and autonomous operations and ultra long-distance remote control. We detail unmanned construction equipment and systems operating in radiation-contaminated environments and examine the effectiveness of monitoring-image technology in improving the operational safety of construction machinery. Finally, future directions and prospects are described.

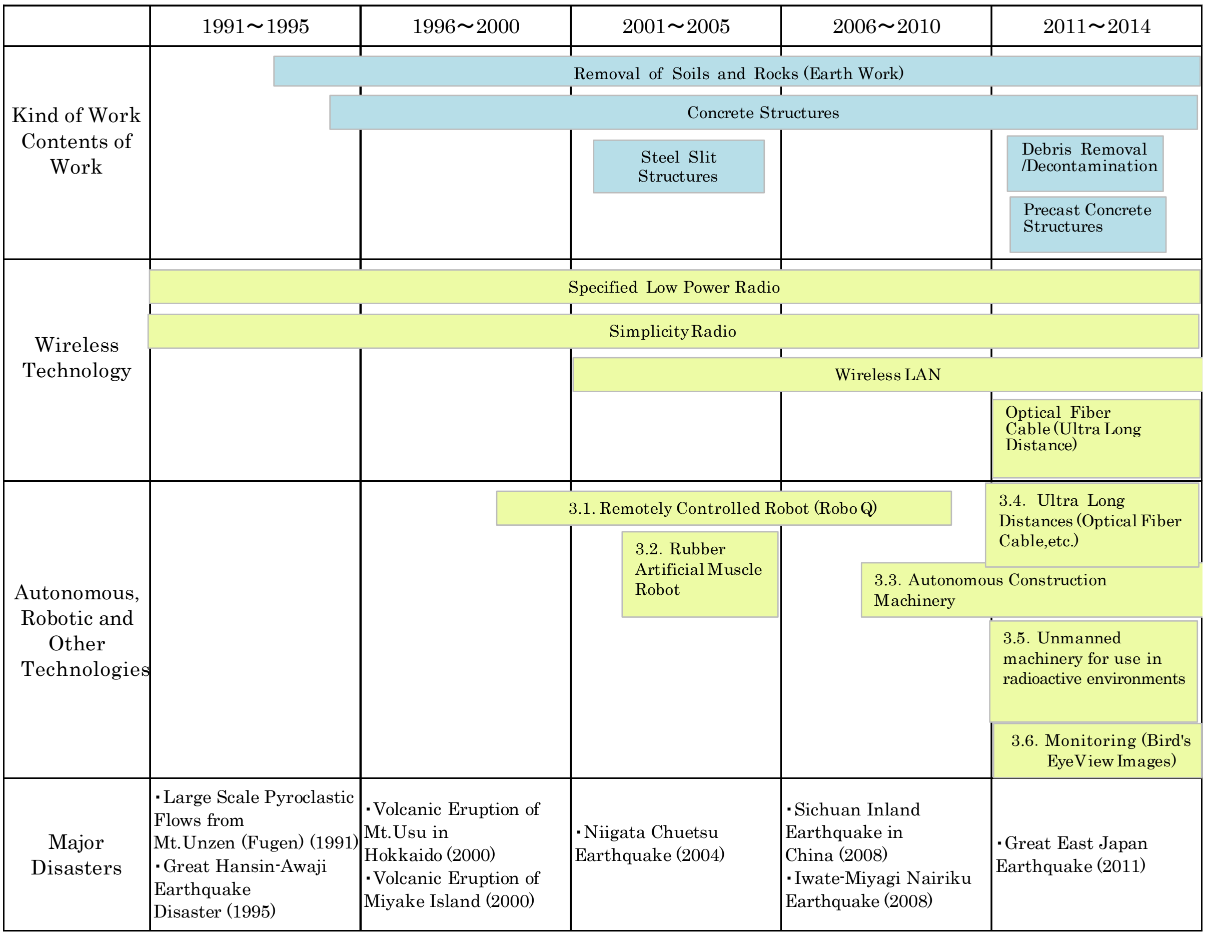
Keywords: unmanned construction system, robotization, autonomous, of ultra-remote (long distance), presentation system of bird's-eye view image

1. Introduction

In recent years Japan has suffered a number of natural disasters – including the 2011 East Japan Great Earthquake, landslide damage, and volcanic eruptions. Rapid response in the immediate aftermath of such disasters is crucial in minimizing loss of life and in preventing secondary damage. However, manned construction operations in disaster areas are inherently hazardous and also run the risk triggering secondary disasters. Unmanned construction systems that enable operators to monitor and operate construction machinery from a safe distance provide many advantages and their development should be encouraged.

Unmanned construction technologies first started to become more common in Japan when the Ministry of Land, Infrastructure, Transport, and Tourism (the Ministry of Construction at that time) requested private companies and institutions to design proposals for post-disaster unmanned debris-removal work in hazardous areas, such as the pyroclastic and debris flows around Mt. Unzen (Fugen). Since then, unmanned technologies have been applied to many disaster recovery operations, with the result the technology is constantly being improved and refined. Specifically, large amounts of time, human resources, and research financing have been allocated to R&D for emergency recovery response technologies using robotic and autonomous operations, and for ultra-long-distance remote control and monitoring. Recently, such unmanned construction technologies have been applied increasingly widely. For example at the site of the damaged Fukushima nuclear power plant, unmanned construction machinery is used to reduce workers exposure to radiation and to improve the efficiency of disposing of rubble and other de-

Table 1. Major technological transition in unmanned construction systems.



	1991〜1995	1996〜2000	2001〜2005	2006〜2010	2011〜2014
Kind of Work Contents of Work	Removal of Soils and Rocks (Earth Work)				
	Concrete Structures				
			Steel Slit Structures		Debris Removal /Decontamination
					Precast Concrete Structures
Wireless Technology	Specified Low Power Radio				
	Simplicity Radio				
			Wireless LAN		
					Optical Fiber Cable (Ultra Long Distance)
Autonomous, Robotic and Other Technologies		3.1. Remotely Controlled Robot (Robo Q)			3.4. Ultra Long Distances (Optical Fiber Cable,etc.)
			3.2. Rubber Artificial Muscle Robot	3.3. Autonomous Construction Machinery	
					3.5. Unmanned machinery for use in radioactive environments
					3.6. Monitoring (Bird's EyeView Images)
Major Disasters	・Large Scale Pyroclastic Flows from Mt.Unzen (Fugen) (1991) ・Great Hansin-Awaji Earthquake Disaster (1995)	・Volcanic Eruption of Mt.Usu in Hokkaido (2000) ・Volcanic Eruption of Miyake Island (2000)	・Niigata Chuetsu Earthquake (2004)	・Sichuan Inland Earthquake in China (2008) ・Iwate-Miyagi Nairiku Earthquake (2008)	・Great East Japan Earthquake (2011)

bris.

This paper focuses on unmanned construction technologies. These include:

1. The original remote-controlled Robo Q robot.
2. Another remote-controlled artificial rubber muscle robot (effectively an improved and enhanced Robo Q model).
3. Autonomous excavation and loading by hydraulic excavators.
4. Ultra-long-distance camera image transmission and remote control of construction machinery (up to 100 km).

We also review cases of unmanned construction equipment used in radiation-contaminated environments and of monitoring system effectiveness in the use of construction machinery in improving operating safety. As construction in Japan increasingly moves from new construction to the maintenance of existing infrastructure, and as Japan's population shrinks and ages it is important to understand the benefits that unmanned construction could provide in the future.

2. Unmanned Construction System Overview

In contrast to the manned operation of construction machinery, e.g., by operators seated in a driver's seat, unmanned construction systems are remote-controlled by radio – usually from safe sites some distance from hazardous areas.

Unmanned construction system technologies are characterized by the following features:

(1) Operating construction machinery from safe sites remote at least a few kilometers from disaster zones or hazardous construction.

(2) Managing real-time construction work and finished work quality using construction support systems such as cameras, GPS, and ground surveys.

(3) Interactive, real-time data exchange with construction machinery to minimize problems and to ensure stable remote operation.

Table 1 lists major technological transitions in unmanned construction systems. Unmanned construction system technologies were initially applied to rubble removal (sedimentary sand and soil), and to limiting the expansion of damage due to large-scale pyroclastic flows

Fig. 1. Remote control room.

Fig. 2. Construction work status.

from Mt. Unzen (Fugen). This was done through removal work such as excavation, loading, and transportation by remote-controlled hydraulic excavators, bulldozers, and wheeled dumpers controlled from a remote, safe control room away from the construction site (**Fig. 1**).

These applications were then extended to include works such as the transportation, leveling, and compaction of ultra-stiff concrete (slump = 0 cm), carried out by remote-controlled wheeled dumpers, bulldozers, and vibration rollers. These in turn were also applied to the construction of concrete structures such as sand-control dam banks. Their applications to other construction machinery and to the introduction of new systems represents an evolution from single-task roles to cooperative working. Further uses included transportation, installation, and concrete placement of steel slit material – 16 units weighing 15 tons each – installed in the overflow section of sand control dams (**Fig. 2**). They were also applied to precast concrete work with box culvert – a task demanding very high accuracy.

As applications of unmanned construction system technologies expanded from earth work to construction of concrete structures, it has become necessary to use wireless technologies with increased range and higher bandwidth. Construction machinery is generally remotely-operated using a specified low-power radio frequency band of 429 MHz, which has a relatively short range. Video transmission is at higher frequencies (in the GHz band). Despite constraints such as the need for visual communication between transmitters and receivers, line-of-sight signals in the GHz band are used for video transmission because these frequencies have a range of several kilometers and provide good data bandwidth. The combined use of wireless LANs, optical fiber cable networks, and mobile phone networks enables construction machinery to be operated remotely and more-detailed camera images to be transmitted at higher speed in greater amounts over longer distances.

Fig. 3. Remote-controlled Robo Q robot.

Purpose-built unmanned construction machinery is difficult to transport quickly to new disaster scenes. As a result a portable robot system (Robo Q) was developed. Robo Q is a portable robot that can be installed on several common makes of hydraulic excavator. Another example is remote-controlled artificial rubber muscle robot, i.e., Robo Q using artificial rubber muscle technology to make it lighter and more capable of performing complex lever operations. Unmanned construction system technologies and their applications have developed steadily and surely, and now include autonomous hydraulic excavators, large demolition machines used in radiation-contaminated environments and demolition attachments, large cranes for lifting work, and failure diagnosis systems. They also include R&D into monitoring systems that enable a virtual bird's eye view (BEV) in the construction machinery images visible to operators.

3. Unmanned Construction System Technologies in Japan

3.1. Remote-Controlled Robo Q

3.1.1. System Overview

To respond rapidly in disaster recovery operations, Robo Q is installed at the driver's seat to enable a general-purpose hydraulic excavator to be remotely operated from a safe place, as shown in **Fig. 3**. Robo Q is controlled by an operator with a direct line-of-sight to the vehicle, or via Robo Q camera images which can be displayed either through a head-mounted display (HMD) or through a monitor in a remote control room [1].

Table 2. Robo Q specifications.

Item	Specifications
Applicable Machine	Hydraulic Excavator
Communications	Wireless Communication System: Control Specified Low Power Radio System Image Spread Spectrum Radio System Communication Channel: Automated search for vacant channel in 429 MHZ Reachable Distance of Wireless Communication: 150-200 m in flat areas with good visibility Communication State Management: Engine is Automatically stopped in the case of poor communication condition.
Power Supply	Power supply: DC 24V or more (Battery Voltage when construction machine engine is running) Electric Power Consumption: Maximum 200W
Pneumatic Pressure	Maximum Working Pressure: 0.7 MPa (7kgf/cm^2) Maximum Air Consumption: Working Pressure: 120 liter/min. (in terms of atmospheric pressure)
Weight	about 180 kg (maximum weight of divided units 25 kg/unit)

Previously, dedicated remote-operation machines were often used in emergency disaster recovery. However, such machines are not commonly available and are relatively large. Moving them to a disaster zone usually entails disassembly, transportation and reassembly at the disaster site, which impairs their ability to respond rapidly to disasters.

Compared to such dedicated remote-controlled equipment, Robo Q has the following benefits [2]:

(1) Quick and easy installation: It takes only a short time to make hydraulic excavator ready for remote-controlled operation.

Machinery dedicated to remote-controlled operation requires a radio system and heavily-customized hydraulics. Robo Q, in contrast, is assembled using seven components after the driver's seat is removed from a general-purpose hydraulic excavator on site. These easy-to-handle components require only a short time to make Robo Q operable and the hydraulic excavator readied for remote operation via the Robo Q arm, which is connected to the hydraulic excavator's operation lever.

(2) Applicability: Robo Q can be installed on many types of hydraulic excavators.

Because it fits in with the operating functions of general-purpose hydraulic excavators, Robo Q can be installed on many types of hydraulic excavator. Dedicated remotely operated machines are mostly large and less available, and emergency disaster recovery operations often require standard-sized hydraulic excavators, i.e., Class 0.7–1.2 m^3.

(3) Portability: Robo Q is transported easily to disaster-affected areas.

Robo Q is broken down into compact, easily transportable sections in emergencies, meaning that it is stored quite easily in a case and carried in a minivan or by parcel delivery service.

(4) Operability: Robo Q is driven pneumatically, permitting a fine level of control.

Robo Q operations do not expose operators to discomfort in use, while ensuring excellent accuracy and safety. Robo Q controls a hydraulic excavator remotely by moving the operation lever as needed to control the actuation unit's four arms using pneumatic pressure from the engine compressor.

Table 2 lists Robo Q specifications.

3.1.2. Examples of Unmanned Construction System Applications

(1) Disaster recovery operations

A long spell of rain during the 2006 rainy season caused landslides that were then followed by secondary landslides 200 m wide and 400 m long. The secondary landslides fluidized collapsed soil, causing it to run down slopes close to populated areas, resulting in an evacuation order being issued to 48 households with a total of 174 residents. We were then requested to dispatch three Robo Qs. These were used for five days and a total of 80 hours to build 1,875 m^2 in temporary roads and 295 m of drainage channels (**Fig. 4**).

(2) Avoidance of stressful tunnel work

In 2005, Robo Q was used to close a temporary drainage channel tunnel to improve working conditions and avoid stressful work among personnel. Robo Q was used for chipping the concrete lining of the drainage tunnel to ensure its adhesion to tunnel concrete. Robo Q conducted chipping using equipment installed on a hydraulic excavator and remote-controlled from a safe site outside the tunnel (**Fig. 5**).

Fig. 4. Disaster recovery operations.

Fig. 5. Chipping work inside tunnel.

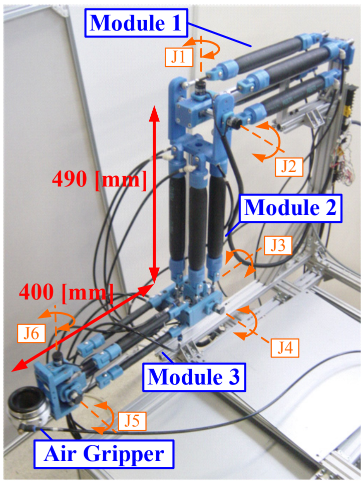


Fig. 6. Pneumatic 6-DOF robot arm.

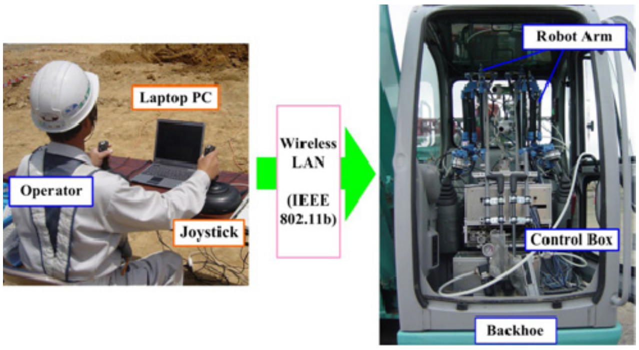


Fig. 7. Remotely operated system.

3.2. Remote-Controlled Robot with Artificial Rubber Muscles

3.2.1. System Overview

We developed a 6-DOF robot arm with pneumatic artificial rubber muscles (**Fig. 6**) to make Robo Q lighter, giving it fewer arms and enabling complex lever operations. A direct-motion actuator using pneumatic artificial rubber muscles was used to generate displacement by expanding radially when an internal tube was pressurized and contracted axially through force conversion by the fiber cord covering the tube – a very light approach capable of generating very large tensile force.

Pneumatic artificial rubber muscles generate only tensile force, so we used a five-port pneumatic servo valve to drive two pneumatic artificial rubber muscles antagonistically to generate rotary motion. We made a 2-DOF arm module by arranging two sets of such mechanisms at right angles to each other. We used MC nylon and aluminum for structural members to minimize weight to 1 kg or less. Such modules give a robot a slimmer profile while making it more extensible, making it very easy to achieve multiple DOF by combining plural modules.

We achieved 6-DOF by connecting three modules in a series, as shown in **Fig. 6**. The resulting robot arm consists of a 2-DOF shoulder that rotates and raises the arm, a 2-DOF elbow that turns inside and outside and bends the elbow, a 2-DOF wrist able to twist up, down, left, and right, and a hand able to open and close in a way similar to a human operator's. The robot arm is very light at 3.0 kg, has a large movable range, and generates sufficient force to operate the lever.

Systems similar to those remotely controlling the robot are divided into slave (robot) and master (operator) sides. **Fig. 7** shows the system and signal flow. When an operator operates the joystick on the master, its signal is transmitted from a notebook PC to the slave through a wireless LAN. At the slave, a robot on the hydraulic excavator makes the same motion as the joystick to operate the lever.

It is difficult for the robot to switch its grasp between different controls in the construction machinery (for example between traveling and bucket-operating levers) in an ad-hoc manner as these motions involve movement in three-dimensions. As a result we recorded lever positions beforehand so that the operator need only press buttons on the joystick to change levers for the robot to hold – a sort of "automation."

The system itself consists of two pneumatic robot arms, three control boxes and the power supply and pneumatic equipment, a base, a construction machine, an AK-HL1030E compressor, and an EGM24L generator. The system weighs about 75 kg or so, meaning that it can

Table 3. Test results for remotely controlled operation.

Test Condition	Excavated Amounts (m^3)	Time Required	Construction Efficiency (m^3/hour)
Remote Control (Visual + Camera)	17.95	32 min. 7 sec.	33.5
Remote Control (Visual + Camera)	12.37	33 min. 36 sec.	22.1
Direct Operation	16.0	17 min. 15 sec.	55.7
Direct Operation	15.0	17 min. 13 sec.	52.3

be carried by one vehicle, thus providing excellent transportability. The system has a large enough movable range to be installed on many different makes of hydraulic excavators.

3.2.2. Test Results

We conducted demonstration tests using a medium-sized hydraulic excavator on a flat construction site with good visibility, where the hydraulic excavator excavated the area in front of it and turned 90° to the right to transfer the excavated soil. The operator controlled the hydraulic excavator remotely by visually checking images from a camera installed between the two robot arms. We evaluated test results for construction efficiency as calculated from the amount of excavation material and the work hours required to complete the task. Construction efficiency is the value obtained by dividing the amount excavation material by working hours required. **Table 3** gives test results, which show that remote-controlled work efficiency is approximately half that of direct operation.

3.3. Autonomous Construction Machinery

3.3.1. Autonomous Construction Machinery Status Quo

It has become commonly recognized throughout the construction industry that autonomous and robotic technologies should be applied both to construction work and to survey and maintenance work. These technologies include automation, remote control, and combinations of the two. The most common autonomous and robotic construction machines are hydraulic excavators, bulldozers, and wheel loaders. Autonomous wheel loaders are being studied for application to stone pits [3]. Using bulldozers to automatically control earth removing plates in finishing work has become so widespread that some bulldozers come equipped with a function limit their areas of operation [4]. In this section, we focus on autonomous and robotic hydraulic excavators as the most representative of construction machines.

3.3.2. Autonomous Hydraulic Excavators Using 3D Information for Motion Planning and Control

The 2003-2007 General Technology Development Project Development of IT System Construction by Robots, etc., launched by the Ministry of Land, Infrastructure, Transport and Tourism of Japan involved studies on how to formulate 3D representation in design and construction drawings and on how to autonomously operate construction machinery for accomplishing model tasks using 3D information [5]. In this section, we describe autonomous hydraulic excavators and their operating systems together as a prototype system using proven technologies as much as possible. In tests, they achieved autonomous ditch digging and loading operations with prescribed accuracy at rates equivalent to those of a human operator's work under certain conditions for homogeneous soil [6–9].

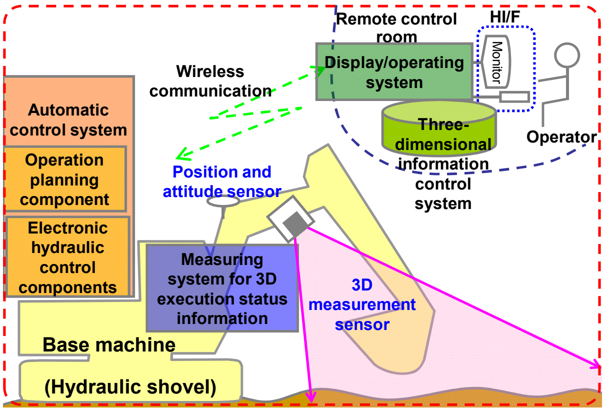


Fig. 8. Prototype system configuration.

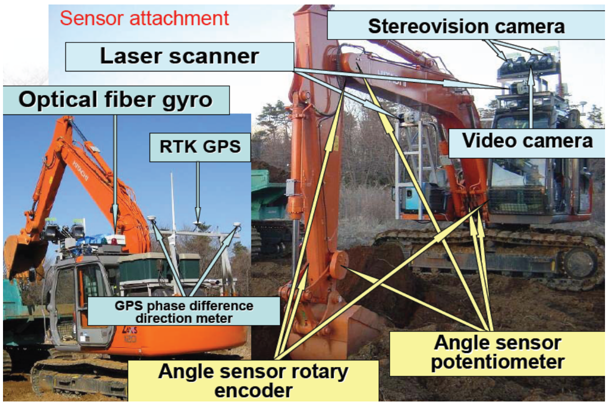


Fig. 9. Sensor locations.

In development, the hydraulic excavator is first given 3D global coordinate data (information) on the shape of the ditch to be worked on. Then the excavator measures terrain changes during work, based on given data, and autonomously controls its operations based on a digging and loading motion plan. The autonomous hydraulic excavator consists of the following (**Fig. 8**):

(1) 3D information measurement system for positioning and work status (**Fig. 9**)

The hydraulic excavator is equipped with RTK GPS to measure its position, an optical fiber gyro to measure its bearings, and a GPS vertex meter to reset drift. It also has an optical fiber gyro to measure its attitude and a rotary encoder on each bucket, arm, and boom to measure bucket position and attitude.

For shape measurement, two 2-D scanning sensors are arranged vertically on each side of the boom to enable 3D measurement as it turns. These synchronized measurements are coordinate-transformed to the correct oscillation.

A stereo camera confirms that work is completed and measures the finished shape. A video camera monitors and manually intervenes where the construction machine measures and records finished shapes, either in autonomous operation or in operator operation, to simultaneously control construction work and finished shape.

(2) Motion planning and automatic control system involving remotely operated movement and travel

Basic motion implemented is modeled after the most representative excavation for digging ditches as is done in operator operations. The operation of the proportional solenoid valve is controlled by calculating angles of the bucket, arm, and boom, the bucket tip trajectory and bucket attitude for the planned digging and loading.

We developed the following systems on the condition that motion instructions and actual situations are monitored from a remote control room to operate the hydraulic excavator as needed.

(3) 3D information management and remote monitoring/display/operating systems

We implemented 3D work information management to manage 3D information about design and work conditions and to communicate it to individual subsystems over a 2.4 GHz band wireless LAN for autonomous operations and by a 429 MHz band low-power radio for direct remote-controlled operation.

The remote monitoring/display/operating system performs traveling operation, sets up autonomous work, and monitors and/or intervenes in operations in case of failures in autonomous operations. With this system, motion instructions are given much more simply and work conditions are checked more easily so that they can all be managed (by an operator) for operating more than one excavator as the need arises. The system displays excavation work and BEV images (CG) of the tilted machine and measurement data concerning work surroundings if there are no cameras available outside for remote operation.

3.4. Long-Distance Remote Control

3.4.1. First Application of Long-Distance Remote Control – Unmanned Construction Systems Used in Response to 2000 Mt. Usu Eruption

Disaster recovery work following the 2000 Mt. Usu eruption entailed building sediment-retarding basins for volcanic products and the removal of damaged bridges. Because of the complex terrain and poor visibility, we could not use a radio relay system, i.e., a simple radio station or specific power-saving radio station, developed for disaster recovery work after the eruption of Mt. Unzen (Fugen). Due to the urgency of the work we were able to use a very high power (2 W) radio system that enabled us to remotely operate construction machinery from a range of 2 km without the need for communication relay vehicles (**Fig. 10**). Thus the Mt. Unzen (Fugen) eruption provided a good opportunity to further develop unmanned construction technologies for disaster recovery work in the field.

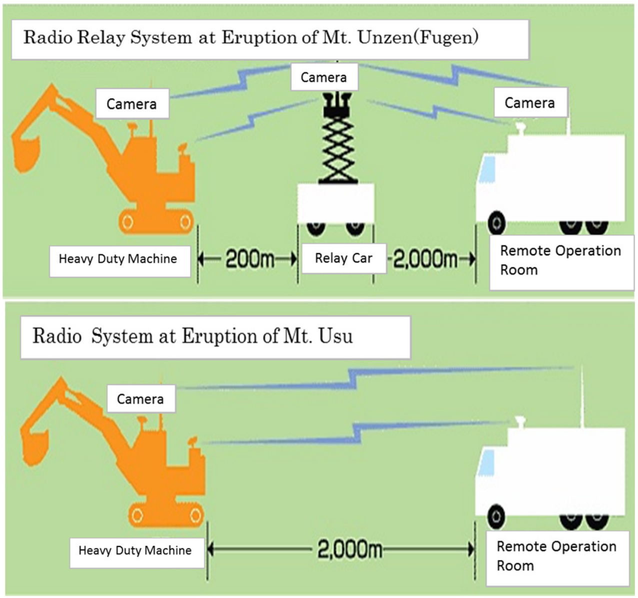


Fig. 10. Differences between relay system (above) and direct system (below).

3.4.2. Demonstration of Next-Generation Networking Unmanned Construction Systems in Optical Fiber Cable Networks (2011)

In March 2011 when the Great East Japan Earthquake occurred, the Ministry of Land, Infrastructure, Transport and Tourism of Japan conducted demonstration tests in ultra-remote (long-distance) controlled operation of unmanned construction systems in the foothills of Mt. Unzen (Fugen) to prepare for future large-scale volcanic disasters. These tests used actual machines and an optical fiber cable network for the first time in Japan and demonstrated the applicability of remote operation technologies to unmanned construction systems operated from a remote control room 30 km away. We also demonstrated that the communication system, combined with wireless mesh LAN, simultaneously transmitted high-definition 1 Mbps images from 20 cameras and that hydraulic excavators could be operated with a high degree of accuracy. We verified the transmission capabilities of alternative long-distance communication means such as public broadband communications, long-distance wireless LANs, satellite communications, etc. (**Fig. 11**).

Introducing advanced image communication technologies using Internet protocol (IP) in demonstration tests effectively solved problems such as radio interference and transmission delay which had not been resolved with earlier unmanned construction systems. IP use did not con-

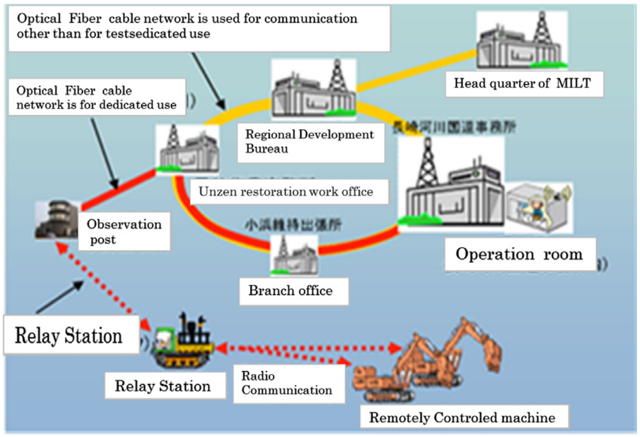


Fig. 11. Unmanned construction system configuration using optical fiber cable.

strain the number of channels – unlike low-power radio system – so a large number of construction machines could be remotely operated from a safe site. IP had not been adopted previously because of large transmission delays caused by converting data to IP packets. In demonstration tests, we checked the degree to which image transmission delays and degraded image quality could adversely affect operator operations and construction work. From these tests we found that where a skilled operator performed common operations – (1) moving a hydraulic excavator, grasping boulders, turning, placing boulders, (2) crushing boulders – that delays of up to 1.5 seconds could be tolerated for rough work and up to one second for relatively detailed work. In terms of transmitted image degradation, we found that image transmission rates of 0.5 Mbps or less started undermining operability. By using the latest consumer product codec in tests, we confirmed that a system combining optical fiber cable about 80 km in total length and wireless mesh LANs would entail delays of 0.8 second or less in image transmission, which posed no problem in operating heavy-duty machinery.

The remote control room for the demonstration tests was at the office of the Ministry of Land, Infrastructure, Transport and Tourism in Nagasaki, where optical fiber cable was already available, which enabled us to complete installing equipment for the remote control room in less than four hours. By so doing, we significantly reduced time required to prepare for responding to emergencies (**Fig. 12**).

3.4.3. Japan's First Disaster Recovery Work Using an Unmanned Network Construction System (2011)

In September 2011, Typhoon No.12 caused 1,200,000 m^3 in landslides and blocked the river channel in Nosakokawa, Nara Prefecture. In recovery operations, four construction machines connected by an unmanned construction system excavated 5,100 m^3 in unstable sediment remaining at the top of the main scarp.

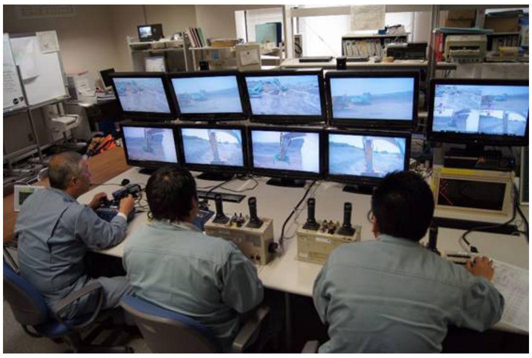


Fig. 12. Remote control room installed in remote Ministry of Land, Infrastructure, Transport and Tourism Office.

With the disaster recovery work site having an elevation difference of 200 m, we installed temporary optical fiber cable from the remote control room to the radio relay station – about 1 km – and conducted on-site communications using a 5 GHz band wireless mesh LAN. Highly accurate, stable remote operation for construction machines was achieved by transmitting all data – camera images from construction machines, control data used by construction machines, and machine guidance data – via IP communications, which greatly sped-up recovery work. In previous unmanned construction systems with limited communication capabilities, a remote control room was installed in the field within several hundred meters of the construction machines. However, with the newly developed unmanned construction systems, the use of optical fiber cable enabled us to install a remote control room in an elementary school, thus providing a safe environment and enabling us to avoid having to install power receiving and distribution equipment, which further enabled disaster recovery work to be undertaken that much sooner.

3.4.4. Strengthening Disaster Prevention Systems by Increasing Next-Generation Unmanned Network Construction Systems Applications

With the next-generation unmanned network construction systems, where all equipment connected together by the network is given IP addresses, we manage camera images, construction machinery operating signals, measured terrain information, design information for machine guidance, and other information, and control construction machines remotely from an ultra-long distance by combining the communication means used in the above demonstration tests.

In disaster recovery work, we must use a wide variety of machinery owned by different construction companies depending on scale and site conditions. Pre-standardizing IP address rules has the advantage of enabling systems to respond rapidly and flexibly in disaster recovery work involving many different institutions and construction companies if additional machinery is needed to cope with an expanded recovery work scope or if many cameras and construction machines must be operated in limited areas.

3.4.5. Issues and Future Directions for Ultra-Long-Distance Remote-Control Unmanned Construction Systems

Although ultra-long-distance remote-control unmanned construction systems are technically applicable to distances of 30 km or more, this raises numerous operational issues, e.g., (1) construction efficiency, (2) worker training, (3) reduced preparation time before the commencement of work, and (4) cost performance.

Next-generation unmanned network construction systems could be an answer to these issues. Taking advantage of the optical fiber cable network for managing national facilities, we could respond to the need for disaster recovery work much faster by bringing a radio relay station and remotely-operable construction machines into disaster-affected areas. Since it is possible to develop a long-distance IP communication system involving shorter delays in transmitting images, it may be a good option for enabling engineers and operators spread over an area of several hundred square kilometers to work together. In the case of volcanic disasters where hazardous areas could be very extensive, we could use monitoring cameras or optical fiber cable already available to set up an unmanned construction system in a short time that can be operated from public offices. As the Ministry of Land, Infrastructure, Transport and Tourism of Japan has enthusiastically promoted the installation of optical fiber cable and other facilities to monitor hazardous areas, both public and private sectors should follow up by establishing IP communications rules for effectively using existing infrastructure and for standardizing interfaces among construction machines owned by different private companies.

3.5. Unmanned Equipment in Radiation-Contaminated Environments

3.5.1. Developmental Needs

The Great East Japan Earthquake on March 11, 2011, catastrophically damaged facilities at the Fukushima No.1 Nuclear Power Plant of Tokyo Electric Power Company. Its recovery has been attempted in an environment contaminated by very high radiation dosages. Specifically, the No.3 reactor building heavily damaged by a hydrogen explosion has been completely covered with a new roof. Prior to this construction, buildings around the No.3 reactor were dismantled and debris on the reactor building roof was removed, then a steel roof cover was constructed. Such work performed by operators in construction machine cabins would have exposed them to significant radiation contamination. For this reason, construction machines were operated by a next-generation unmanned construction system controlled from remote, safe sites where operators would not be exposed to radiation during continuous operation over an extended time.

3.5.2. Next-Generation Unmanned Construction Systems

(1) Remote operation systems

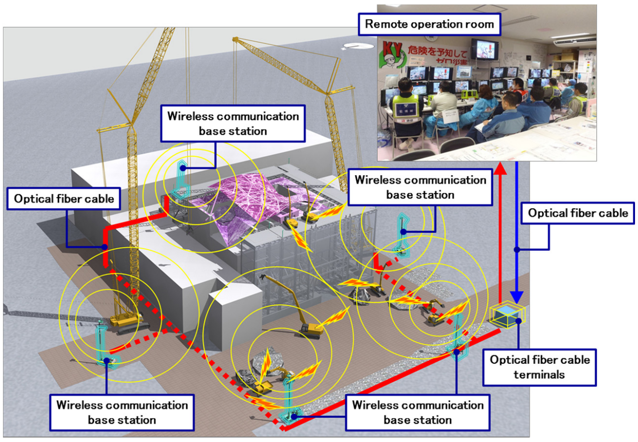


Fig. 13. Remote operation system.

The main remote operation system components for construction machinery include operating signal transmission between construction machines deployed at work sites and a remote control rooms with networking information installed at safe sites. Operators located 500 meters away from work sites in a straight line operate construction machines from a remote control room completely protected by radiation shielding.

Wireless communication base stations were placed at five spots at the work site, where optical fiber cable terminals from the remote control room were connected to create a network (**Fig. 13**). Construction machines communicated with wireless communication base stations. These machines are radio-operated with a specified low-power radio on the 429 MHz band. Camera images are transmitted with mesh wireless LANs on the 5 GHz band. The total number of connected components used exceeded 200, including 120 camera-related equipment, 80 radio- and network-related equipment, and other spare equipment. We used separate frequency bands for the operation signals of construction machines and for camera images to minimize simultaneous malfunctions in the operations of construction machines and the transmission of camera images.

Radio waves on the 5 GHz band used to transmit camera images has such strong directivity that they were very susceptible to the effects of obstacles. To counter this, we created a wireless mesh network so that mobile stations on construction machinery automatically detected connectable base stations and autonomously achieve optimum reconnection. As a result, a network with such optical fiber cables is not affected by disturbances and helps to ensure stable communications. Actual measured delay time for transmitting camera images is 0.1 second or less – much better than initially anticipated and poses no problem to controlling remotely operated systems.

(2) Large remotely operated cranes

Two large remotely operated crawler tower cranes in the 600-ton class. Loads of 750 tons were involved in lifting heavy loads associated with dismantling construction machines and steel roof structures for covering the nu-

Fig. 14. Remote fuel supply system.

clear reactor building. Any failures in radio-transmitting operation or image signals during crane lifting operations could lead to accidents caused by the swinging of heavy hoisted loads. We thus adopted a wire transmission system with highly reliable directly connected optical fiber cable rather than a wireless transmission system to transmit remote operation and camera image signals necessary for operating cranes.

To ensure safe operations, cranes are equipped with cameras to capture lifted load operation in two directions, to capture conditions around the crane and of the winch and instruments inside the cabin, and to capture function for conveying voices inside the cabin to operators.

(3) Remotely operated framework dismantling machines

The unmanned construction system we developed operates eight construction machines, including large crawler cranes, framework dismantling machines, and hydraulic excavators that move around the nuclear reactor building daily. In addition to machine cameras to capture the operator's visual field, there are many other cameras for monitoring the work site itself, so that operators can comprehensively check and view work site conditions from all angles and thereby enhance operability.

We developed a new unmanned oiling device to be operated by a crane and to ensure the timely transfer of a framework dismantling machine installed on a high-altitude stage to a safer place (**Fig. 14**).

Since it has been confirmed that electronic equipment, such as controllers, could malfunction in radiation-affected environments, we shielded vulnerable electronic equipment with lead plates to enhance durability.

(4) Failure diagnosis system

IP addresses are allocated to all network components, such as on-site monitoring cameras, radio transceivers, manipulators, and camera switching units in the remote control room to centrally control all equipment connected in a single network. To respond rapidly to any system failure, we developed and installed a "malfunction search program" to rapidly check for malfunctioning equipment, and a "mesh wireless LAN monitoring program" to rapidly determine whether abnormal camera images may be attributable to problems with the wireless system and to narrow possible causes as quickly as possible.

The above failure diagnosis system enables us to narrow down possible causes for all types of failures without having personnel enter work sites containing radiation-contaminated environments.

3.6. Monitoring Construction Machinery

(1) Arrangement of vehicle with cameras

Unmanned construction system technologies enabling operators to monitor and operate construction machinery from safe, remote sites have become increasingly widespread. Unmanned construction machines tend to be inferior to manned machines in terms of construction work efficiency. According to Reference [10], such inferior work efficiency is mostly – 29% – attributable to vision, which is in turn is most attributable – 44% – to camera positioning. It is thus crucial to resolve the above problems to enhance work efficiency in unmanned construction systems.

Conventionally, the vision problem with unmanned construction systems was dealt with by presenting images from a second vehicle having a camera (hereafter, a camera vehicle). In Reference [11] authors installed a camera in front of a hydraulic excavator and a camera vehicle at a position where they could see and photograph the hydraulic excavator so that they could present images combining these two kinds of images. Images from the camera vehicle, taken from a third-person viewpoint, show both the surroundings and the construction machine itself. Such imaging makes it easy to get a perspective of construction machinery and work and to eliminate blind spots by moving the camera vehicle as needed.

At actual construction sites, however, it is rather problematic and costly to arrange for a camera vehicle just for such images. The camera vehicle also must be moved in coordination with construction machinery and construction work movements, which requires skilled workers. The location for installing a camera poses an even bigger problem. Specifically, in the immediate aftermath of a disaster, work sites are usually covered with soil, stones, and rubble making it next to impossible to locate a camera vehicle appropriately place under such limited, complex terrain conditions, especially for engaging in an efficient emergency disaster response.

(2) BEV image presentation

We have developed a system for presenting BEV images to resolve the above problems. **Fig. 15** shows the BEV image presentation concept. The system we developed presents images from multiple cameras mounted on the construction machine itself and virtually generates BEV images for a construction machine with image processing technology and presents them to operators. Such BEV images represent a third-person view of what camera vehicle images do so as to ensure that they are free of problems in perspective or dead angle. Cameras on a construction machine present surrounding images independent of environmental restrictions such as limited areas. For these reasons, we expect to meet disaster scenes

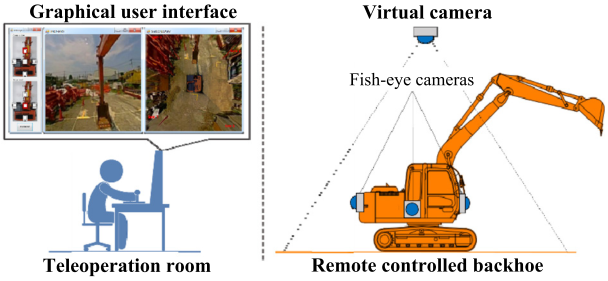


Fig. 15. BEV image presentation system concept.

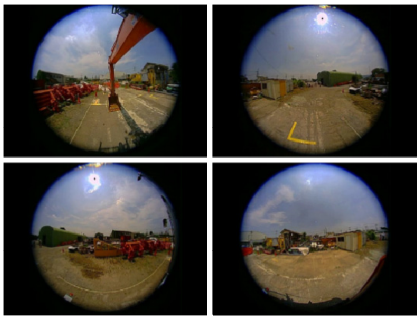


Fig. 16. Images captured by fish-eye cameras on construction machine front, back, left, and right.

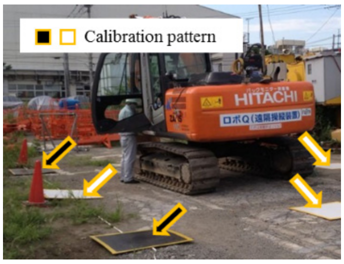
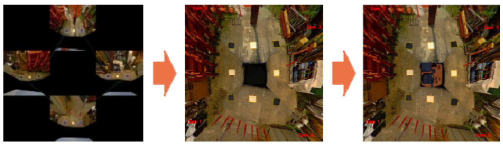


Fig. 17. Calibration execution.



(a) Visual Point Conversion
(b) Image Synthesis
(c) Superimposition of Construction Machines

Fig. 18. BEV image generation overview.

much more efficient responses using the presentation systems of BEV images than with conventional camera vehicle images.

In this study, we installed four fish-eye cameras on the front and back of the construction machine and to the left and right to generate BEV images. These cameras capture any image distortions (**Fig. 16**), which are then corrected as detailed in Reference [12]. Fish-eye cameras may not be free of inherent distortion in the images they capture, but their angle of view of 180° covers a wide area at one shot. When BEV images are generated, any circular distortions of fish-eye images in them are eliminated to create images similar to those taken by ordinary cameras.

After the above distortion correction, images are converted to images shown as if viewed from directly overhead. Image conversion processing is based on methods detailed in References [13, 14].

BEV images are generated through semiautomatic calibration using several different square patterns. Manual work involved in calibration places several square patterns on the ground around a construction machine as shown in **Fig. 17** and obtains vertex positions of patterns in each such fish-eye image. As many such square patterns as possible of the same number or more than installed cameras should be placed in the camera's imaging range, then BEV images are generated automatically.

Procedures for generating BEV images are shown in **Fig. 18**. Images captured by the four fish-eye cameras are first converted to images viewed from right overhead, i.e., image conversion to make square patterns in BEV images look square (**Fig. 18(a)**). Next, one BEV image is generated by synthesizing the four images viewed from directly overhead (**Fig. 18(b)**) so that that square patterns common to neighboring camera images overlap in the BEV image. A photographic image of the construction machine viewed from above and prepared beforehand is then superimposed on the BEV image to give it a realistic feeling (**Fig. 18(c)**). BEV images generated in this way depict environments and construction machines as seen from above, giving operators a feeling of operating construction machines from a third-person points of view in operations that are actually remote.

(3) Remote operation tests

We conducted remote operation tests with a hydraulic excavator, using the above-mentioned presentation system of BEV images. The subjects used for these tests were skilled operators already familiar with unmanned construction systems who operated hydraulic excavators remotely to make them move or to execute excavation work.

The hydraulic excavator used in tests had Robo Q installed. We operated it from a remote-control transmitter via wireless communications. Four fish-eye cameras with an angle of view of 180° were installed on the excavator's front and back, and left and right sides. These camera images are captured by PC on the excavator to generate BEV images.

Figure 19 shows system configurations in the remote control room. Images generated and combined on the excavator are transmitted to a PC in the remote control room, where they are presented on two 21-inch monitors at the operator's console. Images transmitted to the PC can be switched by the GUI displayed on monitors to and from the BEV images, the fish-eye camera images from front, back, left, and right, and distortion-corrected images. The remote control transmitter on the operator's console is a remote control system used exclusively by hydraulic excavators having Robo Q installed.

Fish-eye camera image resolutions are 640 × 480 pixels. The maximum frame rate is 15 fps. Each image pre-

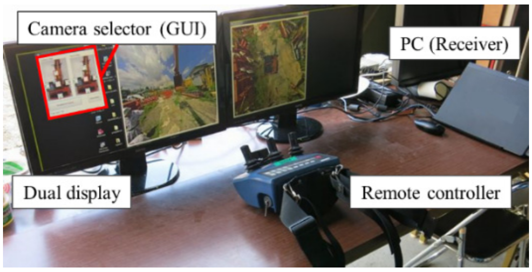


Fig. 19. Remote operation of construction machinery using BEV image presentation.

Fig. 20. Examples of BEV images.

sented has a resolution of 512 × 512 pixels. BEV images presented on monitors have an average frame rate of 9 fps due to delays in image processing and transmission.

Figure 20 shows examples of BEV images presented to the operator. It was confirmed that presenting BEV images to the operator improved construction machinery operability – particularly travel operability – compared with the case in which no BEV images were used.

These demonstration tests prove the effectiveness of presenting BEV images when monitoring and operating construction machinery.

4. Future Prospects

4.1. Problems in Applying Unmanned Construction Systems to Disaster Response

One problem with using unmanned construction systems in disaster response lies in the continuity of technical operation. This system was originally developed and used in 1993 when Mt. Unzen (Fugen) erupted, causing great damage due to pyroclastic and debris flows, and it is still being used today in continuing recovery operations at Unzen. Unmanned construction system technologies were also applied to disaster recovery operations after Mt. Usu erupted in 2000, to rescue operations at tunnel landslides caused by the Niigata Chuetsu Earthquake in 2004, and to many other hazardous operations. The fact that unmanned construction system technologies have been applied continuously to disaster recovery operations at Unzen and other disaster sites each time new disasters occur has led to their rapid deployment in response to the 2011 Great East Japan Earthquake and Fukushima nuclear power plant accident and to recovery work at a landslide dam hit by Typhoon No.12 in 2011. We may lose opportunities to apply unmanned construction system technologies when the recovery operations at Mt. Unzen (Fugen) are completed. It will then become very difficult to maintain unmanned construction system technologies if the opportunities to apply them decrease in ordinary times.

Another is a technical issue. Although unmanned construction systems have been used at a variety of disaster sites, their applicability is very limited. Given that a great variety of disasters and accidents may occur, disaster response robot systems – the same as unmanned construction systems – are required to provide advanced function to cope with the various tasks in diverse and complicated environments.

Unmanned construction systems with currently available functions are only applicable to a relatively limited range of disasters. Compared to a manned construction system, an unmanned construction system is more costly and less efficient, which should be technologically solved in future.

4.2. Recommendations by the Council on Competitiveness – Nippon (COCN)

To promote the implementation of disaster response robots, the Council on Competitiveness – Nippon (COCN) organized a project on Disaster Response Robotic Systems & Their Operations in 2011–2012, where proposals were released on the use and operation of such disaster response robots for hazardous work (or for inspection and maintenance of social infrastructures and facilities) in non-emergency situations and on their rapid deployment in cases of emergency. These proposals are summarized as follows:

(a) New projects establishment for advanced technological developments

For unmanned construction systems to be able to be used in response to a variety of disasters, needs-driven basic research on mobility/access in extreme environment, stable communication, spatial awareness in remote control, autonomy to facilitate remote operation, sensing for inspection, diagnosis and maintenance as well as practical technology development, and operation-proofing work should be conducted. Holding competitions or challenges such as DARPA Robotic Challenge [a] could also effectively further technological advancement in solution derivation and systematization.

(b) Establishment of RT center for disaster prevention and response

Disaster prevention robot centers should be established for (i) operation testing and operator training, (ii) functional evaluation and certification on the explosion-proof, antiradiation, durability, safety and other system functions, (iii) management of technological information of RT including information provision services on demand, (iv) emergency response with device deployment and operation. It is necessary to establish testing fields and mock-up models for operation testing and operator training.

(c) Strategy planning, standardization and regulation design

Long-term strategies must be designed and formulated to continue developing and operating disaster response robots consistently. It is also crucial to implement the following: (i) standardization for functional evaluation and interface specifications, (ii) deregulation including authorization of exceptional zones, (iii) tightening for the regulation of mandatory deployment, (iv) formulation of tax systems for exemptions, etc., (v) preservation of radio frequencies, (vi) insurance plans.

In line with the abovementioned proposals, the Project on Disaster Response Robot Center Establishment was launched in 2013, where specific functions of the Disaster Response Robot Center and implementation plans and management frameworks were discussed. The Disaster Response Robot Center consists of Disaster Response Robot Headquarters and the Disaster Response Robotics Technology Center. Headquarters formulate long-term strategies for technological development and for deploying and operating disaster response robots. The Disaster Response Robotics Technology Center manages technological developments in disaster response robots, their operation testing, functional evaluation, and certifications, their operator training, and their standardization, operation, and deployment in ordinary times. Proposals hold that Disaster Response Robotic Headquarters should be established in a national government cabinet office and the Disaster Response Robotics Technology Center should be managed in cooperation with industry, government, and academia. In ordinary times, disaster response robots could be used for: (1) hazardous tasks or at construction sites, (2) inspection and maintenance of social infrastructures and facilities, (3) training operators.

The Disaster Response Robotics Technology Center should construct and manage complete databases on RT related to disaster response robots and their practical evaluation, needs, etc., and should operate testing fields and mock-up models for disaster response robots as a base for conducting operation testing and functional evaluation and certification so that it performs R&D functions to operation testing to operator training to deployment to actual sites of use.

4.3. Conclusion

In this paper, unmanned construction systems were outlined, introducing a variety of robots and remotely operated equipment used in disaster responses at disaster recovery sites as well as addressing problems to be solved in future. Due to their crucial importance in building a society resilient against disaster through developing and operating robotics technologies applicable to actual sites, including unmanned construction system technologies, national government ministries and agencies and municipalities are currently discussing how to establish bases for conducting disaster response robot and operation R&D. This includes the Fukushima Innovation Coast Study Panel. Technological development and operation of disaster response robots are vital from the viewpoints of national resilience against disaster and also from the viewpoints of maintenance and lifelong duration of social and industrial infrastructures and disaster prevention measures. Technological development and operations involving disaster response robots are expected to generate a great ripple effect in relation to a variety of robotics industries. It is earnestly hoped that on-going studies and proposals by the COCN are realized as soon as possible.

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