https://doi.org/10.20965/jrm.2014.p0486

Paper:

A Basic Framework of Virtual Reality Simulator for Advancing Disaster Response Work Using Teleoperated Work Machines

Mitsuhiro Kamezaki*, Junjie Yang, Hiroyasu Iwata***, and Shigeki Sugano****

*Research Institute for Science and Engineering (RISE), Waseda University
17 Kikui-cho, Shinjuku-ku, Tokyo 162-0044, Japan
E-mail: kame-mitsu@sugano.mech.waseda.ac.jp
**Department of Modern Mechanical Engineering, School of Creative Science and Engineering, Waseda University
3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan
***Department of Modern Mechanical Engineering, School of Creative Science and Engineering, Waseda University
Green Computing System R&D Center, 27 Waseda-machi, Shinjuku-ku, Tokyo 162-0042, Japan

[Received February 24, 2014; accepted June 11, 2014]

A virtual reality (VR) simulator is developed to aid in advancing teleoperated construction machines for disaster response work. VR simulators, which can measure arbitrary data, allow the operator to reproduce desired situations repeatedly, and change the machine and environmental configurations more easily than is possible in real environments, can create teleoperation technologies and quantitatively evaluate them, and can improve operational skills in complex disaster response works. As basic components of a VR simulator, a VR environment, operation-input, and video-output components are developed. The VR environment is built using a basic graphics library and dynamics engine for simplification. The operation-input component consists of control levers for a demolition machine that has a grapple and environmental cameras with yaw, pitch, and zoom functions. The video-output component consists of a two-dimensional monitor that can display an in-vehicle camera view, multiple environmental camera views, and the machine status. Experiments conducted show that operators can adequately transport debris in the VR environment while watching views on the monitor from the in-vehicle and environmental cameras. The experiments also reveal the characteristics that reduce the machine's time efficiency.

Keywords: construction machinery, teleoperation, virtual reality simulator, disaster response work

1. Introduction

It is generally hoped that disaster rescue and recovery could be achieved more safely, effectively, and expediently [1]. In general, disaster rescue and recovery work is performed using construction machinery, which has the advantage of being able to produce massive amounts of force [2]. Construction machinery is maneuvered by an operator in a cockpit installed on the machine (such operation is hereinafter called in-vehicle operation), as shown at the top of **Fig. 1**. However, in disaster response work, the in-vehicle operation often causes two critical problems: the lives of operators are endangered and the applicable environments are limited. The ground, landslides, and collapsed buildings after a disaster are often unstable and complicated [3]. Moreover, the operator may have insufficient visibility due to smoke and obstacles. These factors cause dangerous collapse of piles of rubble, toppling over of machinery, and breakage of surrounding undamaged objects. In-vehicle operation thus endangers operators in secondary disasters. Moreover, disasters and accidents often occur in unusual circumstances and/or create undesirable ones, including anoxic atmospheres (e.g., underwater), noxious gas (e.g., carbon monoxide), and radiation, which are especially dangerous to operators [4]. The disaster response work in such circumstances has social significance, but human operators cannot live in such

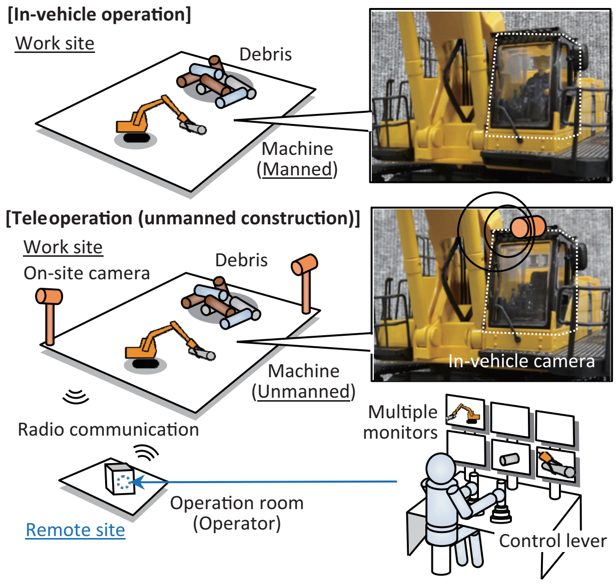

Fig. 1. Unmanned construction using teleoperation technologies.

circumstances biologically. In-vehicle operation therefore cannot be applied in the abovementioned dangerous circumstances.

To address the problems above, teleoperation technologies have been introduced into construction machinery [5–7]. Teleoperation in this field is called unmanned construction, which does not mean an autonomous control system [8]. In unmanned construction, an operator is in a safe operation room located at a location far from the disaster site, as shown at the bottom of **Fig. 1**. Various data are exchanged between the disaster-site and remote-site using radio communication techniques. Operational signals are transmitted to teleoperated machines on the disaster site, such as hydraulic shovels, bulldozers, and dump trucks. Sensory signals include position data received from a satellite positioning system and camera images received from in-vehicle and environmental cameras. The operator maneuvers a teleoperated machine by means of control levers, the same as in the case of an in-vehicle system, and obtains sensor data by watching multiple two-dimensional monitors.

2. Requirements for Advancing Unmanned Construction Systems

The problems of the current unmanned construction systems were first identified, and the work required to address the problems was then proposed.

2.1. Current System in Unmanned Construction

1) Common primordial problems: The safety of operators is physically ensured and the applicable limitations are partially solved by using unmanned construction systems. However, these systems have so far just integrated existing teleoperation, monitoring, and radio communication technologies, so they have recently faced more complex problems. The most critical problem is the decrease in time efficiency. In excavation work using a teleoperation system, the time efficiency is approximately 40% lower than when the in-vehicle operation system is used [9]. This decrease results primordially from different operational conditions which can be classified into the following three components: unsatisfactory visual information, radio communication delay of operational signal and camera image information, and a lack of tactile and body sensory information, as shown in **Fig. 2**. Moreover, in recent years, society has called for improved efficiency and a wider range of applications for unmanned construction [10, 11]. This is because these activities directly relate to faster disaster recovery.

2) Current research and developments: To improve the time efficiency of unmanned construction, the abovementioned three issues must be solved. Various technologies addressing them have been developed. For the incomplete visual information, operation assistance based on markers overlaid on the camera image [12] and an immersive user interface based on augmented reality techniques [13] have been proposed. To decrease the communication delay, the assignment of communication array vehicles [14] and signal processing [15] have been proposed. The radio communication problems, including delay, crosstalk, wave interference, and limitation of communication distance, have been emphasized in recent developments. For missing tactile and body sensory information, haptic interfaces [16] and force feedback systems [17] have been proposed, but they have been incorporated very little in current unmanned construction due to their complex feedback systems.

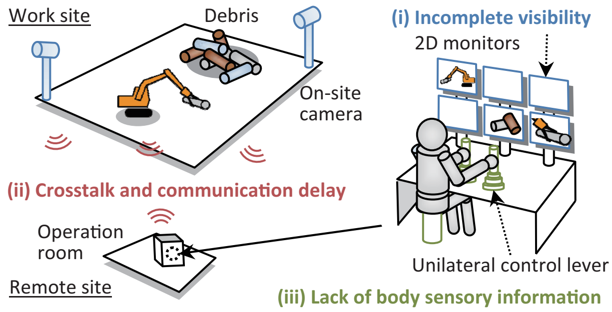

Fig. 2. Problems in current unmanned construction.

2.2. Technology Development Using VR Simulator

Many technologies have been developed in real environments using physical resources, which are quite important for practical fields such as disaster response work. On the other hand, developments in real environments have many constraints, such as high costs, lack of sensors, irreproducible environments, and time-consuming experiments. To prepare for unforeseen disasters, many kinds of situations should be repeatedly experienced, and advanced technologies must be developed on the basis of the quantitative analysis of the experimental results. Therefore, developments in real environments are not effective for that purpose. As one way to address these problems, virtual reality (VR) simulators are often used, such as surgical operation simulators [18, 19] and automobile driving simulators [20]. The advantages of VR simulators are quantitative evaluation at lower cost, high repeatability, and no physical constraints. VR simulators are thus useful for operational skill training, the derivation of comprehensive problems and improvements [18], and the development and evaluation of advanced technologies, although physical behavior is difficult to reproduce precisely. In the construction machinery field, a VR simulator for coaching machine operations has been developed [21], but, VR simulators that address the aforementioned three issues have not been developed in the unmanned construction field.

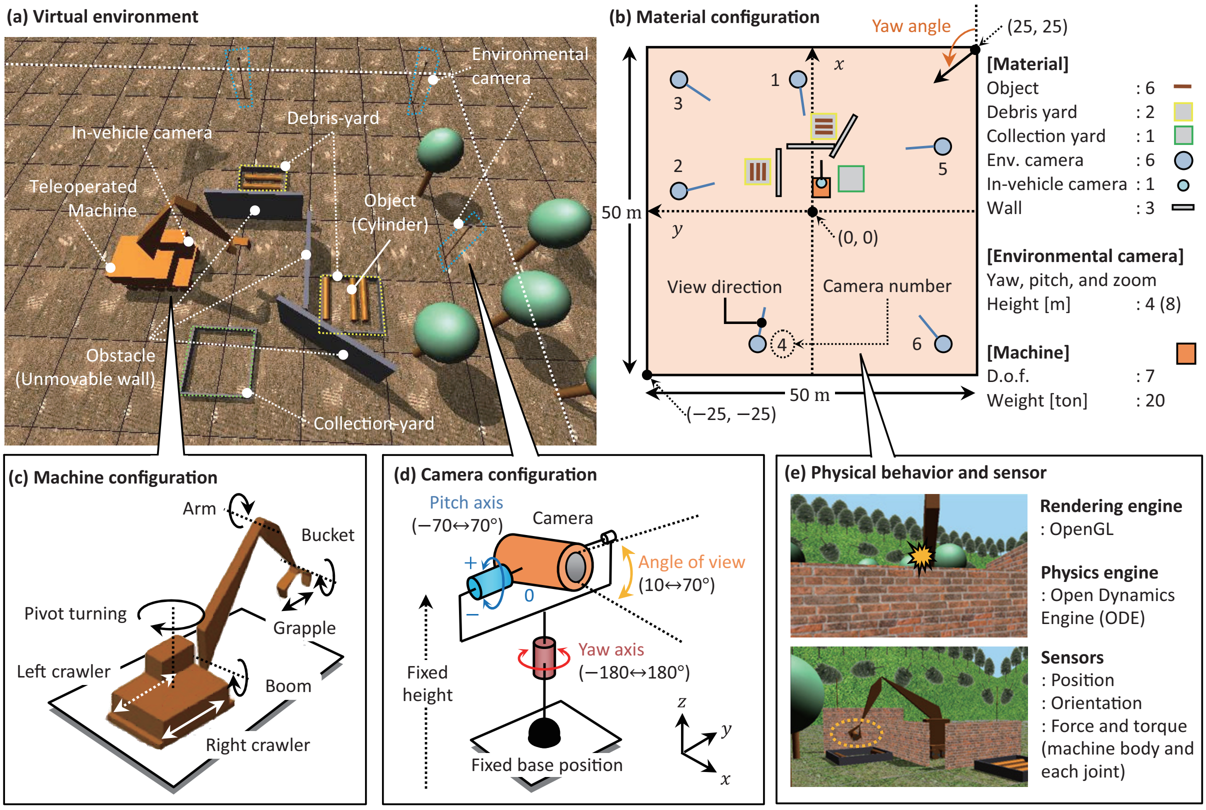

Fig. 3. Virtual reality environment with machine and camera configurations.

2.3. Required Work

In this study, a basic framework for a virtual reality simulator to easily train operators to perform unmanned construction, extract issues to be improved in teleoperation, and develop advanced unmanned construction technologies was proposed. The following developments and experiments were then conducted.

1) Development of VR environment: The VR environment was built using OpenGL to easily reproduce the experimental environment and using Open Dynamics Engine to reproduce basic physical behavior. A demolition machine with a grapple, cameras, and various objects and barricades were created (Section 3).

2) Development of man-machine interface: The operator interface consisted of operation-input and video-output components. Control levers for the machine and controllable cameras with yaw, pitch, and zoom functions as well as a two-dimensional monitor to display camera images and machine status were prepared (Section 4).

3) Evaluation experiments: Through a debris-transporting experiment, the usefulness of the developed VR simulator was evaluated. Moreover, on the basis of analyzing the work results, key areas in which time efficiency could be improved were identified (Section 5).

3. Development of Virtual Reality Environment

Taking the ease of experiment and reproduction of fundamental physical behaviors into consideration, we created the virtual reality environment shown in **Fig. 3**.

3.1. Components

The VR environment was built using OpenGL, which is a basic rendering tool box that can create two- and three-dimensional graphics and can easily adjust the viewport configuration.

1) Teleoperated machine: Arbitrary machine types could be created, and their configurations could easily be adjusted. Debris removal work at disaster sites was targeted in this study, so a demolition machine with a grapple of a size equivalent to a 20-ton-class industrial construction machine was created, as shown in **Fig. 3(c)**. The reproduced machine had seven degrees of freedom: left and right crawlers, a turning mechanism, a grapple (open/close), and a manipulator with three pitch joints, a boom, an arm, and a bucket (named from proximal to distal order of the joint).

2) In-vehicle and environmental cameras: Any number of cameras could be installed in arbitrary positions. In this study, one camera was installed in the machine (called an in-vehicle camera) and six cameras

were set in the environment (called environmental cameras), as shown in **Fig. 3(b)**. The number of cameras was similar to that for current unmanned systems. Cameras were defined by roll, yaw, and pitch rotation, and optical zoom, as well as installation height and base location. The one in-vehicle camera and six environmental cameras were used to provide a view from the cockpit and complement the in-vehicle camera view. In consideration of the fundamental camera parameters, controllable parameters were set to the optical zoom and yaw and pitch angles, which could be adjusted with control levers, as described in Section 4 (**Fig. 4(c)**). By referring to the general camera settings, the adjustable ranges of the angle of view (zoom ratio), yaw (rotation around the z-axis), and pitch (rotation around the y-axis) were set to $10° \leftrightarrow 70°$, $-180° \leftrightarrow 180°$, and $-70° \leftrightarrow 70°$, respectively, as shown in **Fig. 3(d)**. Fixed parameters were then set to the roll rotation (rotation around the x-axis), base location (x, y), and installation height (z). The detailed settings for the experiments are described in Section 5.1.

3) Material: Many types of materials could be created. Complex materials (e.g., sticky, friable, and powdery ones) should be created to reproduce actual complex disaster sites, but, in this study, we focused on debris transport as one of the most basic disaster response tasks. Six cylindrical objects, three wall barricades, two debris yards, and one collection yard were then created, as shown in **Figs. 3(a)** and **(b)**. These materials could be created and rearranged depending on the purposes of the development and evaluation of advanced technologies, and skill training. The settings of the experiments are detailed in Section 5.1.

3.2. Reproduction of Dynamic Behaviors

Physical phenomena, including grasps, collisions, and gravity, are vital for the VR simulators used for disaster response work performed with construction machinery. Therefore, the proposed simulator included a high performance library, called an Open Dynamics Engine (ODE), for simulating rigid body dynamics. ODE has built-in collision detection, as shown in **Fig. 3(e)**. Although the ODE does not completely reproduce dynamic behaviors and lacks in accuracy of calculating contact points, it has the minimum functions required to realize the purpose of this fundamental study, namely to focus on simple debris transport. ODE was employed because of the ease with which it reproduces basic physics. Moreover, the simulator can measure sensory information, such as joint torque, force applied to the end-point, grasping force, and the position and orientation of the end-point, individual joints, and machine body, all of which can be stored in a comma-separated values (CSV) file. The control and sampling frequencies were set to 30 Hz.

4. Development of Man-Machine Interface

On the basis of the actual unmanned construction systems, the operator interfaces consisting of operation-input and video-output components were developed (**Fig. 4**).

4.1. Control Lever (Input)

A total of ten control levers were prepared to control the teleoperated construction machinery and environmental cameras, and two 12-bit analog to digital conversion (A/D) boards were used to read input data. The relationship between the master joints (the control levers) and slave joints (the teleoperated machine and environmental cameras) and arrangement of control levers could be arbitrary adjusted.

1) Teleoperated machine: Two control levers for the manipulator and turning mechanism were placed to the left and right of the operator, as shown in **Fig. 4(a)**. These levers had two degrees of freedom in the x (forward and backward) and y (left and right) directions as well as one rocker switch. The grapple was controlled using the rocker switch of the right lever. The axis relationship between the machine and control levers corresponded to the JIS standard, called left-right-pivot [a]. This relationship could be changed by software. Moreover, two control levers for the right and left crawlers were placed in the front of the operator, as shown in **Fig. 4(b)**. These levers had one degree of freedom in the x (forward and backward) direction. Two control levers for spare usage, which were of the same type as the crawler lever, were placed to the left and right of the crawler levers.

2) Environmental camera: Four control levers for the environmental cameras were placed in the lower front of the crawler levers, as shown in **Fig. 4(c)**. These levers had three degrees of freedom in the x direction (pitch), y direction (yaw), and z rotation (zoom). It was unrealistic to set up control levers for all the environmental cameras, so the number of control levers was set to four in this study.

4.2. Monitor (Output)

One monitor that could project multiple camera views was prepared, and the relationship between view content and projected position in the monitor was defined.

1) Monitor configuration: In the current unmanned construction system, multiple two-dimensional (2-D) monitors were used to display the video received from the cameras [5, 8, 14]. However, the size, resolution, and number of monitors have not yet been analyzed systematically. It is quite important to change the monitor configurations and evaluate them. In this study, a 42" 2-D liquid crystal display (LCD) with a 1920×1080 pixel resolution, was employed, as shown in the upper left of **Fig. 4**. This monitor

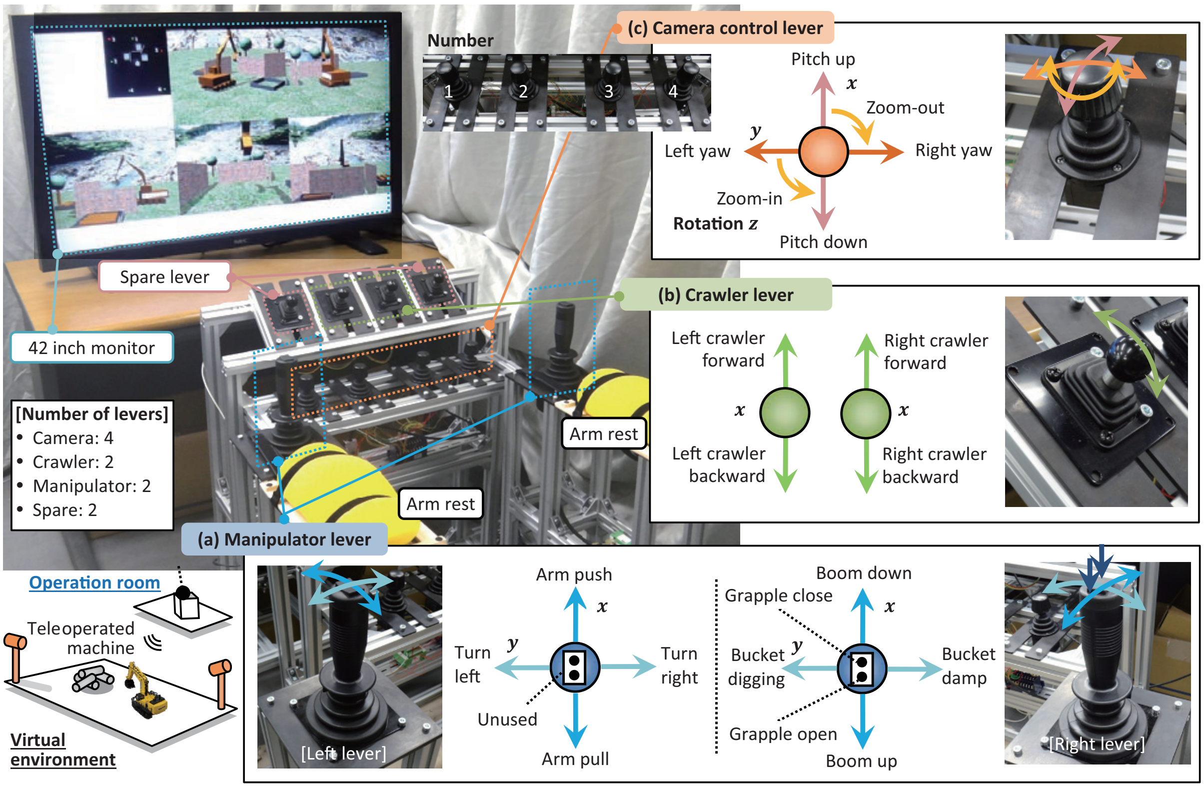

Fig. 4. Operation input: control levers for cameras, crawlers, and manipulator.

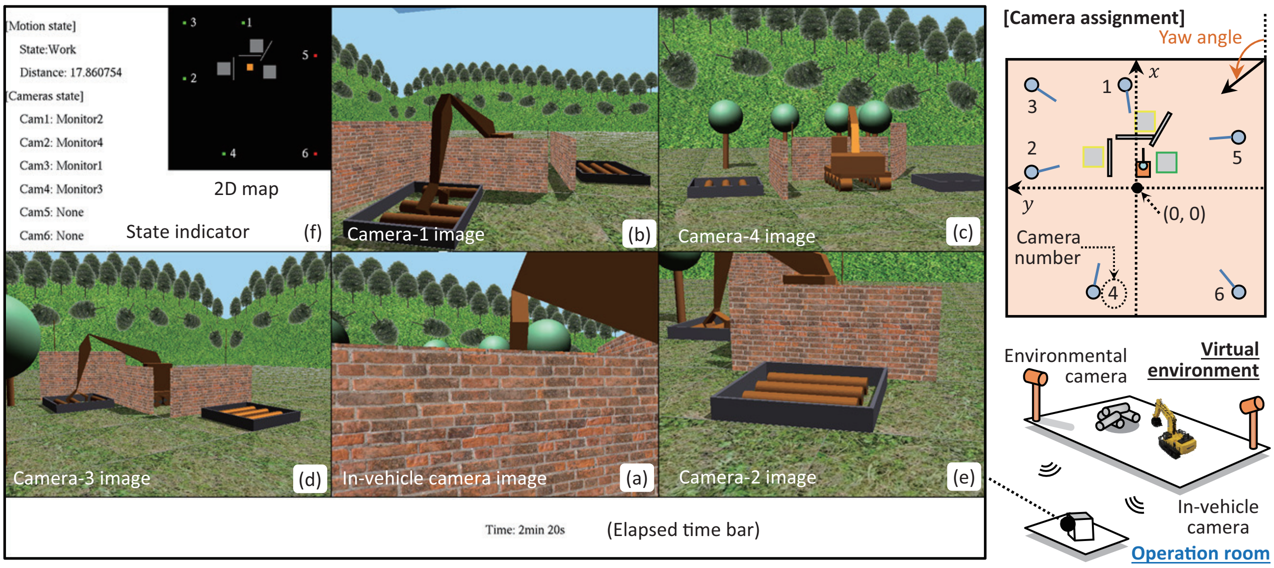

Fig. 5. Video output: multiple views and installation position of cameras.

was placed behind the control levers. The size and number of sections of the display area could be divided arbitrarily. In this study, it was equally divided into 2×3 sections with 4:3 aspect ratios, as shown in **Fig. 5**.

2) Relationship between view content and position: Any camera images and information could be shown in the six sections. The image from the in-vehicle camera had to be set in the center because it was the most fundamental image. It was unrealistic to project all the images from the environmental cameras, so the number of environmental camera views was set to four, corresponding to the number of camera control levers. Moreover, a status view showing the positions of the machine and camera as well as an overview of the environment (top view), should be provided. From the analysis, the relationships between view content and position were defined, as shown in **Fig. 5**. The view (a) at the lower center is

Table 1. Components and adjustable parameters of VR simulator.

Components	Adjustable parameters
VR environment	
- Machine	Type (backhoe, crane, and crasher), size, and degrees of freedom
- Camera	Base position and posture, height, camera angle, angle of view, and the number
- Material	Shape, weight, and friction, and the number * Smoke and fragile and particle objects
Operation input	Arrangement of control lever, relationship between control lever and joints of machine * Force feedback system
Video output	Arrangement and size of monitors, relationship between image content and position * Three-dimensional displays

* Components which should be implemented in the future work

Table 2. Experimental settings.

	Orientation and zoom °*			Position m *		
	Yaw	Pitch	AoV **	x	y	z
Camera 1	−172	−3	70	20	2	4
Camera 2	−77	−14	30	3	20	4
Camera 3	−124	−4	44	20	20	4
Camera 4	−13	−1	31	−20	8	8
Camera 5	94	−16	38	10	−20	4
Camera 6	40	−9	31	−20	−20	8

* Coordinate systems are referred to **Figs. 3 (b) and (d)** ** Angle of view

the in-vehicle camera image. The views, (b)–(e), are the images from the environmental cameras. The relationship between the view letter and camera number was defined as follows in this study: (b) 1, (c) 4, (d) 3, and (e) 2. The view (f) at the upper left shows the camera status and overview map of the environment. Besides these six views, an elapsed time bar was set on the bottom of the screen.

5. Evaluation Experiments

Fundamental experiments were conducted to confirm that the operator could execute unmanned construction work using the developed VR simulator, and to analyze the results.

5.1. Adjustable Parameters in VR Simulator

The purpose of the developed VR simulator was to easily train operators to do unmanned construction work, identify potential improvement areas in teleoperation, and develop advanced unmanned construction technologies, as stated in Section 2.3. In this study, we developed a basic framework for a VR simulator, consisting of the basic components, i.e., the VR environment, operation-input, and video-output, which could be arbitrarily adjusted, as stated in Sections 3 and 4. **Table 1** lists the reproduction components and adjustable parameters. The table also lists components which should be implemented in future work because this study focused on fundamental components. The quality and complexity of each component should be improved in future works.

5.2. Experimental Conditions

The purpose of the experiments was to evaluate the fundamental performance of the VR simulator. The evaluation task was therefore set to sequentially transport debris, as this is one of the most fundamental disaster response tasks. The six cylindrical objects to be transported (3.0 m in length and 0.35 m in diameter) were set in two debris yards (3.8 W × 3.8D × 0.6H m), as shown in **Fig. 3(a)**. To obscure the operator's vision, two walls (7.0 W × 0.3D × 3.0H m) and one high wall (7.0 W × 0.3D × 4.0H m) were placed in front of the debris yards, as shown in **Fig. 3(b)**. Operators grasped each object around the middle without misses or erroneous contact, and transported the objects, without letting them fall, as quickly as possible to the collection yard (the same size as the debris yard). To evaluate the basic framework of the virtual reality simulator, camera parameters were fixed as listed in **Table 2**: the cameras used (1, 2, 3, and 4), yaw (−172°, −77°, −124°, and −13°, line directions in **Fig. 3(b)**), pitch (−3°, −14°, −4°, and −1°), angle of view (70°, 30°, 44°, and 31°), x coordinate (20, 3, 20, and −20 m), y coordinate (2, 20, 20, and 8 m), and z coordinate (4, 4, 4, and 8 m). The 4 m-high cameras were used to provide detailed images of the manipulator, and the 8 m-high cameras were used to provide an overview of the environment. These parameters were determined through the pre-experiments to adequately complement the in-vehicle camera image. In this study, the usefulness of the developed VR simulator as an operational skill improvement tool was evaluated. Seven novice operators who were familiar with how to operate our simulator were chosen as operators, and they each carried out the task six times.

5.3. Results

We first confirmed that operators could complete the task on the VR simulator to evaluate its usefulness as an operational training tool. Second, we analyzed their methods of operation to determine the difference in time efficiency in order to evaluate a quantification function. Third, we identified the situations that tended to lower the time efficiency in order to evaluate the possible areas needing improvement.

1) Task completion and effect of training: The operators completed the debris transport task, including moving the machine body, reaching an object, grasping the object, transporting it, approaching the collection yard, and releasing the object into it, as shown in **Figs. 6(a)–(f)**. The average completion time for all operators is shown in **Fig. 7**. The results indicated that the time efficiency increased, and T-testing indicated that there was a significant difference between trials 1 and 6 ($t = 5.28$, $p < 0.05$). The

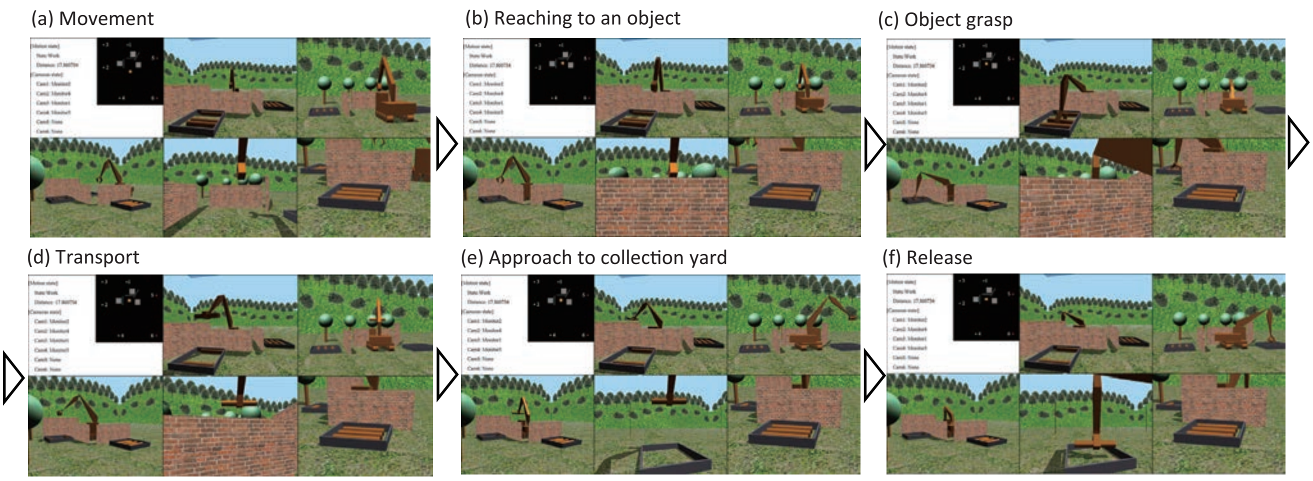

Fig. 6. Sequence of debris transport task.

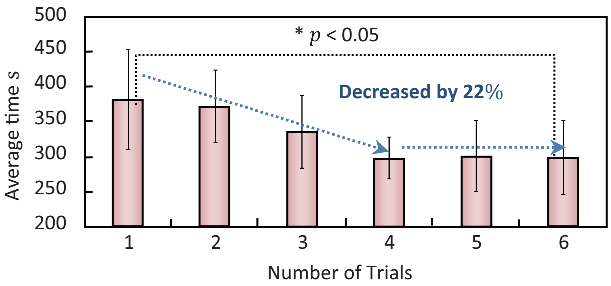

Fig. 7. Improvement of time efficiency.

figure shows that the operators gradually acquired adequate operational skills as they repeated the tasks. These results indicate that the developed VR simulator is useful as a teleoperation skill training for unmanned construction.

2) Analysis of time efficiency between operators: As a basic analysis, factors that affect the machine's time efficiency were analyzed by comparing a slow result (Operator A: 444.6 s) with a fast one (Operator B: 221.7 s). The amount the control levers that were used and the trajectory of the end-point (x and z) for both results are shown in **Fig. 8**. The results for the slow one (Operator A) indicate that the operator frequently wasted operations and stopped the bucket and boom joints, and above all, the operator frequently re-positioned the body of the machine after reaching for objects, as shown in the upper part of **Fig. 8(a)**. The lower part of **Fig. 8(a)** indicates that it took a long time to grasp an object after the end-point has entered the area near the object, meaning that the operator could not control the end-point precisely. Questionnaires indicate that there were sometimes blind spots and the angle of view was not suitable in some situations. The operators felt that these factors lowered their efficiency and preciseness in machine operations. The results for slower operators had the same features as those for Operator A. In

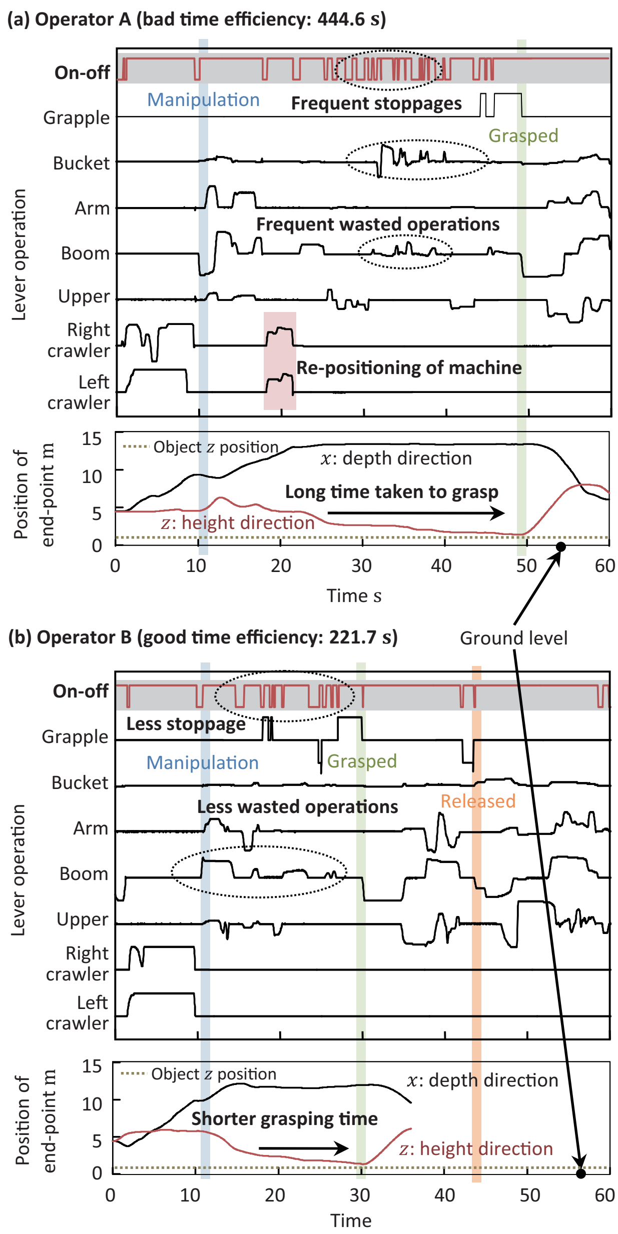

Fig. 8. Analysis of time spent to grasp object.

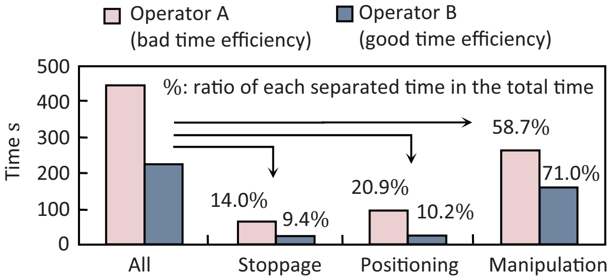

Fig. 9. Casual analysis of decreases in time efficiency.

contrast, the results for faster operators (like Operator B) indicated that they wasted few operations and grasped the objects swiftly, as shown in **Fig. 8(b)**. These results of analysis reveal that operations near the object are the key to improving efficiency, so the developed VR simulator could help to reveal points needing improvement.

3) Analysis of work state decreasing time efficiency: To analyze the causes of degraded time efficiency in detail, the elapsed times during each work state, including stoppage time (when all control levers are stopped), positioning time (when the control lever of the crawler is activated), and manipulation time (when the control levers of the manipulator and/or tuning mechanism are activated) were derived. The ratio of elapsed time in each state to the total completion time was also calculated. The results of the analysis are shown in **Fig. 9**. As the figure indicates, all elapsed time in each state for Operator B was shorter than that for Operator A, the stoppage time was one-third, and the positioning time was one-fourth. An analysis of the ratio revealed that the manipulation ratio for Operator A was 58.7% while that for Operator B was 71.0%. This means that Operator B spent most of the time in actual movement. It was also observed that operators who had shorter completion times tends to have shorter stoppage and positioning times. The experiments showed that smooth positioning of the end-point while grasping the object serves to increase time efficiency.

6. Conclusion

A teleoperation simulator using a virtual reality (VR) environment to advance unmanned construction has been developed. The VR simulator had to have the functionality to create new teleoperation technologies and evaluate them quantitatively as well as to improve operational skills. In this study, basic components, including the VR environment, operation-input, and video-output components, all of which could be arbitrary adjusted, were developed. The VR environment was easily built using OpenGL and ODE. For the operation-input components, control levers for a demolition machine with a grapple and environmental cameras with yaw, pitch, and zoom functions were developed. For the video-output components, a grid of six-different 2-D views, to display one in-vehicle camera image, four environmental camera images, and one machine status, were prepared. Debris transport tasks were conducted by using the developed VR simulator. In the experiments, all operators successfully transported debris. The results of work analysis indicated that the angle of view during the grasping state influenced the time efficiency. The improvement of visual information will be discussed by adding more subjects including skilled operators in the future work. More complex materials (e.g., string-like and friable objects) and natural phenomena (e.g., smoke and rain), simulated time-delay components, and a sensory feedback system (e.g., force feedback) must be implemented in the developed VR simulator. Moreover, the usefulness of sensor data that can be obtained only in a VR space must be quantitatively evaluated, and a method for applying them to real environments will be discussed.

Acknowledgements

This research was supported in part by the research grant FYs 2012 and 2013 from the Japan Construction Machinery and Construction Association, in part by JSPS KAKENHI Grant Number 26870656, and in part by the Research Institute for Science and Engineering, Waseda University, Japan.

References:

[1] S. Tadokoro, "Special project on development of advanced robots for disaster response (DDT project)," Proc. IEEE Workshop on Advanced Robotics and its Social Impacts, pp. 66-72, 2005.

[2] A. Ishii, "Operation system of a double-front work machine for simultaneous operation," Proc. Int. Symp. Automation and Robotics in Const., pp. 539-542, 2006.

[3] M. Guarnieri, P. Debenest, T. Inoh, E. Fukushima, and S. Hirose, "Helios VII: a new vehicle for disaster response-mechanical design and basic experiments," Advanced Robotics, Vol.19, No.8, pp. 901-927, 2005.

[4] C. M. Humphrey and J. A. Adams, "Robotic tasks for chemical, biological, radiological, nuclear and explosive incident response," Advanced Robotics, Vol.23, No.9, pp. 1217-1232, 2009.

[5] S. Nishigaki, K. Saibara, S. Kitahara, H. Iwasaki, K. Yamada, and H. Satoh, "ICT-based work management to support unmanned construction for post-disaster restoration," Proc. Int. Symp. Automation and Robotics in Const., pp. 508-513, 2011.

[6] K. Yokoi, K. Nakashima, M. Kobayashi, H. Mihune, H. Hasunuma, Y. Yanagihara, T. Ueno, T. Gokyuu, and K. Endou, "A tele-operated humanoid robot drives a backhoe in the open air," Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems, pp. 1117-1122, 2003.

[7] Y. Hiramatsu, T. Aono, and M. Nishio, "Disaster restoration work for the eruption of Mt Usuzan using an unmanned construction system," Advanced Robotics, Vol.16, No.6, pp. 505-508, 2002.

[8] Y. Ban, "Unmanned construction system: present status and challenges," Proc. Int. Symp. Automation and Robotics in Const., pp. 241-246, 2002.

[9] T. Xinxing, Z. Dingxuan, H. Yamada, and N. Tao, "Haptic interaction in tele-operation control system of construction robot based on virtual reality," Proc. Int. Conf. Mechatronics and Automation, pp. 78-83, 2009.

[10] K. Nagatani, S. Kiribayashi, Y. Okada, K. Otake, Y. Kazuya, S. Tadokoro, T. Nishimura, T. Yoshida, E. Koyanagi, M. Fukushima, and S. Kawatsuma, "Gamma-ray irradiation test of electric components of rescue mobile robot Quince," Proc. IEEE Int. Symp. Safety, Security, and Rescue Robotics, pp. 56-60, 2011.

[11] T. Hirabayashi, "Examination of information presentation method for teleoperation excavator," J. Robotics and Mechatronics, Vol.24, No.6, pp. 967-976, 2012.

[12] M. Jinki, S. Youngwan, P. Shinsuk, and K. Jinwook, "Development of immersive augmented reality interface for construction robotic system," Proc. Int. Conf. Control, Automation and Systems, pp. 1192-1197, 2007.

[13] N. Fujiwara, T. Onda, H. Masuda, and K. Chayama, "Virtual property lines drawing on the monitor for observation of unmanned dam construction site," Proc. IEEE/ACM Int. Symp. Augmented Reality, pp. 101-104, 2000.

[14] S. Kitahara and Y. Takashi, "Deployment of construction robots applying the information technology and network system," Proc. Int. Symp. Automation and Robotics in Const., pp. 19-23, 2006.

[15] H.-J. Park, S. Lee, S.-K. Kang, M.-S. Kang, M.-S. Song, and C. Han, "Experimental study on hydraulic signal compensation for the application of a haptic interface to a tele-operated excavator," Proc. Int. Symp. Automation and Robotics in Const., pp. 298-303, 2011.

[16] D. B. Kaber, Y. Lee, M. Clamann, and Y. S. Lee, "Investigating human performance in a virtual reality haptic simulator as influenced by fidelity and system latency," IEEE Trans. Systems, Man and Cybernetics, Part A: Systems and Humans, Vol.42, No.6, pp. 1562-1566, 2012.

[17] K. W. Oh, D. Kim, N. H. Kim, and D. Hong, "The virtual environment for force-feedback experiment of excavator using a novel designed haptic device," Proc. Int. Symp. Automation and Robotics in Const., pp. 51-56, 2011.

[18] S. Haque and S. Srinivasan, "A meta-analysis of the training effectiveness of virtual reality surgical simulators," IEEE Trans. Information Technology in Biomedicine, Vol.10, No.1, pp. 51-58, 2006.

[19] C. Basdogan, M. Sedef, M. Harders, and S. Wesarg, "VR-based simulators for training in minimally invasive surgery," IEEE Computer Graphics and Applications, Vol.27, No.2, pp. 54-66, 2007.

[20] S. Nagiri, Y. Amano, K. Fukui, and S. Doi, "The study of driving support system for individual driver," Proc. IEEE Int. Conf. Systems, Man and Cybernetics, pp. 563-568, 2002.

[21] S. Strassburger, T. Schulze, M. Lemessi, and G. D. Rehn, "Temporally parallel coupling of discrete simulation systems with virtual reality systems," Proc. Conf. Winter Simulation, pp. 1949-1957, 2005.

Supporting Online Materials:

[a] Japanese Industrial Standards Committee (JISC), https://www.jisc.go.jp/eng/ [Accessed January 15, 2014]

Name:
Mitsuhiro Kamezaki

Affiliation:
Assistant Professor, Research Institute for Science and Engineering, Waseda University

Address:
17 Kikui-cho, Shinjuku-ku, Tokyo 162-0044, Japan

Brief Biographical History:
2008-2009 Visiting Research Associate, Faculty of Science and Engineering (Global COE), Waseda University
2009 Research Associate, Faculty of Science and Engineering (Global COE), Waseda University
2010-2013 Research Associate, Department of Modern Mechanical Engineering, Waseda University
2013- Assistant Professor, Research Institute for Science and Engineering, Waseda University

Main Works:
• "A Symbolic Construction Work Flow Based on State Transition Analysis Using Simplified Primitive Static States," J. of Robotics and Mechatronics, Vol.24, No.6, pp. 939-948, Dec. 2012.
• "Identification of Dominant Error Force Component in Hydraulic Pressure Reading for External Force Detection in Construction Manipulator," J. of Robotics and Mechatronics, Vol 24, No.1, pp. 95-104, Feb. 2012.
• "A Framework to Identify Task-Phase and Attentional-Condition for Supporting Complicated Dual-Arm Operations," J. of Robotics and Mechatronics, Vol.22, No.4, pp. 447-455, Aug. 2010.

Membership in Academic Societies:
• The Institute of Electrical and Electronics Engineers (IEEE) Robotics & Automation Society
• The Robotics Society Japan (RSJ)
• Society of Biomechanisms Japan

Name:
Junjie Yang

Affiliation:
Ph.D. Candidate, Major in Modern Mechanical Engineering, Graduate School of Creative Science and Engineering, Waseda University

Address:
3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan

Brief Biographical History:
2013- Ph.D. Student, Major in Modern Mechanical Engineering, Graduate School of Creative Science and Engineering, Waseda University
2013-2014 Research Assistant, Faculty of Science and Engineering (Global Robot Academia), Waseda University

Main Works:
• "Analysis of Effective Environmental-Camera Images Using Virtual Environment for Advanced Unmanned Construction," Proc. 2014 IEEE/ASME Int. Conf. Advanced Intelligent Mechatronics, July 2014.
• "A Tele-Operation Simulator for Complicated Unmanned Construction – Development of Operation-Input and Video-Output Components –," Proc. SICE System Integration Division Annual Conf., pp. 2937-2395, Dec. 2012.

Name:
Hiroyasu Iwata

Affiliation:
Associate Professor, Faculty of Science and Engineering, Waseda University

Address:
GCS40-602, 27 Waseda-cho, Shinjuku-ku, Tokyo 162-0042, Japan

Brief Biographical History:
2001- Research Associate, Department of Mechanical Engineering, Waseda University
2005- Assistant Professor, Consolidated Research Institute for Advanced Science and Medical Care, Waseda University
2006-2007 Associate Professor, Consolidated Research Institute for Advanced Science and Medical Care, Waseda University
2007- Associate Professor, Waseda Institute for Advanced Study, Waseda University
2012- Associate Professor, Department of Modern Mechanical Engineering, School of Creative Science and Engineering, Waseda University

Main Works:
• "Usability and Performance of a Wearable Tele-echography Robot for Focused Assessment of Trauma Using Sonography," Medical Engineering & Physics, On-line Journal, http://dx.doi.org/10.1016/j.medengphy.2012.04.011, Apr. 2012.
• "Design of Human Symbiotic Robot TWENDY-ONE," Proc. 2009 IEEE Int. Conf. on Robotics and Automation, pp. 580-586, May 2009.
• "Human-Robot-Contact-State Identification Based on Tactile Recognition," IEEE Trans. on Industrial Electronics, Vol.52, No.6, Dec. 2005.

Membership in Academic Societies:
• The Institute of Electrical and Electronics Engineers (IEEE) Robotics & Automation Society
• The Robotics Society Japan (RSJ)
• The Japan Society of Mechanical Engineers (JSME)
• The Society of Instrument and Control Engineers (SICE)

Name:
Shigeki Sugano

Affiliation:
Professor, Department of Modern Mechanical Engineering, School of Creative Science and Engineering, Waseda University

Address:
3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan

Brief Biographical History:

1986- Research Associate, Department of Mechanical Engineering, Waseda University
1990- Assistant Professor, Department of Mechanical Engineering, Waseda University
1992- Associate Professor, Department of Mechanical Engineering, Waseda University
1998- Professor, Department of Mechanical Engineering, Waseda University
2007- Professor, Department of Modern Mechanical Engineering, Waseda University
2010- Associate Dean, School/Graduate School of Creative Science and Engineering, Waseda University

Main Works:

- "Imitating others by composition of primitive actions: A neuro-dynamic model," J. of Robotics and Autonomous Systems, Vol.60, No.5, pp. 729-741, 2012.
- "Doppler Positioning with a Movable Receiver Antenna and a Single Pseudolite for Indoor Localization," Proc. 2011 IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics, July 2011.

Membership in Academic Societies:

- The Institute of Electrical and Electronics Engineers (IEEE) Robotics & Automation Society
- The Robotics Society Japan (RSJ)
- The Japan Society of Mechanical Engineers (JSME)
- The Society of Instrument and Control Engineers (SICE)