E-Journal of Advanced Maintenance Vol.7-2 (2015) 145-153
Japan Society of Maintenology

Development of an Augmented Reality Based Simulation System for Cooperative Plant Dismantling Work

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ABSTRACT

An augmented reality-based simulation system for cooperative plant dismantling work has been developed and evaluated. In the system, behaviors of virtual objects such as the dismantling target, chain blocks, and trolleys are physically simulated. Their appearance is superimposed on camera images captured with cameras on users' tablet devices. The users can manipulate virtual objects cooperatively via touch operation. They can cut the dismantling targets, lift them on the trolleys using chain blocks, and convey them through narrow passages to ascertain whether the dismantling targets can be conducted without colliding with the passages. During the simulation, collisions between the virtual objects and real work environment are detected based on their three-dimensional shape data measured in advance. The collided parts are visualized using augmented reality superimposition. Four evaluators assessed the simulation system. Results show that the simulation system can be useful for prior examination of dismantling works, but some points were also found to need improvement.

KEYWORDS

Decommissioning, Physics simulation, Three-dimensional scanner, Point cloud, CSCW

ARTICLE INFORMATION

Article history:
Received 4 November 2014
Accepted 3 June 2015

1. Introduction

Nuclear power plants that have completed their operational lifetime must be decommissioned safely. Such dismantling work must be completed by many workers in narrow spaces. The work often includes dangerous tasks such as conveyance of heavy objects using cranes. Therefore, producing a work plan carefully and conducting sufficient training are important. Especially when dismantling work is conducted by multiple workers, it is necessary to decide how the work is divided and how the divided work is conducted cooperatively. However, it is difficult to decide and share the cooperative work plan appropriately because the nuclear power plant is a complicated work environment. Moreover, the cooperative work procedures are much more complicated than those of the solo work: workers must understand not only each work step but also the timing of the work because some tasks must be conducted simultaneously with other workers.

Currently, dismantling work is planned and evaluated mainly referring the past records of the similar works [1][2]. Institute of Energy Technology proposed a system called the Halden Planner, which is useful to evaluate dismantling works using virtual reality technology [3]. With this system, cooperative dismantling work can be planned and visualized using 3D computer graphics. The amount of radiation exposure can be estimated for each worker. The system is actually used to make a plan for dismantling work, but it cannot be used on-site. It must be used in an office, which means that the field workers must associate objects appearing in the plan with real objects in a real environment during the work. This association sometimes fails and might even lead to incorrect operations.

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Augmented reality (AR), an interface design scheme, is applicable to realize intuitive system for prior investigation and training for the dismantling work [4]. In this design scheme, users' views are superimposed with three-dimensional (3D) computer graphics of virtual objects aligned with the real work environment to make the users feel that the virtual objects exist in front of them. Using this design schema, it becomes possible to present the 3D position and orientation in an intuitive manner, which reduces human error and the time necessary for a task.

For this study, the authors developed an AR-based simulation system with which the workers can investigate dismantling work on-site to assess whether a dismantling target can be located in a small space and be conveyed through a narrow passage without colliding with the surroundings. The system's unique characteristic is that the multiple workers can use the simulation system simultaneously and can conduct the dismantling simulation cooperatively to share the dismantling work image. It is expected that the system is useful for both prior investigation and training for the dismantling work.

The remainder of the paper is organized as follows. In Section 2, the developed system configuration is described with subsequent details of the 3D scanner for obtaining 3D shape data used for the dismantling simulation, and the user interface of the cooperative simulation system with which the workers can conduct dismantling simulations cooperatively in a real work environment. Section 3 presents a description of a subjective evaluation conducted to evaluate the acceptance of the developed system and to ascertain points that demand improvement. Finally, the study is summarized and future works are described in Section 4.

2. Developed System

2.1. Design requirements

Design requirements (DR) of the developed system were decided based on interviews of the workers employed at the Fugen Decommissioning Engineering Center, which has a retired nuclear power plant in its preliminary dismantling stage, as shown below:

DR1	It is possible to understand the current situation of a dismantling target and equipment such as chain blocks.
DR2	It is possible to understand the current situation of work environment.
DR3	It is possible to place virtual equipment easily in a real work environment.
DR4	It is possible to move virtual equipment easily in a real work environment.
DR5	It is possible to conduct special operations for equipment such as pulling chains.
DR6	It is possible to understand positions where a virtual dismantling target and equipment collided with the surrounding real environment.
DR7	It is possible to support cooperative work by multiple workers.
DR8	It is possible for workers to recognize all workers' operations.
DR9	It is possible to cancel and redo operations.
DR10	It is possible to record and play operations.
DR11	It is easy to bring to and from the work environment.
DR12	It is easy for workers to understand how to use the system.

2.2. Configuration of the developed system

As depicted in Fig. 1, the developed system consists of a 3D scanner and a cooperative simulation system. The 3D scanner scans a work environment including the dismantling target. Then it generates their textured 3D shapes. The 3D shapes are used in the cooperative simulation system by which the users can locate and manipulate virtual objects cooperatively to conduct conveyance of dismantling target virtually in a real work environment.

2.3. 3D scanner

The 3D scanner consists of a 2D laser range finder (LMS100-10000; SICK Inc.), which provides distance measurements in 2D polar coordinates, a color camera (CMLN-13S2C-CS; Point Grey

Research Inc.), which obtains the appearance of the work environment and a motion base (PTU-D46-70; FLIR Systems Inc.), which rotates the 2D laser range finder and the camera to realize an omnidirectional scan to obtain a point cloud representation of the environment. The scan was repeated at different places in a target work environment. Their scans are integrated using an Iterative Closest Point (ICP) algorithm to reduce the unscanned area caused by occlusion. Then a point cloud that corresponds to a dismantling target is abstracted manually using a GUI software tool. Polygon models (3D shapes) of the dismantling target and the work environment are generated using Delaunay triangulation. Textures for the dismantling target are also generated using the images obtained using the camera. The 3D shapes and the textures are used to show the current position and orientation (pose) of the dismantling target during the simulation. The 3D shapes are also used to detect collisions between the real work environment and the dismantling target, and to calculate its motion using the physics simulation. Physical properties of the dismantling target necessary for the physics simulation such as the weight and friction coefficient are set manually in advance.

The accuracy of the generated 3D shapes depends on the work environment complexity and the distance separating the scanner and the work environment. When the 3D scanner was used to scan a water purification room in the Fugen Decommissioning Engineering Center, which includes several cylinder tanks and many pipes, the maximum error was approximately 0.2 m when the average distance between the 3D scanner and the environment was about 3 m.

To simulate the complete behavior of the dismantling target, it is necessary to ascertain the accurate shape, weight distribution, and coefficient of restitution of the dismantling target and work environment. However, the obtained shape of the dismantling target and work environment using the 3D scanner invariably contains some errors. It is difficult to ascertain the accurate weight distribution and coefficient of restitution because the special knowledge and equipment are necessary to measure them. Moreover, it is also difficult to conduct an accurate simulation because it requires much computational power. Therefore, in this study, models which contain errors are used as it is, and it is assumed that the weight distribution and coefficient of restitution are uniform. Accordingly, the simulated behavior of the dismantling target is definitely an approximation. However, it will be sufficient if the worker can observe the rough movement of the dismantling target for prior investigation of the dismantling work.

2.4. Cooperative simulation system

Functions implemented in the cooperative simulation system were chosen based on an interview of the workers employed at the Fugen Decommissioning Engineering Center.

The cooperative simulation system forms a server-client structure to enable employment of lightweight devices as client's hardware by a load distribution. The server (MacBook Pro 15 inch Early 2011) collects information from clients via a wireless network such as the current pose of each client and operations made by users, then conducts heavy calculations such as a physics simulation and collision detection between the dismantling target and the work environment. For the physics simulation, Bullet Physics library [5] was used. Clients (iPad2 Wi-Fi 16GB) obtain the current pose of

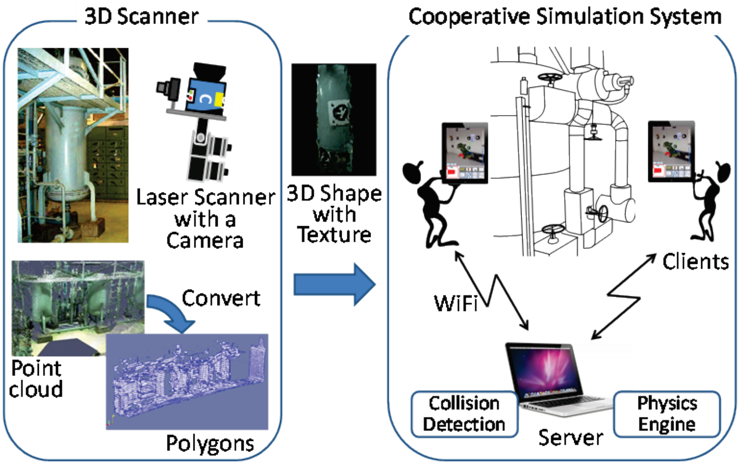

Fig. 1. Configuration of the developed system.

the dismantling target, other clients' poses, and collided parts on the dismantling target and the work environment from the server. The client's camera captures the work environment and estimates the current pose of the client using a marker-based tracking method [6]. Markers are pasted in advance in the work environment and are thereafter measured by the Marker Automatic Measuring System [7].

Fig. 2 depicts the client interface of the cooperative simulation system. The interface consists of a camera view, object icons and a room top view. The user operates the interface via touch operation.

The camera view shows live images captured with a client's camera. Virtual objects such as the dismantling target, chain block, and trolley are superimposed on the image according to the estimation of the client's camera pose so that the users can feel that these virtual objects exist in front of them. The collided parts of the dismantling target and the work environment are also superimposed on the image (collided parts of the dismantling target and the work environment are painted, respectively, with blue and red) so that the users can ascertain whether the dismantling target collides with the work environment.

The room top view shows a bird's eye view of the work environment, by which the user can recognize a positional relation among the work environment, virtual objects, and other users.

The object icons are used to place virtual objects such as a chain block, trolley, and tripod in the work environment. The users drag and drop the icon from the icon list to the room top view. The chain blocks are attached to the ceiling and used to lift the dismantling target up and down. The tripods are used when a ceiling is not available for fixing a chain block. In this system, another chain block is attached at the top of the tripod in advance. The heights of the chain block and the tripod were set in advance as the default. The users can choose virtual objects by tapping the icon on the room top view. The chosen icon's color is changed to enhance the selection. The chosen object can be moved using the buttons which appear when a movable object is chosen on the room top view.

After the user chooses a chain block, a chain can be connected to the dismantling target by tapping a location at which the user wants to connect on the camera image. When the user chooses a chain block that is already connected to the dismantling target, a slider bar appears on the side of the interface. The user can pull and loosen the chain by sliding the bar to lift the dismantling target up and down. The dismantling target can be conveyed with the trolley. The users lift the dismantling target using chain blocks over the trolley, put it down on its side, and convey to the objective location. All the behaviors of the virtual objects are simulated using the physics simulation. It is also possible to undo, redo, record, and replay the operations using the function buttons displayed on the interface.

3. Preliminary Evaluation

3.1 Objective

The system is expected to be useful. However, it remains unknown how acceptable the developed system is for actual field workers, and what problems arise in practical use. An evaluation experiment was conducted to answer these questions.

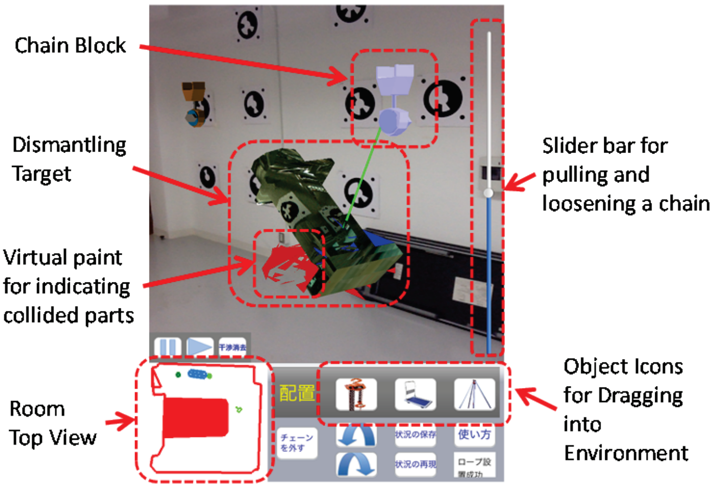

Fig. 2. Client interface on a tablet device.

3.2 Method

In the experiment, only the cooperative simulation system was evaluated. The system was assessed by four evaluators (two Fugen nuclear plant decommissioning workers (Evaluators A and B), one regular plant worker (Evaluator C), and one human interface expert (Evaluator D)). The evaluation was conducted in an experimental room (4 m × 6 m) in which some obstacles were located to simulate the complicated characteristics of the actual work environment. The results might be different from the results that will be obtained if the evaluation is conducted in a real dismantling work environment, but the results obtained in this simulated environment are expected to be useful for future improvement.

The evaluation was structured along the following steps.

1. An experimenter explained how to use the system for about 40 min (including practice).
2. Evaluators used the system along with a scenario for about 50 min.
3. Evaluators answered a questionnaire mainly related to the usability of the system.
4. A group interview was conducted to ascertain reasons underlying the questionnaire responses. The evaluators were asked why they gave the response for every questionnaire item.

Four evaluators formed one team and used the simulation system simultaneously. Evaluator B was designated as the team leader. The three other evaluators played roles of regular workers. The scenario was constructed so that all system functions were used. The scenario was as follows.

Step 1. All regular workers place a chain block around the dismantling target according to the direction of the leader. In all, three chain blocks are placed.
Step 2. All regular workers attach a chain on the dismantling target.
Step 3. Cut the base of the dismantling target and put the dismantling target down on its side by operating the chain cooperatively.
Step 4. The leader moves a trolley to the side of the dismantling target.
Step 5. Lift the dismantling target on the trolley using the chains.
Step 6. Detach all chains.
Step 7. Convey the dismantling target to the objective place by moving the trolley.
Step 8. Repeat steps 1-7 above. This time, tripods are placed instead of chain blocks.

The evaluators were asked to use the undo, redo, record, and replay functions occasionally.

3.3 Questionnaire and Results

The questionnaire includes 32 items for system function and usability. The questions were designed to evaluate whether the design requirements explained in section 2.1 are fulfilled or not. Evaluators answered each questionnaire item as 1–5 (1. completely disagree; 2. disagree; 3. neither agree nor disagree; 4. agree; 5. completely agree). In addition, a free description was added to the end of the questionnaire. Respondents described other problems and points to be improved.

For the function and usability of the simulation system, positive responses were obtained such as “The interface is easy to understand.” and “The simulation system is useful to examine work procedures.” Table 1 shows the questionnaire items to which all evaluators answered with a response 4 or 5. However, some questionnaire items elicited negative responses. Table 2 shows questionnaire items to which at least one evaluator answered with a response worse than 4. The indication (DR--) at the end of each question shows the design requirements which are intended to be evaluated.

The reasons each questionnaire item in Table 2 did not get a 5 response were investigated with the free description and the interview.

Evaluator B gave response 3 to Q20, 22, 24, and 26–31. Evaluator B explained that he gave these responses because he was assigned to be a leader and has few chances to use functions related to these questionnaire items. Therefore, he could not offer a judgment. Evaluators A, B, and C gave responses 3 and 4 to Q1. They commented that the captions of some buttons were not easy to understand. Evaluators A, C, and D respectively gave response 2, 3, and 4 to Q8. Evaluator A was unable to recognize who placed the equipment. Evaluators C and D were unable to recognize what and where the other workers were going to place. Evaluator D gave response 3 to Q12. He commented that he had difficulty when trying to choose one object from an object cluster. Evaluators B and D respectively gave responses 3 and 4 to Q15. Evaluator B wanted to rotate the equipment with smaller

Table 1 Questionnaire results to which all evaluators responded 4 or 5

	Questionnaire	Evaluator			
		A	B	C	D
Q2	It is easy to recognize the 2D position of the dismantling target by watching the bird's eye view. (DR1, DR2)	5	4	5	5
Q3	It is easy to recognize the 2D position of the chain block by watching the bird's eye view. (DR1, DR2)	5	4	5	5
Q4	It is easy to recognize the 2D position of the tripod by watching the bird's eye view. (DR1, DR2)	5	4	5	5
Q5	It is easy to recognize the 2D position of the trolley by watching the bird's eye view. (DR1, DR2)	5	4	5	5
Q6	It is easy to recognize the other workers' 2D positions and orientation by watching the bird's eye view. (DR2, DR7)	5	5	4	5
Q7	It is easy to place the equipment such as chain blocks on the bird's eye view. (DR3)	5	5	5	4
Q9	It is easy to understand the spatial correspondence between the real environment and the bird's eye view. (DR2)	5	4	4	4
Q10	It is easy to recognize the position and orientation of 3D models superimposed on the camera view. (DR1)	4	4	5	4
Q11	It is easy to recognize what the 3D models superimposed on the camera view represent. (DR1)	5	5	4	5
Q13	Making the equipment green when it is chosen by the other workers is good support to recognize it. (DR8)	5	5	5	5
Q14	It is easy to translate the equipment using the bird's eye view. (DR4)	4	4	5	5
Q18	It is easy to switch the camera view and the bird's eye view. (DR2)	5	5	5	5
Q19	It is effective that the camera view can be posed when connecting the chains to the dismantling target. (DR3, DR5)	4	4	4	5
Q21	It is easy to enlarge, reduce, and translate the bird's eye view. (DR2)	5	4	5	5

(DR: Design Requirement)

steps. Evaluator D wanted a function to rotate the equipment using a stylus pen instead of using buttons. Evaluators A and C gave responses 3 and 4 to Q16 and Q17 because they were unable to recognize who was operating virtual objects. Evaluators A and C respectively gave responses 2 and 3 to Q20. Evaluator A sometimes was unable to attach a chain to the intended location. Evaluator C wanted a function to enlarge the camera image to make it easy to attach the chain at the intended location more accurately. Evaluators A and C gave response 3 to Q22. It was difficult for them to predict how fast the dismantling target would move when they operated the chain blocks using the slider bar to pull and loosen the chain. Evaluators A, C, and D gave response 3 to Q23 because they were unable to recognize who operates the chain. All evaluators gave negative responses to Q25 and Q26. They explained that it was difficult to recognize the collided parts accurately. Evaluators A and C gave responses 3 and 4 to Q28 and Q29. They explained that it was difficult to recognize which operation will be canceled and redone using redo and undo functions.

Whether the system fulfills the design requirements or not was also investigated. DR1 and DR2 were fulfilled because the positive responses were obtained to the questions corresponding to DR1 and DR2 as shown in Table 1. The reason these questions received positive responses will be (1) the design of bird's eye view is technically established and easy to be implemented, (2) Augmented Reality representation (superimposition of 3D computer graphics over camera view) is appropriate to represent the positional relation between virtual objects and real environment. Because Q7 and Q20

Table 2 Questionnaire results to which at least one evaluator responded worse than 4

Questionnaire		Evaluator			
		A	B	C	D
Q1	It is easy to identify each button's function.(DR12)	4	3	4	5
Q8	It is easy to recognize the other worker's operation of the equipment. (DR8)	2	5	3	4
Q12	It is easy to choose equipment on the bird's eye view. (DR4)	4	5	5	3
Q15	It is easy to rotate the equipment on the bird's eye view. (DR4)	5	3	5	4
Q16	It is easy to recognize the other worker's operation for translating the equipment. (DR8)	3	5	4	5
Q17	It is easy to recognize the other worker's operation for rotating the equipment. (DR8)	3	5	4	5
Q20	It is easy to connect the chain to the dismantling target on the camera view. (DR3, DR5)	2	3	3	5
Q22	It is easy to pull up and loosen the chain. (DR5)	3	3	3	5
Q23	It is easy to understand the other worker's operation of the chain. (DR8)	3	5	3	3
Q24	Making the chain pink when it is chosen by you is useful to recognize it. (DR5)	5	3	4	5
Q25	It is easy to recognize the collided position on the dismantling target by making the collided position blue. (DR6)	2	1	3	4
Q26	It is easy to recognize the collided position on the environment by making the collided position red. (DR6)	2	3	3	4
Q27	It is easy to use the button to remove all chains from the dismantling target. (DR5)	4	3	5	5
Q28	The function is effective to undo the previous action. (DR9)	3	3	4	5
Q29	The function is effective to redo the undone action. (DR9)	3	3	4	5
Q30	The function is effective to record the current situation. (DR10)	5	3	5	5
Q31	The function is effective to replay the recorded situation. (DR10)	5	3	5	5
Q32	The system is useful easily even at the first use. (DR12)	4	3	4	4

(DR: Design Requirement)

were positively and negatively responded respectively, it seems that placing large objects such as chain blocks, tripod, and trolley is easy but connecting a chain which requires the operation of small object is not easy, which means that DR3 is partially fulfilled. Because Q14 was responded positively but Q12 and Q15 were responded negatively, DR4 is partially fulfilled. As discussed above, it will be possible to fulfill DR4 by making the step smaller to rotate objects and introducing a new interface to choose one object from an object cluster. DR5 was fundamentally fulfilled except that it is difficult to predict how fast the dismantling target would move (Q22). DR6 was not fulfilled because Q25 and Q26 responded negatively. Further improvement is necessary to make it easy for the workers to recognize the collided position. For DR7, it was only confirmed that recognizing the other workers' position and orientation is easy (Q6), but the positive comments such as "I want to use the system for the real work", "I feel that it is effective to investigate the conveyance of the dismantling target by multiple workers" were obtained. Therefore, at least the system is effective to support cooperative work by multiple workers. For DR8, as discussed above (Q8, Q16, Q17, Q23), it is difficult to recognize who is going to do and what is going to be done. Further improvement is necessary to represent this information. For DR9, it is necessary to make what will be canceled clearer (Q28, Q29). DR10 and DR12 are basically fulfilled (Q30, Q31, Q32). For DR11, the portability of the system was not investigated this time because the evaluation experiment was conducted in the experimental room. It is necessary to conduct another evaluation in a real plant as future work.

4. Conclusion and Future Works

For this study, an augmented reality-based simulation system for cooperative plant dismantling work was developed and evaluated. Four evaluators assessed the system. Positive responses were obtained from the evaluators, but some points were also found to need improvement.

The evaluators commented that it was difficult to recognize the collided parts accurately. The reason would be that they were unable to move their device freely to see details of the collided parts because marker-based tracking was used and the superimposed image is apparent only when the camera captures the markers. A possible improvement for this issue is to use markerless tracking, as described later, because the markerless tracking method is useful in a larger area than marker-based tracking is. Another reason is that there is no depth cue to signal the position of the collided parts because a single camera was used to capture the environment and a monaural image was displayed on a small screen. A possible improvement is to draw shadows of the painted parts to represent their depth.

The evaluators requested that the workers' current situation and intentions be easily understandable by the other workers. The current poses of the other workers were displayed as a bird's eye view, but it was insufficient to ascertain the other workers' current circumstances and intentions. A possible improvement is to enable a worker to see other workers' operational history, which can be helpful for workers to ascertain the other workers' circumstances and intentions. However, the problem is that if the dismantling work is conducted on-site, information of this kind is unavailable. In some cases, they must work without understanding the other workers' circumstances and intentions. Even if the system includes a function to show the other workers' operational history, it will be better to make it possible to disable the function as necessary.

Some other requests originate from the inaccurate and clumsy tracking of the client devices. The current system uses a marker-based tracking method to measure camera poses, which is unacceptable for practical use. Several markerless tracking methods have become available in recent years: PTAM [8] and LSD-SLAM [9]. These new markerless tracking methods seem promising because they are much more stable than conventional markerless tracking methods. However, for actual use, several issues must be addressed. First, almost all of these markerless tracking methods assume that the environment will not change or that only a small part of the environment will change, which is not true of a real work environment. If a large part of the environment changes rapidly, then the tracking becomes unstable very quickly. Second, if the camera view is occluded, then the tracking must be terminated. It happens frequently when another worker or instrument is moved around the worker. A possible countermeasure is to use an omnidirectional camera with a 360-degree field of view. The larger the camera view angle becomes, the more stable and accurate the tracking will be. Moreover, it will be rare that all fields of view of the omnidirectional camera are occluded by obstacles such as other workers.

After completing these improvements and confirming the effect of the improvements, further subjective evaluations will be conducted in a real work environment to evaluate the acceptability and the effectiveness of the developed system.

Acknowledgement

This work was partially supported by KAKENHI (No. 23240016).

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