Spatial Clearance Verification Using 3D Laser Range Scanner and Augmented Reality

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Abstract. A spatial clearance verification system for supporting nuclear power plant dismantling work was developed and evaluated by a subjective evaluation. The system employs a three-dimensional laser range scanner to obtain three-dimensional surface models of work environment and dismantling targets. The system also employs Augmented Reality to allow field workers to perform simulation of transportation and temporal placement of dismantling targets using the obtained models to verify spatial clearance in actual work environments. The developed system was evaluated by field workers. The results show that the system is acceptable and useful to confirm that dismantling targets can be transported through narrow passages and can be placed in limited temporal workspaces. It was also found that the extension of the system is desirable to make it possible for multiple workers to use the system simultaneously to share the image of the dismantling work.

Keywords: Augmented Reality, Laser Range Scanner, Nuclear Power Plants, Decommissioning, Spatial Clearance Verification.

1 Introduction

After the service period of a nuclear power plant terminates, the nuclear power plant must be decommissioned. Because some parts of a nuclear power plant remain radioactive, the procedure of its decommissioning differs from that of general industrial plants. Each part of the nuclear power plant must be dismantled one by one by following a dismantling plan made in advance. In some cases, it is desirable to dismantle large plant components into small pieces at different location from their original location; the components are removed from their bases and transported to appropriate workspaces. However, nuclear power plants are not designed to be easily dismantled. Passages are very narrow and workspace is not large enough. Large components may collide with passages and workspace during transportation and placement. Moreover, dismantled components need to be stored at a temporal space

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for a certain period before they are transported to outside of the plant because their radioactive level must be checked. The space for the temporal storage is also not large enough. Therefore it is necessary to verify that the dismantled components can be transported through narrow passages, can be placed in a limited space before performing dismantling work. But the verification is not easy because there are various components in nuclear power plants and their shapes are much different.

In this study, to make it easy for field workers to perform the verification, a spatial clearance verification system was developed and evaluated by a subjective evaluation. The system employs a three dimensional (3D) laser range scanner to obtain 3D surface point clouds of work environment and dismantling targets, and then builds polygon models. Augmented Reality (AR) technology is also employed to allow field workers to perform transportation and temporal placement simulation intuitively using the obtained models to verify spatial clearance between the work environment and the dismantling targets in actual work environments. The developed system was used along with a scenario by field workers who are working for dismantling a nuclear power plant and an interview and questionnaire survey were conducted to confirm whether the system is effective or not, how acceptable the system is, or what problems arise in practical use.

2 Related Work

Various studies have been conducted to apply AR to maintenance tasks in nuclear power plants [1]. In [2], a mobile AR system is investigated as an alternative to paper-based systems to retrieve maintenance procedure from online servers. In [3], a mobile AR system to support maintenance task of a power distribution panel is proposed. The authors have proposed some AR systems to support workers in nuclear power plants [4][5][6]. In [4], an AR support system for water system isolation task is proposed and evaluated. In [5], AR technology is used to support field workers to refer cutting line of dismantling target and record the work progress. In [6], field workers are supported to make a plan of preparation for dismantling work by deciding how to layout scaffolding and greenhouses. In this study, the authors focus on a spatial clearance verification task as a new support target in which real time interaction between virtual objects and real environment need to be realized.

3 Spatial Clearance Verification System

3.1 Basic Design

Most crucial requirement for spatial clearance verification is to make it possible to perform the verification using accurate 3D models of work environment and dismantling targets. The 3D models are used to detect collisions between work environment and dismantling targets. One possible way to obtain the 3D models is to use existing CAD that was made when the plant was designed. But the CAD usually includes only large components and is not updated since it was made; they do not represent the current status of the plant properly. Therefore, the authors decided to employ 3D laser range scanner to make 3D models of work environment and dismantling targets.

Concerning an interface for performing the verification, one possible way is to develop GUI application with which users can manipulate 3D models in a virtual environment. But such interface may be difficult to use because it is necessary to indicate 3D position and orientation of dismantling targets. Moreover, it is difficult to obtain concrete image of spatial relation between work environment and dismantling targets. In this study, therefore, the authors aimed at developing an AR-based application that can be used in actual work environment. The transportation path and layout of the dismantling target can be investigated intuitively by manipulating real objects, and the users can confirm which part of the work environment and dismantling targets collide each other in an intuitive way.

The whole system can be divided into two subsystems; Modeling Subsystem and Verification Subsystem.

3.2 Modeling Subsystem

The Modeling Subsystem is used to build 3D surface polygon models of work environment and dismantling targets. These models are used to detect collisions during using the Verification Subsystem. The accuracy of the models is not necessary to be an order of millimeter but should be better than an order of meter. It is not clear how much accurate the models should be, the authors, therefore, tried to make the total cost of the system reasonably low, and then tried to make the models as accurate as possible with the available hardware. Further study is necessary to reveal the required accuracy of the models used for the spatial verification.

The Modeling Subsystem consists of a laser range scanner, a motion base and a color camera to obtain 3D point clouds of work environment and dismantling targets, and a software to make 3D polygon models from the obtained point clouds as shown in Figure 1. The hardware specifications are shown in Table 1. The laser range scanner employed in this study is a kind of line scanner and can obtain 3D positions of surrounding environment in a 2D plane. Therefore, the scanner is mounted on a motion base; the motion base rotates the scanner to obtain point clouds of whole surrounding environment. The color camera is used to capture visual images. The position and orientation of the camera when the images are captured are also recorded.

The obtained point clouds are based on a local coordinate system which origin is the intersection of rotational axis of the motion base when they are obtained. But the point clouds need to be based on a world coordinate system when they are used for the spatial verification. In this study, the authors employed a camera tracking technique proposed in [7]. Multiple markers are pasted in work environment and their position and orientation based on the world coordinate are measured in advance. By capturing these markers with the color camera, the position and orientation of the camera is estimated. Then positions of the obtained point clouds are transformed into the world coordinate.

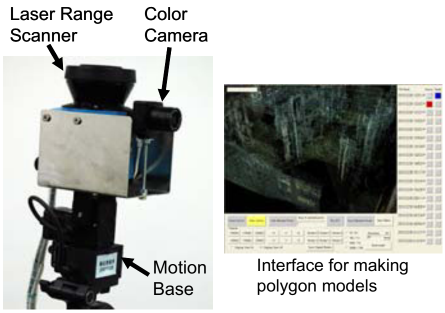

Fig. 1. Configuration of Modeling Subsystem

Table 1. Hardware specifications for Modeling Subsystem

Laser range scanner	Vendor	SICK Inc.
	Model	LMS100-10000
	Scan angle	270 deg.
	Angular res.	0.25 deg.
	Max. error	40mm
Motion base	Vendor	FLIR Systems Inc.
	Model	PTU-D46-70
	Angular res.	0.013 deg.
Camera	Vendor	PointGreyResearch Inc.
	Model	CMLN-13S2C-CS
	Resolution	1280×960
	Focal Length	4.15mm

Another problem is that a single point cloud does not include enough points of work environment and dismantling targets. Only one side of work environment and dismantling targets can be measured at once. It is necessary to use the scanner at multiple positions to obtain whole surface of work environment and dismantling targets. The obtained point clouds need to be combined into one point cloud. One possible solution is to use the camera tracking again. If the camera can capture the markers at all measuring positions, the point clouds can be combined without any additional operation because all the point clouds are based on the world coordinate. But in some cases, it is difficult to capture markers. In this study, the authors tried to use ICP (Iterative Closest Point) algorithm to transform one point cloud to be matched with another point cloud that is already transformed into the world coordinate. But in our case, ICP algorithm can not be directly used because the point cloud obtained in nuclear power plants includes much noise and two point clouds do not always contain enough part of the environment in common. Therefore, a GUI application was developed to set an initial transform of the target point cloud by hand, and then two point clouds are combined with the following algorithm. (It is assumed that Cloud1 is already transformed into the world coordinate. The goal is to transform Cloud2 into the world coordinate.)

Step 1. Smooth Cloud2 to remove random error of the measurement.
Step 2. Locate a sphere which radius is 200 cm randomly inside Clouds2 and clip the points that are inside of the sphere.
Step 3. Perform ICP algorithm to adjust the clipped points to Cloud1 and obtain its transformation matrix.
Step 4. Apply the transformation matrix to all the points of Cloud2.
Step 5. Count the number of points of Cloud2 which distance from nearest point of Cloud1 is less than 5 cm.
Step 6. Repeat Step2 to Step5 10 times and choose the transformation matrix with which the number of points in Step5 is largest.
Step 7. Apply the transformation matrix to all the points of Cloud2.
Step 8. Repeat Step 2 to Step7 until the number of points in Step5 does not increase.

After applying the above algorithm, an area that contains the necessary points is set by hand. Then the clipped point cloud is converted into polygon model with Quadric Clustering Algorithm [8].

Concerning the polygon model for the dismantling targets, it is necessary to make a texture to increase its visibility. In this study, the texture is automatically generated using the captured images during obtaining point clouds of the dismantling targets. Figure 2 shows an example polygon models made with the Modeling Subsystem.

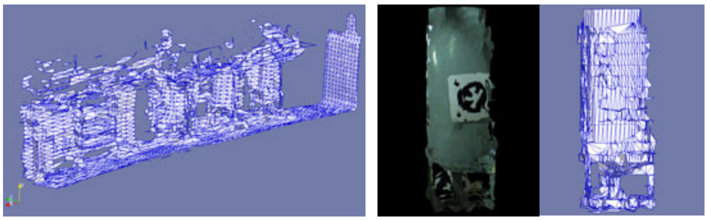

Fig. 2. Polygon models obtained with Modeling Subsystem

3.3 Verification Subsystem

The Verification Subsystem is used to conduct simulations of transportation and placement of dismantling targets in actual work environments intuitively using Augmented Reality technology. The most significant feature of the Verification Subsystem is a function to detect collisions between virtual dismantling targets and real work environment.

Figure 3 shows a conceptual image of the Verification Subsystem. The system consists of a marker cube, a tablet PC, a camera and environmental markers. The marker cube is used to indicate 3D position and orientation of a virtual dismantling target. The table PC is mounted on a tripod and a dolly, which enables users to move the system easily. Six markers are pasted on the marker cube and used to measure the relative position and orientation between the marker cube and the camera. The environmental markers pasted in work environment are used to measure the position and orientation of the camera relative to the work environment. For both the marker cube and environmental markers, the markers proposed in [7] are used.

The system is supposed to be used by two workers; a cube operator and a system operator. When the camera captures the marker cube and the environmental markers, 3D models of the dismantling target made with the Modeling Subsystem is superimposed on the camera image based on the current position and orientation of the marker cube. When the cube operator moves the marker cube, the superimposed model follows its movement. When the virtual dismantling target collides with the work environment, the collided position is visualized as shown in Figure 4. The yellow area shows the collided part of the virtual dismantling target and the red area shows the collided part of the work environment. (At the initial state, 3D model of the Work Environment is invisible and the user can see the camera image. When collision occurs, only the nearest polygon from the collided position is made visible and its color is changed to red.)

Table 2 shows the hardware specifications used in the Verification Subsystem. To capture wide view angle images of the work environment, a lens that has short focal length is used. It results on the necessity to use the large markers (41cm×41cm) to make the tracking of the camera and the marker cube accurate and stable.

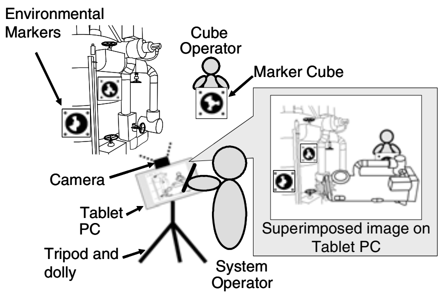

Fig. 3. Conceptual image of Verification Subsystem

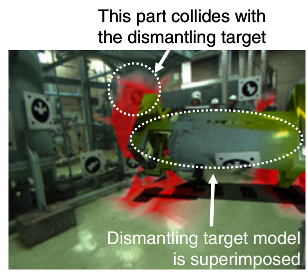

Fig. 4. Visualization of collided part

Table 2. Hardware specifications for Verification Subsystem

Tablet PC	Vendor	Panasonic Corp.
	Model	CF-C1AEAADR
	CPU	Core i5-520M
	GPU	Intel HD Graphics
	Memory	1GB
Camera	Vendor	PointGreyResearch Inc.
	Model	CMLN-13S2C-CS
	Resolution	1280×960
	Focal Length	3.12mm

Fig. 5. Interface for verification

By using the marker cube, it is expected that the position and orientation of the virtual dismantling target can be changed intuitively. But there may be a case that it is difficult to move the virtual dismantling target only with the marker cube. For example, the intended position is too high or very small adjustment is necessary. Therefore, in this study, GUI is also implemented as shown in Figure 5. The system operator can change the position and orientation of the virtual dismantling target by using the buttons and also can drag the virtual dismantling target with a stylus pen. In addition, following functions are also implemented.

1. A function to record the 3D position and orientation of the virtual dismantling target. The superimposed image is also recorded simultaneously.
2. A function to make the virtual dismantling target invisible.
3. A function to reset all the indication of the collided part. (The color of the virtual dismantling target is set to its original color and the model of the work environment is made invisible.)

The application was developed on an operating system Windows 7 (Microsoft Corp.) using compiling software Visual C++ 2008 (Microsoft Corp.). Open GL, Visualization Tool Kit Library [9] and Bullet Physics Library [10] were used to render 3D models, implement ICP algorithm and conduct collision detection respectively.

4 Evaluation

4.1 Objective

It is expected that it is possible for field workers to simulate transportation and placement of dismantling targets using the proposed system. However, it remains unknown how acceptable the system is for actual field workers, what problems arise in practical use. An evaluation experiment was conducted to answer these questions. In this evaluation, the authors mainly focused on the evaluation of the Verification Subsystem because the pre-evaluation showed that combining multiple point clouds by hand using the Modeling Subsystem is difficult for novice users. The Modeling Subsystem will be improved and evaluated as a future work.

4.2 Method

Before the evaluation, the experimenters pasted environmental markers and measured their position and orientation relative to the work environment using Marker Automatic Measurement System [11]. The experimenters demonstrated how to use the Modeling Subsystem and the Verification Subsystem for about 10 minutes each. Then four evaluators used the Modeling Subsystem and the Verification Subsystem with the assumption that one plant component will be dismantled. The evaluators used the Modeling Subsystem only to obtain point clouds and did not try to combine the point clouds into one point cloud. The polygon models used with the Verification Subsystem were prepared in advance by the experimenters. Each evaluator played only a role of the system operator. The experimenter played a role of the cube operator. After using the system, the evaluators answered questionnaire, then an interview and a group discussion were conducted.

The dismantling target was assumed to be a water purification tank as shown in the right hand side of Figure 3. The evaluators were asked to use the Verification Subsystem under the assumption that the tank will be removed from its base, placed temporarily at the near space, and then transported through a narrow passage.

Of the four evaluators, three (Evaluator A, B and C) were staffs at Fugen Decommissioning Engineering Center. One (Evaluator D) was a human interface expert working at a university.

4.3 Questionnaire and Results

The questionnaire includes 36 items for system function and usability as shown in Table 3. Evaluators answer each question as 1 – 5 (1. completely disagree; 2. disagree; 3. fair; 4. agree; 5. completely agree). In addition, free description is added to the end of the questionnaire. Respondents describe other problems and points to be improved.

Each evaluator used the system for about 40 minutes. Table 3 presents the results of the questionnaire. Table 4 presents answers of the free description, interview and group discussion.

Table 3. Questionnaire results

	Questionnaire	Evaluator			
		A	B	C	D
Q1	Is it easy to set up the system?	5	4	5	5
Q2	Is it easy to remove the system?	5	4	5	5
Q3	The situation of temporal placement becomes easy to be understood by superimposing the dismantling target over the camera view.	5	4	4	5
Q4	The situation of transportation becomes easy to be understood by superimposing the dismantling target over the camera view.	5	5	4	5
Q5	It is easy to recognize the collided position on the dismantling target by making the collided position yellow.	4	2	5	4
Q6	It is easy to recognize the collided position in the work environment by making the collided position red.	5	4	5	5
Q7	It is effective to make it possible to change the position and orientation of dismantling target by moving the marker cube.	4	2	4	5
Q8	It is easy to translate the dismantling target by using the marker cube.	4	2	3	5
Q9	It is easy to rotate the dismantling target by using the marker cube.	2	4	3	5
Q10	It is effective to translate the dismantling target using a stylus pen.	5	4	5	5
Q11	It is effective to rotate the dismantling target using a stylus pen.	5	4	5	5
Q12	It is easy to translate the dismantling target using a stylus pen.	5	4	5	5
Q13	It is rotate to translate the dismantling target using a stylus pen.	3	5	5	3
Q14	It is easy to operate the system using a stylus pen.	5	3	3	4
Q15	It is effective to translate dismantling target using the buttons.	5	3	4	5
Q16	It is easy to translate dismantling target using the buttons.	5	4	5	5
Q17	It is effective to set the position and orientation of dismantling target at its initial position using the button.	4	5	5	5
Q18	It is effective to record the position and orientation of dismantling target.	5	5	5	5
Q19	It is easy to record the position and orientation of dismantling target.	5	5	5	5
Q20	It is effective to refer the recorded position and orientation of dismantling target visually.	5	5	5	5
Q21	It is easy to refer the recorded position and orientation of dismantling target visually.	5	5	5	4
Q22	It is effective to choose the recorded capture images using the buttons.	5	5	5	5
Q23	It is easy to choose the recorded capture images using the buttons.	5	5	5	5
Q24	The function is effective to make dismantling target invisible.	5	5	5	5
Q25	The function is effective to reset the color of dismantling target.	5	5	5	5
Q26	The size of the area to display the camera image is adequate.	5	5	4	5
Q27	The size of the PC display is adequate.	5	5	4	5
Q28	The size of the system is adequate and it is easy to carry in.	5	4	4	5
Q29	The size of the buttons is adequate.	5	5	3	5
Q30	The system can be used easily even if it is the first use.	4	4	4	4
Q31	The system response is quick enough.	5	4	5	5
Q32	It is easy to rotate the system to change your viewpoint.	5	4	4	5
Q33	It is easy to move the system to change your viewpoint.	4	5	4	5
Q34	It is effective to make dismantling target models by measuring with the system and use them for the verification.	5	4	5	5
Q35	It is effective to verify temporal placement and transportation work by referring dismantling target model at actual work environment.	5	4	5	5
Q36	I could use the system without feeling stress.	3	3	5	4

Table 4. Free description and interview results (Partially extracted)

Evaluator A	
A1	It is difficult to tell the cube operator how to move the marker cube only by gesture.
A2	It is difficult to conduct detail operations using the stylus pen especially for the model rotation.
A3	The models should be more stable when the camera does not move.
Evaluator B	
B1	It is a little difficult to notice the change of the color. It may be better to change only the color of the work environment.
B2	The marker cube is not necessary if the same operation can be done with the buttons.
B3	It is better if the virtual model follows the marker cube more quickly.
Evaluator C	
C1	The size of the marker cube should be smaller.
C2	Sometimes it was difficult to see the display because of the reflection of the light.
C3	It is better if it is possible to change the amount of model movements by the button operation.
Evaluator D	
D1	Using the marker cube is intuitive.
D2	The system is useful to confirm that dismantling targets can be transported through passages.
D3	Changing the color of the dismantling target is useful to decide which part of the dismantling target should be cut to be transported through a narrow passage.
D4	The system will be more useful if multiple workers can use the system simultaneously. This extension will enables us to check what other workers will see from their positions.

4.4 Discussion

As shown in Table 3, all evaluators gave positive responses to almost all questionnaire items. But for several items, some evaluators gave negative responses. Evaluator B gave a negative response to Q5. For Q5, he also gave a comment B1 as in Table 4. The authors decided to change the colors of both dismantling target and work environment because it will give more information to the workers. In fact, Evaluator D gave a comment D3 that is a positive response to changing the color of the dismantling target. Therefore, it will be better to add a function to enable and disable the color of dismantling target and work environment separately. Evaluator B gave negative responses to Q7 and Q8. He also gave a comment B2. On the other hand, Evaluator D gave a positive comment D1 to the marker cube. The possible cause of this difference is that Evaluator B is much younger than Evaluator D and very familiar with computers. Evaluator B is good at using GUI therefore he may think that the marker cube is not necessary. Evaluator A gave a negative response to Q9. He also gave a comment A1. It was difficult to give orders by voice because the work environment is very noisy. Therefore, the evaluators must give orders to the cube operator by gestures. But the authors did not teach the evaluators anything about which gesture should be used to give orders to the cube operator. A set of standard gestures should be designed and shared between the cube operator and the system operator in advance.

Evaluator D gave an interesting comment D4. It is easy to make it possible for multiple workers to use the system by introducing multiple hardwares and exchanging information via wireless network. This extension will enable us to share the work image that is very important to increase the safety and efficiency.

5 Summary and Future Works

In this study, a spatial verification support system using a 3D laser range scanner and Augmented Reality was developed and evaluated by a subjective evaluation. The results show that the system is basically acceptable and useful for the spatial verification. Artificial marker based tracking was employed in this study, because the authors intended to prioritize stability and accuracy rather than practicability. For practical use, it is necessary to decrease the number of markers and make it possible for workers to move more freely. Another problem is that there is a case that the scanner can not be used to make surface models of dismantling targets; the target is at high location or obstructed by other components. One possible solution is to employ a modeling method using only small cameras. One promising extension of the system is to make it possible for multiple workers to use the system simultaneously. This extension will enable workers to share the image of dismantling work that is very important to increase the safety and efficiency of the dismantling work.

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References

1. Ishii, H.: Augmented Reality: Fundamentals and Nuclear Related Applications. International Journal of Nuclear Safety and Simulation 1(4), 316–327 (2010)
2. Dutoit, H., Creighton, O., Klinker, G., Kobylinski, R., Vilsmeier, C., Bruegge, B.: Architectural issues in mobile augmented reality systems: a prototyping case study. In: Software Engineering Conference, pp. 341–344 (2001)
3. Nakagawa, T., Sano, T., Nakatani, Y.: Plant Maintenance Support System by Augmented Reality. In: IEEE International Conference on Systems, Man, and Cybernetics, vol. 1, pp. 768–773 (1999)
4. Shimoda, H., Ishii, H., Yamazaki, Y., Yoshikawa, H.: An Experimental Comparison and Evaluation of AR Information Presentation Devices for a NPP Maintenance Support System. In: 11th International Conference on Human-Computer Interaction (2005)
5. Ishii, H., Shimoda, H., Nakai, T., Izumi, M., Bian, Z., Morishita, Y.: Proposal and Evaluation of a Supporting Method for NPP Decommissioning Work by Augmented Reality. In: 12th World Multi-Conference on Systemics, Cybernetics, vol. 6, pp. 157–162 (2008)
6. Ishii, H., Oshita, S., Yan, W., Shimoda, H., Izumi, M.: Development and evaluation of a dismantling planning support system based on augmented reality technology. In: 3rd International Symposium on Symbiotic Nuclear Power Systems for 21st Century (2010)
7. Ishii, H., Yan, W., Yang, S., Shimoda, H., Izumi, M.: Wide Area Tracking Method for Augmented Reality Supporting Nuclear Power Plant Maintenance Work. International Journal of Nuclear Safety and Simulation 1(1), 45–51 (2010)
8. Lindstrom, P.: Out-of-core simplification of large polygonal models. In: 27th Annual Conference on Computer Graphics and Interactive Techniques, pp. 259–262 (2000)
9. Visualization Tool Kit, `http://www.vtk.org/`
10. Bullet Physics Library, `http://bulletphysics.org/`
11. Yan, W., Yang, S., Ishii, H., Shimoda, H., Izumi, M.: Development and Experimental Evaluation of an Automatic Marker Registration System for Tracking of Augmented Reality. International Journal of Nuclear Safety and Simulation 1(1), 52–62 (2010)