Proceedings of ISSNP 2018
9th International Symposium on Symbiotic Nuclear Power Systems for 21st Century
July 9-11, 2018, Heilongjiang, China

Distance Information Display System for Supporting Decommissioning Work of Nuclear Power Plants

Miki Naoya[1], Harazono Yuki[2], Ishii Hirotake[3], Shimoda Hiroshi[4], and Kouda Yuya[5]

1. *Graduate School of Energy Science, Kyoto University, Yoshida honmachi, Sakyo-ku, Kyoto-shi, Kyoto, 606-8501, Japan (miki@ei.energy.kyoto-u.ac.jp)*
2. *Graduate School of Energy Science, Kyoto University, Yoshida honmachi, Sakyo-ku, Kyoto-shi, Kyoto, 606-8501, Japan (harazono@ei.energy.kyoto-u.ac.jp)*
3. *Graduate School of Energy Science, Kyoto University, Yoshida honmachi, Sakyo-ku, Kyoto-shi, Kyoto, 606-8501, Japan (hirotake@ei.energy.kyoto-u.ac.jp)*
4. *Graduate School of Energy Science, Kyoto University, Yoshida honmachi, Sakyo-ku, Kyoto-shi, Kyoto, 606-8501, Japan (shimoda@ei.energy.kyoto-u.ac.jp)*
5. *Fugen Decommissioning Engineering Center, Japan Atomic Energy Agency, Myojin-cho, Tsuruga-shi, Fukui, 914-0842, Japan (kouda.yuya@jaea.go.jp)*

Abstract: For this study, a Distance Information Display System (DIDS) was developed and evaluated. Through its very simple operation, the system captures images of target objects with an RGB-D camera and automatically measures target object lengths and gaps. The system extracts and displays the lengths that workers might want to measure using a heuristic filtering process. An experiment was conducted to evaluate the DIDS and to compare the system with existing systems. The experimentally obtained results demonstrate that the DIDS can resolve problems of manual measurement and reduce the measurement time. Furthermore, results show that the DIDS is superior to existing methods in terms of ease of operation.

Keyword: Augmented reality; RGB-D camera; Metric information; Walk-down support; Contact-less distance measurement

1 Introduction

More than 400 nuclear power plants (NPPs) are operating worldwide, some of which must be dismantled in the near future. In NPP dismantling work, it is sometimes necessary to measure object dimensions, such as those of pipes and tanks, to estimate the total amount of waste. Additionally, gap lengths between equipment must be measured to ascertain space requirements for installing dismantling equipment. These lengths are usually measured manually with tape measures or laser measuring instruments. However, manual measurement presents the difficulty that workers must measure each length, which requires much labor. Manual measurement presents another difficulty: that of measuring the lengths of places that are out of reach.

Working support using augmented reality is anticipated for nuclear power plant dismantling work [1]. Contactless measurement systems using augmented reality have been developed as systems aimed at solving manual measurement difficulties [2] [3]. They are classifiable into two types according to the designation of the measurement targets.

The first type is a system with an interface by which a user designates two points as measurement targets manually on video images acquired using a camera equipped on a tablet. An example is the AR measure, which is useful on tablets [2]. This application solves an important difficulty of manual measurement: it is difficult to measure lengths of places, such as high places, that are out of reach. Nevertheless, the workers must still measure each length, which requires much labor.

The second type is a system that automatically displays lengths of objects when a measurement target is captured with a camera, with no indicative instructions by users. In this system, multiple measurement results are displayed simultaneously on the acquired image. One system that realizes this interface was developed by Handa et al. [3]. Fig. 1 portrays a screenshot of the system. The system requires no complicated operations. Additionally, it can measure places out of reach; users need not measure each length. However, because targets given length information are decided solely by a simple algorithm for recognizing line segments in an image and because all measurement results are displayed on the screen, the possibility exists that it is difficult for users to recognize the measurement results. Moreover, with this method, gaps that are not recognized as line segments are not displayed.

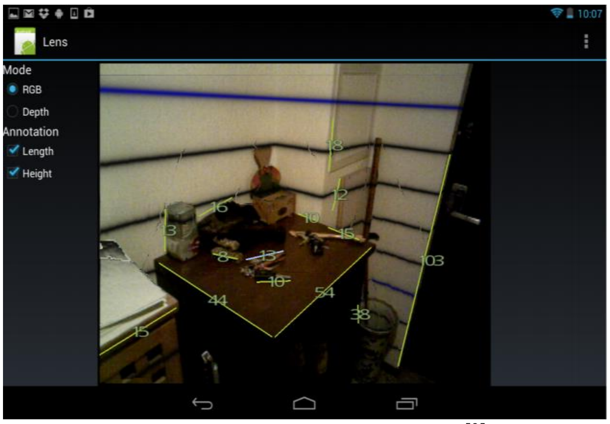

Fig. 1 Screenshot of the Handa system [3].

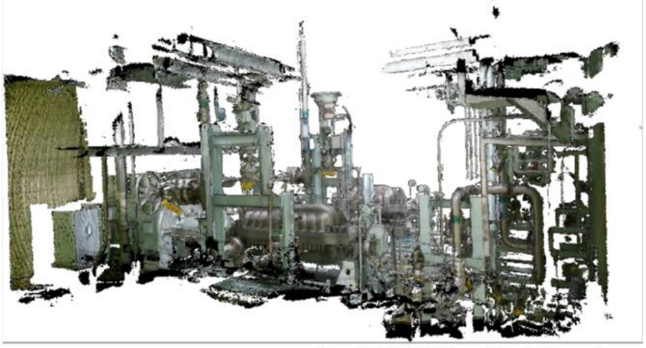

Fig. 2 Example of the 3D model.

Some system must be realized to resolve these difficulties. The operations are extremely simple. The system allows users to recognize the length information easily in a short time. Therefore, the objective of this study is to develop a Distance Information Display System (DIDS) that is useful with very simple operations, and to measure the lengths of objects and gaps that the workers might want to measure automatically. The interface is based on an augmented reality style: the measured values are shown over target objects on the system screen so that workers can refer to the values very intuitively.

2 Developed system

2.1 System overview

From preliminary interviews of NPP dismantling workers, results showed that major targets for measurement in demolition works are the lengths of pipes, and gaps between pipes and walls or floors. Therefore, the system should display the lengths of these objects and gaps. With the recent development of measurement technology, it has become easy to obtain three-dimensional shape of the plant including dimensional information [4] [5], as presented in Fig. 2. It is therefore easy to obtain metric information between two points if workers are able to specify the part to be measured. However, it is difficult for workers to operate the system carefully because they sometimes must wear gloves at the site. Therefore, the system must be able to display metric information with simple operation.

Table 1 Necessary DIDS specifications

	Required specifications
(A)	The system can be brought to the site easily.
(B)	The system does not prevent work.
(C)	The system requires no complicated operations.
(D)	It is possible to measure the intended part accurately.
(E)	The display is readily visible.
(F)	Measurement can be done in a short time.
(G)	It is easy to use, even for people using it for the first time.
(H)	It is possible to measure even places that users cannot reach.

The system developed in this study allows a user to ascertain the object and the gap lengths with extremely simple operation so that workers wearing gloves can work easily during NPP disassembly.

Table 1 presents the required DIDS specifications. These specifications were found based on interviews of NPP dismantling workers. Fig. 3 shows a DIDS usage image. It might be possible to refer to three-dimensional CAD models to obtain distance information, but it is necessary to update the model when the site changes. Accordingly, to display correct values even if the sites change, it was decided to measure the sites using a RGB-D camera that can obtain metric information of the target object in real time in this study, considering the specifications shown in Table 1. When the target object is captured with a RGB-D camera, the image is displayed on the tablet PC screen. The target is automatically measured; then the metric information is superimposed on the displayed target object. However, it is difficult to manipulate the tablet PC when one is wearing gloves, so we made it possible to operate the DIDS using only externally attached button. From the above, it was decided that the DIDS hardware would consist of a tablet PC, an RGB-D camera, and an external button.

2.2 System flow

Fig. 4 shows the overall flow of this system process. The system sequentially transits two modes: a photo mode and a length display mode. When the system is started, it first enters the photo mode. In this mode, the RGB image acquired by the RGB-D camera is displayed on the tablet PC screen and is updated in real time. When the button is pressed in this mode, the screen stands still because, if the screen is constantly updated, it is expected that the measuring portion will be unstable because of camera shake at the time of photographing, which is regarded as causing difficulty in measurement. The mode transits to the length display mode. The measurement results are superimposed on the screen.

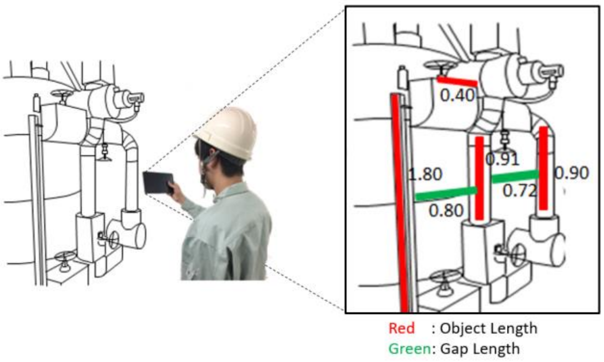

Fig. 3 Using the DIDS image.

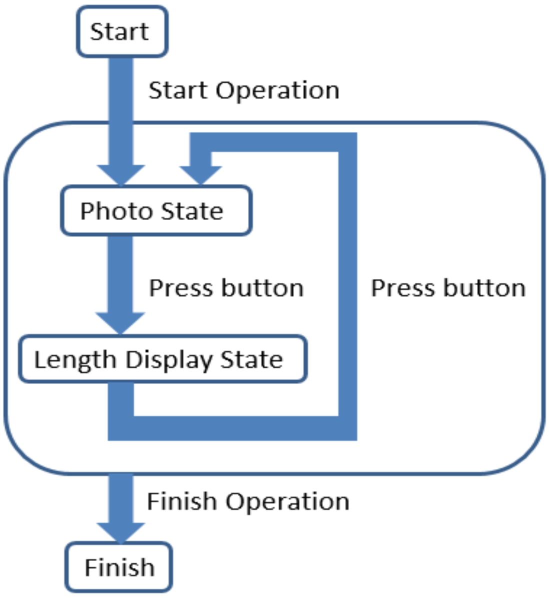

Fig. 4 Flow of the system process.

When the button is pressed in the photo mode, the measurement targets are captured with the RGB-D camera. The RGB image and the depth image are obtained. Line segments in these images are extracted using Line Segments Detection (LSD) [6]. Then the object lengths are obtained by taking three-dimensional coordinates of the ends of the line segments from the depth image. As portrayed in Fig. 5, line segment detection sometimes fails with the RGB image. This failure might occur when the color near the boundary is similar. However, these boundary lengths should be measured. Accordingly, LSD is applied also for depth image. The line segment at the boundary can be detected stably as depicted in Fig. 6.

At the same time, the gap lengths are obtained using the point cloud acquired from the depth image. The processes below are executed to measure the gap lengths.

- A point cloud is made from the depth image.
- Planes and pipes in the point cloud are recognized.
- Lengths of gaps between the planes and the pipes are obtained.

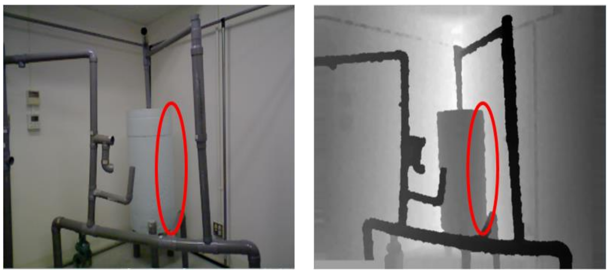

Fig. 5 Example of the part where a line cannot be detected in an RGB image, but can be detected in a depth image.

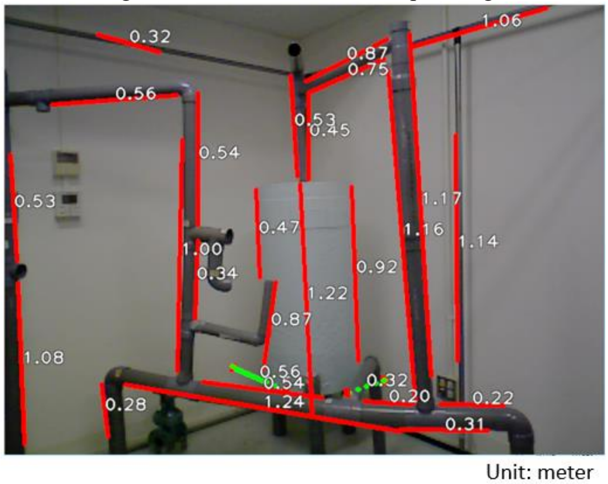

Fig. 6 An RGB image with all extracted line segments superimposed simultaneously.

The screen can show all line segments and their detected lengths. However, the measurement results might be difficult to recognize when all line segments are superimposed on the RGB image. Fig. 6 presents the original RGB image with all extracted line segments are superimposed simultaneously. Therefore, a filtering function is used to reduce the displayed metric information. The metric information priority is determined based on the rule below.

- When two line segments are mutually close or intersecting, either line segment is prior to the other.
- A line segment with depth less of the two line segments is prior to the other.
- The line segment representing the gap length is prior to the line segment representing the object length.

Based on the rule above, which is applied for all combinations of line segments, a filtering function is implemented. It makes the presumably unnecessary line segments less noticeable. Fig. 7 shows photo mode and length display mode screenshots. Object lengths are displayed as red line segments. Gap lengths are displayed as green line segments. Panel (b) of Fig. 7 shows lighter line segments. The metric information becomes easier to recognize.

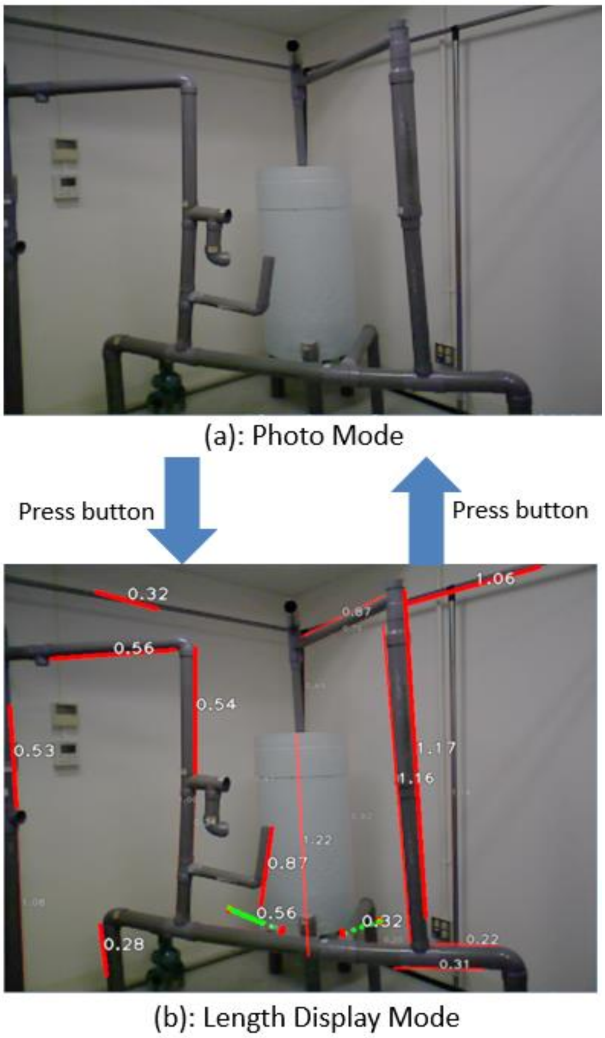

Fig. 7 Screenshots of photo mode and length display mode.

2.3 Hardware and Software Components

The hardware and software components of the DIDS are as follows. The tablet PC (Surface Pro 4; Microsoft Corp.) was used with an RGB-D camera (Xtion Pro Live; Asustek Computer Inc.), and a Bluetooth mouse as an external button. Fig. 8 shows the external appearance of the system.

System software was developed (Visual Studio Community 2017; Microsoft Corp.) in C++ language. Furthermore, software (OpenCV library Ver.3.2.0) [7] was used for line segment recognition and for point cloud processing (Point Cloud Library Ver.1.8.1) [8].

Fig. 8 Appearance of the developed system.

3 Evaluation

3.1 Evaluation purpose

This evaluation was conducted to confirm that the DIDS satisfies the required specifications and that the purpose of the system is achieved. This evaluation, comparing two methods, also investigates whether our method or an existing method is superior in terms of the required specifications.

3.2 Evaluation method

The authors chose the AR measure for comparison. Although a number of similar applications have already been produced, the AR measure achieved the highest rating from users installing applications on January 15, 2018. In this evaluation, iPad (5th generation) was used for the AR measure. Fig. 9 presents a screenshot of the AR measure.

On January 15, 2018, an evaluation experiment was conducted with five workers engaged in dismantling work at Fugen Decommissioning Engineering Center: evaluators (a), (b), (c), (d), and (e). They used the DIDS and AR measure [2] in the water purification room there. Fig. 10 shows the water purification room interior. To prevent the influence of measurement places and orders, the places and orders were changed for each evaluator. Then evaluators responded to questionnaires shown in Table 2. Then we asked for the reason for each of their answers. Table 2 presents correspondence between the required specifications and questionnaire items related to each system.

Fig. 9 Screenshot of AR measure.

Fig. 10 Appearance of the water purification room.

Presumably, required specification (H) is satisfied using a contactless measurement method with a camera, so questionnaire items related to required specifications (H) are not included.

The evaluator was asked to evaluate each question item shown in Table 2 using one of five responses: "1, do not agree"; "2, not so likely"; "3, neither"; "4, slightly agree"; or "5, think so."

3.3 Results and discussion

3.3.1 Distance Information Display System

The average DIDS usage time was 2 min 32 s. Table 3 shows answers to each DIDS question item.

Regarding required specification "(A) The system can be brought to the site easily," a slightly lower evaluation was obtained at A-1 from evaluators (c), (d), and (e). In this regard, the evaluators responded that "it is troublesome to obtain permission to bring equipment into the plant." Application is necessary for bringing equipment such as cameras and PCs into NPPs from the viewpoint of security. If these systems are brought to the site more frequently, then the application might be simple or unnecessary. The evaluation at A-1 was low also because the system equipment was somewhat bulky.

For required specification "(B) The system does not prevent work," a high evaluation was obtained at A-2. However, opinions that "equipment was thick, difficult to hold, bulky," were also obtained. The equipment should be smaller.

Regarding required specification "(C) The system requires no complicated operations," a slightly higher evaluation was obtained at A-3; higher evaluations were obtained for each item of A-4, A-5, and A-17. From this result, probably the DIDS satisfies required specification (C).

As for required specification "(D) It is possible to measure the intended part accurately," was given a low evaluation at A-8. At A-8, many opinions were obtained that "I do not know whether it is accurate." However, an opinion was also obtained that "obviously inappropriate length values were never displayed."

Furthermore, from A-9, results showed that each evaluator measured the target places repeatedly. In addition, a slightly lower rating was obtained at A-18. At A-18, many opinions indicated that the measurements were possible, but the evaluators were unable to measure all measuring objects once, such as "it is necessary to measure repeatedly by changing viewpoint," "the desired length might not be obtained in one measurement." Particularly there were many responses indicating that the gap lengths could not be measured once. Results showed that the DIDS does not satisfy required specification (D) sufficiently. Future systems with improved algorithms must be used so that the gap lengths can be recognized more stably.

With respect to required specification "(E) The display is readily visible," quite low evaluations were obtained with each question from A-14 to A-16. This result showed that the filtering process was ineffective. A slightly higher evaluation was obtained at A-10. A high evaluation was obtained at A-12. However, slightly lower evaluations were obtained at A-11 and A-13. Particularly, evaluator (e) gave scores of 2 for both A-11 and A-13. Results showed the possibility that filtering processes disturb recognition of the desired lengths because the opinion "The necessary measurement results were not noticeable because of unnecessary lengths" was given. These results show that the DIDS probably does not satisfy required specification (E). Rules of filtering functions should be improved.

Regarding requirement "(F) Measurement can be done in a short time," high evaluations were obtained from most evaluators for questions A-6, A-7, and A-20. Therefore, probably the DIDS meets required specification (F).

Regarding requirement "(G) It is easy to use, even for people using it for the first time," all evaluators gave scores of 5. Therefore, probably the DIDS meets required specification (G).

Finally, regarding the usefulness of the DIDS for dismantling work, three evaluators gave scores of 5; the others gave 4.

Table 2 Relation between required specifications for respective systems and questionnaire items

	Required specifications		Questionnaire Items of the DIDS		Questionnaire Items of the AR measure
(A)	The system can be brought to the site easily.	A-1	Equipment can be easily brought into the plant.	B-1	Equipment can be easily brought into the plant.
(B)	The system does not prevent work.	A-2	Equipment does not interfere with work.	B-2	Equipment does not interfere with work.
(C)	The system requires no complicated operations.	A-3	It is easy to orient the camera in the intended direction.	B-3	It is easy to orient the camera in the intended direction.
		A-4	The operation of displaying the length by touching the screen can be understood easily.	B-4	The operation of indicating location to measure can be understood easily.
		A-5	The operation of displaying the length by touching the screen can be executed easily.	B-5	The operation of indicating location to measure can be executed easily.
		A-17	It is easy to use the system even when wearing gloves.	B-9	It is easy to use AR measure even when wearing gloves.
(D)	It is possible to measure the intended part accurately.	A-8	The displayed length value seemed accurate.	B-6	The displayed length value seemed accurate.
		A-9	How many places have you measured repeatedly since the intended length could not be measured?	B-10	One can measure the length of the intended part.
		A-18	One can measure the length of the intended part.	-	
(E)	The display is readily visible.	A-10	One can easily understand which line length the displayed number shows.	B-7	The displayed lines are readily visible.
		A-11	The display of the number of the required length is not difficult to see because of unnecessary length information.	B-8	The displayed numbers representing the lengths are readily visible.
		A-12	One can easily understand where the line shows the length.	-	
		A-13	The display of the line of the required length is not difficult to see because of unnecessary length information.	-	
		A-14	Reducing the number size makes it easier to see other displays.	-	
		A-15	Thinning the line makes it easier to see other displays.	-	
		A-16	By making the display of the lengths semitransparent makes other display easier to see.	-	
(F)	Measurement can be done in a short time.	A-6	You do not feel stressed in the waiting time until the lengths are displayed after touching the screen.	B-12	Measurement using AR measure is less time consuming than measuring with tape measure.
		A-7	It is effective to display multiple lengths once.	-	
		A-20	Measurement using the system is less time consuming than measuring with a tape measure.	-	
(G)	It is easy to use, even for people using it for the first time.	A-19	It is easy to use, even for people handling it for the first time.	B-11	It is easy to use, even for people handling it for the first time.
-		A-21	Using the system is useful for dismantling work.	B-13	Using AR measure is useful for dismantling work.

Results showed that the DIDS might be useful for disassembly work.

3.3.2 AR measure

The average usage time of the AR measure was 2 min 27 s. Table 4 shows the responses to each question item of AR measure. The results show whether the DIDS is superior to the AR measure in terms of the required specifications.

Table 3 Results of DIDS questionnaire

	Questionnaire Items	Evaluator				
		(a)	(b)	(c)	(d)	(e)
A-1	Equipment can be brought easily into the plant.	5	5	3	3	3
A-2	Equipment does not interfere with work.	5	5	5	4	4
A-3	It is easy to orient the camera in the intended direction.	5	4	4	4	5
A-4	The operation of displaying the length by touching the screen can be understood easily.	5	5	5	5	5
A-5	The operation of displaying the length by touching the screen can be executed easily.	5	5	5	5	5
A-17	It is easy to use the system even when wearing gloves.	5	5	5	5	5
A-8	The displayed length value seemed accurate.	3	3	3	4	3
A-9	How many places have you measured repeatedly since the intended length could not be measured?	1	1	3	5	2
A-18	One can measure the length of the intended part.	4	4	4	5	4
A-10	One can easily understand which line length the displayed number shows.	5	4	5	4	4
A-11	The display of the number of the required length is not difficult to see because of unnecessary length information.	4	5	5	3	2
A-12	One can easily understand where the line shows the length.	5	4	5	5	5
A-13	The display of the line of the required length is not difficult to see because of unnecessary length information.	5	5	5	3	2
A-14	Reducing the number size makes it easier to see other displays.	2	2	2	3	3
A-15	Thinning the line makes it easier to see other displays.	2	4	3	3	3
A-16	By making the display of the lengths semitransparent makes other display easier to see.	2	2	3	3	3
A-6	You do not feel stressed in the waiting time until the lengths are displayed after touching the screen.	5	4	5	5	5
A-7	It is effective to display multiple lengths once.	5	4	5	5	4
A-20	Measurement using the system is less time consuming than measuring with a tape measure.	5	5	4	5	5
A-19	It is easy to use, even for people handling it for the first time.	5	5	5	5	5
A-21	Using the system is useful for dismantling work.	4	4	5	5	4

Regarding required specification "(A) The system can be brought to the site easily," a slightly lower evaluation was obtained at B-1 from evaluator (d). Applying the system for bringing in equipment is regarded as troublesome, but an almost identical opinion to that on the DIDS was obtained. Therefore, results suggest that there is no superiority in terms of required specification (A).

For required specification "(B) The system does not prevent work," a high evaluation was obtained for B-2, perhaps because the AR measure device is smaller than that of the DIDS. Therefore, in terms of required specification (b), one can infer superiority in the AR measure.

Regarding required specification "(C) The system requires no complicated operations" high evaluation was obtained with B-3, B-4, B-5, and B-9. From this result, one can infer that probably the AR measure satisfies required specification (C). However, an opinion such as "It was difficult to designate measurement points by camera shake" was obtained at B-5. Camera shake probably occurred at the time of measurement because the screen does not stop. In addition, at B-9, an opinion that "it is troublesome to stick a seal so that AR measure is useful even wearing gloves" was obtained. Therefore, it is considered that the DIDS presents advantages in terms of required specification (C).

As for required specification "(D) It is possible to measure the intended part accurately," slightly higher evaluation was obtained for B-6. For B-6, opinions such as "I do not know whether it is accurate" and "obviously inappropriate length values were never displayed" were obtained. In addition, at B-10, high evaluation was given. Therefore, it is considered that some superiority exists in the AR measure in terms of required specification (D).

With respect to required specification "(E) The display is readily visible," high evaluation was obtained at B-7. A slightly lower evaluation was obtained at B-8. Especially, evaluator (a) answered 2 at B-8. At B-8, opinions were gained such as "the color of the digits was assimilated with the background and it might be difficult to see." In addition, evaluator (d) gave the opinion that "When piping and wall color are the same, it is difficult to understand the boundary between piping and wall on the screen." This might be attributable to the camera resolution. Therefore, it is considered that there is superiority in the AR measure in terms of required specification (E).

Table 4 Results of AR measure questionnaires

	Questionnaire Items	Evaluator				
		(a)	(b)	(c)	(d)	(e)
B-1	Equipment can be brought easily into the plant.	5	5	4	3	4
B-2	Equipment does not interfere with work.	5	5	5	5	5
B-3	It is easy to orient the camera in the intended direction.	5	5	5	5	4
B-4	The operation of indicating location to measure can be understood easily.	5	5	5	5	5
B-5	The operation of indicating location to measure can be executed easily.	4	3	5	5	5
B-9	It is easy to use AR measure even when wearing gloves.	5	2	5	5	2
B-6	The displayed length value seemed accurate.	5	3	5	3	3
B-10	One can measure the length of the intended part.	4	5	5	5	4
B-7	The displayed lines are readily visible.	5	5	5	5	5
B-8	The displayed numbers representing the lengths are readily visible.	2	5	5	5	4
B-12	Measurement using an AR measure is less time consuming than measuring with a tape measure.	4	5	5	5	5
B-11	It is easy to use, even for people handling it for the first time.	5	5	5	5	5
B-13	Using AR measure is useful for dismantling work.	4	4	5	5	4

Regarding requirement "(F) Measurement can be done in a short time," at B-12, high evaluation was obtained. However, only evaluator (a) answered 4 because he thought that "the tape measure is better than the AR measure if it can measure only one point at a time." Of the five evaluators, three finished all measurements using DIDS were faster than those using AR measures. The DIDS presents the difficulty that users sometimes need to take measurements repeatedly. With AR measurement, users must indicate one-by-one the locations to measure. Therefore, it seems that not much difference exists between the time necessary for measurements in both cases. Therefore, presumably no superiority exists in terms of required specification (F).

Regarding requirement "(G) It is easy to use, even for people using it for the first time," all evaluators answered 5 at B-11. For DIDS, they also gave 5 points for A-19. Therefore, it is considered that there is no superiority in terms of required specification (G).

Finally, regarding the usefulness of the AR measure in the dismantling work, at B-13, three of the evaluators answered 4. The others answered 5. Based on this result, the AR measure is also useful for disassembly work.

Table 5 shows the extent to which each system meets each required specification in three grades of "1, do not meet"; "2, neither"; and "3, meet." According to Table 5, in terms of required specification (C), the DIDS is better than the AR measure. However, AR measure is superior to DIDS in terms of required specifications (B), (D), and (E). Future efforts must improve the DIDS in terms of required specifications (D) and (E), especially.

4 Conclusion

For this study, a DIDS was developed to make measurement of the lengths of objects and gaps at NPPs more efficient and make it easy for dismantling workers to measure them. We asked five evaluators to try out the system and evaluated the usefulness of the system based on questionnaires and interviews. In addition, comparison with AR measure was done to compare the DIDS with existing methods.

Results showed that the DIDS can be used easily with extremely simple operation by dismantling workers at NPPs. The workers can also measure the lengths in a short time. Based on this result, the system can probably resolve difficulties of measurement. Moreover, measurements can be performed with shorter times using this system. However, results also show that the hardware is bulky and that the measurement results are difficult to view because the filtering process was ineffective. Furthermore, the lengths of parts, especially the gap lengths, could not be displayed in some cases. Comparison of the DIDS with the AR measure showed that the DIDS is superior to the AR measure for ease of operation.

We can conclude that although there are many rooms to improve, a contact-less measurement tool using a camera is basically acceptable and useful for estimating metric information of nuclear power plants. Future work will make the hardware smaller, improve the filtering process, and develop an algorithm to make gap length recognition more stable. Another possible strategy to improve the contact-less measurement tools would be integrating both automatic and manual measurement functions into one measurement tool; users will switch the functions by changing the tablet orientation to landscape or portrait.

Table 5 Results of comparing the Distance Information Display system with AR measure

Required specifications		DIDS	AR measure
(A)	The system can be brought to the site easily.	2	2
(B)	The system does not prevent work.	2	3
(C)	The system requires no complicated operations.	3	2
(D)	It is possible to measure the intended part accurately.	2	3
(E)	The display is readily visible.	1	2
(F)	Measurement can be done in a short time.	3	3
(G)	It is easy to use, even for people using it for the first time.	3	3

References

[1] Hirotake Ishii: Augmented Reality: Fundamentals and Nuclear Related Applications, International Journal of Nuclear Safety and Simulation, Vol. 1, No. 4, pp. 316–327, 2010.

[2] AR measure, http://armeasure.com/ (on Ninth February, 2018).

[3] Daiki Handa, Hirotake Ishii, Hiroshi Shimoda: Enhancing Metric Perception with RGB-D Camera, Proceedings of the 15th International Conference on Human-Computer Interaction, Vol. 18, pp. 23–31, 2013.

[4] O. K¨ahler, V.A. Prisacariu, D.W. Murray, (2016). Real-time large-scale dense 3d reconstruction with loop closure. In *ECCV 2016*, pp. 500–516.

[5] Heung-Yeung Shum, Qifa Ke, Zhengyou Zhang: Efficient Bundle Adjustment with Virtual Key Frames: a Hierarchical Approach to Multi-Frame Structure from Motion, Proceedings IEEE Conference on Computer Vision and Pattern Recognition (CVPR), pp. 2538-2543, June, 1999.

[6] Rafael Grompone von Gioi, Jeremie Jakubowicz, Jean-Michel Morel, Gregory Randall: LSD: a Line Segment Detector, Image Processing On Line, 2012.

[7] OpenCV, https://opencv.org/ (on Ninth February, 2018).

[8] Point Cloud Library, http://pointclouds.org/ (on Ninth February, 2018).