Augmented Reality Applications for Nuclear Power Plant Maintenance Work

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Abstract: Augmented Reality is a promising technology that will improve the efficiency and safety of nuclear power plant maintenance work. To apply Augmented Reality to maintenance work, various studies must be done, such as improvement of tracking technology, improvement of the user interface and human-centered evaluation of the Augmented Reality system. The authors have conducted several studies of these issues for almost five years. This paper presents results of some of these studies.

Keywords: Augmented reality, Maintenance work support, Tracking technology

1. INTRODUCTION

Augmented Reality (AR) allows users to see virtual objects generated by computers and real objects in a real environment simultaneously. It provides the feeling that the virtual objects exist in the real environment. Because of this important feature of the AR, not only does the reality of the virtual objects increase, it also becomes possible to indicate their three-dimensional (3D) position more intuitively than using a legacy interface such as paper instruction documents or two-dimensional displays.

Application of AR to maintenance support activities might include the following:

1. Navigating workers to the workplace

The periodic maintenance of nuclear power plants is not a common daily task; a worker does not remember all the maintenance target locations and the routes to a workplace. It might even occur that the route to the workplace has changed because large equipment is disassembled and their parts occupy the worker's passage. In this case, intuitive navigation that leads workers to a workplace properly is a helpful function, particularly for novice workers (Fig. 1, left).

2. Indicating dangerous locations

Nuclear power plants have many dangerous areas that workers should not approach without noticing. To avoid undesired worker behavior, the AR is an effective solution to attract a worker's attention. For example, the AR can indicate rotating parts of a motor that might catch a worker's clothes or body (Fig. 1, second from left).

3. Making the invisible visible

Many plant parameters can not be referred directly at the workplace, but they are very important for safety and effective maintenance. For example, to avoid the incorrect disassembly of pipes, workers must know which pipes are isolated and which are not. The AR can show such information to workers intuitively by superimposing various information on the worker's view (Fig. 1, second from right).

Visualization of the dose rate of the work area is another promising AR application (Fig. 1, right). Because of high-radiation surfaces and air contamination, some nuclear power plant areas are inaccessible. Workers face a radiation-exposure risk; the total radiation exposure during the work period should be minimized. In such cases, AR can improve awareness of a work area's radiation distribution.

2. OBSTACLES TO APPLICATION OF AUGMENTED REALITY TO MAINTENANCE WORK SUPPORT

As described in section 1, AR can improve maintenance work efficiency and safety, but many issues must be resolved before AR is actually applied

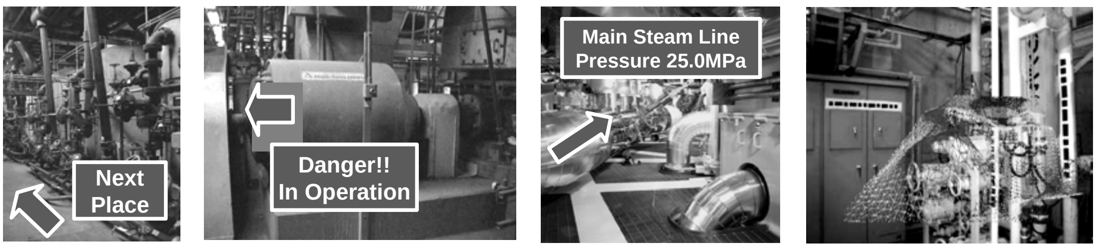

Fig. 1 Application Examples of Augmented Reality.

for maintenance work support.

A salient issue is that elemental technologies that are necessary to realize AR applications must provide higher performance than legacy AR applications such as amusement and training. Four elemental technologies are necessary to realize an AR application: tracking technology, display technology, calibration technology, and registration technology. Among these technologies, tracking technology that measures the position and rotation of workers in real time, and display technology that allows workers to view a computer screen must provide much higher performance than is available from legacy AR applications.

Nuclear power plants are huge. Workers must move in a large area during maintenance work. On the other hand, a user of a legacy AR application need not move in such a large area. This difference greatly affects the requirements of a tracking technology. To date, myriad tracking technologies have been developed and applied to many AR applications, but these are intended for use in a small area and are inapplicable to a large area. Therefore, a new tracking technology must be developed that is useful in a large area. The accuracy of tracking for maintenance work must also be very high compared to that of the legacy AR applications because, if the tracking accuracy is low, the AR application might give wrong information to the workers, engendering human error.

The complexity of nuclear power plants affects the requirements of display technology used for AR. Workers in nuclear power plants must watch their feet during walking because the floors of the nuclear power plant are not flat and many objects are placed on the floor. In addition, workers must be careful not to hit their head on protuberances such as pipes and valves. Legacy head-mounted displays (HMDs, Glasstron; Sony Corp.) limit the workers' view and are unacceptable from a safety viewpoint. The display weight is also important because a worker will wear the display for a long time. A heavy display will fatigue a worker, perhaps leading to a severe accident.

Cultural customs of workers in nuclear power plants are an important factor that must be examined for applying AR to maintenance work support. Workers are typically conservative about adopting new technology because they consider that the current maintenance methods are sufficient: it is not necessary to use the new technology to challenge establish methods and introduce risk. To persuade them to use the new technology, it is insufficient that the technology be better than the current practice: it must be sufficiently superior that the new technology dramatically changes maintenance practices.

3. RESEARCHES TO ENABLE AUGMENTED REALITY TO BE APPLIED TO MAINTENANCE WORK SUPPORT

As described in section 2, many issues must be resolved before introducing the AR into maintenance work support. The authors have conducted several studies of these issues for almost five years: i) Development of Tracking Method using Circular Markers[2]; ii) Development of Tracking Method using Line Markers[2][3]; iii) Development of Hybrid Tracking Method[4]; iv) Marker Arrangement Optimization[5]; v) Comparison of Head Mounted Displays[6], and vi) User Centered Evaluation of Decommissioning Support System using AR[7]. The remainder of this paper will describe these studies.

3.1 Improvement of Tracking Technology

As described above, to apply AR to maintenance support, the positions and orientations of workers who move in a large area in real time must be measured with high accuracy. Among the tracking technologies proposed in previous studies, marker-based tracking, which uses image-processing technique to measure the relative position and orientation between a camera and markers, seems to be the most appropriate for use in nuclear power plants. However, the most popular marker-based tracking method, which uses square markers[8], can not be used in nuclear power plants because large markers must be used to make the distance between a camera and markers long. That situation is unacceptable because no such large spaces exist to paste large markers inside a nuclear power plant. The authors have therefore developed two types of marker-based tracking methods. One is a method that employs circular markers; the other is a method that employs line markers. These two methods can recognize smaller markers at a long distance and assess workers' positions and orientations. However, these methods present the disadvantages that many markers must be pasted in the work environment and that their 3D positions must be measured in advance. This preparation is burdensome and spoils the advantages of marker-based tracking, which is inexpensive and useful inside of buildings. The authors therefore developed a hybrid tracking method, by which fewer markers must be pasted in the environment.

As described above, the accuracy of tracking used for the AR maintenance support must be very high. However, an inappropriate marker arrangement radically decreases its accuracy. It is difficult to paste the markers properly without any reference. The authors therefore developed a marker arrangement optimization method using a generic algorithm. This method determines a better marker arrangement rapidly by evaluating various marker arrangements.

3.1.1 Development of Tracking Method using Circular Markers

The edges of the square on the image become jagged, if a square is captured by a low resolution camera from a long distance. This jagged edge affects the accuracy of the tracking strongly because the tracking calculation for square markers is based on the intersections of the four lines that the jagged edges form. In contrast, even if a circle is captured from a long distance, a center of the circle can be recognized accurately. Therefore if a marker consists only of circles and the tracking calculation is based on the center of the circles, the accuracy of the tracking will not decrease even if the marker is captured from a long distance.

Another idea is the relationship between a number of the markers captured by a camera and the distance between the camera and the markers. Figure 2 left shows that the captured markers become very numerous and the size of the marker on the image becomes very small when the distance between the camera and the markers is long. It therefore becomes difficult to obtain plural feature points from one marker because the marker size on the image is too small, but plural feature points are obtainable from plural markers. Moreover, the distances among the feature points can be long because markers can be pasted so as not to be so near with each other. On the other hand, as shown in Figure 2 right, when the distance between the camera and the markers is short, the number of the captured markers becomes small and the size of the markers on the image becomes very large. In this case, it becomes possible to obtain plural feature points from one marker because the marker size on the image is sufficiently large.

Based on the idea described above, the authors have designed circular markers as shown in Fig. 3. This marker consists of one black outer circle (with thickness of 30% of the marker radius), one white center circle (the radius is 30% of the marker radius), and a middle circle (with thickness of 40% of the marker radius), which consists of 10 black or white fans that represent a binary code and four small circles (the radius is 24% of the marker radius) at the corner of the marker.

The black outer circle and the white center circle are used for determining the threshold to analyze the binary code of the middle circle. The markers that can be used simultaneously are 99. The four small circles at the corners can be recognized when the marker is captured at a short distance and the centers of these small circles are used as four feature points to execute the tracking using a P4P solution. Thereby, even if only one or two markers are captured by a

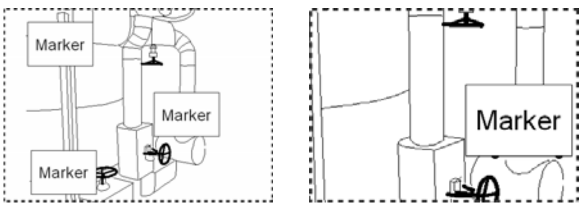

Image captured by a camera at a long distance

Image captured by a camera at a short distance

Fig. 2 Relationship between a number of captured markers and the camera distance.

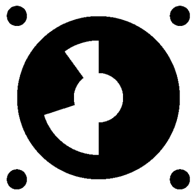

Fig. 3 Circular Marker Design.

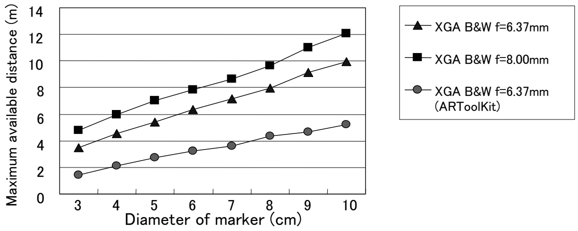

Fig. 4 Comparison of Maximum Detection Distance (a Circular and a Square Marker).

camera because the distance between the camera and the markers is too short, the tracking can be continued if the marker size on the image is sufficiently large. Therefore the marker shown in Fig. 3 is useful in two-layer modes: long distance mode with plural markers, and short distance mode with single marker.

To estimate the maximum detection distance of the circle marker, one circular marker was pasted on a wall and the maximum distance was measured under the condition that the tracking system can correctly recognize the code of the circular marker. The result shown in Fig. 4 verifies that the maximum detection distance of the circular marker is about twice that of the square marker.

To confirm that the circular marker is useful for two-layer tracking, a simple experiment was conducted. In the experiment, five circular markers of 8 cm diameter are pasted on a wall and the camera (Dragonfly II XGA black-and-white) was moved from a short distance (about 30 cm) to a long distance (about 8 m). This experiment verified that the tracking can be executed properly at all distances. In addition, the change between the tracking using single marker and the tracking using plural markers were unnoticeable to the extent that the calibration of the camera lens distortion was done properly.

3.1.2 Development of Tracking Method using Line Markers

It is difficult to paste large square markers inside buildings of nuclear power plants because many instruments are installed inside such buildings: few large spaces can be used for the markers. However, many pipes with thin rectangular surfaces exist in nuclear power plants. The authors considered that these surfaces are useful for pasting the markers and designed line markers as shown in Fig. 5.

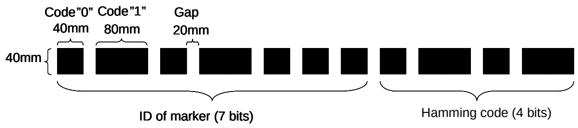

Fig. 5 Line Marker Design.

The line marker is a combination of black elements: each element corresponds to one bit. The square element signifies “0”. The double-sized rectangle element denotes “1”. The shape of the line marker is almost a single line. Consequently, it is easy to paste them on the pipes that are ubiquitous in the plants.

Figure 6 shows the estimated camera position error when 6 line markers of about 50 cm were pasted in a room (10 m × 20 m) and the camera was moved in the room with 1 m steps. The maximum detection distance at which the markers were recognized without any failure was about 11 m and the maximum distance with some recognition failure was about 17 m under the condition that an XGA black-and-white camera with 6.37 mm focal length lens was used. This maximum distance is mush longer than the case of the square markers. About 96% of the tracking was executed with less than 30 cm position errors when the markers were recognized without any failure.

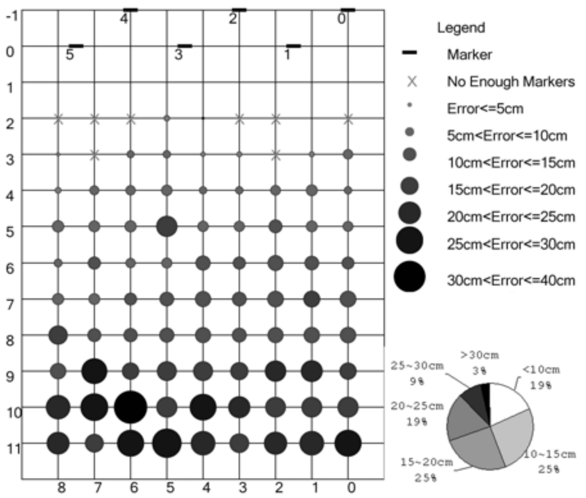

Fig. 6 Estimated Camera Position Error.

3.1.3 Development of Hybrid Tracking Method

One candidate to decrease the number of markers which must be pasted in the environment might be the use of a wide-angle camera that can capture wide angle images. But the resolution of the images captured with a wide angle camera becomes very low and the distortion of the images also becomes very large. This might decrease the maximum detection distance and the tracking accuracy. The authors, therefore, have developed a hybrid tracking method using a multi-camera unit and gyro-sensor.

In this study, a multi-camera unit with three cameras which view angle is about 40 degrees was developed as shown in Fig. 7. These three cameras are located with about 40 degrees relative angle and

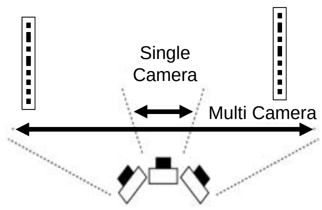

Fig. 7 Extension of Viewing Angle using a Multi-Camera Unit.

can capture three-times-wider angle images than a single camera. Of course, using the multi-camera unit, the users can obtain a three-times-wider angle of view than in the case of a single camera without increasing the number of markers pasted in the environment. However, tracking can not be executed by a tracking algorithm developed only for a single camera when two line markers are captured separately by two cameras. In this study, therefore, a new tracking algorithm for multi-camera units was developed.

Using the multi-camera unit described above, the number of the line markers that must be pasted in the environment can be decreased at a certain level. But when a part of the line marker is hidden by a user’s body or tools used for maintenance, the tracking will not be able to continue. In this study, therefore, a hybrid tracking method that combines a gyro-sensor and the line marker has been developed. From the gyro-sensor, only the orientation is obtainable at all times, but the output is not so accurate and the cumulative error will increase as time passes. Therefore, the gyro-sensor is useful only for a very short period of time.

The process using the gyro-sensor and the line marker is divisible into three parts.

A case in which more than two markers can be captured by a camera : In this case, the position and the orientation of the camera are calculated based on the two line markers and an output from the gyro-sensor is recorded. Then the amount of the error of the tracking result based on the two line markers is estimated. A weighted average of the tracking result based on the two line markers and the output from the gyro-sensor is calculated if the amount of the error is larger than a threshold value. The result is used as the final tracking result. Otherwise, the tracking result based on the two line markers is used directly as the final tracking result. The accumulated error of the gyro-sensor is corrected if the amount of the error is smaller than a threshold value.

A case in which only one marker can be captured by a camera : In this case, the position of the final result of the previous frame is set as the position of a temporary tracking result. The output from the gyro-sensor is also set as the orientation of the temporal tracking result. Then the position of the line marker on the camera image is estimated using the temporary tracking result. The temporary tracking result is adjusted nonlinearly to minimize the difference between the estimated position and the actual position of the marker on the image. The adjusted result is used as the final tracking result.

A case in which no marker can be captured by a camera : In this case, the output from the gyro-sensor is used as the orientation of the final tracking result; the position of the final result of the previous frame is used as the position of the final tracking result. Therefore, if the camera moves in parallel, the error of the final tracking result will be the amount of the parallel movement.

To evaluate the effectiveness of introducing the hybrid tracking method, an evaluation experiment was conducted in a room of Fugen, which is a real but retired nuclear power plant in Japan. Figure 8 shows a comparison between the case of the hybrid tracking and the case of a single camera when the worker walks along with 2 kinds of routes which was assumed in a room (8 m × 9.5 m). Figure 8 shows that the areas for which the tracking are available with the hybrid tracking method are 3 times (Route 1) and 17 times (Route 2) larger than when using the single camera. This result confirmed that the hybrid tracking method can enlarge the available area without increasing the number of markers.

3.1.4 Marker Arrangement Optimization

The best marker arrangement from the perspective of tracking accuracy can be determined based on 1) the area where the tracking is required, 2) the area where markers can be pasted, and 3) parameters of a camera. Nevertheless, it is difficult to determine a marker arrangement directly from this information using geometrical analysis. In this study, therefore, various marker arrangements are evaluated; then the best is selected using a generic algorithm. In this case, a method which can calculate the tracking accuracy rapidly under a given marker arrangement is necessary as a fitness function of generic algorithm. In this study, a new method is used to calculate the possible maximum tracking error from the recognition uncertainty of markers on the screen, as derived from the limits of camera resolution and imperfection of lens distortion correction. In this method, under the assumption that the recognition uncertainty of markers Δ is known: 1) for every two markers among all recognized markers, calculate the position set for which the horizontal position of the two markers on the screen is between $x_1 \pm \Delta$ and $x_1 \pm \Delta$ (x_1 and x_2 are the horizontal positions of the two markers on the screen when a camera is at the right position and orientation); 2) for all recognized markers, calculate the position set for which the vertical position of the marker on the screen is between $y \pm \Delta$ (y is the vertical position of the marker on the screen when a camera is at the right position and orientation); and 3) the size of the common area of the position sets calculated in 1) and 2) is considered as the possible maximum tracking error.

In the marker arrangement optimization method proposed in this study, one gene corresponds to the position of one marker and one chromosome has all positions of all markers pasted in the area for which tracking is necessary. The other generic algorithm conditions are: i) the population of one generation is 100; ii) the crossover rate is 60%; iii) the mutation rate is 40%; and (iv) 10 chromosomes are selected using the roulette wheel method for the next generation.

To evaluate the effectiveness of the above marker arrangement optimization method, a simulation-based experiment was conducted by constructing a room resembling that of a power plant building. The experimental conditions are: i) 8 m×10 m×4 m room size; ii) areas where markers can be pasted were six line-shaped areas and three planar areas; iii) evaluation points were 24 poses (position and orientation); and iv) a Dragonfly2 XGA (f=3.94 mm) was used as a camera.

Figure 9 shows results of the experiment, in which optimization was conducted until the 200th generation. In the figure, the average, the best case, and the worst case over 20 time trials of the possible maximum tracking error are shown. The tracking error, which was about 150 mm at the first generation, decreases until about 50 mm at the 50th generation. The experimental optimization application was developed using Visual Studio 2005 (Microsoft Corp., the language is C#) and run on a machine with an Core 2 Duo 2.66 GHz processor (Intel Corp.). In this case, the calculation for one generation required 1–2

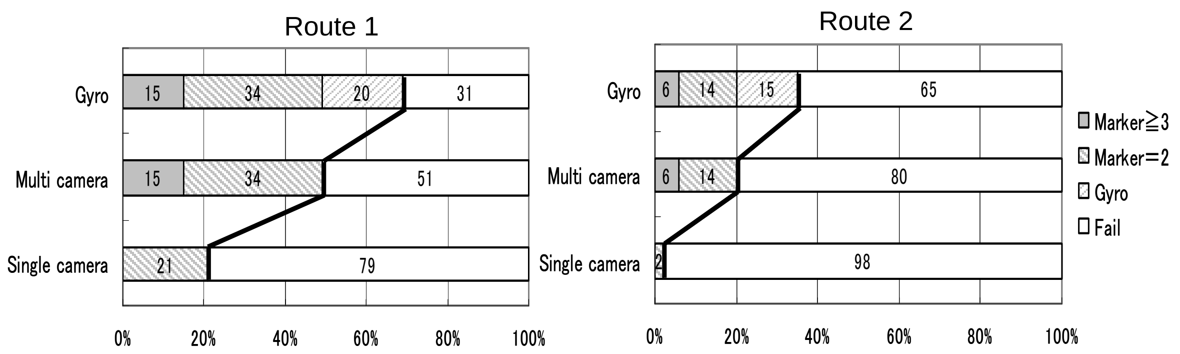

Fig. 8 Comparison between Hybrid Tracking and Single Camera.

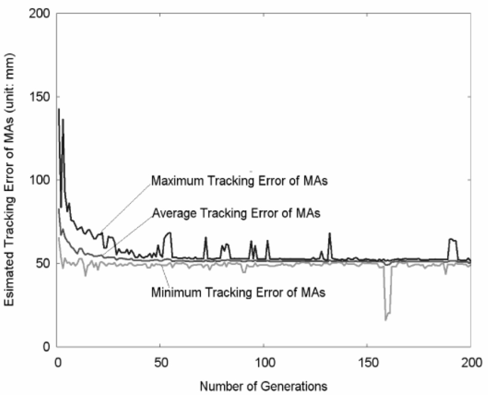

Fig. 9 Estimated Tracking Error over Generations.

s. The marker arrangement optimization must be determined only when markers are newly pasted in the work area. Therefore, we can say that the marker arrangement optimization method proposed in this study is sufficiently fast for practical use.

3.2 Comparison of Head Mounted Displays

A suitable display device has been sought by conducting subject experiments using psychological experimental technique. A water system isolation task was selected as a support target and five display devices were compared, as shown in Table 1. The subjects were required to look for 10 designated valves using navigation by the experimental support system in the simulated power plant room (15 m × 10 m), in which 50 valves are located. The task completion time, the number of errors and NASA-TLX were measured. Then a usability questionnaire was administered.

Results of the experiment showed that a one-eye video see-through HMD is a suitable device in a wearable configuration; a compact screen device was suitable as a handheld configuration.

3.3 User-Centered Evaluation of Decommissioning Support System using AR

Workers' feelings when they are asked to use the maintenance support system using AR are another important research target. In this study, a concrete method of supporting the decommissioning work of nuclear power plant using AR and 3D CAD has been proposed and a prototype system realizing the proposed method was developed. The prototype system has a small tablet PC equipped with a small camera, which captures the work environment. Two functions were developed onto the prototype system. One is a function by which 3D CAD data are colored in cutting lines and dangerous parts are superimposed on the captured image. The other is a function by which users can record the cutting parts using a stylus pen, with accompanying comparison of the 3D CAD and the real environment.

Fig. 10 Small Tablet PC used in Evaluation.

Figure 10 shows the small tablet PC used for the prototype system; Fig. 11 shows the software interface of the prototype system.

In the evaluation experiment, three workers of Fugen NPP were asked to use the prototype system along with a scenario of dismantling an ion tower of a water purification facility. Then questionnaires and interview investigations were conducted.

Results showed that the proposed method, which records the cutting parts on the CAD data using a stylus pen, was easier to use than the legacy recording method using paper documents. However, a new tablet PC with a lighter and larger screen is needed to apply the proposed method to decommissioning work.

In addition, results showed that the proposed method can be expanded for application to accumulation of know-how for decommissioning work, training for novice workers, composing reports, and public relations for NPP decommission.

On the other hand, it has been indicated by workers that when many obstacles exist, such as pipes and other equipment between the user and the target system, it might be difficult for a user to recognize CAD data superimposed onto real target equipment.

Table 1 Compared Display Devices

Device	Dataglass 2	SCOPO	Glasstron	Tablet PC	Compact TV
Appearance					
Type	Wearable	Wearable	Wearable	Handheld	Handheld
Model	Dataglass2, Shimadzu Corp.	SCOPO, Mitsubishi Electric Corp.	Glasstron, Sony Corp.	Travel Mate C100 TMC102I, Acer	SY-4100, Casio Corp.
Features	One-eye optical see-through	One-eye video see-through	Both-eye video see-through	10.4 inch display, 1.4 kg weight	4 inch display, 0.58 kg weight

Fig. 11 Software Interface of the Prototype System.

4. FUTURE WORK

The authors have conducted various studies for applying AR to nuclear power plant maintenance-work support. However, further studies are indispensable to realize an effective and practical support system.

Regarding the tracking technology, the authors tried to reduce the number of markers that must be pasted in the work environment by developing a hybrid tracking method. The number of the markers can thereby be reduced, but the method remains insufficient. The field requirements are more severe. The use of fiducial markers is unavoidable because nuclear power plants necessitate highly reliable tracking; also, tracking using only feature points[9] can not provide the necessary reliability. The simultaneous use of fiducial markers and feature points might be a solution for this issue.

Authoring is another important issue. An important index by which industrial leaders judge whether to use a technology or not is its investment efficiency. Preparing the contents of an AR application is a painstaking process. The current authoring technology can not provide sufficient efficiency to introduce AR into a real application. We must propose and evaluate a more effective authoring method that can enable us to prepare contents without special knowledge or much effort.

The development of new hardware that is specialized for the use in nuclear power plants is also important future work. Almost all AR studies use commercially available hardware. From an economical perspective, it is important to try to use consumer products, but field requirements are severe. It is insufficient that the hardware be wearable: it should be comfortable for the workers. The computer must be sufficiently light for workers to carry for a long time. The display must be sufficiently large and easy to carry and must not obstruct the worker's view.

Of course, these issues are not easily resolved, but we believe that AR can change the practice of nuclear power plant maintenance. Efforts at improving these technologies will pay off in the future.

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