Wide area tracking method for augmented reality supporting nuclear power plant maintenance work

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Abstract: A new fiducial marker for augmented reality was designed along with a method that recognizes the markers captured by a camera and calculates the relative position and orientation between the markers and the camera. These markers can be used at both long and short distances without increasing their number in the environment. Results of the experimental evaluation show that the new marker can be used in a larger area than legacy markers such as square markers and circular markers.
Keyword: tracking method; augmented reality; maintenance support; fiducial marker

1 Introduction

Augmented Reality (AR) is a technology that makes us feel as if virtual objects and symbols actually exist in front of us by superimposing computer-generated images on our view [1]. This technology can be used in various ways to assist workers in nuclear power plants (NPPs), because it can provide them with three-dimensional positions and orientations more intuitively than legacy interfaces such as paper-based instruction documents [2–4]. For example, workers are able to navigate safely and effectively by having the direction in which they should walk displayed according to their current position and orientation (Navigation function). AR is also able to show dangerous areas (Safety function) and working procedures (Instruction function) intuitively to the workers.

In order to apply AR to support NPP workers, a tracking method that measures the position and orientation of the workers in real time is indispensable. However, existing tracking methods such as Global Positioning System (GPS), magnetic sensors, ultrasonic sensors, and inertial sensors can not be used in NPPs: GPS can not be used inside buildings; magnetic sensors and ultrasonic sensors are not useful in complicated environments with many metal instruments; and inertial sensors' error increases over time [1].

In this study, we specifically examine marker-based tracking methods [5–10], which calculate the relative position and orientation between a camera and markers using image processing and geometric calculation. Such methods present the following advantages: they can be used inside buildings, are unaffected by metal and loud noise, and remain accurate even over a long time. However, existing marker-based tracking methods are useful only under limited conditions. For example, square markers [5–7] are useful only for short distances between a camera and markers. On the other hand, line markers [8–9] and circular markers [10] are useful only at great distances. Therefore, when AR is used in NPPs, where workers are expected to move throughout a large area, both square markers and line/circular markers must be pasted in work areas. However, it is difficult to paste many markers in NPPs because of the complex and narrow interior of NPP buildings, which do not offer sufficient space to paste many markers.

Taking the above mentioned aspects into consideration, in this study, we designed a new marker that is useful at both long and short distances. Furthermore, we developed a method that recognizes the markers captured by a camera and calculates the relative position and orientation between the markers and the

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camera. Moreover, experimental evaluations were conducted to evaluate the newly designed markers' performance. The required performance of the tracking method used in NPPs varies according to the application (the purpose of the support). For this study, we aimed at developing a tracking method with a position accuracy of about 20 cm (half of an average human stride) and an orientation accuracy of about 20 deg (18 directions). This is expected to be sufficient for realizing the Navigation function, Safety function, and Instruction function, which support the operation of large instruments such as pumps and motors in NPPs.

2 Proposal of a tracking method using multi-range markers

2.1 Design of multi-range markers

Figure 1 portrays a design example of the multi-range marker proposed in this study. This marker consists of one large circle located in the marker's center and four small circles in the marker's four corners. The centers of one large and four small circles are used as feature points of the marker. The feature points are to be recognized by image processing; they are used for the tracking calculation. To obtain a unique solution, four or more feature points must be recognized simultaneously on the camera image [11].

The large circle is composed of one black outer circle, one white center circle, and one middle circle. The middle circle consists of 10 black or white fans, which represent a binary code through their color. The thickness of the outer circle, center circle and middle circle are respectively 30%, 30% and 40% of the large circle's radius.

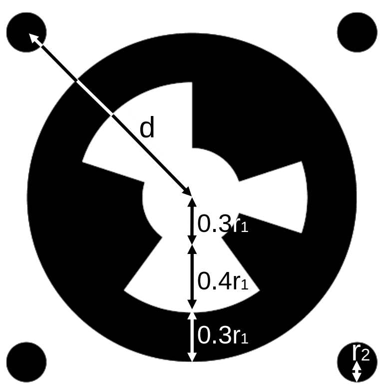


Fig. 1 Design example of multi-range marker.

In order to use this multi-range marker in NPPs, the markers are pasted on the surface of instruments that are to be maintained as well as on walls near the instruments. The three-dimensional positions and orientations of the markers must be measured in advance. The camera used for tracking is mounted on the worker's helmet or on the backside of a portable computer or PDA.

When they use the Navigation function or the Safety function, workers refer to information provided by AR while they remain far from the instruments and walls. In this case, there is a long distance between the camera and markers. As a consequence, the camera captures plural markers, but they are small on the resulting image. When a marker on the image is small, recognizing the large circle is easy while recognizing the small circles is difficult. Therefore, only one feature point is obtainable from one marker, but a sufficient number of feature points for tracking are obtainable from the plural markers. On the other hand, when the Instruction function is used, workers stand near to the instruments and walls while they refer to information provided by AR. In this case, there is only a short distance between the camera and markers. Therefore, few markers can be captured, but they appear large on the image. When a marker on the image is large, it is easy to recognize the small circles. Therefore, a single marker provides with sufficient feature points for tracking.

2.2 Algorithm to recognize multi-range markers

An algorithm to recognize multi-range markers is described in this section. For the following algorithm, it is assumed that multi-range markers are printed out on white paper with printers and that the image obtained from a camera is in gray-scale format: each image pixel has a value ranging from 0 to 255.

Step 1-1. Obtain an image from the camera and convert each pixel ($I(x,y)$) using Eqs. (1) and (2).

i) If $0 \le I(x,y) \le 127$, then

$$J(x,y) = \log_{10}(I(x,y)+1). \tag{1}$$

ii) If $128 \le I(x,y) \le 255$, then

$$J(x,y) = 4.243 - \log_{10}(266 - I(x,y)). \tag{2}$$

Step 1-2. Apply a 3×3 Sobel edge detector to the image obtained in Step 1-1 and binarize the result with a threshold value of 0.8.

Step 1-3. Label the binarized image by collecting the connected pixels and assigning a unique label to them. Eliminate candidates with an area narrower than 10 or wider than 100,000.

Step 1-4. Trace the edges of each labeled area and number each edge pixel.

Step 1-5. Select one edge pixel randomly and two other edge pixels so that the differences between the pixel numbers are all equal. Furthermore, calculate the ellipse that passes through the selected three edge pixels. Repeat this calculation 150 times and calculate the average of the center (x_{ell}, y_{ell}), major radius r_a, minor radius r_b, and rotation angle θ_{ell} (angle of major radius and horizontal line on the camera image), respectively.

Step 1-6. Eliminate the ellipse candidates for which the major radius r_a is smaller than 10 pixels or for which the ratio of the major radius to the minor radius is larger than 3.5.

Step 1-7. Calculate the average of the squared distance between the ellipse calculated in Step 1–5 and each edge pixel. Eliminate candidates for which the average is greater than 0.02.

Step 1-8. Normalize the recognized ellipses to a circle using the ratio of the major axis to the minor axis, and the rotation angle θ_{ell} of the ellipse, as depicted in Fig. 2. Set the baseline on the major radius of the ellipses. The outer circle and the center circle of the marker are divided into five rings along with the radius, and each ring is divided into 20 pixels along with the arc. The middle circle is divided into 100 elements along with the arc. Each element is divided into 10 pixels along with the radius.

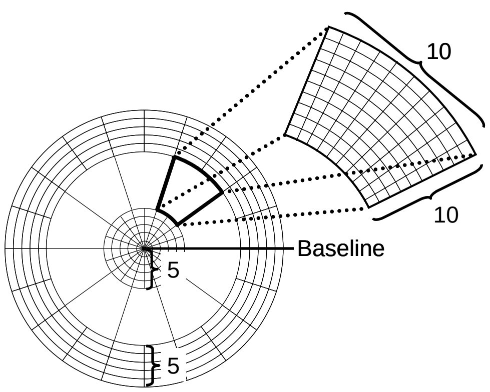


Fig. 2 Normalization of marker.

Step 1-9. Calculate the variance v_{out} and average a_{out} of pixels in the black outer circle, as well as the variance v_{in} and average a_{in} of pixels in the white center circle using the original image captured by the camera. Eliminate candidates for which v_{out} is larger than 5×10^8 or for which v_{in} is larger than 5×10^7. Set the average of a_{out} and a_{in} to a threshold th.

Step 1-10. For each element of the middle circle divided in Step 1-8, count pixels for which the brightness is greater than th and less than th. Set the results as s_w and s_b, respectively.

Step 1-11. Find an element of the middle circle which is $s_w > s_b$. Perform the search from the baseline in counterclockwise order.

Step 1-12. Starting from the element isolated in Step 1-11, look in counterclockwise order for an element which is $s_w < s_b$ in the middle circle. The element found in this step is set as the basis for analyzing the binary code of the middle circle. Calculate N_{scn} by counting the elements between the baseline and the element found in this step. The element found is considered as a boundary between two fans of the middle circle.

Step 1-13. Starting from the element found in Step 1-12, count in counterclockwise order the number of elements which is $s_w > s_b$ and $s_w < s_b$, respectively, for each fan. Set the results as S_w and S_b, respectively.

Step 1-14. Eliminate candidates which have a fan verifying $|S_w - S_b| < 3$.

Step 1-15. In total, 10 bits are obtained from the middle circle, assuming that a fan for which $S_w > S_b$ has a binary value of 0, whereas a fan for which $S_w < S_b$ has a binary value of 1.

Step 1-16. Shift the 10 bits obtained in Step 1-15 10 times (circular shift in 1 bit step) and find the smallest bits. Set the result as the number (ID) of the marker. Set the number of the shift operation when the smallest bits appear as N_{sft}.

Step 1-17. Estimate four vectors $(x_{cnr}(i), y_{cnr}(i))$ (i=0,1,2,3) from the center of the marker to the four small circles using Eq. (3).

$$\begin{aligned}
x_{cnr}(i) &= x\cos(\theta_{ell}) - y\sin(\theta_{ell}) \\
y_{cnr}(i) &= x\sin(\theta_{ell}) + y\cos(\theta_{ell}) \\
x &= \cos(\theta_{ell})\sin(\alpha) + \sin(\theta_{ell})\cos(\alpha) \\
y &= \{\cos(\theta_{ell})\cos(\alpha) - \sin(\theta_{ell})\sin(\alpha)\} r_b / r_a \\
\alpha &= \theta_{ell} + 3.6N_{scn} + 36N_{sft} + 45 + 90i
\end{aligned} \tag{3}$$

Step 1-18. Calculate the distance l between the center of the marker and each ellipse, which were recognized in Step 1-7 but not identified as a marker yet. Furthermore, find ellipses that are $r_b < l < 1.7r_a$.
Step 1-19. Calculate a vector v_e from the center of the marker to the center of the ellipses found in Step 1-18. Find four ellipses for which the angle between v_e and $(x_{cnr}(i), y_{cnr}(i))$ is at most 60 deg. and the distance between the center of the marker and the center of the ellipse is the shortest. The four ellipses are inferred to be the four small circles of the marker.

The algorithm described above can recognize five feature points from one marker at the maximum. It is assumed that the recognition of four small circles failed and that only one feature point is obtainable from one marker if Step 1-18 or Step 1-19 has failed.

2.3 Algorithm to calculate the relative position and orientation between a camera and markers

After recognizing markers on the image, the relative position and orientation (6 degrees of freedom) between a camera and markers are estimated using the following algorithm.
Step 2-1. If four or more markers are recognized, select the two markers that are the most distant from each other on the image. Then calculate a line which passes through the two markers and select the marker that is the most remote from the line. Solve the P3P using the three markers selected, and obtain a maximum of four possible solutions.
Step 2-2. If fewer than four markers were recognized, find markers for which four small circles are recognized. Then solve the P3P using three small circles selected from the four small circles, and obtain a maximum of four possible solutions. The tracking fails if no marker exists for which four small circles are recognized.
Step 2-3. Estimate the position of all feature points recognized on the image using the four solutions obtained in Step 2-1 or Step 2-2, inertial parameters of the camera, and the three-dimensional position of the feature points, which were measured in advance. Then calculate the difference between the estimated position and the recognized position using the algorithm described in 2.2. That difference is called the re-projection error. Select the solution for which the re-projection error is smallest.
Step 2-4. Obtain 12 new solutions by rotating the solution by ±0.01 deg around the *x*, *y*, and *z* axes and shifting the solution by ±10 mm along the *x*, *y*, and *z* axes. Calculate the re-projection error for all new solutions. Then select the solution with the smallest re-projection error.
Step 2-5. Repeat Step 2-4 a maximum of 30 times until the re-projection error becomes less than 20 pixels.

3 Evaluation of the proposed method

Some experiments were conducted to evaluate the tracking method. The tracking method performance changes according to the radius of the large circle r_1, the radius of the small circle r_2, and the distance between the large circle and the small circle d. However, it is difficult to evaluate the relationship between these parameters and the tracking performance in detail. In this study, therefore, one design of a multi-range marker ($d = 1.42r_1$, $r_2 = 0.12r_1$, $r_1 = 5$ cm) was evaluated. In this case, the gap separating the contour of the small circle and the large circle is equal to the outer black circle's thickness; the small circle and each fan of the middle circle are almost equal in size. The marker is about 14.2 cm large including the white area allocated outside of the small circles, which is meant to stabilize the recognition of the marker. (The thickness of the white area is the same as the one of the outer black circle.)
Table 1 shows the main specifications of the hardware used for the evaluation. The program was built with a compiler (Visual C++ 2005; Microsoft Corp. and C++ Compiler Ver.10.0; Intel Corp.) under a widely used operating system (Windows XP; Microsoft Corp.). The camera shutter speed was fixed to 10 ms; the gain was adjusted automatically during the evaluation.

Table 1 Hardware specifications used for evaluation

PC	CPU	Pentium Core2Duo 2.66 GHz
	Memory	DDR2 800 MHz, 2 GB
Camera	Vendor	Point Gray Research Inc.
	Model	Dragonfly2 XGA Black&White
	Interface	IEEE1394a
	Resolution	1024 × 768
	Frame rate	30 fps
	Focal length	8.00 mm

3.1 Recognition range

One marker was located in front of the camera so that the camera would capture the marker at the center of the image. The distance between the camera and the marker was changed to evaluate the maximum and minimum distance at which the system could flawlessly recognize the marker ID 1000 times consecutively. The distance at which the system could recognize the four small circles was evaluated similarly. The brightness on the marker was 700 lux. Table 2 presents the results.

Table 2 Maximum and minimum distance (mm)

Marker ID		Four small circles	
Max.	Min.	Max.	Min.
5344	251	4980	289

3.2 Stability of marker recognition under variable illumination conditions

One marker was located in front of the camera so that the camera would capture the marker at the center of the image. The distance between the camera and marker was fixed at 1.5 m. The brightness was changed to determine the maximum and minimum brightness at which the system could flawlessly recognize the marker ID 1000 times consecutively. The brightness at which the system could recognize the four small circles was evaluated similarly. Table 3 presents the results. The marker could be recognized under wide illumination variability.

Table 3 Maximum and minimum brightness (lux)

Step 1-1	Marker ID		Four small circles	
	Max.	Min.	Max.	Min.
Enable	3.90×10^3	6	3.88×10^3	6
Disable	3.54×10^3	12	3.46×10^3	12

3.3 Processing speed of tracking

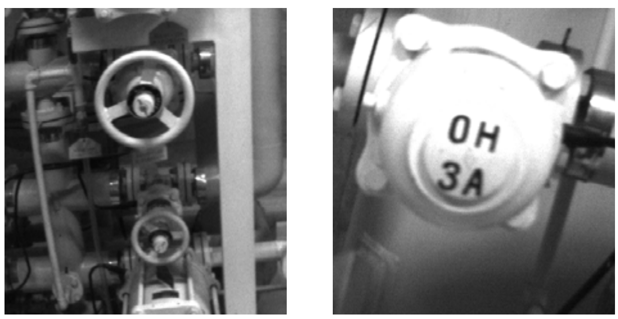
One marker was located in front of the camera so that the camera would capture the marker at the center of the image. The distance between the camera and the marker was fixed at about 1.5 m. We measured the time necessary for executing each process described in section 2.2 and 2.3 with the marker. Then, nine markers were placed in front of the camera on a 3×3 grid (0.5 m vertical step, 1.0 m horizontal step); the distance between the camera and the marker was fixed at about 5.0 m. We measured the time necessary for executing each process described in sections 2.2 and 2.3 with the nine markers. Table 4 presents the results. The tracking could be executed more than 60 times per second that will be sufficient for the applications described in chapter 1.

Table 4 Necessary tracking time (ms)

Process	Required Time	
	1 marker	9 markers
Step 1-1 – Step 1-2	8.5	8.5
Step 1-3 – Step 1-4	2.9	3.4
Step 1-5 – Step 1-16	0.4	3.9
Step 1-17 – Step 1-19	0.01	Not used
Step 2-1 – Step 2-5	0.03	0.06
Total	11.9	15.9

3.4 Misrecognition of markers

To evaluate whether the algorithm described in 2.2 misrecognizes non-marker objects as markers, images captured in a water purification room of the Fugen nuclear power plant were processed using the algorithm. The images were captured by a camera held by a worker according to a scenario in which the worker walked around the water purification room to check instruments. 19,742 images were processed; for 121 of them (0.61%), the algorithm misrecognized objects that were not markers as markers. In all the misrecognized cases, only the large circle was recognized; the small circles were not recognized. Figure 3 depicts two images in which the algorithm misrecognized the centers of circular valves and "0" character as markers. To avoid the misrecognition, the markers which ID is 1 and 2 should not be used for the tracking because in 59.5% of the misrecognition, non-marker objects were misrecognized as these two markers, which design seems to be too simple to be used in NPPs.



(Left) The center of the upper valve was misrecognized.
(Right) The "0" was misrecognized as a marker.

Fig. 3 Examples of misrecognized images.

3.5 Area within which tracking can be executed

It is difficult to check whether the tracking can be executed at every point in a real environment if the environment is large. For this study, therefore, the area within which tracking can be executed with enough accuracy was evaluated using computer simulation. In a virtual environment, nine markers were placed on a 3×3 grid (x = -1.0, 0.0, 1.0 m; y = -0.5, 0.0, 0.5 m; z = 0.0 m). The textures of nine markers were generated at a resolution of 512×512 pixels conforming to the design described in 2.1, and they were pasted on the virtual markers. A virtual camera for which inertial parameters (focal length, vertical and horizontal view angle and resolution) were set referring to the camera in Table 1 was moved in 1 cm steps in an area (-3.0 ≤ x ≤ 3.0 m; -0.5 ≤ y ≤ 0.5 m; 0.0 ≤ z ≤ 6.0 m) in front of the markers. The camera direction was fixed to -z direction. We then checked whether tracking can be executed at every point by generating the camera image using the OpenGL library and applying the algorithm described in 2.2 and 2.3 (Total 601×101×601 = 36,481,301 points). Figure 4 shows an image generated using the OpenGL library. In this image, the imperfection of the distortion correction and the illumination variance were not accurately simulated. Still, we could roughly estimate the area within which the tracking can be executed.

Fig. 5 shows the points at which the position and orientation error of the tracking is less than 20 cm and 20 deg respectively when the camera was moved on a plane (y = 0). When the distance between the marker and the camera is greater than about 3 m, the accuracy and stability of the tracking is not good enough if the camera can capture less than four markers. When the distance is greater than about 5 m, the accuracy and stability is not good enough even if the camera can capture not less than four markers. This means that tracking with the small circles is effective at less than 3 m whereas tracking with the large circle is effective at less than 5 m. The number of points at which the algorithm used not less than four markers at a distance ranging from 3 m to 5 m, and at a range shorter than 5 m were, respectively, a = 4,269,416 and b = 4,898,851. The number of points at which the tracking can be executed with a single marker at less than 3 m distance was c = 5,635,046. Therefore, the area within which the tracking can be executed using multi-range markers is (c-b+a)/a×100 = 117.2 % and a/c×100 = 75.8 % larger than that of the circle marker and the square marker respectively.

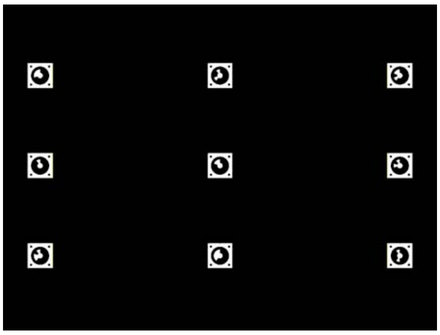


Fig. 4 Example of an image generated using OpenGL.

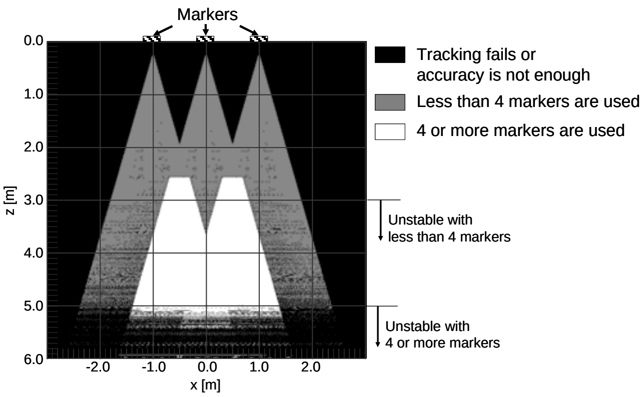


Fig. 5 Points at which tracking can be executed with enough accuracy (Top view of the area).

4 Conclusions

In this study, a new marker that is useful for both long and short distances was designed. An algorithm for recognizing the markers and using them for augmented reality tracking was also developed. Results of evaluation experiments demonstrate that the new marker can increase the area usable for tracking compared to that for circular and square markers. Moreover, the algorithm can recognize markers under severe environmental conditions, with very high and very low brightness, and when the distance between a camera and the markers is great. Future studies will evaluate the feasibility of the proposed markers and the algorithm in a real nuclear power generation environment.

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