Development of Marker-based Tracking Methods for Augmented Reality Applied to NPP Maintenance Work Support and its Experimental Evaluation

Hirotake Ishii, Hidenori Fujino, Bian Zhiqiang, Tomoki Sekiyama, Hiroshi Shimoda and Hidekazu Yoshikawa

Information and Energy, Graduate School of Energy Science, Kyoto University
Gokasho, Uji, Kyoto, Japan 611-0011
hirotake@uji.energy.kyoto-u.ac.jp

Abstract – *In this study, two types of marker-based tracking methods for Augmented Reality have been developed. One is a method which employs line-shaped markers and the other is a method which employs circular-shaped markers. These two methods recognize the markers by means of image processing and calculate the relative position and orientation between the markers and the camera in real time. The line-shaped markers are suitable to be pasted in the buildings such as NPPs where many pipes and tanks exist. The circular-shaped markers are suitable for the case that there are many obstacles and it is difficult to use line-shaped markers because the obstacles hide the part of the line-shaped markers. Both methods can extend the maximum distance between the markers and the camera compared to the legacy marker-based tracking methods.*

I. INTRODUCTION

In order to stabilize energy supply, it is necessary not only to improve power generation systems themselves, but also to improve their human-machine interface. Especially, in the field of maintenance work of nuclear power plants (NPPs), there are some rooms to improve its efficiency and safety by introducing state-of-the-art information technology. Augmented Reality (AR) is one of the promising technologies that will be able to improve the efficiency of the maintenance work and reduce human errors. The AR expands the surrounding real world of the users by superimposing computer-generated information on the user's view and represents various information more intuitively than with legacy interfaces such as paper-based instruction documents[1].

In order to apply the AR to the maintenance work in the NPPs, a tracking method that measures position and orientation of workers in real time is indispensable. Until now, many kinds of tracking methods have been developed and applied to many AR applications, but it is difficult to apply these conventional tracking methods to the NPP maintenance work because these methods does not meet all requirements from the viewpoint of accuracy, stability and availability to be used in the NPPs.

In this study, therefore, two types of new tracking methods have been developed. One is a method which employs line-shaped markers and the other is a method which employs circular-shaped markers. These two methods recognize the markers by means of image processing and calculate the relative position and orientation between the markers and a camera in real time. The line-shaped markers are suitable to be used in the NPPs because there are many pipes in the NPPs and it is easy to paste line-shaped markers on them while the legacy markers such as square markers of ARToolKit[2] are difficult to be pasted in NPPs because the size is too large and the accuracy is not enough when the distance between the markers and the camera is long. On the other hand, the circular-shaped markers are suitable for the case that there are many obstacles and it is difficult to paste line-shaped markers on the pipes because the obstacles hide the part of the line-shaped markers. Both methods can extend the maximum distance between the markers and the camera compared to the legacy marker-based tracking methods. In this study, some experiments have been conducted in order to evaluate the performance of the developed tracking methods and the results show that the covering area can be greatly improved compared to the legacy marker-based tracking methods.

II. TRACKING METHODS FOR AUGMENTED REARITY

It is necessary to measure the position and orientation of the user's view with high accuracy in real time in order to superimpose computer-generated information on a user's view in the correct position. This technique is called "tracking". Many tracking methods have been developed and applied to many applications. Those methods employ vision sensors[2][3], ultrasonic sensors[4], magnetic sensors[5], inertial sensors[6] and so on: each has strengths and weaknesses.

II.A. Tracking Method Employing Vision Sensors

A tracking method employing vision sensors captures the surrounding view using video camera(s). The relative position and orientation of the camera(s) is calculated against the working environment. Two kinds of tracking methods employ vision sensors. One is an artificial marker method with which artificial fiducial markers are pasted in the environment and the position and orientation of the markers are recognized through image processing. The other is a natural feature method, by which natural features such as lines and corners that exist in the working environment are extracted. Then their position and rotation are recognized. The artificial marker method is rather accurate and stable and is applied to several applications. The natural feature method is more convenient for users because it eliminates the need to paste markers in advance. The accuracy and stability of current technology, however, are rather low.

II.B. Tracking Method Employing Ultrasonic Sensors

Although the tracking method employing ultrasonic sensors is accurate and stable, it is necessary to place ultrasonic sensors or sources in the environment in advance. This requirement hinders its use in a severe environment such as NPPs. The range covered by one ultrasonic sensor is not so long; for that reason, numerous ultrasonic sensors must be placed to cover a wide area. The ultrasonic sensors are expensive, therefore, it is not cost effective to use this method in a large environment. Moreover, the accuracy cannot be maintained in a complicated environment because of ultrasonic reflection.

II.C. Tracking Method Employing Magnetic Sensors

Tracking methods employing magnetic sensors and transmitters are applied also in the field of VR because their accuracy and stability are good in a well-controlled environment. Magnetic sensors are, however, easily affected by metal obstacles and the range covered by one magnetic transmitter is short. Magnetic transmitters must be placed in the environment in advance.

II.D. Tracking Method Employing Inertial Sensors

Two kinds of inertial sensors are applicable for the tracking: acceleration sensor and gyro sensors. Both are very convenient for users because it is not necessary to place anything in the environment in advance. However, drift error cannot be avoided. Accuracy will decrease over time because of error accumulation. Moreover, with inertial sensors, only relative values are obtainable against its initial position and rotation. Therefore, some other method must be applied to obtain the initial position and rotation of the inertial sensors.

II.E. Strategy for Developing a Tracking Method Used in NPPs

As mentioned above, all of the existing tracking methods have weakness and cannot be introduced into NPPs. A tracking method used in NPPs must meet the following requirements;

1. It can be used inside a building.
2. Accuracy and stability should be enough to overlay the information on worker’s view at correct position.
3. It is not affected by environmental noise such as metallic obstacles, magnetic source and so on.
4. It is not necessary to locate large and/or expensive apparatus in the working environment.

Among the existing tracking method, only the tracking method employing vision sensor meets the above 4 conditions. But the existing tracking method using artificial markers requires that the distance between the markers and the camera is short. In this study, therefore, we decided to try making the available maximum distance between the markers and the camera much longer.

The basic idea is to apply line-shaped and circular-shaped markers instead of square markers. The square markers are used in many existing marker-based tracking methods and the position and orientation of a camera can be calculated by using 4 edges from single marker. But the calculation of the position and orientation of the camera is easily affected by jaggy-shaped edges that will appear when the distance between the marker and the camera is long. Therefore, large size markers are necessary in order to make the distance between the markers and the camera long. But it is very difficult to paste the large markers in the NPPs because there are many pipes, motors, tanks etc. in the NPPs and there is not enough space for the large markers.

On the other hand, if the marker’s shape is linear, the marker can be easily pasted and installed into the NPPs because there are many pipes in the NPPs. The marker’s length can be longer and the tracking distance can be extended. And the calculation of the center of the circular marker is not affected by jaggy edge. This means that even if the distance between the circular marker and the camera is very long, the center of the marker can be calculated accurately. We decided to develop these 2 kinds of marker-based tracking system and evaluate its performance.

II.F. Tracking System Design

Fig. 1 shows the conceptual image of the tracking method proposed in this study. The field worker wears a helmet with Head-Mount Display (HMD) and a small camera. The markers are captured by the camera on the helmet; then the image data are transmitted to a laptop PC carried by the user and processed to detect markers’ position on the image. Thereby, the laptop PC can compute the camera's orientation and position according to the markers' positions on the image and relevant global coordinate positions. Comments and instructions etc. can be superimposed on the HMD's exact position.

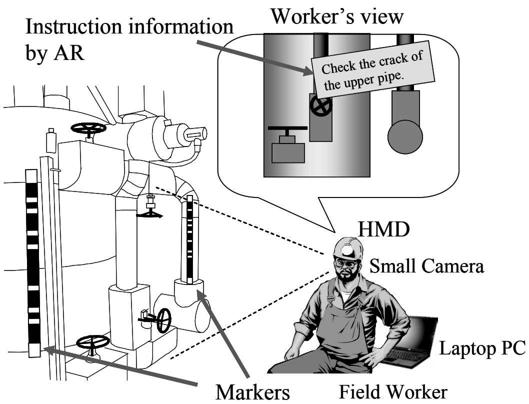

Fig. 1. Conceptual image of the tracking system.

III. LINE-SHAPED MARKER

III.A. Design of Line-Shaped Marker

In this section, the design of line-shaped marker and its parameters (such as marker size, distance between markers, etc.) determination method are presented when the tracking range is decided.

Fig. 2 shows a conceptual illustration of the line-shaped marker. The line-shaped marker is a combination of black elements: each element corresponds to one bit. The square element means "0". The double-sized rectangle element means "1".

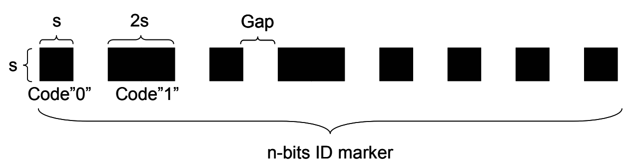

Fig. 2. Conceptual image of line-shaped marker.

The line-shaped markers' size, bit number and configurations can be decided as follows.

The maximum distance for stable recognition of markers depends on the marker's element size. Therefore, the line-shaped marker's element size can be decided according to equation (1).

$$s = \frac{L_{\max} n_p p}{f} \quad (1)$$

In that equation, s is the element size, $L_{\max}$ is the expected maximum stable recognition distance, n_p is the expected pixel number of images when the recognition distance is $L_{\max}$, p is the pixel size of the camera and f is the focal length of the camera lens. The gap size is set as equal to the element size.

The distance between markers can be determined from the nearest expected recognition distance, as expressed in equation (2).

$$d_{\max} = k \frac{L_{\min} w p}{f} \quad (2)$$

Therein, $d_{\max}$ is the maximum distance between each marker, w is the pixel width of the camera screen, and $L_{\min}$ is the expected nearest recognition distance. In addition, k is a scalar that is smaller than 1 for adjusting for more possible camera positions to capture enough markers in the same image.

The bit number of markers can be determined according to the expected covering area. The area covered by the line-shaped markers can be estimated as

$$A \approx 2^n d_{ave} L_{ave} \quad (3)$$

where A is the expected covering area, n is the marker's bit number, L_{ave} is the average recognition distance, d_{ave} is the average distance between two markers.

III.B. Recognition of Line-Shaped Marker

Recognition of the line-shaped marker is the key technology of the proposed method. The details of the recognition procedure are as follows;

1. Transform the captured image to a black-and-white binary-value image with a certain threshold value. Collect the connected pixels; mark a unique label on the area, then calculate the area's center of gravity.
2. Exclude areas that cannot be elements of markers according to their area and shape. The acceptable range of connected area is determined by the maximum and minimum distance between the camera and marker.
3. Select one of the areas as the first bit of line-shaped marker.
4. Search for the second bit of the line-shaped marker nearest the first area.
5. Find subsequent areas until the bit number reaches a determined bit number. After the second bit, the direction of the marker and the code of previous bit are known. Therefore, the necessary search area is quite limited. If there is no area which can be the next bit, jump to step 8.
6. Search the largest area and the smallest area from the areas found in step 5. Calculate the average of these 2 areas and let the result a threshold to judge whether the each area is "0" or "1". Recognize the code of the marker candidate with the threshold.
7. Compare recognized code with the information prepared in advance and decide the code.
8. Choose the next area which is not a bit of other recognized markers as the first bit and jump to step 4. When all areas are investigated, the algorithm ends.

III.C. Calculation of Position and Orientation

In order to obtain a unique solution of the relative position and orientation between the camera and the markers, at least 4 feature points are necessary that 2-dimentaional position on the camera image and 3-dimensional position in the environment are known. These feature points must not be on the same line and the accuracy depends on the distance between the feature points. Therefore, we decided to obtain 2 feature points from each line-shaped marker (2 terminals of the line-shaped marker), so at least 2 line-shaped markers must be recognized on the camera image simultaneously.

The method to calculate the relative position and orientation from n feature points is well known as PnP (Perspective n-Points) problem and many algorithms are proposed in the literatures. In this study, P3P solution algorithm and non-linear algorithm are adopted to minimize the error between the estimated position of the 4 feature points calculated using the tracking result and the actual position on the camera image.

III.D. Evaluation Experiment

In order to evaluate the line-shaped marker's performance, an experiment has been conducted in a large room. The evaluation points include tracking accuracy, maximum tracking distance, frame speed and stability.

III.D.I. Hardware and Software Specifications

The specification of hardware components are shown in Table 1. The tracking system was developed using Visual C++ 6.0 with Windows XP as the operating system and compiled using Intel Corp. C++ Compiler 8.0.

Table 1 Hardware Specifications

Laptop PC	Model	ThinkPad X31
	CPU	Pentium M 1.6GHz
	Memory	512MB
CCD Camera	Model	Dragonfly B&W XGA
	Interface	IEEE1394a
	Resolution	1024x768
	Frame rate	15fps
	Focal length	6.37mm

III.D.II. Line-shaped Marker Parameters

The detail parameters of the line-shaped marker can be determined from the hardware specifications and the equations in section III.A.

To allow stable recognition, the minimum pixel number of the marker on the camera image should be 4 or more. Now let the longest distance for recognition 10m. Then the marker element size is determined as 3cm from equation (1). Therefore, the 3cm x 3cm bit means "0", the 6cm x 3cm bit means "1"; the space between each bit is 3cm. In equation (2), L and k are determined respectively to 3.0m and 0.7. Consequently, the distance d between the two markers is determined as 1.5m.

The element number of the line-shaped marker is determined using equation (3). Set $A = 1000m^2$, $L = 3.0m$, $d = 1.5m$. Thereby, the bit number should be 8. (The covering area can be enlarged by increasing bit number.) The length of 8-bit line-shaped marker can be from 450mm to 690mm with 3cm width, which facilities the search for locations for pasting in the NPP field.

III.D.III. Experimental Configurations

Fig. 3 portrays the experimental configuration. The global coordinate is defined as the origin at O in Fig. 3, x direction is set to downward, the y direction is set towards the reader, and the z direction is set to the left. All markers are placed in vertically.

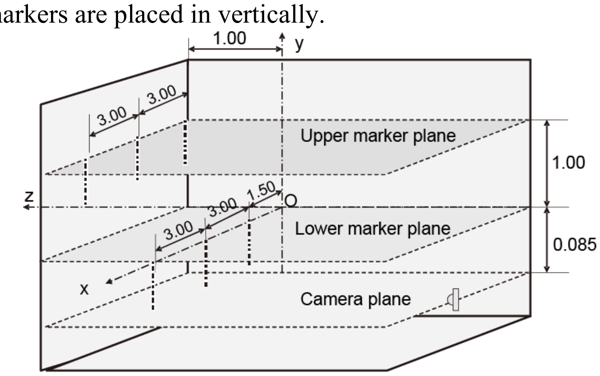

Fig. 3. Experimental Setup (Unit: m)

The camera is placed in front of the markers and the camera is moved from 0 to 8 m in the x direction and -2 to -11 m in the z direction. The camera was rotated at every point with 0, 20, 40 degrees (to the direction in which markers can be captured). The average illumination condition in the room is 1050 lux. There are no line-shaped marker-like articles in the experiment room.

III.D.IV. Experimental Results

Regarding the accuracy of the tracking, the estimated position and orientation and its actual one of the camera were compared.

The manual measured position of camera is (X_c, Y_c, Z_c) and the estimated position of camera is (X'_c, Y'_c, Z'_c) . Therefore, the estimated camera position error is defined as

$$E = \sqrt{(X_C - X'_C)^2 + (Y_C - Y'_C)^2 + (Z_C - Z'_C)^2}$$

The estimated camera position errors when the camera is placed at 0, 20 and 40 degrees are shown respectively in Fig. 4, 5, and 6. The distance error is illustrated using circle's diameter. The circle's diameter is fixed and the error (unit: mm) is drawn on the circle if the error is greater than 40cm.

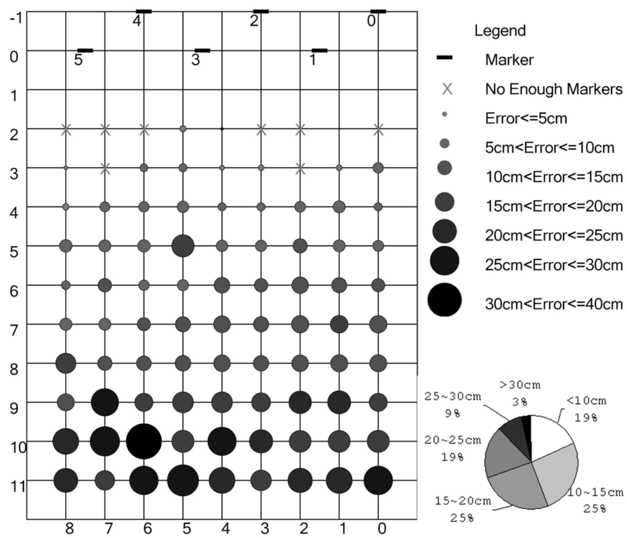

Fig. 4. Estimated camera position error at 0 degree.

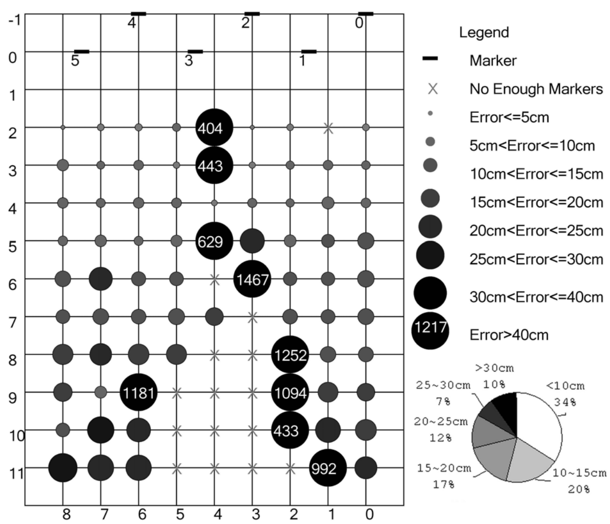

Fig. 5. Estimated camera position error at 20 degrees.

As we expected, the error becomes larger in proportion to the distance between the camera and the markers. Errors smaller than 30cm occupy about 95% of all results. Several results that exist at 40 degrees achieve large errors. Some of them are even larger than 1 m. The reason of the large error is that the camera could capture only 2 markers which distance is very short and the camera captured these markers right in front of the plane which includes 2 markers. This result is similar to the case of the square markers in which case the error becomes large when the marker is captured from the right front of the marker. In order to avoid the larger error, it is necessary to avoid pasting the markers on the same plane.

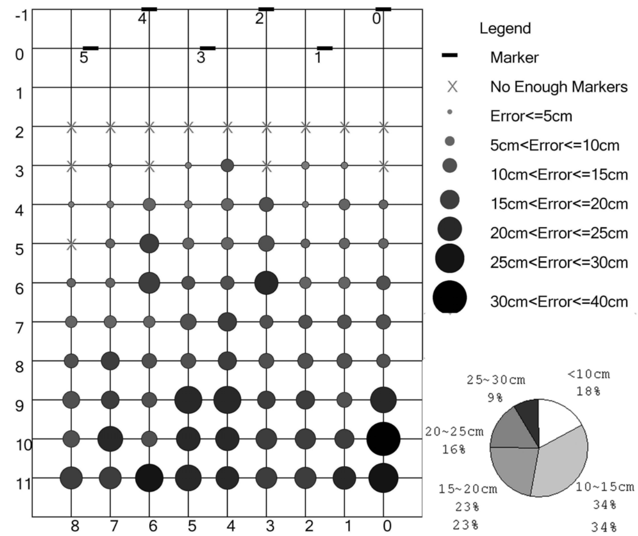

Fig. 6. Estimated camera position error at 40 degrees.

The tracking frame rate depends on the complexity of the camera image because the computational load to recognize the feature points from the camera image will change according to the number of the connected pixels. Actually, the recognition time which includes all procedure to recognize the markers, calculate the position and orientation of the camera and superimpose simple information during the experiment changed according to the position of the camera from 42.5ms to 87.0ms. This means that the frame rate changed from 23.5 to 11.5. Considering that the computational load will increase because superimposing some information will consume the PC resource, this result may not be enough for the actual use. But this will not be a problem because there are some rooms to improve the programming code of the tracking system and new laptop computer with higher performance will be available in the near future.

IV. CIRCULAR-SHAPED MARKER

IV.A. Design of Circular-Shaped Marker

Fig. 7 shows examples of the circular-shaped marker. The circular-shaped marker consists of one black outer circle (the circle thickness is 30% of the marker radius), one white center circle (the radius is 30% of the marker radius) and middle circle (the circle thickness is 40% of the marker radius) which consists of several black or white fans that represent binary code by its color. The outer black circle and the center white circle are used for determining the threshold to analyze the binary code and the number of distinguishable markers depends on the number of the fans. When the middle circle is divided into 10 fans, 99 different markers can be used simultaneously. The number of the fans and the radius of the marker can be changed according to the maximum and minimum distance between markers and camera.

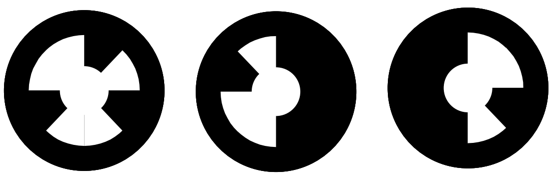

Fig. 7. Examples of circular-shaped marker.

As mentioned in the section III.C, in order to obtain a unique solution of the position and orientation between the markers and the camera, at least 4 feature points which are not on a same line are necessary. But it is difficult to obtain plural feature points from one circular-shaped marker. Therefore, the position and orientation will be calculated using plural markers. The requirement that plural markers need to be captured in one frame may be a weakness from a viewpoint of workload to setup the working environment because more markers need to be pasted than the line-shaped markers and square markers. But in the case of line-shaped markers and square markers, the minimum distance between the feature points obtained from the markers are limited by the size of markers. On the other hand, the minimum distance between the feature points is the minimum distance between circular-markers. This means that it is possible to make the minimum distance between the feature points very long. This will greatly improve the accuracy of the tracking.

IV.B. Recognition of Circular-Shaped Marker

The recognition of the circular-shaped marker can be divided into 2 steps, ellipse recognition and marker code recognition.

IV.B.I. Ellipse Recognition

The procedure to recognize ellipses on the captured camera image as candidates of markers is as follows;

1. Capture an image with a camera and take logarithm of each pixel of the image.
2. Apply 3x3 Sobel edge detector and binarize the result with single threshold.
3. Labeling the binarized image by collecting the connected pixels and mark a unique label. Eliminate candidates which area is too small or large.
4. Trace edges of each labeled area and calculate center of mass of each group of edges. The center of mass is assumed to be a center of ellipse.
5. Calculate 150 ellipses that through 3 edges which are selected randomly.
6. Calculate an ellipse by averaging the result of step 5.
7. Calculate a sum of square distance between the calculated ellipse and the each edge point. Eliminate candidate which distance is larger than a threshold.
8. Calculate a ratio of major axis vs. minor axis of the calculated ellipse. Eliminate candidate which ratio is larger than a threshold.

The important feature of the above algorithm is that it is not necessary to adjust the thresholds even if the light condition of the captured image is changed and the running speed of the process is very fast.

IV.B.II. Marker Code Recognition

The procedure to analyze the binary code of the middle circle is as follows;

1. Normalize the recognized ellipses to a circle using the ratio of major axis vs. minor axis of the ellipse as shown in Fig. 8.
2. Calculate variance and average of brightness of white center circle and black outer circle. Eliminate candidate which variance is larger than a threshold. Calculate a threshold to analyze the binary code from the average of the brightness of the white center circle and black outer circle.
3. Count pixels which brightness is larger than the threshold calculated in step 2 for each fan of middle circle. The fan which number of the counted pixels is larger than a threshold is assumed as 0 and the fan which number of the counted pixels is smaller than a threshold is assumed as 1.

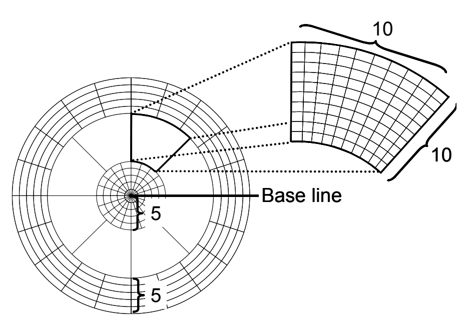

Fig. 8. Normalization of captured circular-shaped marker.

IV.C. Calculation of Position and Orientation

As mentioned above, in order to obtain a unique solution of the position and orientation using PnP algorithm, at least 4 feature points are necessary. For example, when only 3 feature points are available, there are a maximum of eight possible solutions, of which only four occur in real 3-dimensional space in front of the camera. But in the case of circular-shaped marker, using the shape of the each marker itself, maximum 2 other solutions can be obtained. Therefore, in this study, P3P algorithm is used to get maximum 4 solutions and these solutions are compared with the 2 solutions obtained by using each marker's shape to obtain a unique solution. The detail of the process is as follows;

1. Calculate the position and orientation of each marker relative to the camera from the size and shape of the marker on the captured image. Maximum 2 solutions are obtained..
2. Calculate the position and orientation of the camera from 3 markers with P3P algorithm. Maximum 4 solutions are obtained.
3. Compare the result of step 1 with the result of step 2. One of the results of step 2 which is most similar to the result of step 1 is adopted.
4. Calculate the 2 dimensional positions of all circle markers recognized on the captured image by using the result of step 3.
5. The result of step 3 is optimized by making the difference between the result of step 4 and the result of the Ellipse Recognition process minimum.

When some markers are pasted in different angle in the environment, the above process works well. When only 3 markers can be recognized and all of them are pasted on a same plane, maximum 2 solutions are obtained and the solution which is the most similar to the latest tracking result will be adopted.

IV.D. Evaluation Experiment

The tracking accuracy depends on the layout of the feature points obtained from the markers. Therefore, when the circular-shaped markers are pasted in the environment in the condition that the center of the circular-shaped markers are aligned to all edges of the line-shaped markers, the tracking accuracy will be almost same as the evaluation experiment of the line-shaped markers. In this study, therefore, only the relationship between the maximum distance and the size of the circular-shaped marker and the relationship between the number of the markers on the image and its tracking frame rate have been evaluated. The evaluation of the tracking accuracy is a future work.

The tracking system is developed using Visual C++ 6.0 with Windows XP as an operating system and compiled using Intel Corp. C++ Compiler 8.0.

IV.D.I. Evaluation of the Maximum Distance

Circular-shaped markers were pasted on a wall and the maximum distance under the condition that the tracking system can recognize the code of the circular-shaped markers properly was evaluated. The diameter of the circular-shaped marker was changed from 3cm to 10cm by 1cm step and 4 kinds of the cameras were used. In order to compare the maximum distance between the circular-shaped marker and the legacy square marker, various size of ARToolKit square markers were also pasted on a wall and the maximum distance was measured.

Fig. 9 shows the relationship between the marker's size and the maximum distance. As we expected the maximum distance between the markers and the camera increases with the increase of the size of the markers. Under the condition that the size of the marker is same, the maximum distance of the circular-shaped marker is about 2 times of the maximum distance of the square marker.

Regarding the type of the cameras, the maximum distance of the circular-shaped marker with gray scale camera (B&W) is about 1.5 times of the maximum distance with color camera. That is because the CCD of the color camera employs Bayer pattern color filter array and each pixel is filtered to record only one of three colors, then demosaicing algorithms is used to obtain a full-color image. Therefore, the edge of the image is gradated and it affects badly on the maximum available distance.

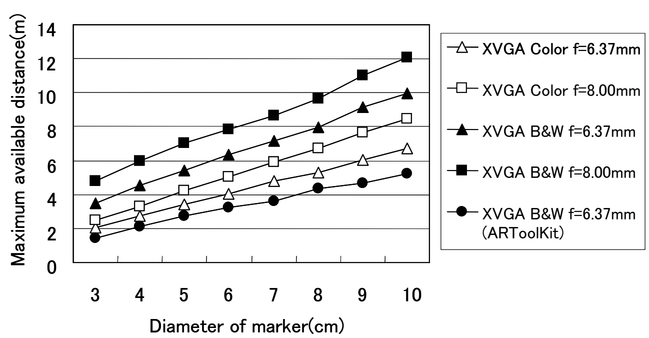

Fig.9 Relationship between size of markers and maximum distance.

IV.D.II. Evaluation of the Tracking Frame Rate

Circular-shaped markers which radius was 3cm were pasted in front of the camera under the condition that the distance between the markers and the camera was about 2m (the size of each marker on the image was about

50x50pixels) and the number of the pasted markers was changed from 3 to 12. The time consumed for each frame was measured. The specification of the hardware components used in this experiment is shown in table 2.

Fig. 10 shows the result of the measurement, the relationship between the number of the markers on the image and its processing time. The time for processing each frame increases linearly in proportion to the number of markers. According to the result, the processing time to recognize and analyze one marker is about 0.8ms (43.9-36.8/9=0.78). The number of the markers on one image depends on the situation such as how many markers are pasted in the environment, the position and orientation of the worker and so on. But, it will not be larger than 20, so the maximum processing time for each frame will be 50ms (20fps). It is necessary to evaluate how the complexity of the image affects on the tracking performance in order to confirm that the proposed method can be used in real time in the actual NPPs but considering that a higher performance laptop computer will be available in the near future and there is also some rooms to improve the programming code, the running speed of the proposed method will be acceptable for the actual use in the NPPs.

Table 2 Hardware Specifications

Laptop PC	Model	ThinkPad X60
	CPU	Core Duo T2300 1.66GHz (used in single core mode)
	Memory	512MB
CCD Camera	Model	Dragonfly II B&W XGA
	Interface	IEEE1394a
	Resolution	1024x768
	Frame rate	30fps
	Focal length	6.37mm

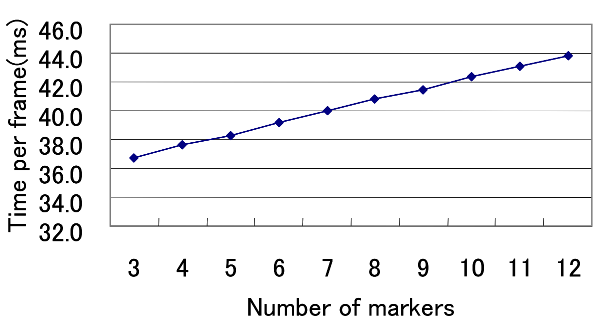

Fig.10 Relationship between number of markers and processing time.

V. CONCLUSIONS

In this study, two types of marker-based tracking methods for Augmented Reality have been developed. Both methods recognize plural markers simultaneously and calculate the position and rotation of the camera with high accuracy. Some experiments have been conducted in order to evaluate the performance of the proposed methods and it has been confirmed that the distance between the marker and the camera can be long compared to the conventional methods such as square markers.

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