Development of an Augmented Reality System for Plant Maintenance Support

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Abstract

It is required to improve reliability and economical efficiency of nuclear power plant (NPP) at the same time. There is a room to achieve this goal by introducing state-of-art information technology into maintenance work of NPP. In this study, a maintenance support system using Augmented Reality (AR) has been proposed to support water system isolation task that is one of the important works during a periodic maintenance of NPP. In order to apply the AR to the water system isolation task, a tracking method that measures position and orientation of workers in real time is indispensable. The existing tracking methods applied in some AR applications, however, does not fulfill the requirements from the viewpoint of accuracy, stability and availability when using in NPP. In this study, therefore, a new tracking method that combines plural tracking methods has been developed. Concretely, the existing tracking methods employing vision sensor and inertial sensors were improved and combined into one tracking method. Concerning to the method employing vision sensor, a tracking method which recognizes artificial markers and natural features at the same time has been developed to decrease the number of markers which need to be placed in working environment in advance. Concerning to the method employing inertial sensors, a new drift cancel method employing two same sensors placed symmetrically has been developed. These improved tracking methods were combined into one tracking method and evaluated by some experiments.

1. Introduction

In order to stabilize energy supply, it is necessary not only to improve power generation system as machines itself but also to improve its human machine interface. Especially, concerning to maintenance work in a nuclear power plant (NPP), there are some rooms to improve its efficiency and safety by introducing state-of-art information technology to support workers[1]. For example, in NPP periodic maintenance work, some water systems need to be isolated by valve operation in order to disassemble and check plant equipments. Although there are more than 30,000 valves in one NPP, workers use only paper-based instruction documents generated by "Water System Isolation Support System" implemented on a workstation in a central control room. It is really difficult and time consuming to find a specified valve to be operated and human errors may occur. Therefore, a group that consists of plural workers conducts the valve operation task. It is apparently inefficient and total man-hour becomes large.

In this study, therefore, a maintenance support system using Augmented Reality (AR) has been proposed to support the water system isolation task. The AR is a technology in which a user's view of the real world is enhanced or augmented with additional information generated by a computer[2]. The AR can overlay 3 dimensional virtual models on the real world and the user can acquire various information more intuitive than with legacy interfaces such as paper-based instruction documents. If the AR can be applied to the water system isolation task, various useful information can be supplied to workers. For example, in case of finding a specified valve, a location of the valve and dangerous area can be represented to the workers intuitively. The AR is expected to be able to support the worker's cognitive tasks and reduce working time and human errors.

In practice, however, some technological innovations are required to apply the AR to the maintenance work in NPP. Especially, the existing tracking methods which measure the worker's position and orientation in real time can not be applied for maintenance support in NPP[3]. In this study, therefore, a new tracking method that employs plural tracking methods has been developed. Concretely, the existing tracking methods employing vision and inertial sensors were improved and combined into one tracking method. And some experiments were conducted to evaluate the improved method.

The remains of this paper consists of an introduction of water system isolation task in NPP, application of AR technology to water system isolation task, improvement of vision sensor and inertial sensors, development of hybrid tracking method, experiments for the evaluation of developed tracking method and conclusion.

2. Water system isolation task in NPP

In NPP periodic maintenance work, some water systems need to be isolated by valve operation in order to disassemble and check plant equipments. There are, however, more than 30,000 valves in NPP. Although some of the valves are controlled remotely, most of them need to be operated manually. At present, the water system isolation task is supported by "Water System Isolation Support System", which is realized on a workstation and it manages the valve operation plans and the current status of the valves in a central control room. As shown in Figure 1, the water system isolation task is conducted as following;

Step 1. Supplied a paper-based instruction sheet at a central control room, which describes information about valve operation such as procedure of work, IDs of valves.
Step 2. Walk to the valve location according to the instruction sheet.
Step 3. Identify a specified valve and confirm its status.
Step 4. Operate the valve and mark the work list.
Step 5. Walk to the next valve location. (Repeat from Step 2 to Step 4 for the all valves)
Step 6. Input the performed valve operations at the central control room.

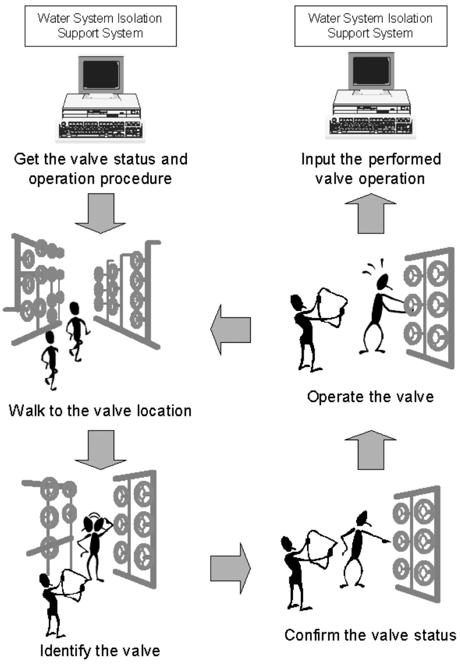

Figure1. Water system isolation task in NPP.

It is, however, difficult to find the specified valves because there are a huge number of valves in NPP and the valve operation requires some experiences. This task, therefore, needs a pair of workers (an operator and a director) although one worker can conduct the valve operation. If the specified valve can be found and confirmed easily without error, it would become possible that the valve operation is conducted only by one worker. Moreover, it would be possible to improve the reliability and reduce total man-hour for the maintenance work.

3. Application of AR to the water system isolation task

3.1. Augmented reality

The AR expands the surrounding real world by superimposing computer-generated information on the user's view. It can represent various information more intuitively than with legacy interfaces and can be applied to various fields such as amusement and industrial applications. The AR can also be applied in the maintenance field because the AR can decrease worker's workload in complicated environment.

For example, as shown in left side of Figure 2, in case that a worker uses a paper-based instruction document, the worker has to look at the document and apparatuses alternately. Moreover the worker has to understand the document by himself and seek target equipment in the environment. It means that the amount of the worker's eye movement will increase and the worker has to do some intellectual judgments during the work.

On the other hand, as shown in right side of Figure 2, in case that the worker's view is overlaid with the indication that represents the location of the target equipment directly, the amount of the worker's eye movement can decrease and the worker can understand the indication intuitively. It is expected that working time and human errors can decrease. Moreover, in case that a worker walks to another working place, the route to the destination and dangerous area where the worker should not approach can be represented intuitively. And if workers can use a head mounted display, they can refer various information with free of their both hands. Free of worker's hands is very important because it makes possible for them to refer various information while they are performing manual tasks in cramped positions.

3.2. Maintenance support system using AR

The concept of the maintenance support system using AR is shown in Figure 3. A worker equips a potable computer that can access a server computer placed at a central control room via wireless network and retrieves the information of the maintenance work. The worker also equips a HMD to refer the information and a video camera attached on his helmet captures his surrounding view. The system is supposed to lead a worker to a work place and provide various information via AR function. Since the worker can recognize the target valves

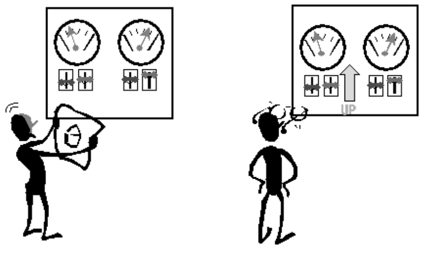

Figure 2. Maintenance work using paper document (left) and AR (right).

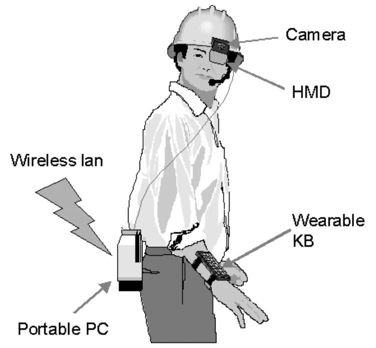

Figure 3 Image of maintenance support system using AR.

intuitively, it is expected that the efficiency can be improved and human errors can be reduced. Refer the literature[4] for more details of the support system.

3.3. Tracking methods for AR applications

In order to superimpose computer-generated information on user's view at correct position, it is necessary to measure position and orientation of the user's view in real time. This technique is called "tracking". In various fields, many kinds of tracking methods have been developed[5] and applied in many applications[2]. Those are the methods that employ vision sensors[6][7], ultrasonic sensors[8], magnetic sensors[9], inertial sensors[10] and so on.

3.3.1. Tracking method employing vision sensors. Tracking method employing vision sensors is a method with which the surrounding view is captured by video camera(s) and relative location of the camera(s) against the working environment is calculated. There are two kinds of tracking method employing vision sensors. One is an artificial marker method with which artificial markers are pasted in the environment and the position and orientation of the markers are recognized by image processing. The other is a natural feature method with which natural features such as lines and corners that exist in working environment are extracted and their position and orientation are recognized. The artificial marker method is rather accurate and stable and is applied in several applications. It is, however, necessary that the artificial markers are pasted in advance and if the work area is large, a huge number of artificial markers have to be pasted. The natural feature method is more convenient for users because it is not necessary to paste markers in advance. With the current technology, however, its accuracy and stability is not enough.

3.3.2. Tracking method employing ultrasonic sensors. Although tracking method employing ultrasonic sensors is accurate and stable, it is necessary to place ultrasonic sensors or sources in working environment in advance. The range covered by one ultrasonic sensor is not so long that a lot of ultrasonic sensors need to be placed in order to cover large area. Since the ultrasonic sensors are relatively expensive, it is not cost effective to use it in large environment. Moreover, there is a problem that the accuracy cannot be kept in complicated environment because of diffuse reflection of ultrasonic.

3.3.3. Tracking method employing magnetic sensors. Tracking method employing magnetic sensors/ transmitters is applied also in the field of virtual reality because its accuracy and stability is good in well-controlled environment. Magnetic sensors are, however, easily affected by metal obstacles and a range covered by one magnetic transmitters is short. The magnetic transmitters need to be placed in working environment in advance.

3.3.4. Tracking method employing inertial sensors. There are two kinds of inertial sensors that can be applied for the tracking. One is an acceleration sensor and the other is a gyro sensor. In both sensors, since it is not necessary to place anything in working environment in advance, it is very convenient for users. However drift error cannot be avoided and the accuracy will decrease with time passed because of error accumulation. Moreover, with the inertial sensors, only the relative values can be obtained against its initial position and orientation. The other method, therefore, needs to be applied in order to obtain the initial position and orientation of the inertial sensors.

4. Design of the tracking method applied in the maintenance support system

In case of selecting the tracking method applied in the support system, characteristics of the working environment have to be taken into consideration. In this section, several conditions that the tracking method should fulfill are described, then a basic strategy for developing a new tracking method will be discussed.

4.1. Characteristics of the water system isolation task

The environment where the water system isolation task is conducted has following characteristics;

1. There are a huge number of valves and they are distributed all over the plant.
2. There are a lot of metal obstacles in working environment.
3. It is difficult to place a lot of new apparatuses because lack of space.
4. There are many types of equipment in the plant and working environment is very complicated.
5. Since information supposed to be supplied to workers is mainly location of valves, required accuracy of the tracking will be about 20cm.

And there are limitations concerning to the workers who conduct the water system isolation task as follows;

1. A worker must equip a helmet.

2. A worker cannot have equipment that restricts his movement.

And there are requirements come from the economical reason.

1. Additional cost must be little.
2. It is not practical to paste a huge number of markers in a plant. However a few markers can be pasted in advance.

Then, it is very difficult to realize a tracking method that can be used in NPP only by single tracking method. Because:

1. The area of the work environment is very large, so that a huge number of markers have to be pasted in advance in case of using artificial marker method.
2. The accuracy and stability is not enough in case of using natural feature method.
3. Ultrasonic sensors cannot be applied because it is too expensive and it is difficult to place a lot of sensors in a plant. And diffuse reflection of ultrasonic will depress the tracking accuracy.
4. Magnetic sensors cannot be applied because there are a lot of apparatus made of metal in a plant.
5. The accuracy of the tracking method employing only inertial sensors is not enough. The accumulation of drift error will be too large. And it is necessary to measure the initial position and orientation of the sensors with the other method.

Therefore, it is necessary to improve the existing tracking methods and/or develop a new tracking method for the use in NPP.

4.2. Basic strategy for developing a tracking method for the maintenance support system

In order to meet the condition that no apparatus is placed in working environment, only the tracking method employing vision sensor and/or inertial sensors are applicable. Since the worker equips a helmet and it will not be a problem that small video camera(s) and small inertial sensors are attached on it, it is possible to apply the vision sensor and the inertial sensor at the same time. As described above, it is impractical to place many artificial makers in a plant while the accuracy and stability of the inertial sensors is not enough. However the vision sensor can be applied to compensate the lack of the accuracy of the inertial sensors. And the natural feature method can be applied to reduce the number of artificial markers that need to be in working environment. Moreover the inertial sensors always work even when the vision sensor cannot be used.

In this study, therefore, the artificial marker method is used as a main tracking method and in case that the vision sensor cannot recognize any artificial marker, the natural feature method is used to compensate artificial marker method. And in case that the vision sensor cannot recognize both of artificial markers and natural features, the inertial sensors are used. The error accumulation of the inertial sensors is corrected when the artificial marker or natural features are recognized by the vision sensor.

For each tracking method, a new method is developed to improve its accuracy and stability. For the natural feature method, a new method has been developed to select only reliable natural features. And for the tracking method employing inertial sensors, a new drift cancel method has been developed which uses a pair of same inertial sensors at the same time.

5. Development of a tracking method for the maintenance support system

5.1. Tracking method employing a vision sensor

In this study, the tracking method employing a vision sensor consists of 2 kinds of tracking method, an artificial marker method and a natural feature method.

The artificial marker method is realized by ARToolKit. ARToolKit is a library that can be applied for calculating the relative position and orientation of a camera against artificial markers. The natural feature method is realized by recognizing natural features and calculating their 3 dimensional positions.

In order to recognize natural features, a new algorithm that recognizes corners of objects has been developed. In many studies, Harris operator is employed to recognize corners. Only with its original algorithm, however, the accuracy of the recognition is in pixel order and the result will include uncertainty of at least 1 pixel. And the Harris operator cannot distinguish real corners of objects and pseudo corners that come from some undesirable effects such as shadow of objects or reflection of light. In this study, therefore, line features are recognized besides the corners and their intersections are extracted as reliable corners of artificial objects in the environment. And the corners that exist near the intersections are treated as reliable corners. The procedure to recognize corners is as follows;

Step 1. Apply Sobel filter to the images captured by a camera.

Step 2. Extract pixels which brightness gradient is larger than a threshold. (The extracted pixels are supposed as a part of edges.)

Step 3. Recognize lines by Hough transform from the pixels extracted in Step 2.

Step 4. Calculate the intersection of recognized lines.

Step 5. Detect feature points by Harris operator from the images captured by a camera.

Step 6. Extract feature points which distance from the intersection is less than a threshold distance. Extracted feature points are recognized as corners.

After recognizing corners, their 3 dimensional positions are calculated. The calculation is conducted by using 2 sequential images (2 sequential frames) as follows;

Step 1. Extract corners from 2 sequential images by the above-described method.

Step 2. Compare the similarity of extracted corners in 2 sequential images and make pairs of 2 similar corners as shown in Figure 4. In this study, the comparison is conducted by a matching method using rotation-invariant picture matching based on autoregressive model of orientation histogram[11].

Step 3. The 3 dimensional position of each corner is calculated by a triangulation technique. The camera position and orientation at each frame can be obtained from the ARToolKit or the 6 feature points which 3 dimensional positions are already known.

Step 4. The information about extracted corners and their 3 dimensional positions are stored into a database.

Step 5. The camera position and orientation is obtained from the 6 feature points which 3 dimensional positions are already known by a method of the literature[12].

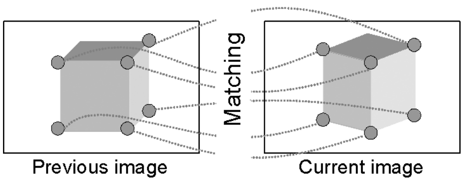

Figure 4. Matching between feature points.

5.2. Tracking method employing inertial sensors

Concerning to the tracking method employing inertial sensors, the orientation of the worker (the orientation of the sensor mounted on his/her helmet) is measured by gyro sensors. After that, acceleration of gravity is eliminated based on the measured orientation, and the position variation of the worker is measured by acceleration sensors. Basically, the drift error of gyro sensor and acceleration sensor come from the fluctuation of the environmental factors such as temperature. These factors cannot be canceled completely because they cannot be predicted. In general, the expanded Kalman filter is applied, however this method does not cancel the drift errors but predict the movement of values. In this study, a pair of inertial sensors is used at the same time in order to cancel the drift errors. As shown in Figure 5, a pair of two sensors is placed symmetrically and they are mounted on the helmet. The values from two sensors are subtracted because the drift errors can be expected to be within a value when they work in the same environment. The result of the subtraction will be the twice of the value which does not include the drift errors.

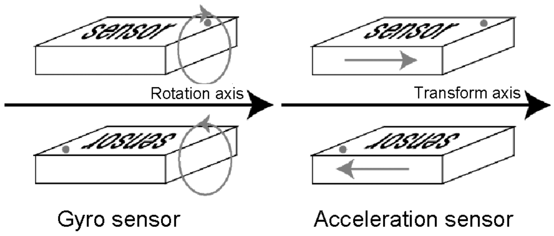

Figure 5. Layout of inertial sensors.

5.3. Hybrid tracking method

In this study, a hybrid tracking is realized by changing the tracking method in accordance with the situation.

The algorithm of the hybrid tracking method is shown in Figure 6. The position and orientation are firstly measure by inertial sensors and artificial markers are recognized by the vision sensor. If the vision sensor can recognize at least one artificial marker, the output from the artificial marker method is used because this method is most accurate and reliable of the three methods. After the measurement by the artificial markers, natural features are recognized and their positions are calculated. If the vision sensor cannot recognize any artificial markers, the method that tracks natural features is used as a substitute method. Also in the case of using the natural feature method, new natural features are recognized and their 3 dimensional positions are calculated. In case that both of the artificial markers and natural features cannot be recognized, the output from

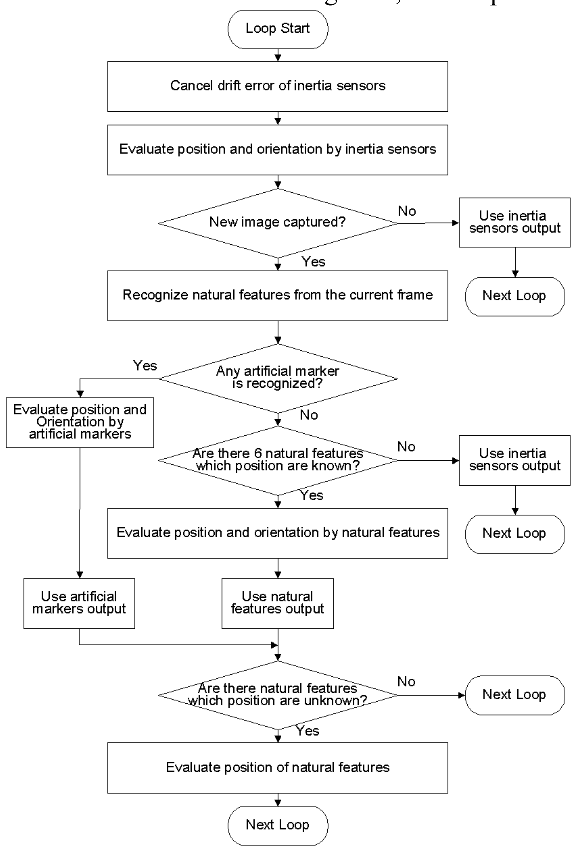

Figure 6. Flowchart of hybrid tracking.

the inertial sensors is used and when one of the artificial markers or 6 natural features can be recognized again, the position and orientation by the inertial sensors is compensated.

6. System Integration

The configuration of the developed system is shown in Figure 7. The system consists of a laptop computer, a camera, gyro sensors, acceleration sensors, an A/D converter and a microcomputer. The detailed specification of the hardware is shown in Table 1.

The application to control and integrate the sensors has been developed by Microsoft Visual C++ 6.0. In this system, all the sensors should be used in parallel to control accurate time step, so that the application to control the sensors is executed in multi thread environment.

Images captured by the camera are transferred to the laptop computer via IEEE1394 interface and image processing is executed on the laptop computer. The outputs from the inertial sensors are transferred to the microcomputer. Calculation such as integration of the values from the inertial sensors are executed on the microcomputer and the result is transferred to the laptop computer via RS232C interface.

7. Evaluation experiment

The authors have conducted several experiments in order to evaluate the developed tracking methods.

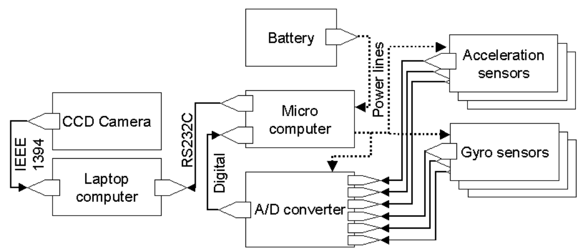

Figure 7. Hardware configuration.

Table 1. Hardware specification

Notebook computer		CCD camera	
Manufacturer	Toshiba	Manufacturer	Pointgray research
Model	P7/X28PME	Model	FireFly Color VGA
CPU	Pentium4 2.8(GHz)	Resolution	640x480
Memory	768(MB)	Color	24bit(RGB)
OS	Windows XP	Frame rate	up to 30(frames/sec)
		Shutter speed	1/25 - 1/15000(sec)
		Focal distance	4, 6, 8(mm)
Gyro sensor		Acceleration sensor	
Manufacturer	Murata	Manufacturer	Analog Devices
Model	ENC-03	Model	ADXL105
Measurement range	±300(deg/sec)	Measurement range	±5(g)
Lineality	±5(%FS)	Resolution	2(mg)
Responsibility	50(Hz)	Bandwidth	10(kHz)
A/D converter		Micro computer	
Manufacturer	Analog Devices	Manufacturer	HITACHI
Model	AD7856	Model	H83048F
Resolution	14(bits)	Maximum clock	16(MHz)
Throughput	285(kSPS)	Operation Speed(Add)	125(ns)
Input channel	8	Operation Speed(Multi)	875(ns)

7.1. Evaluation of the natural feature method

Two kinds of experiments have been conducted in order to evaluate the natural feature method.

7.1.1. Calculation of position and orientation from 6 natural features.

The accuracy of the calculation of position and orientation based on 6 natural features depends on the distance between the used natural features. In this experiment, the accuracy was evaluated depending on the distance between the natural feature points.

For the experiment, a marker box, on which 2 artificial markers are pasted side by side, was made as shown in Figure 8. It was placed in front of a camera and the angle of the marker box against the camera was fixed to 45 degrees. The distance was changed from 300(mm) to 2300(mm) by 500(mm) step. 6 corners of the artificial markers were captured as natural features. The location and orientation of the marker box was calculated 100 times and their average was calculated.

Figure 9 shows the relationship between the minimum distance of natural features and the error of the calculation. The average time of the calculation was 10ms approximately. As shown in Figure 9, the longer the minimum distance is, the more accurate the calculation result is. Especially, when the distance between the natural features becomes less than 20 pixels in the captured image, the result becomes worse. It was found that natural features should be selected so that their minimum distances are more than 20 pixels.

7.1.2. Extracting of reliable natural features.

In order to evaluate the effectiveness of the proposed

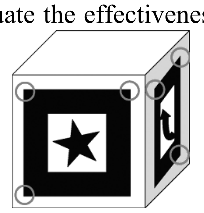

Figure 8. Marker box used in the experiments. (Circles are the corners used as feature points)

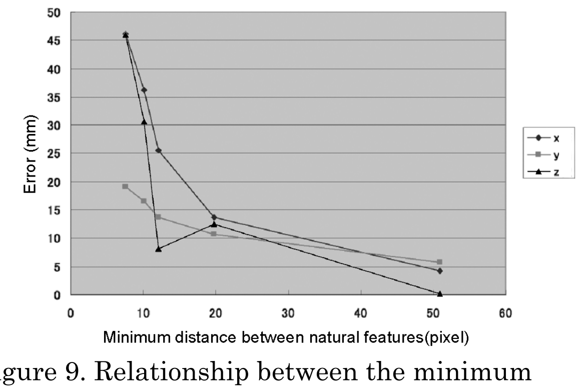

Figure 9. Relationship between the minimum distance of natural features and the error .

method for selecting reliable natural features, the method using only Harris operator was compared with the method that selects reliable feature points by using information of line intersections.

An image of an electric motor was captured and feature points were extracted by Harris operator. Then, the reliable feature points were selected by the proposed method. Figure 10 shows the feature points that were extracted by Harris operator. Figure 11 shows the recognized lines by Hough transform and the feature points selected by the proposed method.

As shown in Figure 11, it was confirmed that the proposed method could pick up only real corners of the motor and eliminate pseudo corners that come from light reflection and shadow. In order to calculate the relative position and orientation of the camera against the motor, at least 6 natural features are necessary. It was found that too many natural features are eliminated with the proposed method. It is necessary to improve the method to select more natural features stably.

7.2. Evaluation of the tracking method employing inertial sensors

The authors have conducted two experiments in order to evaluate the effect of the proposed drift cancel method.

7.2.1. Gyro sensors. Two gyro sensors (A and B) were mounted on a tripod symmetrically and the tripod was rotated by hand. The output from the sensors was recorded by an oscilloscope separately. The output from the sensors was recorded for 5 seconds with 10msec interval and the sensors were rotated from 1.6 seconds to 3.4 seconds. Figure 12 and 13 shows the output from each gyro sensor respectively. During the period of 0 - 1.6 seconds and 3.4 – 5.0 seconds, the sensors were steady state so that the output from the sensors should be constant. However, because of the drift error, the output decreased with time passed. Figure 14 shows the result of subtracting the output of sensor B from that of sensor A. It can be confirmed that the proposed method can cancel the sensor drift.

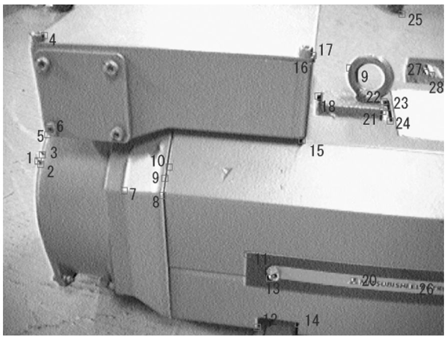

Figure 10. Extracted feature points by Harris operator (Indicated by numbers).

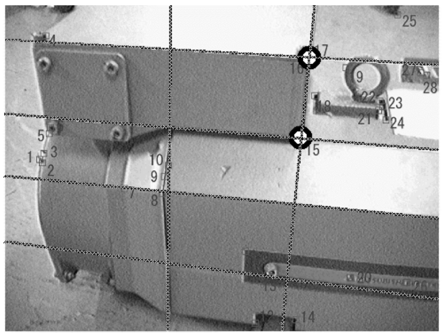

Figure 11. Recognized lines and selected feature points (Indicated by circles).

7.2.2. Acceleration sensors. Two acceleration sensors (C and D) were packed into a sensor unit symmetrically and the sensor unit was moved along with a straight gage by hand. The output from the sensors was recorded with a digital oscilloscope separately. The output from the sensors was recorded for 2 seconds with 10msec interval and the sensors traveled from 0.3 seconds to 1.2 seconds. Figure 15 and 16 shows the output from each acceleration sensor respectively. Figure 17 shows the result of subtracting the output of sensor D from sensor C. Also in this experiment, it can be confirmed that the proposed drift cancel method can cancel the sensor drift.

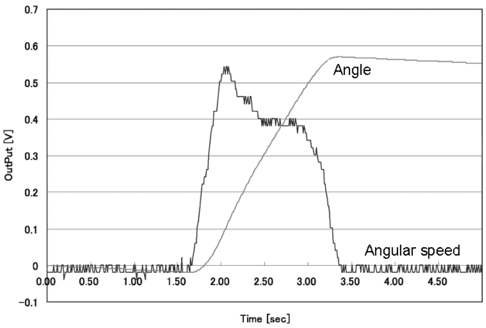

Figure 12. Output from gyro sensor A.

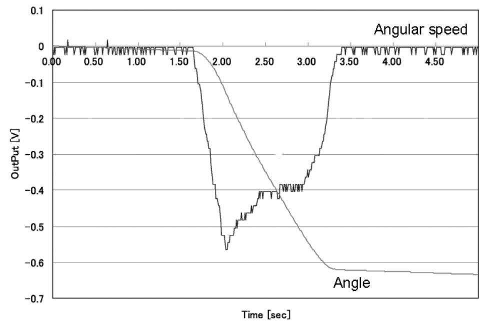

Figure 13. Output from gyro sensor B.

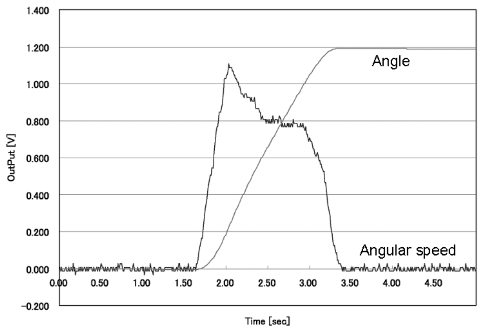

Figure 14. Result of subtraction (gyro sensor).

7.3. Trial use of the hybrid tracking method

The developed hybrid tracking method has been used in a laboratory environment where a electric motor was placed in front of the camera. The 3 tracking methods were switched correctly according to the situation but the natural feature tracking method could not be used effectively because the number of extracted natural features was too small. The algorithm to extract natural features need to be improved as a future work.

8. Conclusion and future works

In this study, the existing tracking methods employing vision sensor and inertial sensors have been improved and combined into one tracking method. And some experiments were conducted to evaluate each improved method. Concerning to the natural feature method, it was confirmed that the calculation of the poison and orientation of the camera by using 6 natural features can be conducted well and the new method can select reliable natural features. However, the number of the natural features that the proposed method can select is too little so that it cannot be applied to the maintenance support system yet. On the other hand, concerning to the inertial sensor method, the proposed drift cancel method worked well to improve the accuracy of the inertial sensors.

As the future works, the method to select reliable natural features will be improved and the whole hybrid tracking method will be evaluated.

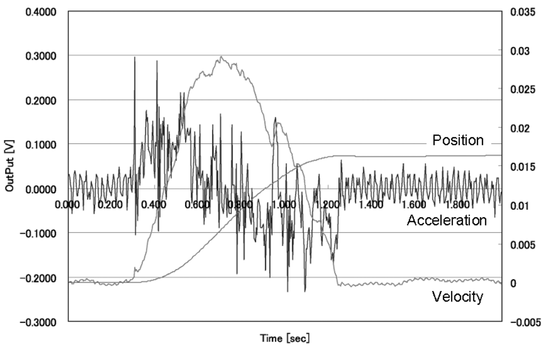

Figure 15. Output from acceleration sensor C.

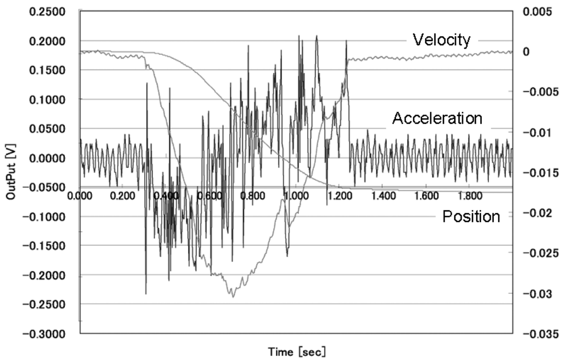

Figure 16. Output from acceleration sensor D.

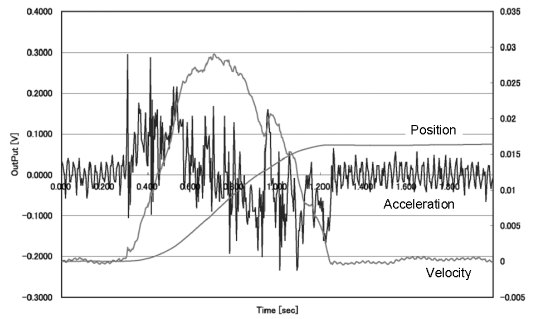

Figure 17. Result of subtraction (acceleration sensor).

9. References

[1] M. Reigstad, and A. Droivoldsmo, "Wearable control rooms : New technology can change collaboration, communication and information flow in future field operations", *Proceedings of the 22nd European Annual Conference on Human Decision Making and Control*, 2003.

[2] R. Azuma, Y. Baillot, R. Behringer, S. Feiner, S. Julier, and B. MacIntyre, "Recent Advances in Augmented Reality", *IEEE Computer Graphics and Applications*, Vol. 21, No. 6, pp. 34-47, 2001.

[3] N. Navab, "Developing Killer Apps for Industrial Augmented Reality", *IEEE Computer Graphics and Applications*, Vol. 9, No. 3, pp. 16-20, 2004.

[4] H. Shimoda, H. Ishii, Y. Yamazaki, and H. Yoshikawa, "A Support System for Water System Isolation Task in NPP by Using Augmented Reality and RFID", *Proceedings of NUTHOS-6*, 2004.

[5] J. Borenstein, H. R. Everett, L. Feng, D. Wehe, "Mobile Robot Positioning - Sensors and Techniques", *Journal of Robotic Systems*, Vol. 14, No. 4, pp. 231-249, 1997.

[6] Y. Genc, S. Riedel, F. Souvannavong, C. Akinlar, N. Navab, "Marker-less Tracking for AR : A Learning-Based Approach", *Proceedings of the International Symposium on Mixed and Augmented Reality*, pp. 295-305, 2002.

[7] H. Kato and M. Billinghurst, "Marker tracking and HMD calibration for a video-based augmented reality conferencing system", *Proceedings of IWAR*, 1999.

[8] S. Feiner, B. MacIntyre, and D. Seligmann, "Knowledge-based Augmented Reality", *Communications of the ACM*, Vol. 36, No. 7, pp. 52-62, 1993.

[9] S. Feiner, B. MacIntyre, M. Haupt, and E. Solomon, "Windows on the World: 2D Windows for 3D Augmented Reality", *Proceedings of UIST '93*, pp. 145-155, 1993.

[10] E. Foxlin, M. Harrington, and Y. Altshuler, "Miniature 6-DOF Inertial System for Tracking HMDs", *SPIE Helmet and Head-Mounted Displays III*, Vol. 3362, 1998.

[11] S. Igarashi, S. Hashimoto, A. Miyamoto, and S. Kaneko, "Rotation-invariant Picture Matching based on Autoregressive Model of Orientation Histogram", *Journal of Japan Society for Precision Engineering*, Vol. 68, No. 9, pp. 1519-1523, 2001. (In Japanese)

[12] K. Deguchi, Fundamentals of Robot Vision, Korona Publishing, Tokyo, 2000. (In Japanese)