Robustness of Visual-Servo against Air Bubble Disturbance of Underwater Vehicle System Using Three-Dimensional Marker and Dual-Eye Cameras

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***Abstract*—After the Tohoku Earthquake on March 11, 2011, FUKUSHIMA prefecture has been afflicted by disasters like earthquake, tsunami and nuclear power accident, then decontamination work has been needed to be done in radioactive contamination area. A visual-servo type underwater vehicle system with binocular wide-angle lens has been developed and it has expanded the sphere for surveying submarine resources and decontaminating radiation from mud in dam lake, river, regulation pond, sea in FUKUSHIMA. This paper studies the robustness of visual-servo type underwater vehicle system using three-dimensional (3D) marker under air bubble disturbance on real-time pose (position and orientation) tracking for visual servo. The recognition of vehicle's pose through 3D marker is executed by Genetic Algorithms (GA). The proposed system does not merely calculate the pose information, but can recognize the target pose information through GA while visual servo, because the system utilizes a 3D marker shape and color to recognize the marker. In our previous research, a performance of the system to regulate the vehicle's pose to the relative desired pose against the 3D marker was explored under the condition that there was no disturbance on images. Therefore this paper studies the robustness of the proposed system for air bubble disturbance on the image, aiming at confirming the robustness of the proposed visual servo system. The following results were derived; (1) The proposed system is robust to time-variant target position in z-axis (front-back direction of the vehicle). (2) Although the fitness value of GA is influenced by disturbance, the system can keep recognizing the pose of 3D marker, and (3) tracking by visual servo could be stably kept under the air bubble disturbances.**

I. Introduction

With the initial goals being set on data gathering, the role of underwater vehicle has been exploring in several domains of applications for commercial, offshore and defense. Researches concerning homing/docking using several types of proximity sensors in the field of underwater vehicle has been extended [1]-[3]. However the more sensors are used, it means the more expensive in cost and space in vehicle design. Survey on visual measurement and control for underwater vehicles are discussed in [4].

In spite of limitations of image sensors for real-time applications such as image-acquisition-quantization accuracy and processing rates, image information provided by optical camera offer several advantages over other types of non-contact sensors with the rapid progresses in computer vision. Even through there seems to be delayed in conducting research in term of utilizing the visual information for underwater vehicle comparing to the land and space systems, a number of researches on underwater vehicle using visual servo have been conducted in world wide recently. Each of them is with different merits and certain considerations. Some researches are based on the monocular vision [5]-[8] and some are binocular vision [9][10]. In addition to vision sensors, other sensors or landmarks are used in some applications where 3D information are dominant [11]-[14]. Most of them [11]-[14] using different image processing techniques, are limited when underwater environment poses difficulties against image recognition such as disturbances by marine snow.

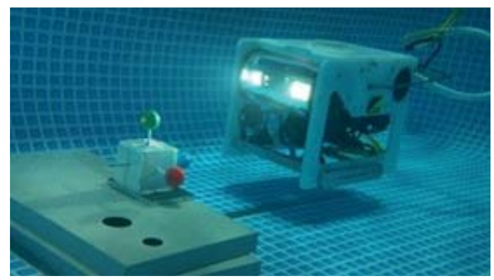

Fig. 1. Visual Servo using 3D Maker and Dual-eye Cameras

To overcome these issues, In this paper, visual servo system utilizing image recognition using Model-based Matching method and GA has been proposed, which is composed of dual-eye cameras and 3D known maker shape and color, being different from [13] which is one of the notable works. In [13], colored cable is used for positioning and guiding the vehicle to the target (Signboard system). In signboard system, four colored balls are fitted in frame type structure. Based on known information about signboard system, distance and orientation (only heading angle) of vehicle to the target are calculated for position and heading error correction. Assumption for the vehicle to be in horizontal plane with the same level of three balls makes the accuracy be much dependent on the other sensors such as altimeter as well as stability control of the

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vehicle. In this proposed approach, dual-eye cameras and the 3D target with predetermined 3D information are used for relative pose estimation between ROV (Remotely Operated Vehicle) and the target. The proposed system (underwater vehicle) can be regulated at desired pose through 3D real-time visual servo by dual-eye cameras.

In order to assess the effectiveness of the proposed system against noises in camera images, this report presents how the dual-eye real-time image recognition system be robust against air bubble disturbances and how the visual servo system maintains the servo performance even through the bubbles disturb the image feedback. Fig. 1 shows the visual servo of underwater vehicle using 3D maker and dual-eye cameras.

The paper is organized as follows: Section II presents the problem statement of the visual servo for underwater vehicle. Section III describes the proposed visual-servo system along with the detail explanation of the system. Experimental results to assess the performance of the proposed system are described in Section IV with discussion. The final section concludes the paper.

II. Problem Statement

A. 3D Recognition by 1-Step GA

Visual servo system should know not only 3D position but also 3D orientation in real time. Most of works address the usage of camera image for 2D information and additional sensor units for measuring 3D information. Even through they achieved in dealing with 3D pose estimation or measurement, the cost and space were dominant. Therefore, a number of researches have been published on 3D recognition using camera. Although there are many modern recognition methods that are suitable for pose estimation, they are still curbed by significant limitation and constraints against disturbances appearing input images. On the other hand, robust visual servo systems need recognition schemes that are invariant to scale, rotation, and change in 3D viewpoint. In conventional approaches, the 3D model and the pose of the object are extracted from 2D images using different techniques which are based on the idea of 2D to 3D reconstruction, i.e., epipolar geometry . In response, feature extraction and matching of feature points in dual cameras become non feasible in term of computational load as well as reliability of mapping features.

In order to overcome the disadvantages of the related works, we proposed 3D recognition method using model-based matching utilizing GA as main contribution to apply in underwater vehicle environment. This method has been conducted in previous works in our laboratory [15]-[20].

B. Disturbance

Unlike land or space systems, underwater environment provides undesirable disturbance in terms of physical ones such as current and difficulties in image processing under lighting non-uniformly, marine snow and background irregularities in images and so on. Therefore, the main disturbance appearing in image is assumed to be given in this work by the appearance of air bubble, and visual servo experiments with dual-eyes 3D pose tracking are conducted under such disturbance.

C. Real-time Performance

In visual servo control, real-time performance of object recognition with pose estimation has been an significant challenge in terms of expensive computational cost. Therefore, there are big space for researchers to modify the algorithm not only for pursuing accurate result but also with the promise of better computational performance with robustness against noises in images.

D. Application

The common applications of visual servo of underwater vehicle are cable tracking, station keeping, docking and reconstruction of the large image about underwater environment such as mosaicking. The proposed system is demonstrated with experiments especially for station keeping application in which target object as station is moving.

III. Proposed Visual-Servo System

A. Assumptions of Proposed Experiment

The information of the target object such as size, shape and color is foreknown to the system. In the 3D recognition process, it is assumed that the target object exists in the GA searching space. In the control system, the desired pose (x_d[mm], y_d[mm], z_d[mm] and ϵ_{2d}[deg]) between the target and the ROV are predefined so that the robot will perform station keeping through visual servo. Controlling rotations around x and y-axes of $\sum_H$ as shown in Fig.2 (ϵ_{1d}[deg], ϵ_{3d}[deg]) are neglected because of their less effectiveness to ROV's motion in this experiment due to the predesignated self-stable character.

B. Vision-based Control System

Fig.3 shows the overall block diagram of the proposed vision-based control system. The desired pose of the ROV related to the target is predefined. Based on known information about target (size, shape, color), the target's pose information are updated in real time through recognizing process which is the feedback system using model-based matching method. Genetic Algorithm (GA) is utilized for pose estimation through dual-eyes cameras. Model-based recognition approach is applied because of its performance in terms of less sensitive on camera calibration, comparing to other methods like feature based recognition in which the pose of the target object should be determined by a set of image points, resulting in complex searching the corresponding points and time consuming.

The control parameters for the ROV are x_d[mm], y_d[mm], z_d[mm] and ϵ_{2d}[deg]. The control concept to compensate the error is to apply the Proportional controller with optimized tuned gain parameter. The control algorithm is implemented in PC whose performance enables the real time pose tracking and visual servo. The image signal and control signal are transferred through flexible cable with less influential to visual-servo due to less cable tension.

C. Model-based Matching using 1-Step GA

Pose of target object is estimated using model-based matching based on known 3D model of the target projected to

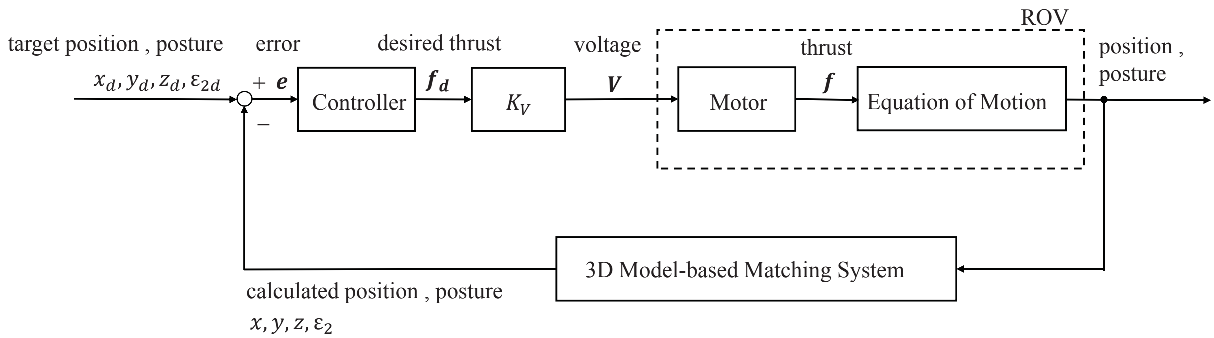

Fig. 3. Block Diagram of the Vision-based Control System

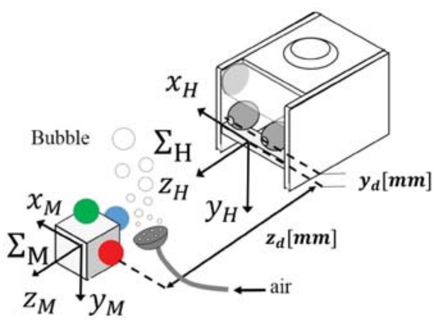

Fig. 2. Experimental Layout

2D images. Target object is the 3D marker that consists of three spheres (40[mm] in diameter) whose colors are red, green and blue. Knowing the information of the target and predefined relative pose to the ROV, the solid model of the target is predefined and projected to 2D images. Comparing the projected solid model image with the captured 2D images by dual cameras, the relative pose difference is calculated. Fig.4 shows Model-based matching system using dual-eyes vision system.

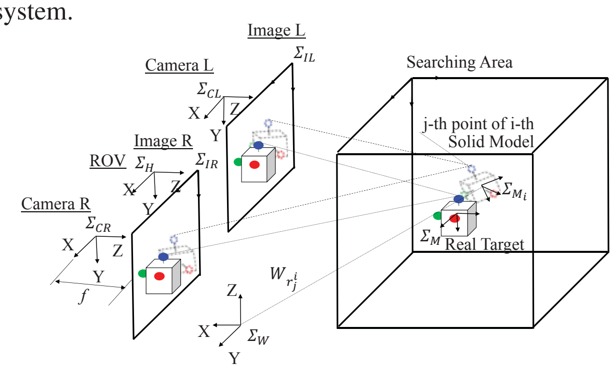

Fig. 4. Model-based Matching System using Dual-eyes Vision System

Since the control parameters are x,y,z and rotational angle around each axis, genes representative to these parameters are initiated randomly as shown in Fig. 5. Therefore the problem of pose recognition addresses to the searching problem. The solution is GA with promise speed and accuracy of performance. Through the steps of GA (Selection, Cross over and Mutation), a number of genes that represent different poses are evaluated by the defined fitness function to get the best gene with the most truthful estimated pose. A correction function representing a matching degree of projected model against the real target in the image, which is a correction function of real target projected in camera images with the assumed model represented by poses in genes, is used as a fitness function in GA process. Since we have confirmed the gene that has the highest fitness function value represents the pose of the real target, the searching problem of real target pose addresses the optimization problem of time-varying multi-valuable function. The convergence of GA is realized in the sequences of dynamic images input by video rate [30 frames/s]. Since the GA process to recognize the target's pose is executed at least one time during the time that one frame of image is input, 33 [ms], it is named " 1- Step GA. " Detail discussion about 1-Step GA and

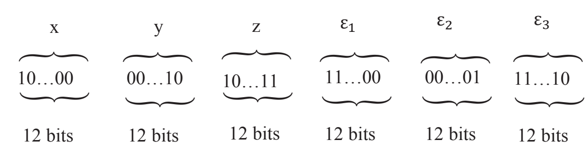

Fig. 5. Gene Representation for Position and Orientation

fitness function are explained in [16]. The effectiveness of this method has been confirmed in our previous researches [15]-[20]. The number of evolving generations in this experiment is 9 per 33 [ms] and the number of genes is 60.

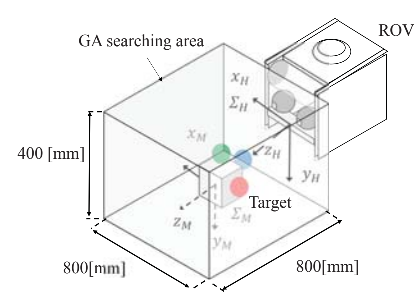

Fig. 6. GA Searching Area

D. Controller

Proportional controller is considered as the main compensator of the error between target's pose and recognized one. The control voltages of four thrusters are calculated by the following proportional control laws.

$$\begin{aligned} v_1 &= k_{p1}(z_d - z) + 2.5 \quad (1)\\ v_2 &= k_{p2}(\epsilon_{2d} - \epsilon_2) + 2.5 \quad (2)\\ v_3 &= k_{p3}(y_d - y) + 2.5 \quad (3)\\ v_4 &= \begin{cases} 5 & : x_d - x < -5[mm] \\ 0 & : 5[mm] < x_d - x \end{cases} \quad (4) \end{aligned}$$

where x_d, ϵ_{2d} and z_d are relative desired value based on Σ_H against 3D marker (see Fig.6), and v_1,v_3 and v_4 are the voltages for thrust of z-axis, yaxis and x-axis direction respectively. According to the thruster characteristics which is configured to stop for 2.5 voltage, the output voltages for thrust is the differentiated value gained by proportional gain value and added by offset value, 2.5. v_2 means the voltage for torque around y-axis. The control voltage v_4 for x-axis direction is just on-off control. Based on experimental performance, the error range for defined output voltages are tuned. Based on not only equation of motion and thrusters' characteristics but also experimental results, gain coefficients are tuned to have better performance in regulator processes. The controller in the figure indexed control schemes in eq. (1)-(4) using desired values and real-time tracking pose by 1-Step GA.

E. Experimental Environment

Even though the error from the relative target's pose appears constantly and the system operates the four thrusters simultaneously, recognition error changes with the water pressure due to reaction force during robot's movement and reflected wave from the experimental pool sides. Besides, aiming to make natural environment, the appearance of bubbles in front of the 3D marker is to perform as the main disturbance to image recognition with random noise and physical disturbance to the movement of the ROV. The underwater experiment is conducted in a pool filled with water. The size of the pool is 3[m] in length, 2[m] in width, 0.75[m] in depth. The regulated performance of underwater robot was confirmed in the cases of 3D marker is in periodic motion with different duty cycles and amplitudes.

F. ROV as a Test-bed

The ROV shown in Fig. 7 manufactured by Kowa corporation, is used as the main test-bed for the proposed experiment. Two fixed cameras (binocular camera) and four thrusters (traverse, horizontal and vertical direction) are installed in the ROV. The specification of ROV is given in TABLE.I.

TABLE I. KEY FEATURES OF ROV

Dimension [mm]	280 (W) × 380 (L) × 310 (H)
Dry weight [kg]	15
Number of cameras	2 (Front, fixed) and 2 (Downward, fixed), 1 (Tile, Manual controlled)
Maximum thrust force [N]	9.8 (Horizontal), 4.9 (Vertical, Traverse)
Number of LED light Sources	2 (5.8 [W])

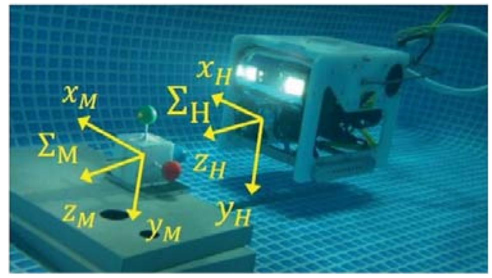

Fig. 7. ROV with Reference Coordinate Frames

IV. RESULTS AND DISCUSSION

A. The accuracy of GA recognition and Regulator performance in water

Fig.8 (a) shows the time variation of the fitness value of GA recognition in underwater robot, which was regulated to the relative target's pose, with the appearance of bubbles in front of the three-dimensional marker as the glare disturbance exists in recognition image. We might say that, in general, the recognition accuracy of GA is to be kept while the fitness function in GA exceed more than 0.5 to perform visual servo precisely. Fig.8 (b) ∼ (e) show the errors between the pose of the 3D marker recognized by GA and the relative target's pose. Fig.8 (g) ∼ (j) represents the thrust to regulate them. Also, Fig.8 (f) shows the 3D trajectory of the ROV during the regulation process. Although the fitness value is reduced sometimes to about 0.4, that is minimum value as shown (a), it is confirmed that the underwater robot is regulated in relative target's pose vicinity as shown in Fig.8 (b) ∼ (j).

B. 3-Dimensional Marker is in Periodic Motion

The regulated performance of underwater robot was confirmed in the case of a 3D marker was in periodic motion with the relative target's pose as the same value as in previous work. Fig.9 shows regulated process when the 3D marker is in periodic motion in the z direction with duty cycle of 20 seconds and 280 mm distance from the robot. The positional relationship between the ROV and a 3D marker is shown in Fig.9 (left column), and the position of the 3D markers seen from the underwater robot is shown in Fig.9 (right column). Each image is taken in every 10 seconds. Circles which are drawn in almost the same position as each of the 3D marker spheres; green, blue and red, represent GA recognizing process in real time. Matching between these drawn circles and 3D spheres respectively shown in Fig.9 (right column) indicates the degree of recognizing the pose of the 3D marker.

Fig.10 (a) ∼ (d) which shows the fitness value, position of underwater vehicle, tracking error, and thrust in z-axis direction respectively. The right arrow described with (A) shown in Fig.10 (a) and (b) highlights the period of the experiment in which 3D marker is in period motion after the first 20 seconds. According to the results from these figures, it can be confirmed that the proposed system can keep regulation of the relative target position even though the 3D marker is in periodic motion.

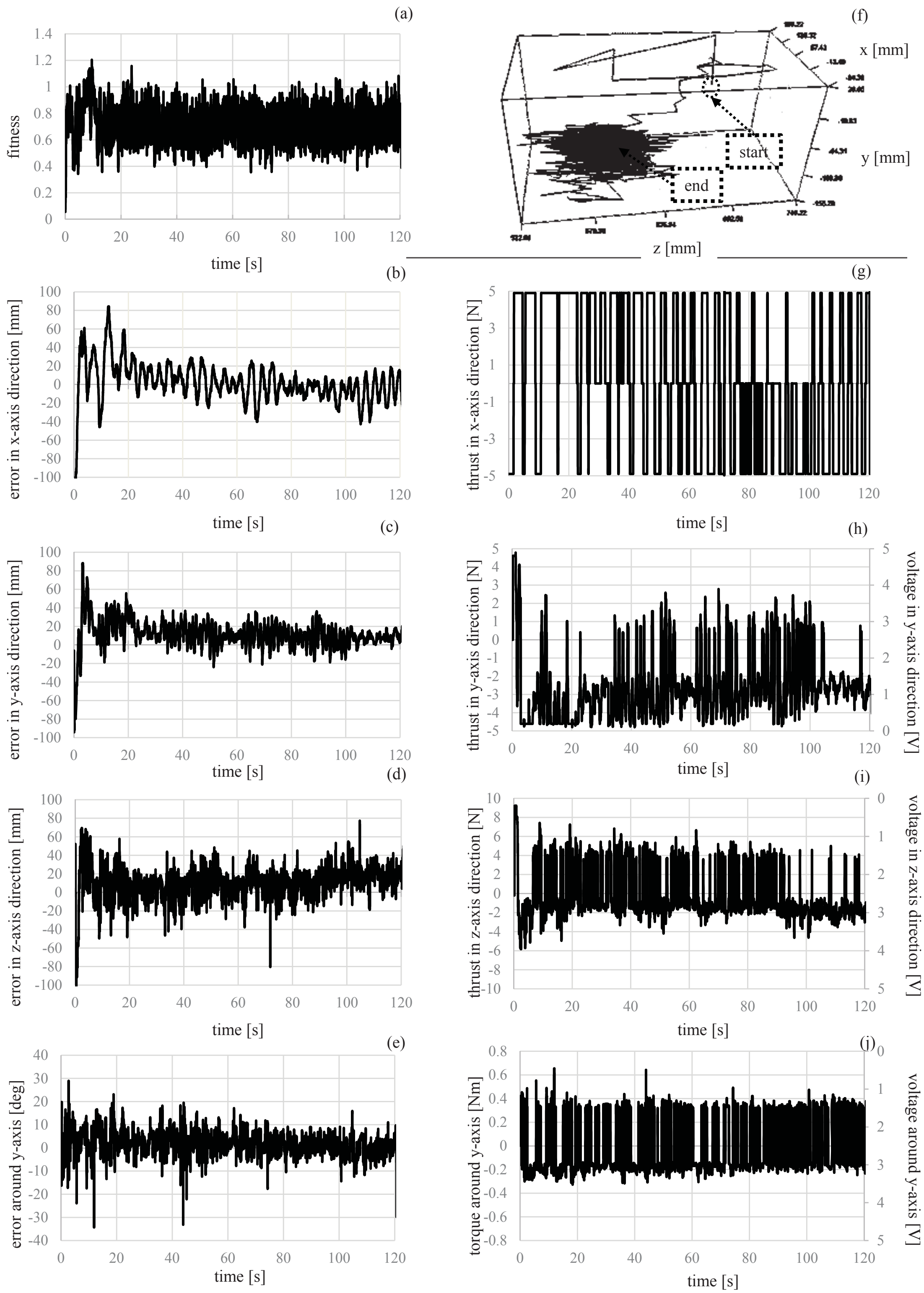

Fig. 8. Regulator performance with additional disturbance made by air bubbles against dual-eye image recognition: (a) fitness value, (b) error in x-axis direction, (c) error in y-axis direction, (d) error in z-axis direction, (e) error around y-axis, (f) 3D trajectory of underwater vehicle (g) thrust in x-axis direction, (h) thrust in y-axis direction, (i) thrust in z-axis direction and (j) torque around y-axis

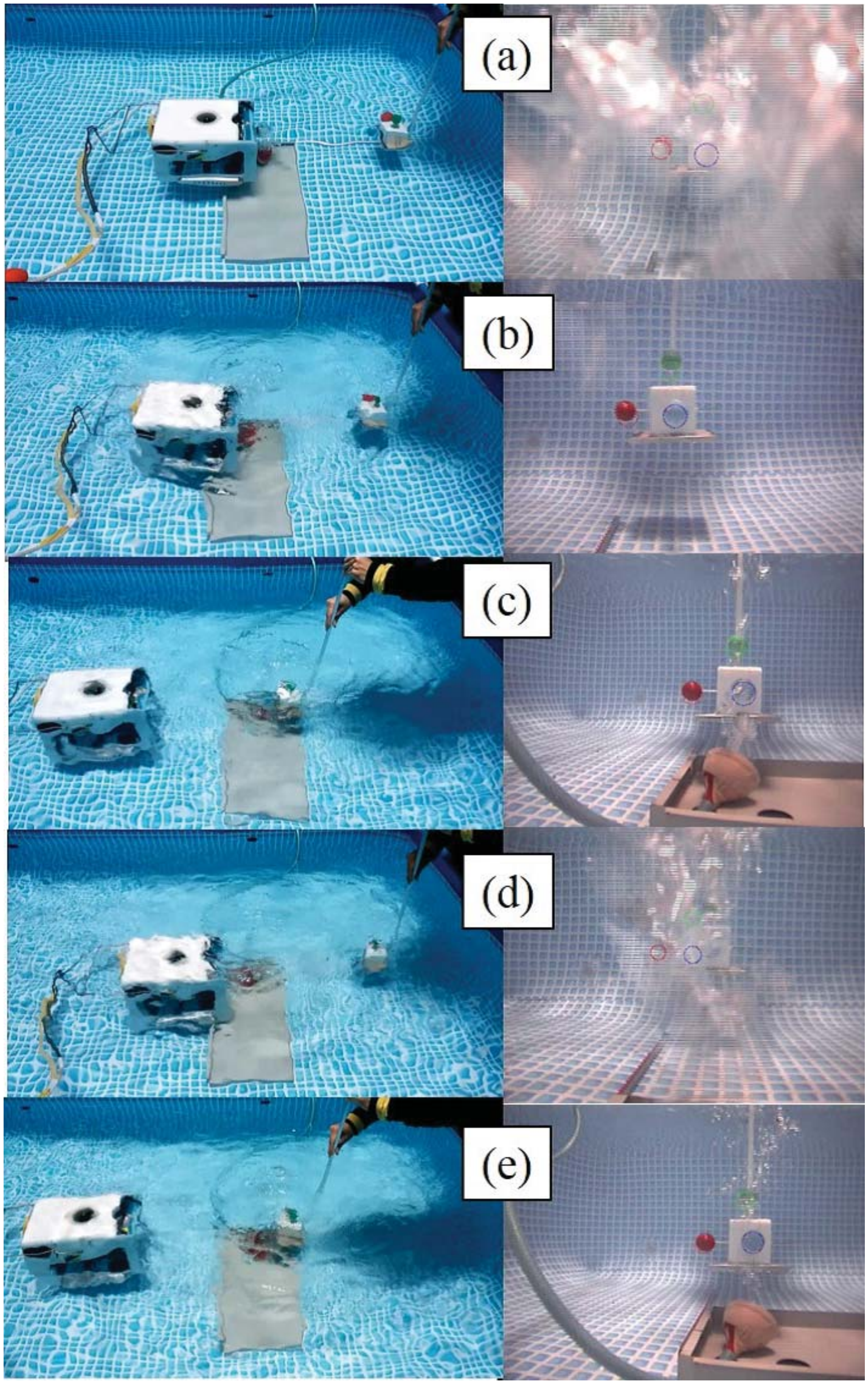

Fig. 9. Actual snapshot of underwater vehicle (left column) and its camera images (right column) with disturbance on images after starting experiment: (a) 10 seconds have passed, (b) 20 seconds have passed, (c) 30 seconds have passed, (d) 40 seconds have passed and (e) 50 seconds have passed

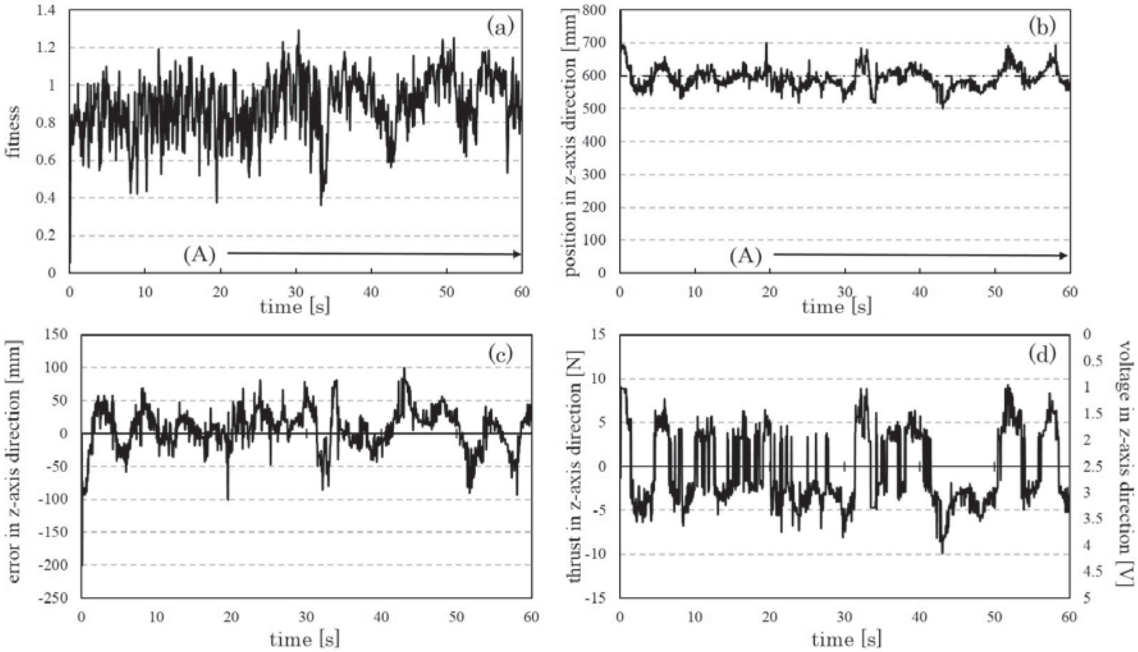

Fig. 10. Tracking performance without additional disturbance on image in the case that (A) 3D marker is moving with amplitude 280 [mm] and period 20 [s] after 20 [s]: (a) fitness value, (b) position of underwater vehicle in z-axis direction, (c) tracking error in z-axis direction, and (d) thrust in z-axis direction

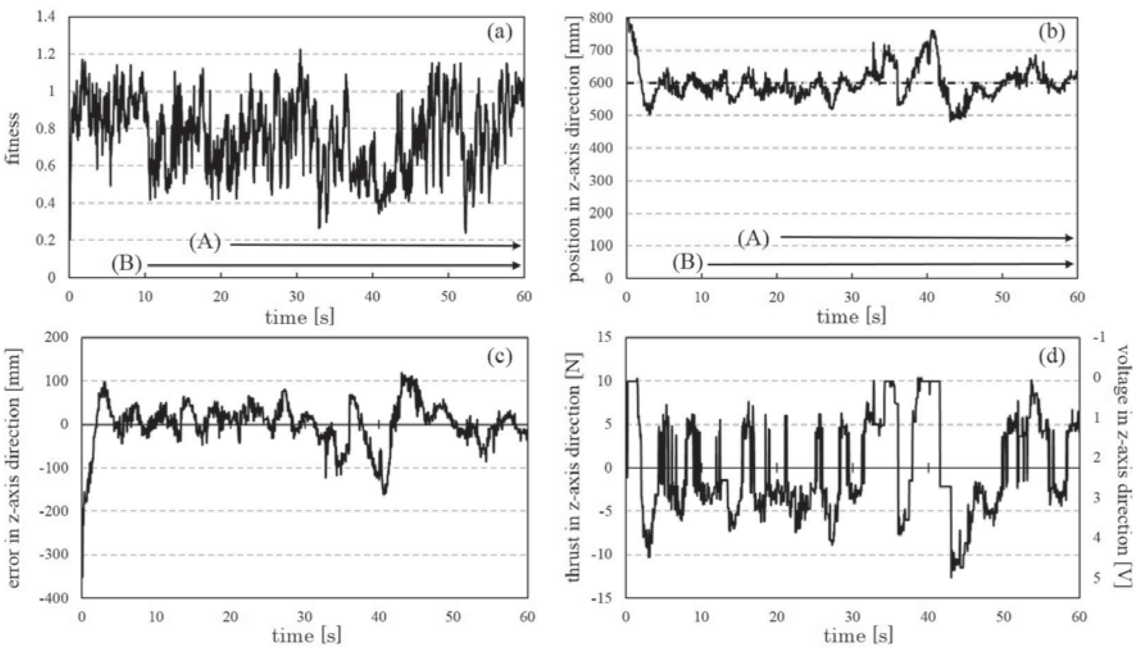

Fig. 11. Tracking performance with additional disturbance made by air bubbles against dual-eye image recognition in the case that (A) 3D marker is moving with amplitude 280 [mm] and period 20 [s] after 20 [s] and (B) disturbance is added after 10 [s]: (a) fitness value, (b) position of underwater vehicle in z-axis direction, (c) tracking error in z-axis direction, and (d) thrust in z-axis direction

Then, Fig.11 shows the tracking performance with the disturbance in term of the appearance of air bubbles after the first 10 seconds to the same condition in which 3D marker is moving with amplitude 280 mm and period of 20 seconds after the first 20 seconds. Despite of the disturbance (bubbles) which reflect on recognition image, it can be seen that the relative positions of the markers and the underwater robot is maintained constantly. Even though the pose of the 3D markers recognized by GA in real-time seems to be matched roughly as shown in Fig.9 (a) $\sim$ (e), it can be seen that the real-time 3-dimensional recognition is maintained. As a result, it addresses to high regulation performance to the relative target's pose. In addition, the data for the results of this experiment is shown in Fig.11 (a) $\sim$ (d) show the fitness value, position in the z-axis direction of the underwater robot, error of the relative target position and graph of thrust to restore the error respectively. Furthermore, the right arrows described as (A) and (B) in Fig.11 (a) and (b) represent the period that was allowed to exercise 3D marker in amplitude after 20 seconds of the beginning of the experiment, and the period that has the appearance of bubbles in the recognition image after 10 seconds of the start of the experiment respectively. Although the fitness value is reduced as indicated in Fig.11 (a) comparing to that in Fig.10 (a) due to the appearance of the bubbles, the result in Fig.11 (b) (c) confirm that the relative target position is regulated properly. In other words, even the proposed system is reflected to the disturbance in recognized image, it has been shown to have ability to regulate the relative target's pose.

V. Conclusion

In this paper, visual servo system is proposed for underwater vehicle ROV focusing on the regulator performance with disturbance especially to recognized image. A real-time pose detection scheme was designed by means of model-based 3D recognition and GA using the information provided by a binocular wide-angle lens system and 3D marker as the passive target. The regulated performance of underwater robot was also confirmed in the case of the target was in periodic motion with different duty cycles and amplitude. The system was evaluated for both with and without air bubbles disturbance. The paper shows the robustness of the verification experiments of the position and attitude control, to obtain the following conclusions. (1) The proposed system can follow the target marker even in moving in the z-axis direction. (2) Although the environment in which the bubble disturbance reflected on the fitness of GA which is reduced as compared with the case of no disturbance, the proposed system can continue to recognize the relative pose of a 3D marker robustly. Furthermore, it is possible to carry out follow-up control to the time-variant target value by visual servo robustly even under bubbles disturbance.

Acknowledgment

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