Applying Lighting Marker and Stereo-vision to V-shaped-thruster Vehicle for AUV Deep Sea Docking

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***Abstract*—A stereo-vision-based system of autonomous underwater vehicles (AUVs) for sea-bottom docking that enables for battery recharging to extend persistence time of underwater operation has been developed. This paper presents the docking experiment using a developed V-shaped-thruster typed underwater vehicle. A real-time 3D pose (position and orientation) estimation method using a real-time multi-step genetic algorithm (RM-GA) has been proposed by the authors in previous works and used for docking based on 3D recognition as a feedback pose information in real-time, named as 3D Move on Sensing (3D-MoS). Sea docking experiment results have confirmed the functionality and practicality of proposed docking approach using a hovering typed ROV in previous works. Since the hovering typed underwater vehicles are limited in mobilities concerning speed and operational space, verification of the 3D-MoS system using underwater vehicle that has more mobility deem to be meaningful direction for vision-based docking system to expand the utility value of AUVs. Therefore, in this study, control system for a new V-shaped-thruster typed vehicle is developed and docking experiment is conducted. This paper presents the development of the hardware design of V-shaped-thruster typed underwater vehicle and improvement of controlling with consideration of coupled configuration of thrusters.**

***Index Terms*—Pose estimation, Dual camera, RM-GA, 3D-Mos, AUV**

I. Introduction

AUVs play an important role in many undersea operations, such as the inspection of underwater structures (e.g., dams [1] and bridges), ship hull inspections [2], and deep-water archaeology [3]. Despite recent advancements to power storage technologies, the operation time of underwater vehicles is a limiting factor. A recharging unit with an underwater docking function can enable the extended operation of AUVs in the sea independent of a surface vehicle to which they must return for recharging. Docking operation has become very essential in advanced applications such as underwater batteries recharging, uploading and downloading data, sleeping under a mother ship, and doing some tasks in a vehicle-manipulator system. Generally, there are three phases in docking operation. They are long distance navigation, approaching and final docking. Among them, final docking is the critical capability for autonomous underwater vehicle especially when a docking station is unidirectional one that has a single angle for entry. There are many studies on the docking system using various homing sensors [4] – [5] and techniques [7] – [8] for the underwater robot. Recently, a vision-based system has been highlighted as a promising navigation system due to the progress in computer vision. With this motivation, we have developed vision based docking system for unidirectional docking station.

Our research group has conducted a number of studies on our vision-based docking system, which uses the real-time multi-step genetic algorithm (RM-GA) method [12] – [16]. Docking trials using a remotely operated vehicle (ROV) as a test bed were also successfully conducted in a real sea environment near the city of Wakayama in Japan [15]. In

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[16], docking experiments with the AUV Tuna-Sand 2 were conducted in a pool. The robustness of the 3D pose estimation system against air bubbles [12] and target occlusion [17] has been verified experimentally. The effectiveness of the proposed system in tracking the pose of a moving 3D object has been reported in [12]. In [13], visual servoing while a physical disturbance was applied in a specific direction by pushing the AUV with a stick and the docking performance of the AUV were tested. Through these experiments, the authors have demonstrated the robustness of the proposed RM-GA method against a number of disturbances.

In this study, a new ROV (DELTA-150) is developed and docking experiments are conducted in the pool to assess the system performance. Why a new ROV is developed, and what are the problem to be resolved and contribution are described in details in Section II. Since the configuration of thrusters in the new ROV is not simply same as the one we used in previous experiments, the hardware structure of the DELTA-150 is developed to be stable in rolling, pitching and yawing. The stability of the ROV is improved by means of optimal design of stabilizer. Visual servoing performance using different design of tail is analyzed and the best shape was selected for docking operation. Finally, the docking performance is verified by conducting docking experiment in the pool.

This paper is organized as follows: Section III describes the problem statement and contribution. Section III presents the hardware implementation of underwater vehicle docking experiment. Section IV describes software implementation of docking experiment. Section V describes the docking experiments in the pool. The final section contains the conclusions of this study and plans for future work.

II. Problem Statement and Contribution

Normally, vision-based docking systems are based on hovering typed underwater vehicle. On the other hand, high speed of torpedo typed underwater vehicle limits the ability of vision-based system. Since AUV has its own main task rather than docking operation, vision-based docking system should be verified by using underwater vehicle that has enough mobility for its main task. However, the more mobility the ROV have, the more difficult for visual servoing will become and the more stability is necessary. By this motivation, our proposed stereo-vision-based docking approach needs to be verified by using underwater vehicle that has more mobility than the ones in previous works [12] – [16]. In [12] – [15], hovering typed ROV with limited mobility due to simple configuration of thrusters was used. In [16], hovering typed AUV (Tuna-sand2) was used for docking experiment using proposed approach. In this study, V-shaped-thruster vehicle is chosen to extend the mobility of vision-based underwater vehicle. The ROV used in this study can dive up to 150 m comparing to the ROV that can dive up to 50 m used in previous researches [12] – [15]. According to the V-shaped-thruster configuration and design of ROV that can be said semi-torpedo typed one, motions in vertical and forth-back directions are faster than that of former ROV. However, demerit of this kind of ROV lies in its coupling effects among thrusters, such as coupling between yawing and surge, rolling and sway. These kinds of coupling may address unstable condition for docking operation in which high accuracy is necessary for homing.

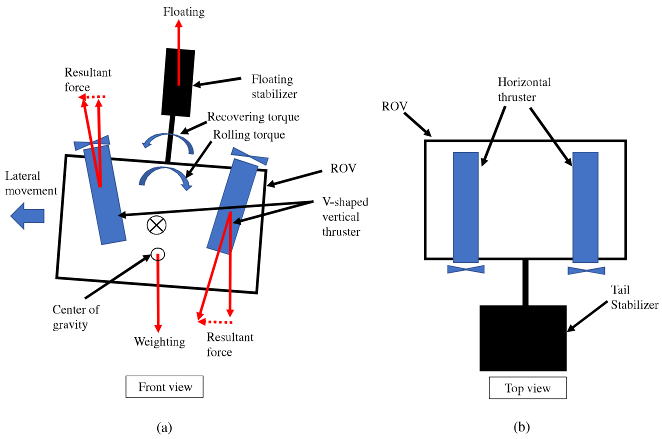


Fig. 1. (a) ROV with floating stabilizer for damping and recovering torques, (b) ROV with tail stabilizer to compensate rolling and pitching effect. Photography of ROV is illustrated in Fig. 2.

Here is the explanation of how the V-shaped-thruster addresses coupling between lateral movement and rolling, and how these effects can be compensated by using floating stabilizer and tail stabilizer. In Fig. 1 (a), the ROV is supported to move to the left side by giving V-shaped-thrusters with opposite thrust to each other. Consequently, the ROV suffers from rolling effects with certain tilted angle that can disturb docking operation. To overcome this problem, the floating stabilizer is attached at the top of ROV as shown in Fig. 1 (a). As a result of attaching floating stabilizer against the weight of the ROV, the recovered angle can happen to compensate the rolling effects. However, the balancing between tiled angle and recovered angle can still cause certain degree of rolling effects. Therefore, a tail stabilizer as shown in Fig. 1 (b) is considered to compensate not only the rolling but also pitching effects using damping effect.

Our main contributions of this study are to increase with mobility of ROV that are coming the stability issue. That solution is to reduce coupling by improving the hardware design of ROV using stabilizers that can recover decoupling with damping effect (The concept is explained above and detailed discussion is described in Section III). Since the development of V-shaped-thruster vehicle for sea docking experiment is emphasized in this study, discussion on robustness against turbidity is not included in the present paper. Experimental verification of developed underwater vehicle using stereo-vision-based docking approach is performed indoor pool.

III. Hardware Implementation of Underwater Vehicle

A. Underwater vehicle

The remotely controlled underwater robot (QI, maximum depth 150 m) used in this experiment is shown in Fig. 2 (a).

The specification of the ROV is shown in Table I. Two fixed forward-facing cameras with the same specifications (imaging element: CCD, pixel number: 640 × 480, pixel focal length: 2.9 mm, signal system: NTSC, minimum illumination: 0.8 lx, no zoom) were mounted on the ROV as shown in Fig. 2 (b). These two cameras were used for 3D object recognition. The thruster system of the ROV consists of two vertical thrusters (Note that they are not perpendicular to horizontal ones), and two horizontal thrusters with a maximum thrust of 30 N each. In this experiment, the ROV has been equipped with stabilizers and fixed actuators as shown in Fig. 2 (b). The development of ROV especially with fixed actuators and optimal design of tail fin will be discussed through experimental results in this paper.

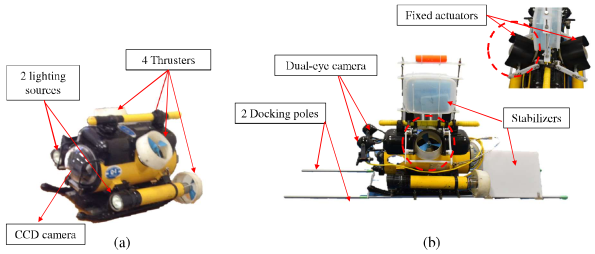


Fig. 2. Photograph of ROV manufactured by QI (a) before hardware development, (b) final developed design of ROV.

TABLE I
SPECIFICATION OF THE ROV (DELTA-150)

Max. depth [m]	150
Dimensions [mm]	450 × 600 × 395
Weight [kg]	20
Actuators	Horizontal thruster x 2 Vertical thruster x 2
Number of cameras	3
Structure materials	Corrosion resisting aluminum
Maximum thrust force [N]	30

B. Development of Underwater vehicle using fixed actuators and floating stabilizer

Since the thrusters of ROV are configured as shown in Fig. 3 (a) originally in initial product design, there are some complex couplings between each thrust. In the intended application that is docking operation for battery recharging, the precise motion of ROV is essential. On the other hand, it is needed to improve the configuration of the ROV hardware to reduce the effort in control method. Therefore, hardware design of ROV by attaching fixed actuators and stabilizers for stability especially in rolling and pitching are developed.

As shown in Fig. 3 (a), the initial design of thrusters causes difficulty in controlling ROV because of tilted vertical thrusters. Therefore, to help floating stabilizer (explained in Section II) reduce the tilted thrust direction as shown in Fig. 3 (a), the fixed actuators are attached above of vertical thrusters as shown in Fig. 3 (b). The angle of fixed actuators as shown in Fig. 3 (c) are experimentally adjusted.

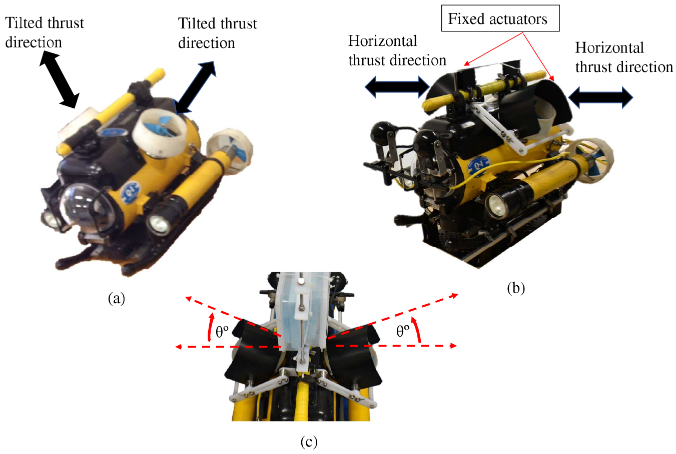


Fig. 3. (a) ROV with tilted thrust direction, (b) developed ROV with fixed actuators for horizontal thrust direction, (c) Fixed actuators with optimal slope angle, $\theta°$.

C. Development of Underwater vehicle using tail stabilizer

According to literature, different shapes of stabilizers and configuration of propellers are used in different vehicles as shown in Fig. 4. Generally, common concept among stabilizers is based on triangular shape. By this concept, different shape of tail fin including triangular shaped one is developed. To stabilize the ROV in rolling and pitching, the tail stabilizer is designed as shown in Fig. 5. Experimentally verification of the different tail fin will be discussed in next section.

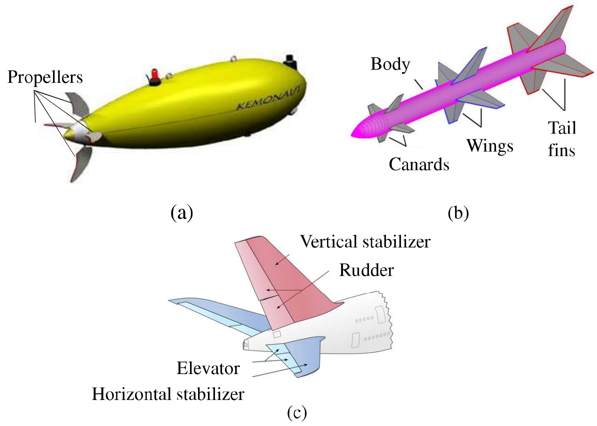


Fig. 4. Different stabilizer and propeller in different vehicles : (a) AUV, (b) Missile, (c) Airplane.

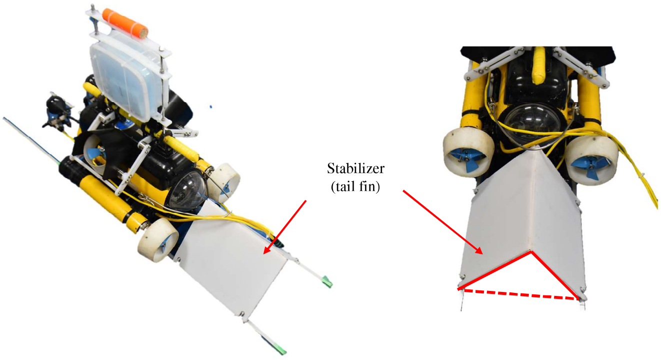


Fig. 5. ROV with triangular shaped tail fin for stabilization.

IV. Software Implementation of the Proposed System

A. Stereo-vision-based real-time 3D pose estimation

The relative pose between the ROV and the 3D marker is determined from six parameters: x, y, z, ϵ_1, ϵ_2, and ϵ_3; the first three are the Cartesian coordinates of the 3D marker in the ROV frame of reference, and the latter three are the orientation of the marker in the ROV frame represented by a unit quaternion avoiding singularities. A real-time pose estimation using RM-GA were proposed in previous study. We introduced and explained about why and how RM-GA was developed for real-time 3D pose estimation in previous study [6]. Therefore, the real-time pose estimation using RM-GA is discussed briefly in this session for reader's convenient. Please refer to [6] for more detailed about RM-GA.

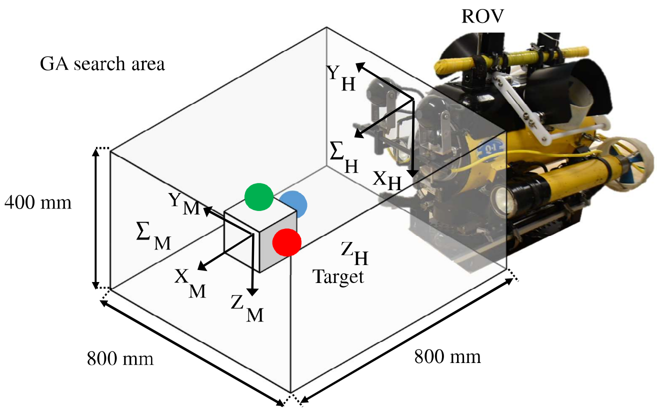


Fig. 6. Coordinate systems of the ROV and 3D marker. Σ_M and Σ_H denote the coordinate systems of the 3D marker and the ROV, respectively. The pose of the marker relative to the ROV, represented by the position and orientation of Σ_M with respect to Σ_H, is considered to be the unknown in the 3D pose estimation process.

B. Real-time multi-step genetic algorithm

In the process of 3D pose estimation, it is assumed that there are many models with different poses in the search area, as shown in the top left image in Fig. 7. To determine which model is closest to the actual target, the fitness function is used

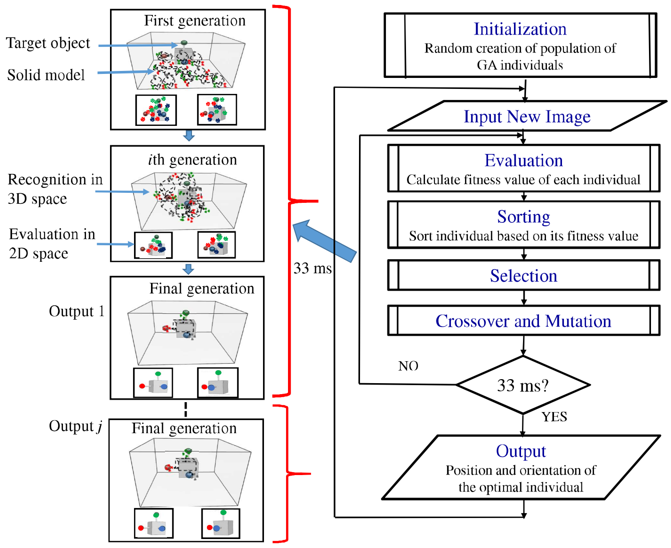


Fig. 7. Pose estimation using the RM-GA. In the initialization step, 40 models with different random poses are generated. The models with the best fit are selected based on their fitness values and evaluated using GA processes (selection, crossover, and mutation). The pose of the model with the highest fitness value in the final generation of the GA process within 33 ms is output as the estimated pose of the 3D marker relative to the vehicle.

to quantify the correlation between the models and the target. The main task of the pose estimation process is to search for the optimal model with the pose that is most strongly correlated with that of the real 3D marker. Therefore, the problem of finding the target object and detecting its pose can be converted to searching for the pose ϕ_M^j that maximizes the fitness value $F(\phi_M^j)$. To solve this optimization problem, the RM-GA was developed. The time convergence performance of the RM-GA as a dynamic evaluation function has been confirmed by Lyapunov analysis in [18]. Real-time 3D pose estimation using 3D-model-based recognition and the RM-GA has been presented in detail in previous papers [17], [6]. Figure 7 shows the flowchart of the RM-GA and how the best model is obtained. The real-time pose can be estimated for every image with an image frame rate of 30 fps. We explained why and how RM-GA was developed for real-time 3D pose estimation in a previous study [6].

C. Docking method

In an underwater battery recharging operation, the AUV must navigate to a seafloor station and dock at the station for recharging. Normally, a cone-shaped docking station with light sources mounted around its entrance is used for a torpedo-shaped AUV. The hovering-type AUV studied in [10] docks by descending to the station. To perform docking experiments for underwater automatic charging using the proposed approach, a rod was installed on the right side of the underwater robot, and a matching cylindrical hole was attached to the left side of the target. When the ROV is in the correct pose relative to the object, it must move forward to insert the rod into the hole. A flowchart of the proposed docking method is shown in Fig. 8. This method is divided into the five steps: (a)approaching, (b)visual servoing, (c)docking, (d)docking completion, and (e)stay and data storing. In the approaching step, the ROV estimates its approximate position relative to the station using other methods, such as an acoustic method, and approaches the station. The approaching step is performed manually in this study. In the visual servoing step, the ROV measures the precise relative pose using stereo-vision-based estimation and remains at the entry point for the final docking step, as shown in Fig. 9(a).

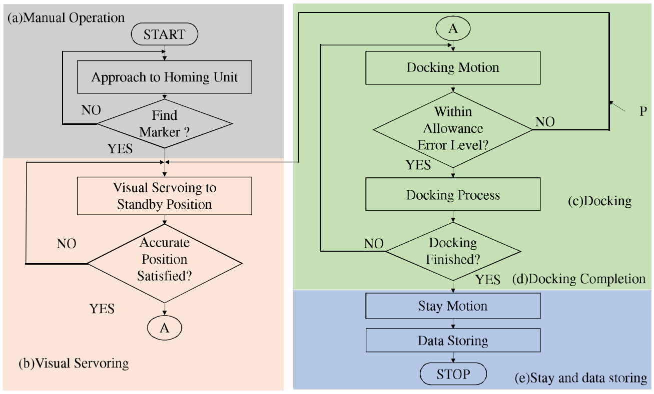
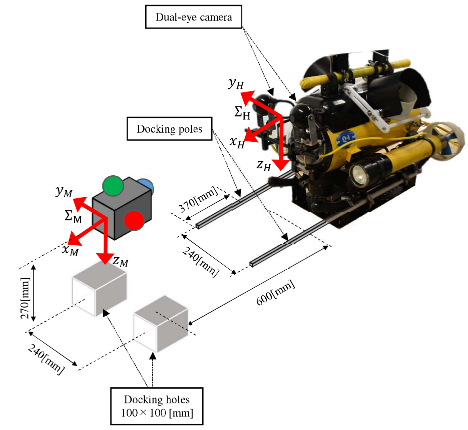
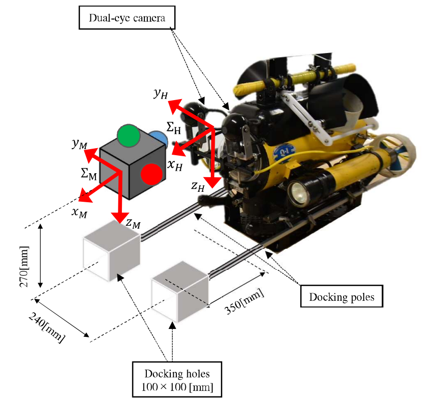


Fig. 8. Docking operation steps, including approaching, visual servoing, and docking. Note that approaching is performed by manual control at the beginning of the docking operation in this study. The error allowance for docking is ±40 mm in the y- and z-directions and ±7° in the rotation about the z-axis.

In the docking step, the ROV moves to the final desired pose, as shown in Fig. 9 (b) as long as the errors of the y- and z-components of the position of the ROV and that of its orientation about the z-axis relative to the target remain within ±40 mm and ±7°, respectively, for a minimum of 165 ms (five times the length of the control loop). Whenever any of these components of the error of the relative pose exceeds this allowance, the process switches to visual servoing, as shown by the path labeled "P" in Fig. 8. This process of switching between the visual servoing and docking steps was implemented to avoid any physical damage that could result from contact between the rod and the hole in the target. In the completion of docking step, the ROV keeps the desired pose especially at the 350 mm distance in x-axis direct to store the experimental data from memory to hard-disk of PC. This process was named as stay in this docking strategy. After storing the experiment data, the vehicle moves back to 600 mm distance in x-direction for next docking operation.



(a)



(b)

Fig. 9. Layout of the docking experiment showing the process of aligning the ROV with the 3D marker. (a) Desired pose in the visual servoing step. (b) Desired pose at the completion of the docking step. Σ_M and Σ_H denote the coordinate systems of the 3D marker and the ROV, respectively. The pose of the marker relative to the ROV, represented by the position and orientation of Σ_M with respect to Σ_H, is considered to be the unknown in the 3D pose estimation process.

V. Experiment in a Pool

We conduct a docking experiment using the DELTA-150 ROV with different shaped tail fins in a pool. The docking experiment is conducted in the pool (length 2870 mm × width 2000 mm × height 1000 mm) filled with 4000 L of clear water. The different shaped tail fins are shown in Fig. 10.

Figures 11, and 12, 13 show the docking performance using different shaped tail fins respectively. The fitness value, the position in x, y, z-axes and rotation around z-axis are shown in Fig. 11, and 12, 13 (a) through (g). In docking experiment without tail fin as shown in Fig. 11, there are relatively large fluctuations in position in y-axis and rotation around x, y, z-axis. They are about three times as large as those in docking experiments using rectangular and triangular ones as shown in Figs. 12, 13. According to experimental results, the performance of docking without tail fin is the worst one among others. Consequently, docking could not complete successfully. In docking experiment using rectangular shaped tail fin as shown in Fig. 12, it takes about 65 s until ROV finish docking completely. On the other hand, in docking experiment using triangular one as shown in Fig. 13, it takes about 42 s until ROV finish docking completely. Therefore, the docking using triangular tail fin is more smooth than that of experiment using rectangular tail fin. Furthermore, the position in y-axis in Fig. 13 converge to the desired position within allowance

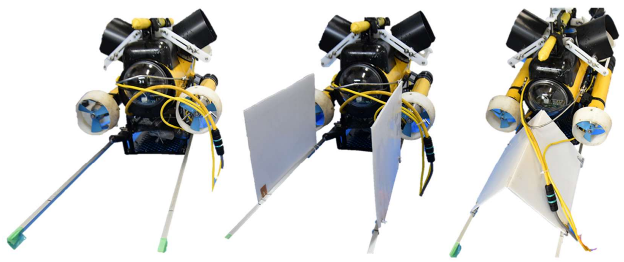


Fig. 10. ROV with different shaped tail fins: (a) no tail, (b) rectangular, and (c) triangular.

error range gradually comparing to that of Fig. 12. From these results, the triangular shaped tail fin is experimentally chosen to be used in our docking system.

VI. Conclusion

In this work, a stereo-vision-based underwater vehicle was developed for sea docking experiment. Visual servoing using two cameras for an underwater vehicle was implemented by using the system called 3D-MoS and an active 3D marker. Model-based pose estimation using two cameras was validated for real-time docking experiment. The ROV manufactured by QI was developed with designed stabilizers and triangular tail fin. The experiment was conducted in the pool to verify the robustness of the proposed system before conducting sea docking experiment. In the future, sea docking experiments will be conducted in the sea near Ushimado, Japan.

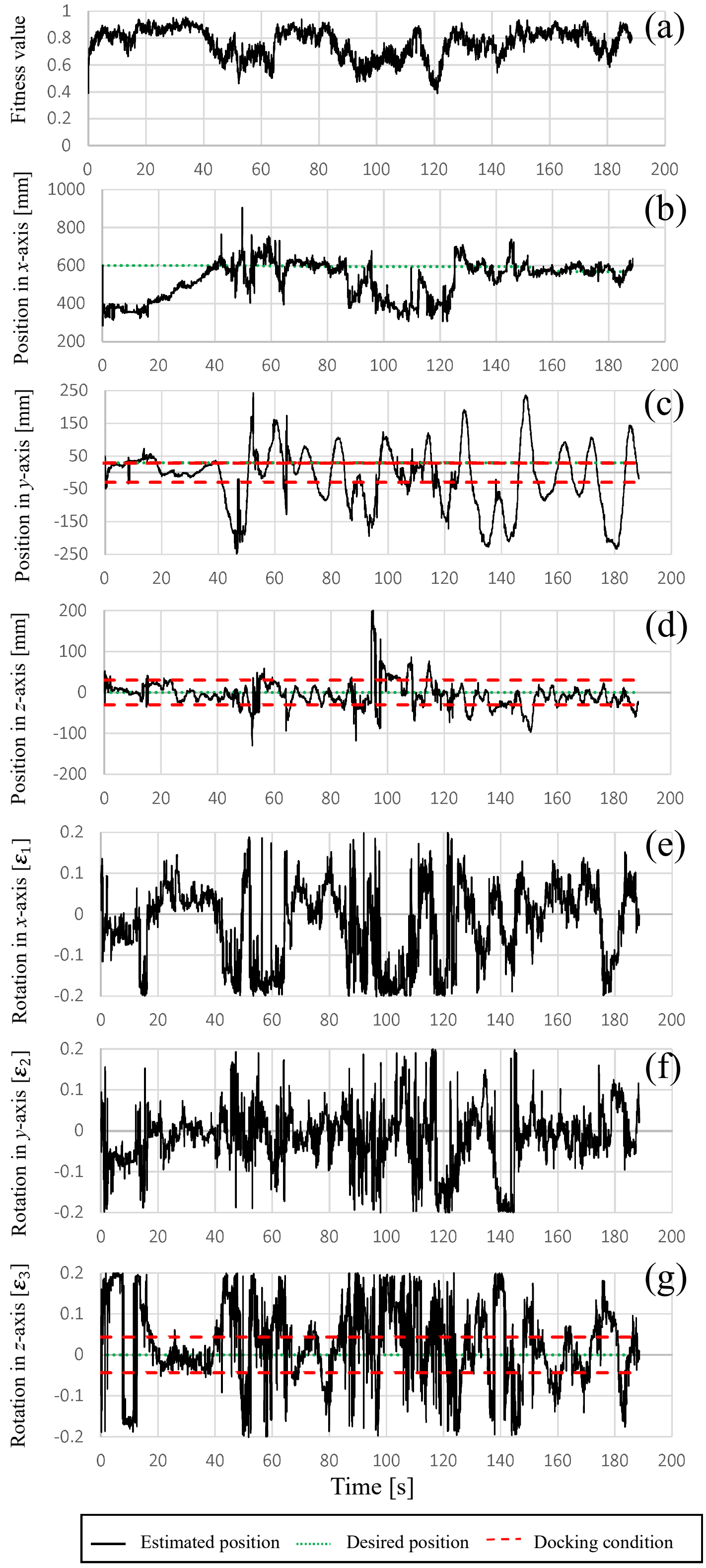


Fig. 11. Docking experimental result with no tail fin (See Fig. 10 (a)): (a) Fitness value, (b) Position in x-axis, (c) Position in y-axis, (d) Position in z-axis, (e) Rotation in x-axis, (f) Rotation in y-axis, and (g) Rotation in z-axis.

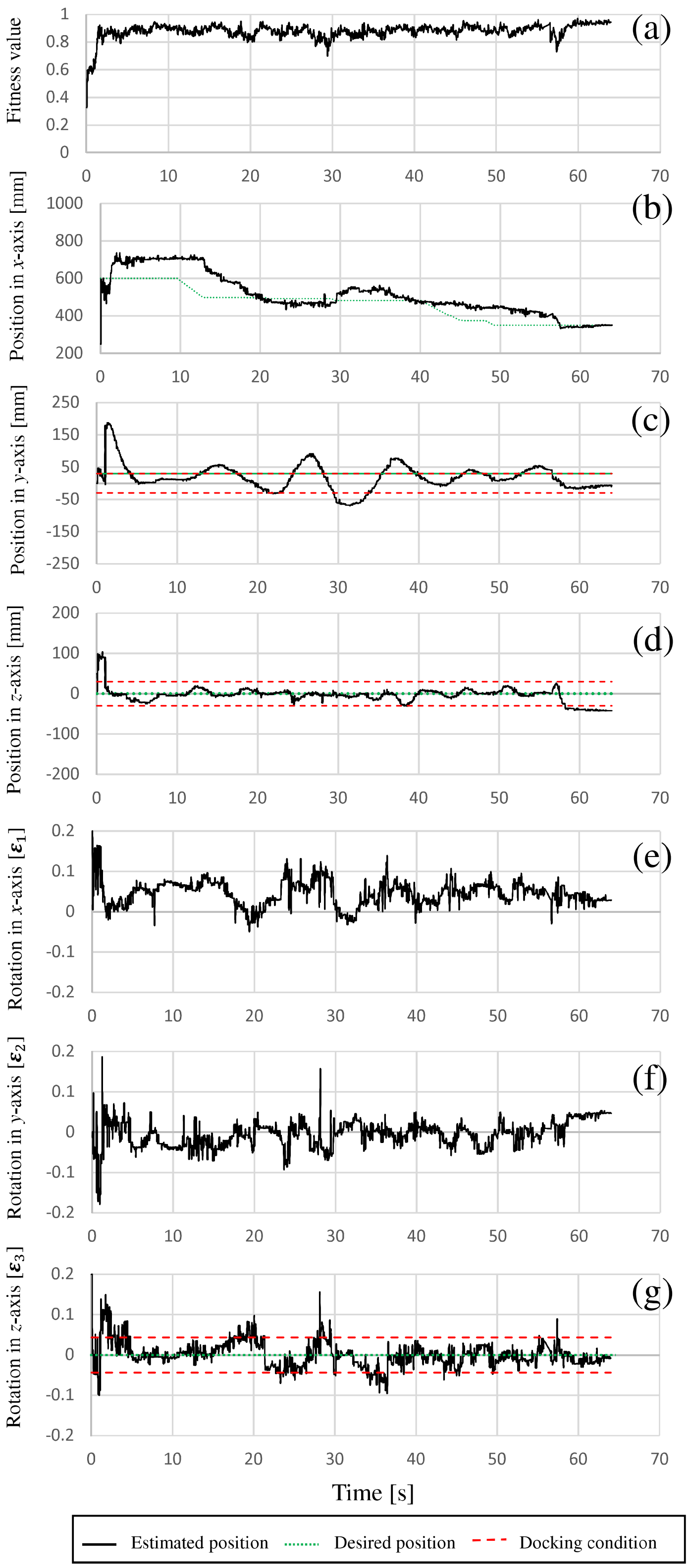


Fig. 12. Docking experimental result with rectangular shaped tail fin (See Fig. 10 (b)): (a) Fitness value, (b) Position in x-axis, (c) Position in y-axis, (d) Position in z-axis, (e) Rotation in x-axis, (f) Rotation in y-axis, and (g) Rotation in z-axis.

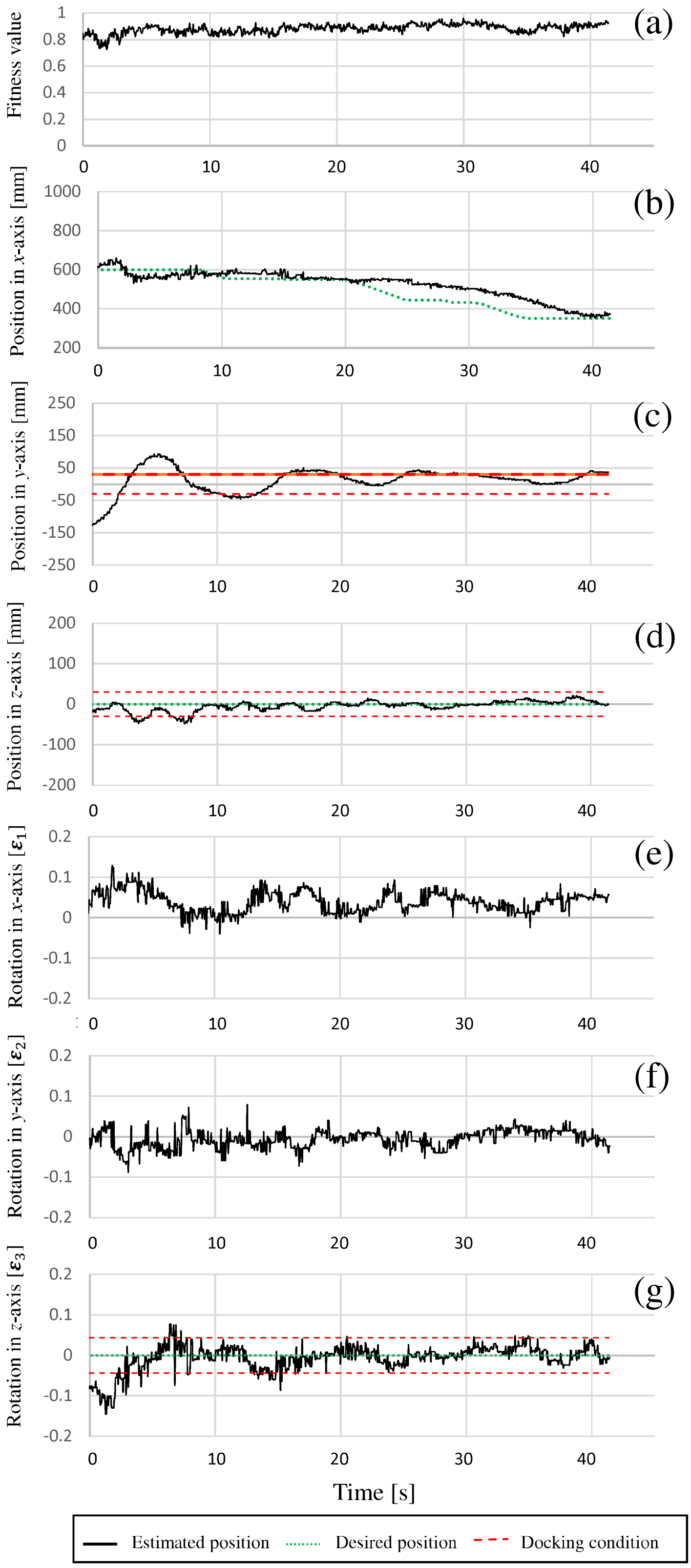


Fig. 13. Docking experimental result with triangular shaped tail fin (See Fig. 10 (c)): (a) Fitness value, (b) Position in x-axis, (c) Position in y-axis, (d) Position in z-axis, (e) Rotation in x-axis, (f) Rotation in y-axis, and (g) Rotation in z-axis.

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