

Dual-eyes Visual-based Sea Docking for Sea Bottom Battery Recharging

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Abstract—In this paper, a robust stereo vision-based sea docking for autonomous underwater vehicles (AUVs) for sea bottom battery recharging is presented. Docking station is unidirectional one which requires high homing accuracy and robustness against difference disturbances. Real-time pose tracking was developed using stereo vision from two cameras and known 3D marker. Real time relative pose estimation was implemented as software implementation utilizing 3D model-based matching method and real-time multi-step GA. Remotely Operated Vehicle (ROV) with maximum depth 50 m is used as a test bed. Successful docking operation using proposed system demonstrated for underwater battery recharging was conducted in the sea, near Wakayama City, Japan. Experimental results confirmed the robustness of the system proving homing accuracy on the order of centimeter under real-world conditions.

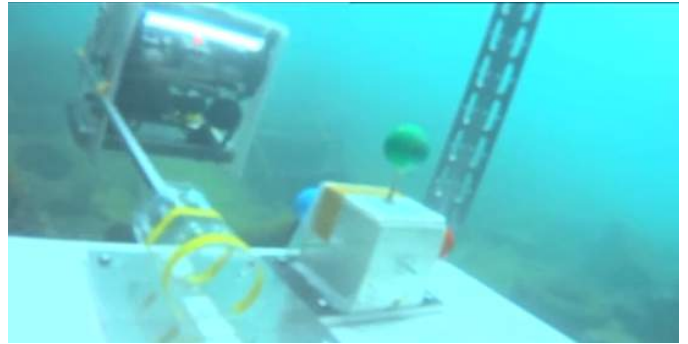


Fig. 1. Sea docking system for underwater battery recharging

I. INTRODUCTION

Nowadays, AUVs are being used in many applications such as underwater cable tracking, sea bottom surveying and inspection of underwater structures (dams, bridges). However, there is limitation for underwater vehicles for operations that take longer duration than power capacity of underwater vehicles. Even though advanced technology related to power devices provides long operation period, underwater vehicles has to come surface vessel for recharging when operations take couples of days. To overcome this issue, underwater recharging station with docking function has being implemented recently using different kinds of approaches. On the other hand, docking operation has become noble capability of AUVs for advanced applications such as sleeping under mother ship, downloading next target instruction, navigation and intervention using some manipulators. With this motivation, we have developed vision-based docking system for underwater battery recharging to extend the operations of AUVs.

There are many studies on underwater docking using different approaches [1]-[11]. Depending on docking station's structure for specific application, approaching method and sensors were utilized. According to the simplicity and effectiveness for intended application, we also selected and designed unidirectional station to which underwater vehicle has to approach in appropriate path and dock in a single entry. Therefore, accurate homing accuracy and robustness against disturbances due to water current came in picture as critical requirements for docking operation. To fulfill these demands, many studies has been conducted recently. Localization of vehicle and station

has being implemented using different kinds of sensors and techniques. Navigation and homing accuracy are from meter level to centimeter level depending on applications. Aiming for precise accuracy for battery recharging application, docking home with diameter of 7 cm was designed in this work. For this kind of precise accuracy, vision information is dominant among other sensors. Therefore, we have developed vision-based docking system using two cameras and a known 3D marker.

In previous works [12]-[14], several assumptions and design considerations are made. We confirmed regulating performance in which the vehicle performs visual servoing in desired pose using real time estimated pose. In [12], real time pose tracking was also confirmed when the target was moving even though there were some noise in captured images due to air bubble in front of cameras. Not only noise disturbance in image but also physical disturbances due to ocean current were considered to make proposed robust to be able to operate in real sea. In [13], we implemented docking procedure and conducted for demonstration of underwater battery recharging. As a follow-up work, we also checked the robustness of our system under varying light environment in [14]. These previous works were conducted in indoor pool. Finally, we have conducted docking operation in the sea, near Wakayama city in Japan for demonstration of sea battery recharging. Experimental results are discussed as the main contribution of this paper. To the best of authors knowledge, this work is very new and the first one in underwater vehicle environment about docking operation using standalone dual-eye camera.

This paper is organized as follows: Section II presents the proposed docking system for underwater vehicle. Section III and IV describe sea docking experiments, and results and discussion respectively. The final section contains the conclusion and further work.

II. DUAL EYES VISION BASED DOCKING SYSTEM

Figure.2 shows the block diagram of proposed system. Images from dual-eye camera installed on a ROV are sent to the PC. Real-time pose estimation using 3D model based matching method and real-time multi-step GA is implemented as software implementation in PC. Based on the error between the desired pose and estimated pose, 3D motion controller outputs control signals to control the thrusters of the vehicle. Interface unit is for image capturing and digital to analog converting between the vehicle and PC.

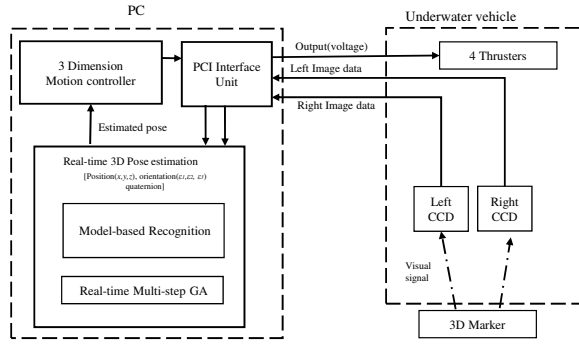


Fig. 2. Block diagram of the proposed System

A. Underwater vehicle

Hovering type underwater vehicle (manufactured by Kowa cooperation) is used as a test bed as shown in Fig.3. Two fixed cameras installed at the front of the vehicle are used for real time pose tracking. In thruster unit, four thrusters with maximum thrust force of 4.9 each are controlled to move the vehicle along desired path. The vehicle can dive up to 50 m and two LED light sources are also installed on the vehicle.

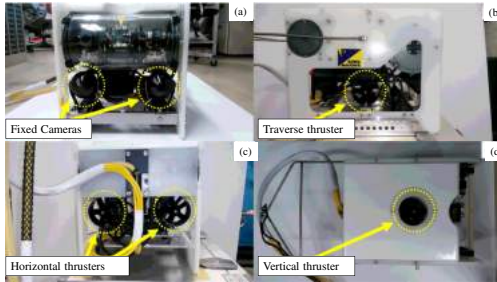


Fig. 3. Overview of ROV (a)Front view (b)Side view (c)Back view (d)Top view

B. Docking Station

Docking station that is unidirectional type was designed to demonstrate sea underwater battery recharging as shown in Fig.4. The size of the docking station is 60 cm × 45 cm × 180 cm. Since docking hole with diameter of 7cm and 3D marker was fixed in docking station, the vehicle has to approach and performs docking operation in one direction precisely.

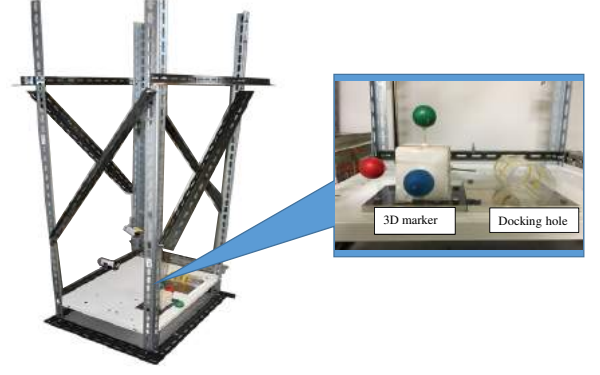


Fig. 4. Docking station with 3D marker

C. Docking Procedure

We designed docking procedure as shown in Fig.5. There are three steps to complete docking operation.

1) *Approaching step*: Normally, this step is performed using long distance navigation sensor unit. In this work, the vehicle was controlled by manually to approach the docking station till 3D marker was detected by proposed system.

2) *Visual servoing step*: After detecting 3D marker, relative pose between the vehicle and 3D marker is estimated using 3D model-based matching method and real-time multi-step GA. Using estimated pose, the vehicle was controlled automatically using proposed system to follow the desired pose.

3) *Docking step*: When the vehicle is stable in defined position for defined period for docking operation while visual servoing, docking step is performed in which the vehicle inserts its docking pole into the dock hole. Please note that whenever the relative pose error exceeds allowance range, the process switches to the visual servoing as shown as P in Fig.5.

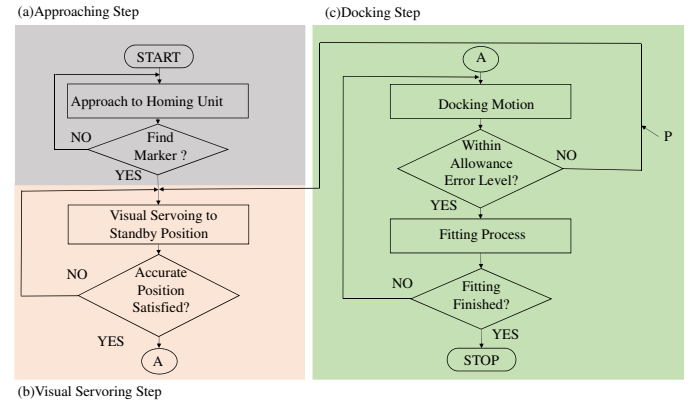


Fig. 5. Flowchart of Docking Strategy

D. Real time pose tracking using stereo vision

Instead of calculation of absolute position of vehicle and target in docking station, estimated relative pose is input as feedback to the control system. Avoiding to the limitation of features based recognition especially wrong mapping corresponding features in images, 3D model-based recognition based on 3D to 2D projection was applied in proposed system.

The information of 3D marker that are size, shape, color information are known and defined as model in computer system. Models with different pose are projected to 2D images and compared with captured images from two cameras. Then estimated pose of the best model that is matched totally to the captured images is assumed to be truthful estimated pose for control system. To perform in real time, we used GA with long history and modified as real-time multi-step GA for searching the best model. Matching degree is evaluated using fitness function based on voting performance. The detail explanation of fitness function is discussed in [16]. Figure.6 shows the flowchart of real-time multi-stpe GA and how the best model is searched. Real time pose is estimated every image with image frame rate of 33 ms.

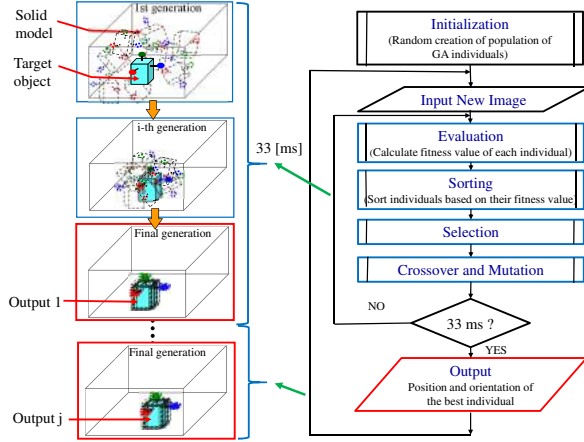


Fig. 6. Pose estimation using real-time multi-step GA

Because of self stabilization and less effective, roll and pitch angle are neglected in controlling of movement of vehicle. Therefore, 4 DoF (x_d [mm], y_d [mm], z_d [mm] and ϵ_{3d} [deg]) are considered in 3D pose tracking control system. P controller is applied in control system with feedback using estimated pose from 3D model based recognition. The control voltages of four thrusters are calculated by the following proportional control laws.

$$v_1 = k_{p1}(x_d - x) + 2.5 \quad (1)$$

$$v_2 = k_{p2}(\epsilon_{3d} - \epsilon_3) + 2.5 \quad (2)$$

$$v_3 = k_{p3}(y_d - y) + 2.5 \quad (3)$$

$$v_4 = k_{p4}(z_d - z) + 2.5 \quad (4)$$

where x_d , y_d , ϵ_{3d} and z_d are desired relative value based on Σ_H against 3D marker (see Fig.7), and v_1 , v_3 and v_4 are the voltages for thrust of x-axis, y-axis and z-axis direction respectively. ϵ_{3d} stands for rotation angle around z-axis. v_2 means the voltage for torque around z-axis. 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. Based on experimental results, gain coefficients are tuned to have better performance in virtual servoing.

III. SEA TRIAL EXPERIMENT

Our team conducted the first at-sea docking trials near Wakayama city, in Japan. The docking station was a rectangle of 60 cm $\times$ 45 cm, oriented with the long sides perpendicular

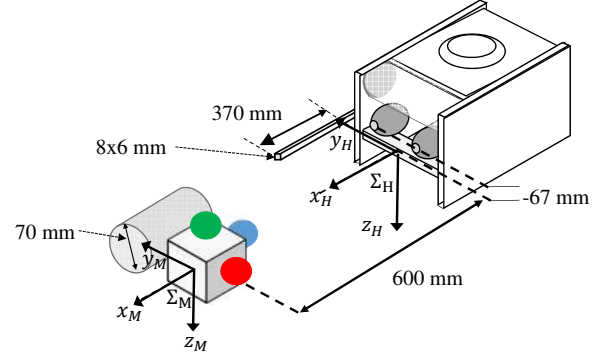


Fig. 7. Docking Experimental Layout

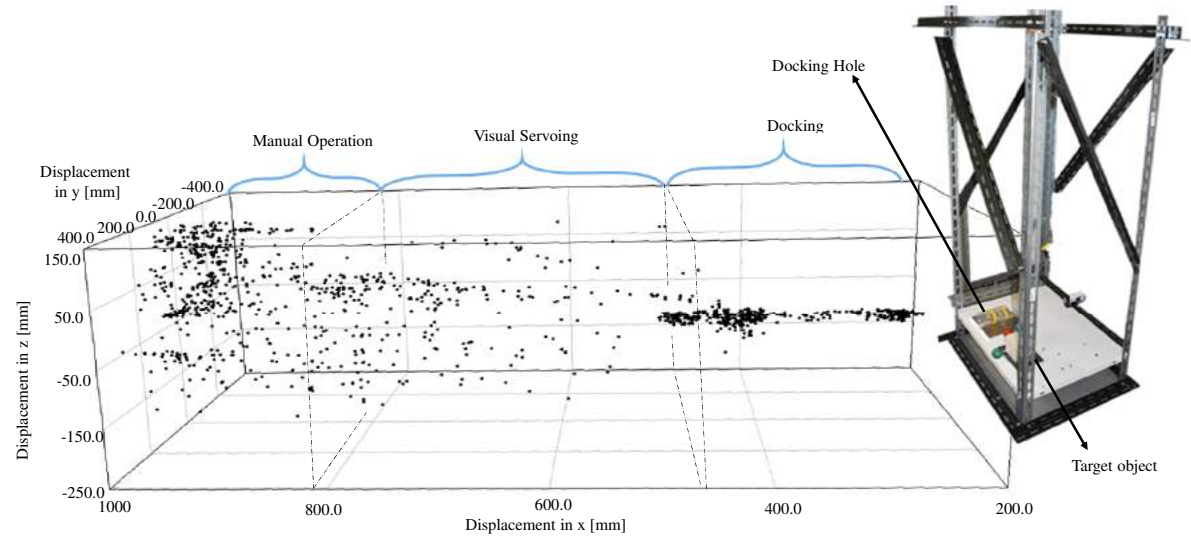
to the shore. Docking tests began with the vehicle in front of dock with distance of 3.5 m from the dock. The buoyancy force was nearly 1.03 times than that of fresh water, and there was some gentle waves while conducting experiments. The ROV was tethered and connected by a cable with 200 [mm] length to the onshore platform. For demonstration of underwater battery recharging, docking pole attached on vehicle and docking hole fixed with 3D marker as shown in Fig.7 was designed. Therefore, the main task is to insert docking pole into the docking hole automatically controlling the vehicle by visual servoing. Firstly, the vehicle approached to the dock by manually until the 3D marker was in the field of view about 1.5 m distance. In visual servoing step, the vehicle goes to the desired pose as shown in below for docking. When the vehicle is stable with position of ± 20 mm in image plane (y, z) for 165 ms, the vehicle goes ahead to insert decreasing the distance between vehicle and target in x-axis direction gradually until it reaches 350 mm.

$$\begin{aligned} x_d &= {}^H z_M = 600 \text{ (350)} [mm], \\ y_d &= {}^H x_M = 0 \text{ (0)} [mm], \\ z_d &= {}^H y_M = -67 \text{ (-67)} [mm], \quad \epsilon_{3d} = 0 \text{ (0)} [deg] \end{aligned}$$

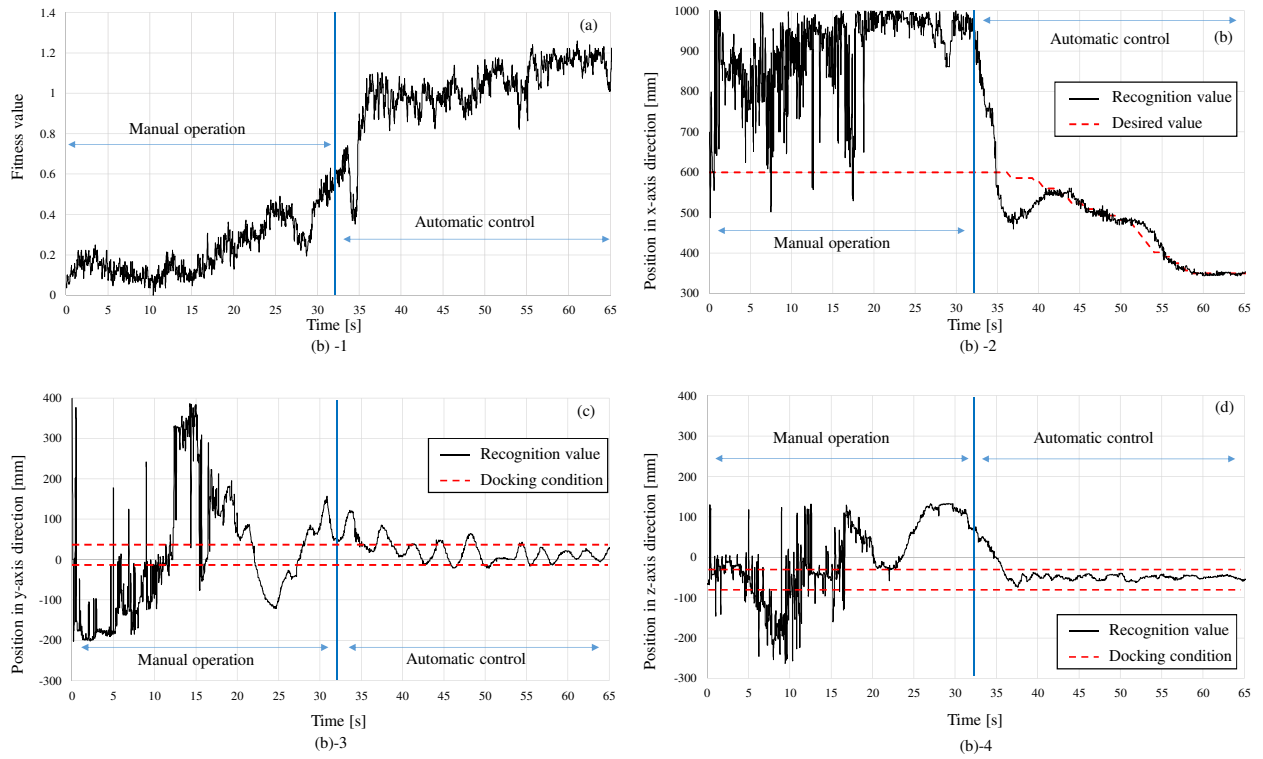
IV. RESULT AND DISCUSSION

We conducted docking operation in the sea for four times successfully. Figure.8 shows experimental results of the first docking operation. Figure. 8 (a) shows recognized position tracking of the vehicle during docking process. According to the results, visual servoing step was started when fitness value was above 0.6 and the distance between the vehicle and the station was about 800 mm. Time profile of fitness value is shown in Figure. 8 (b-1). Recognized position of vehicle in x, y, and z axis is illustrated in Fig.8 (b)2-4. It can be seen that docking step was performed when the position errors in y-axis and z-axis were within predefined range that was ± 20 mm. It can be confirmed that the docking operation was success within 40 s after recognition 3D marker.

Serial docking results are shown in Fig.9-11. It can be seen in Fig.9-11 (a) that fitness value was above 1 when 3D marker was detected by proposed system. All docking operations were finished successfully within 40 s after automatically control started. There were some pose fluctuations because of sea current. However, the vehicle can be maintained by visual servoing using proposed system and finally performed docking operation successfully.



(a) Position trajectory during docking operation



(b) Time profile of fitness value, position and pose during docking operation

Fig. 8. Docking result 1 : (a) Position trajectory and time profile of fitness value((b)-1) and recognized positions in x,y,z axis direction((b)-2,3,4)

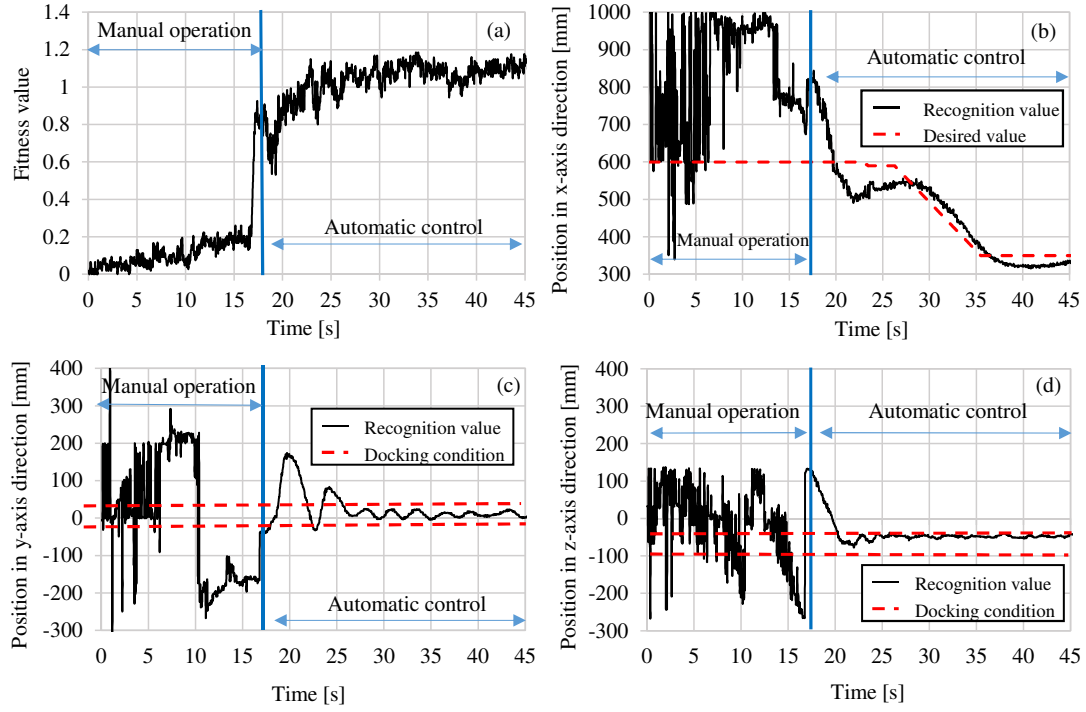


Fig. 9. Docking result 2 : (a) fitness value, ((b)-(d)) recognized positions in x,y,z axis direction

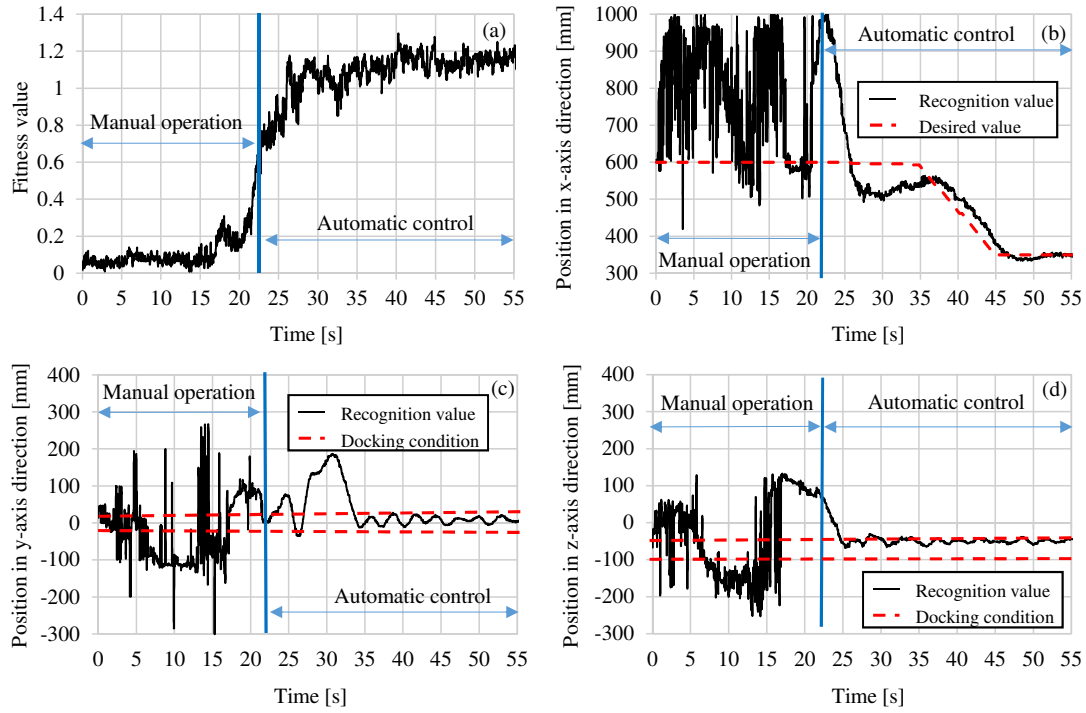


Fig. 10. Docking result 3 : (a) fitness value, ((b)-(d)) recognized positions in x,y,z axis direction

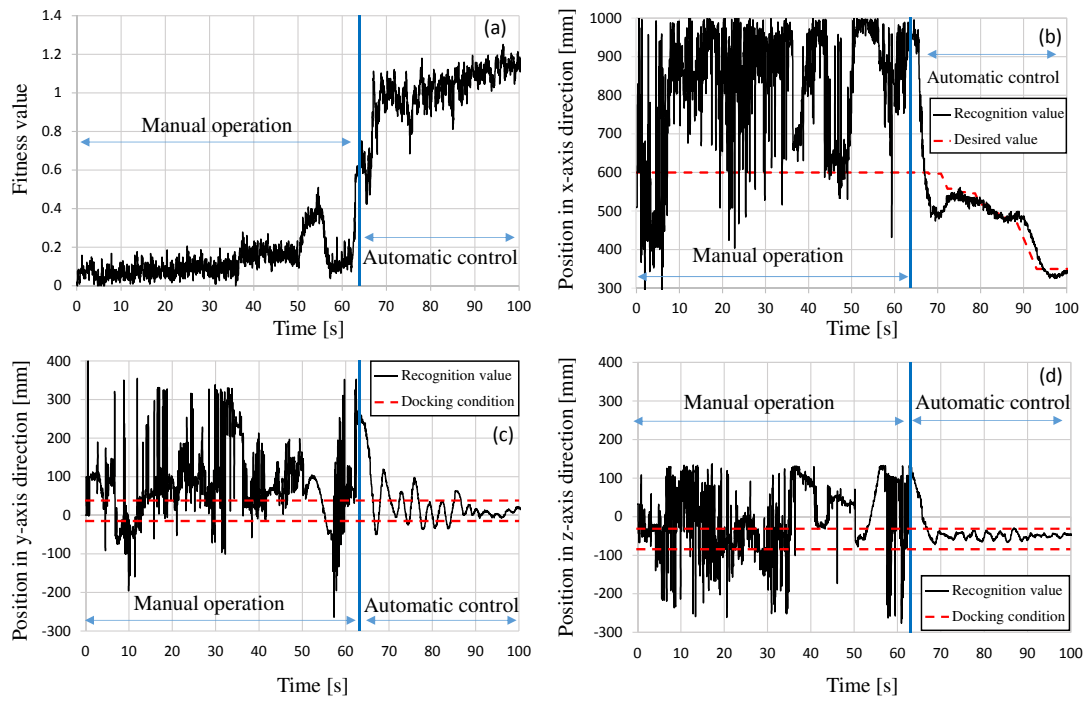


Fig. 11. Docking result 4 : (a) fitness value, ((b)-(d))recognized positions in x,y,z axis direction

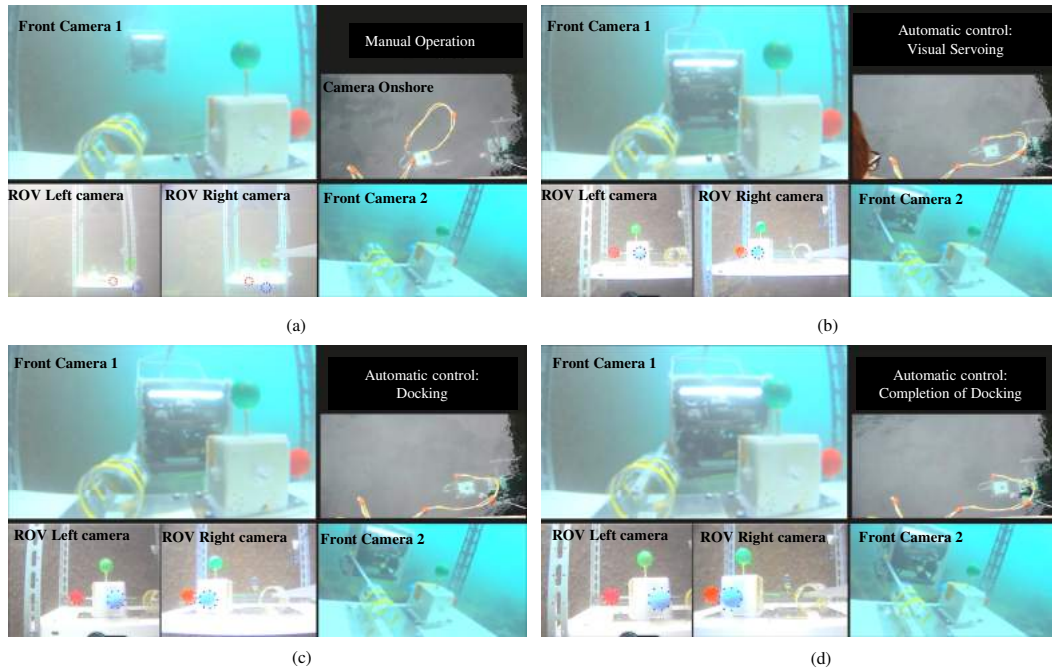


Fig. 12. Docking process : (a) Approaching step by manual control, (b) Visual servoing step, (c) Docking step, and (d) Docking completion

Please note that the recognized poses during manual control are not truthful ones and not used in feedback system because detection of 3D marker was defined by fitness value that is 0.6. Therefore, automatically control was started itself when the fitness value is above 0.6 and docking operation was performed in automatic control. Regarding to accuracy, it was confirmed experimentally that both recognition and docking accuracy is centimeter level because docking hole radius is 35 mm and allowance error is ± 20 mm. Figure.12 shows docking steps while conducting sea trials.

V. CONCLUSION

In this work, sea docking experiment of underwater vehicle using two cameras and 3D marker was implemented. A docking station was designed and deployed at sea for demonstration of sea bottom battery recharging. Serial docking trials were conducted in the sea to evaluate the proposed docking effectiveness. Performance of real time pose tracking using standalone two cameras and 3D marker was confirmed to be able to provide accurate recognition and docking accuracy. Docking operation with an actual AUV in sea trials is our future work.

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