Vision-based Docking Simulation of Underwater Vehicle Using Stereo Vision under Dynamic Light Environment

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Abstract– This paper presents a visual-based docking simulation for autonomous underwater vehicle (AUV) under unknown environment that offers huge challenges for visual servoing. For relative pose estimation in real-time, model-based recognition approach is applied using two cameras and 3D marker. Real-time Multi-step Genetic Algorithm (GA) is utilized to evaluate the gene candidates which represent relative poses until getting the best gene with the most trustful pose. The proposed system is implemented in PC, and the Remotely Operated Vehicle (ROV) is tethered through the cable with 200 m length to receive image information and control signals. We conducted experiments in simulated environment in which light is changing dynamically to confirm whether the proposed system can operate docking task under unknown environment. Experimental results showed that docking operation under unknown lighting environment was completed successfully by only mean of virtual servoing using proposed system following designed docking strategy with promising effectiveness.

Key Words: Visual servoing, Underwater vehicle, Docking experiments, Dynamic light envrionment

1 Introduction

Nowadays, docking operation has become very essential in advanced applications such as underwater batteries recharging, up loading 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 docking. Among them, docking step is a 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 [1)-3)] and techniques [4)-6)] for the underwater robots. Different kinds of sensors such as global navigation satellite system (GNSS), inertial navigation system (INS) and acoustic sensor have been used for vehicle localization. In spite of expensive navigation sensor suit and large scale dead reckoning sensors being used to provide accurate position data, the final approach of docking process especially for unidirectional docking station is still a difficult task. 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.

However, one of the challenging problems to be solved for vision-based systems in unknown environment is illumination variation. There are few studies with discussion on the problems of illumination variation for underwater vehicles especially for docking applications. To achieve docking process with adaptability to illumination variation, therefore, we have developed vision-based docking system with light adaptation system for dynamic light environment.

The structure of this paper is as follow. Section II describes concepts and the structure of proposed docking system for underwater vehicle. Experimental results to assess the performance of the proposed system are described in Section III with discussion. The final section concludes the paper.

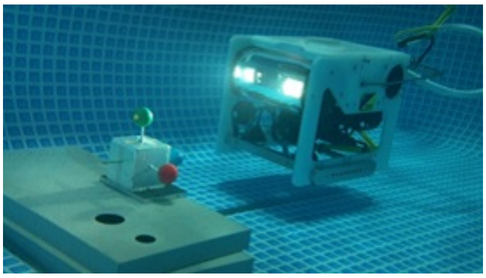

Fig. 1: Underwater vehicle and 3D marker.

2 Proposed Docking System

2.1 Visual Servoing System

Fig.2 shows the block diagram of proposed visual servoing system using two cameras. 3D marker consists of three balls with red, green and blue color. In this system, series of images with video frame rate of 33 ms captured by the dual-eye cameras installed on underwater vehicle are sent to the PCI interface unit in PC through the cable. Real-time relative pose of underwater vehicle is estimated using 3D model-based pose estimation algorithm. Then, based on the error between estimated and desired pose, the 3D motion controller outputs voltage signals as the feedbacks to control the vehicle in desired pose. The control parameters for the ROV are x_d[mm], y_d[mm], z_d[mm] and ϵ_{3d}[deg].

2.2 Model-based recognition using real-time Multi-Step GA

3D model-based recognition based on 3D to 2D projection is utilized to estimate relative pose between

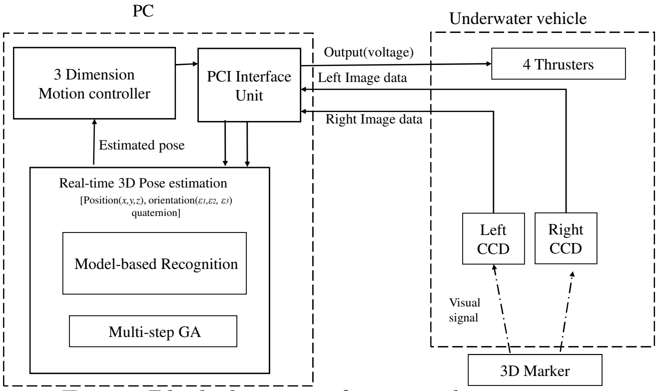

Fig. 2: Block diagram of proposed system.

vehicle and 3D marker. Knowing the information of the target and predefined relative pose to the ROV, the solid model of the target is predefined in computer system and projected to 2D images. Then the desired pose relationship is established by comparing the virtual projected images and the captured ones.

Fig.3 shows Model-based recognition system using dual-eyes vision system. Models representative to six pose parameters; (x, y, z, ϵ_1, ϵ_2, ϵ_3), where the (x, y, z) is position in Cartesian coordinate frame and the (ϵ_1, ϵ_2, ϵ_3) shows the orientation defined by quaternion, encoded by 12 bit each are initiated randomly. The model that has the highest matching degree with target represents the estimated relative pose.

Therefore, the problem of pose recognition addresses to the searching problem. The solution is GA with promising speed and accuracy of performance. According to the performance in time-domain, GA is selected and modified as real-time Multi-step GA in this work even though there are advanced optimized techniques. Detail discussion about real-time Multi-step GA is explained in [14].

2.3 Docking Simulation

There are three steps in proposed docking operation. In approach step, the vehicle will approach to docking station until the 3D marker is detected. However, according to the space of indoor pool in this experiment, we implemented approach step just to control the vehicle to go forward and detect the 3D marker. After detecting the 3D marker with minimum fitness value that is 0.6 in this experiment, visual servoing step is performed to control the vehicle

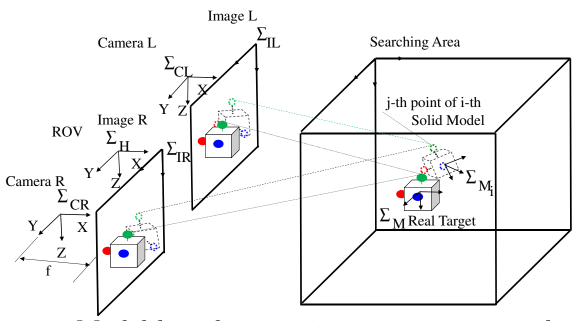

Fig. 3: Model-based recognition system using dual-eyes vision system.

to be regulated in desired pose (x_d = 600 mm, y_d = 0 mm, z_d = -67 mm, ϵ_{3d} = 0 deg). To transit to docking step, we set up allowance error level to check whether the vehicle is in suitable pose to make docking. There are two checking criteria before docking. Firstly, the vehicle has to stable with defined tolerance of position error in image plane. We defined tolerance of position error to be ±20 mm because the radius of docking hole is 35 mm. Then, the vehicle has to stable for defined period that is 165 ms in this experiment. When these two conditions are satisfied during visual servoing, the vehicle performs docking process in which the rod attached to the vehicle fit into the docking hole fixed besides 3D marker. Note that switching between docking and visual servoing step based on allowance error makes the docking operation more smoothly with gentle surfacing the dock hole. Due to field of view of camera, the search area is defined as shown in Fig.5.

2.4 Controller

The proposed control system is 4 DoF (x_d, y_d, ϵ_{3d} and z_d) based on Σ_H against 3D marker (see Fig.5). Controlling rotations around x and y-axes of $\sum_H$ (ϵ_{1d}[deg], ϵ_{3d}[deg]) are neglected because of their self-stability and less effectiveness to ROV's motion in this experiment. Conventional Proportional controller is used to compensate the error between desired pose and recognized one. 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.5), and v_1, v_3 and v_4 are the voltages for thrust of x-axis, y-axis and z-axis direction respectively. v_2 means the voltage for torque around z-axis.

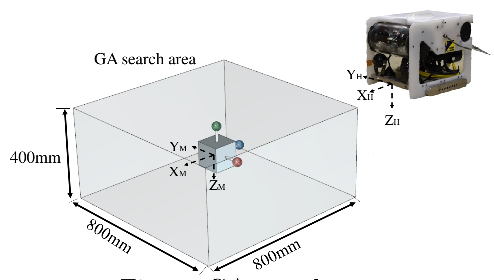

Fig. 5: GA search area.

2.5 ROV as a Test-bed

The ROV shown in Fig. 6 manufactured by Kowa corporation, is used as a main test-bed for proposed

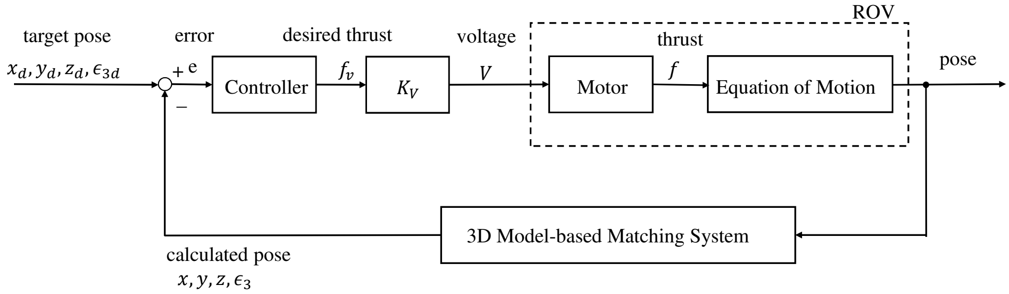

Fig. 4: Block diagram of the vision-based control System.

experiment. Two fixed forward cameras with the same specification (imaging element CCD, pixel number 640 × 480, pixel focal length 5 mm, signal system NTSC, minimum illumination 0.8 Lx, no zoom) are mounted on the ROV. The thruster system of the ROV consists of two horizontal thrusters with a maximum thrust of 4.9 N each, one vertical thruster and one lateral thruster with a maximum thrust of 4.9 N each. In addition, the ROV is equipped with two units of LED lights (5.8 W) as the illumination source.

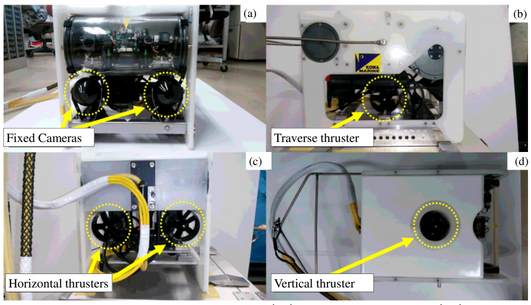

Fig. 6: Overview of ROV (a)Front view (b)Side view (c)Back view (d)Top view.

2.6 Proposed Light Adaptation System

The proposed light adaptation system is based on the concept that the information of illumination variation due to dynamic light environment can be enquired from sequential images captured in real-time. Therefore, two criteria of light adaptation system for 3D model-based recognition against illumination variation are as follow;

2.7 Detection of 3D marker in hue value

Due to less sensitive to environment, hue space is used to detect 3D marker. Then, due to the distance in degree in hue space, three basic colors (blue, red and green) are selected for 3D marker.

2.8 Active hue range

In stead of using fixed hue range to detect 3D marker in every images, hue range for next images are updated from the distribution of histogram of color objects in hue space from previous image.

The proposed lighting adaption algorithm is as follow:

1. Initiate recognition process using defined standard hue values for each basic color.
2. Select the sampling points in previous recognized object area through projection from estimated pose.

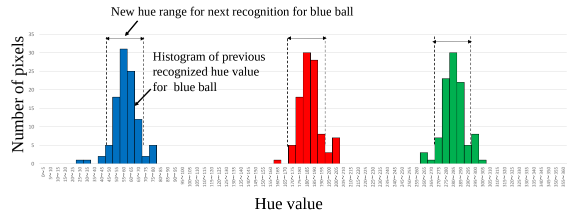

Fig. 7: Updating new hue ranges based on distribution of previous recognized object histogram.

3. Get the hue value corresponding to each point on the image.
4. And automatically adjust the range of hue values to be used for follow-up recognition according to the distribution of the hue.

3 Experimental Results and Discussion

3.1 Experimental Environment

Experiments were conducted in indoor pool (3 m in length, 2 m in width, 0.75 m in depth). To simulate dynamic lighting environment in term of both illumination intensity and direction variation, LED light source installed on ROV was configured to provide different illumination intensity and direction.

3.2 Docking Performance using Proposed System

Finally, we conducted experiments to confirm whether the proposed system using light adaptation system can operate docking task under unknown environment. In order to perform docking experiments, a rod on the right side of the underwater robot and cylinder hole on the left side of the target are designed as shown in Fig.10. When the robot is in the right relative pose to the object, then it has to move ahead to insert the rod into the cylinder hole. The desired pose before and after docking operation is assigned as below. The values in bracket are the desired pose when the docking operation is completed. Fig.10 shows docking experimental layout with coordinates of vehicle and 3D marker.

$$x_d = {}^H z_M = 600\ (350)[mm],$$
$$y_d = {}^H x_M = 0\ (0)[mm],$$
$$z_d = {}^H y_M = -67\ (-67)[mm], \quad \epsilon_{2d} = 0\ (0)[deg]$$

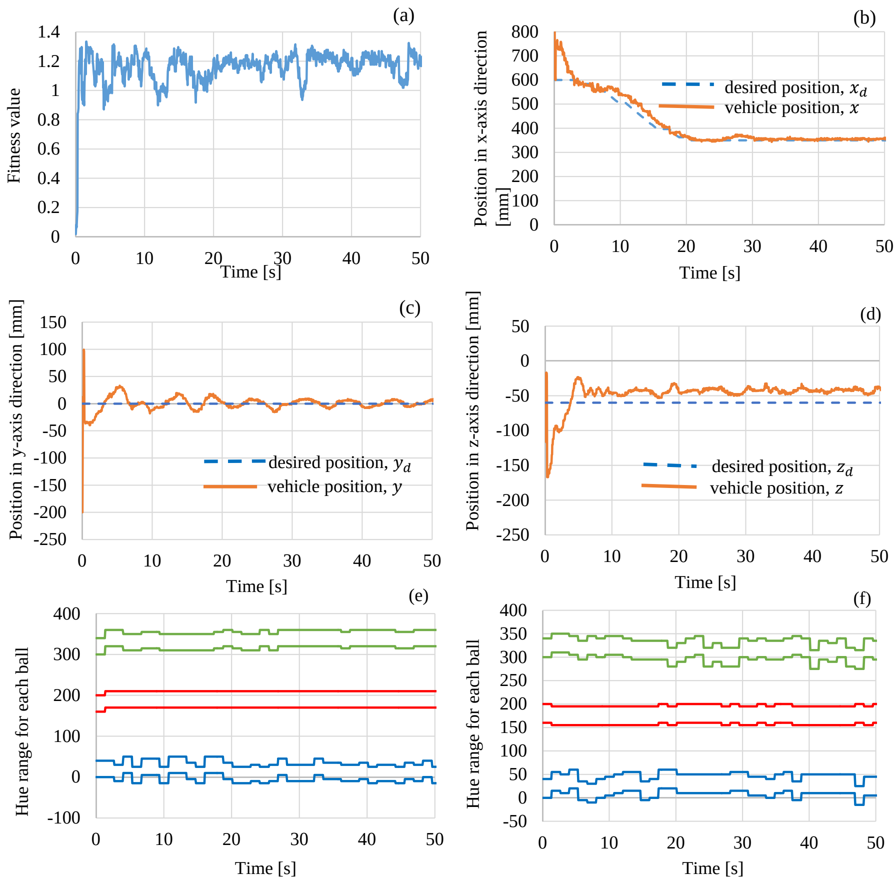

Fig. 8: Docking Performance with Lighting Adaptation System: (a) fitness value, (b) position in x-axis direction, (c) position in y-axis direction, (d) position in z-axis direction (e) hue range to detect 3D marker in left image, and (f) hue range to detect 3D marker in right image.

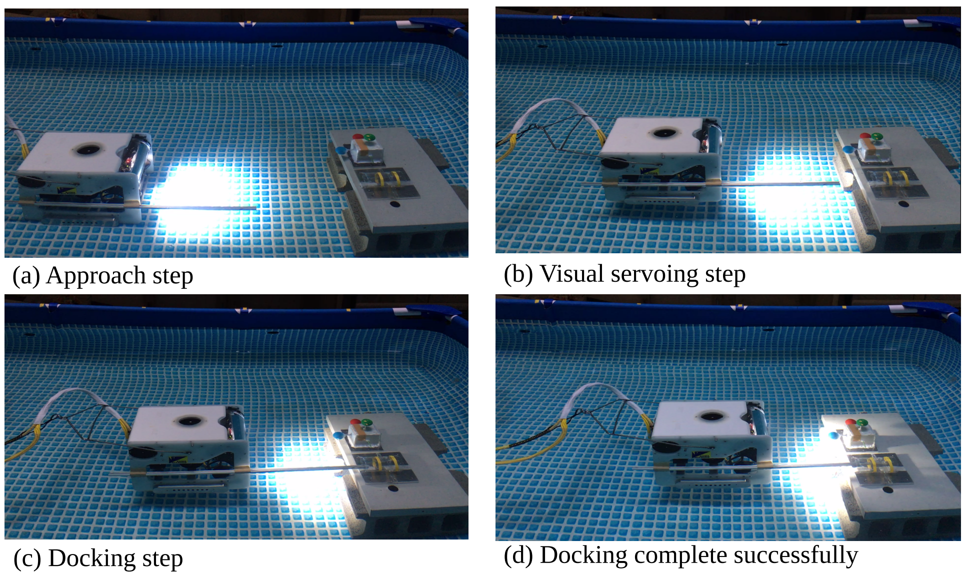

Fig. 9: Docking Process: (a) Approach step, (b) Visual servoing step, (c) Docking step, (d) Docking completed successfully.

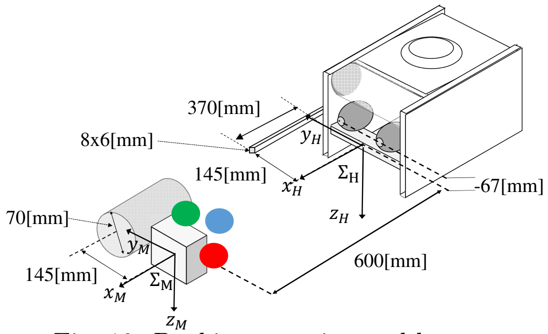

Fig. 10: Docking experimental layout.

Fig.8(a) shows the fitness value of recognition during docking operation under unknown light environment. As showm in Fig.8(c), visual servoing step was transited to docking step after 10 seconds when the vehicle is stable with allowance position errors ± 20 mm for 165 ms. Fig.8(b), (c), (d) show the real-time position of vehicle following desired pose. Fig.8(e), (f) shows the active hue range updated in real-time for recognition in left and right images. Fig.9 shows the docking process step by step. Therefore, we concluded that docking experiment under unknown lighting environment is completed successfully by only mean of virtual servoing using adaptive system following designed docking strategy within 50 seconds.

4 Conclusion

In this work, vision-based docking system for underwater vehicle was implemented. A unidirectional docking station with 3D marker was simulated in indoor pool. A real-time pose tracking using 3D model-based recognition and real-time Multi-step GA was proven for high homing accuracy. In addition, to overcome illumination variation problem due to dynamic light environment, light adaptation system was designed and implemented. Finally, docking experiment was conducted successfully using proposed system under unknown light environment. Follow-up docking experiments in an actual AUV in sea trials will be conducted in future.

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