Experiment on Underwater Docking of an Autonomous Underwater Vehicle 'ISiMI' using Optical Terminal Guidance

Jin-Yeong Park†, Bong-Huan Jun‡, Pan-Mook Lee‡, Fill-Youb Lee‡ and Jun-ho Oh†

†Humanoid Robot Research Center, Korea Advanced Institute of Science and Technology
373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea
‡Maritime and Ocean Engineering Research Institute, Republic of Korea

***Abstract*— An AUV (Autonomous Underwater Vehicle) being able to dock without surfacing to a launcher or an underwater station can give us long-time duration. It is important for the AUV to be guided to the dock safely. This paper introduces a test bed platform AUV named ISiMI and her optical terminal guidance system. ISiMI uses the optical terminal guidance system for underwater docking. The guidance system consists of a hardware part and a software part. One CCD camera and a frame grabber constitute the hardware part. An image process and a final approach algorithm based on visual servo control are the software part. A dock center which is a final approach target position of ISiMI is estimated by the image process and a reference yaw and pitch are generated by the final approach algorithm. We developed, also, an auxiliary controller to reinforce the final approach algorithm. This additional controller is necessary because there is an area where ISiMI cannot see the target lights near the dock. This makes the performance of docking better. Underwater docking experiments were conducted and the results are included in this paper.**

***Key Words*—Autonomous Underwater Vehicle, Final approach algorithm, Optical terminal guidance, Underwater docking**

I. Introduction

Underwater docking of an AUV to an launcher without surfacing makes the AUV have a long-term duration and repetitive investigations. Data uploading, mission downloading and recharge of batteries are essential duties of the docking system. Many methods are being developed to guide an AUV into the launcher safely. An Electromagnetic Homing (EM) system was proposed as one of them [1]. A magnetic field generated by coils on the dock was used. An AUV who sensed the magnetic field by coils had been developed. The range of the EM system was limited to 25-30m. An optical terminal guidance system was introduced [2]. This system was simple but highly effective. The optical docking system was provided targeting accuracy on the order of 1 cm under real-world conditions, even in turbid bay water. Ref. [3] showed autonomous docking demonstrations. An USBL (Ultra -Short Base Line) acoustic homing array was used. The acoustic system is capable of acquiring a dock mounted transponder at ranges of 3,000m or more.

We have adopted an optical system with a visual servo algorithm as a docking method. We introduced a visual servo control algorithm using one camera for underwater docking [4]. Ref. [4] developed an optical flow equation. This optical flow equation was combined with linearized equation of motion of the AUV. A state equation for the visual servoing AUV was derived. Also, a MIMO controller minimizing a cost function was designed. Simulations were performed to demonstrate the performance of the developed controller. We used the equation of motion of REMUS AUV. The equation of REMUS came from [5]. We supposed that a CCD camera was installed at the nose part of REMUS AUV. The results of the simulations showed that the controller could regulate the AUV to track the docking path into her target within 5 seconds. When the AUV was within 1.4m from the dock, the lights installed on the dock were outside of the viewing range of the camera. In this area, the visual servo controller was invalid. A necessity of an auxiliary method to reinforce the visual servo controller was suggested.

We developed a homing and docking algorithm [6]. For homing, the shortest homing path generated by a cubic spline function with optimization technique was proposed. For docking, we used a vision system. We assumed that 5 lights were installed on the entrance of the funnel-shaped dock and the AUV knew the geometric arrangement of the lights. It was proposed that the relative position and pose between the AUV and the dock could be calculated by using the geometric fact.

To prove the designed and proposed algorithm, we have developed a test bed platform AUV named ASUM (Advanced Small Underwater Model) [7]. She is 1.2m length and 0.17m diameter. She is a prototype of ISiMI, whom we will introduce. She has a role as a platform to test and try with low cost new developed algorithms and systems. Lead acid batteries were used. One CCD camera was equipped. A PC/104+ type single-board computer with 300MHz CPU was used. OS (Operating System) was Windows 98, Microsoft. A main

Corresponding Author: Jinyeong Park
E-mail: mypleasure@kaist.ac.kr, Phone: +82-42-869-3263,

1-4244-0635-8/07/$20.00 ©2007 IEEE

controller based on TMS320F240 DSP was designed to interface actuators and sensors. A real-time controller could not be embedded because the CPU of the computer was not enough fast. A docking system was introduced. Five lights were installed in the entrance of the dock. Locations and brightness of the lights are adjustable.

We have improved the inner system of ASUM and gave her a new name, ISiMI. ISiMI is an acronym of Integrated Submergible for Intelligent Mission Implementation. A newly upgraded single-board computer gives her a real-time control ability and a fast image process. Also, in this paper, we introduce her optical terminal guidance system. A final approach algorithm of this guidance system is based on visual servo control. But as stated above, just visual servo control is insufficient and invalid in the area near the dock where the lights of the dock are out of the viewing range of the CCD camera. We mentioned the necessity of the auxiliary methods. These methods have roles to reinforce the visual servo controller and to make more precise approach when ISiMI is near the dock. By showing experimental results, we prove the necessity of the auxiliary method. Underwater docking experiments without the auxiliary method showed imprecise approaches just before the contact of ISiMI to the dock. Additional lights may be one of the auxiliary methods. At present, lights are installed just around the rim of the entrance of the dock. A light in the center of the dock can be a good reference point for ISiMI. But additional lights mean additional cost. Hence, we focused improvement of the final approach algorithm so that it could be a proper solution. This paper will describe how we reinforce the final approach algorithm and its availability showing experimental results. Experiments with the improved algorithm show more precise approach and docking. Also, image process and how ISiMI estimates a position and a distance of the dock are described.

II. System of ISiMI

A. Appearance and Specifications of ISiMI

ISiMI has a torpedo-type appearance. Two elevators and two rudders are in her buttock. One propeller drives back- and forward movements. [Fig.1] shows the appearance of ISiMI and the specification is shown in [Table.1].

B. Schematic of Control System

There is a single-board computer as a main controller. This is a PC/104+ type with 900MHz CPU and its operating system is Windows XP, Microsoft. To realize the real-time control, we use RTX(Real Time eXtension) commercial software. Control command routine is executed with 10Hz. Both wireless RF (Radio Frequency) communication and wired LAN (Local Area Network) are available. ISiMI equips an optical terminal guidance system. This system will be described in the next section.

Fig. 1. Appearance of ISiMI: Torpedo-type, 2 rudders, 2 elevators, 1 propeller

TABLE I
SPECIFICATIONS OF ISIMI

Dimension	1,200m Length, 0.170m Diameter
Weight in Air	21 kgf
Max. Operating Depth	20m Water Depth
Operation Time	2 hours@3knots

C. Dock

We made a dock to conduct underwater docking experiments [7]. [Fig. 2] is a photograph of the dock and [Fig. 3] shows the arrangement of the lights in the entrance of the dock. From [Fig. 2], you can see that the dock is funnel-shaped. This shape makes ISiMI be possible to have a successful docking with sliding even though she has some positional error.

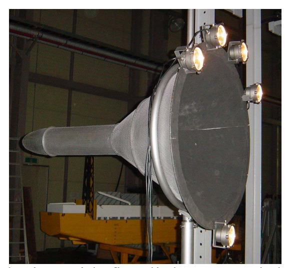

Fig. 2. The docking device with five lights around the rim of the entrance: Each location and intensity of lights is adjustable.

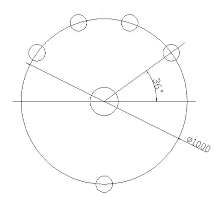

Fig. 3. Arrangement of lights: 5 lights are installed. The small circle in the center is not a light.

III. Optical Terminal Guidance System

As an underwater docking method, we have adopted the optical terminal guidance system with a visual servo algorithm. The optical terminal guidance system consists of a hardware part and a software part.

A. Hardware Part

Hardware part of this system consists of a CCD camera and a frame grabber. Block diagram is shown in [Fig.4]. [Table.2] and [Table.3] show specifications of the camera and the frame grabber respectively. The CCD camera transmits the CCIR signal to the frame grabber. The frame grabber is a PC/104+ type and grabs image frames with 10-15 Hz. [Fig.5] shows the camera and the frame grabber.

TABLE II
SPECIFICATIONS OF CCD CAMERA

Model	OceanSpy
Manufacturer	Tritech
Scanning	2:1 Interlace
Lens	3.6mm F2
Angular View in Air	51° Vertical, 40° Horizontal
Iris	Auto Iris
Operating Depth	6,000m Water Depth
Power	12~30V, 120mA
Dimension	10cm Length, 3.4cm Diameter

TABLE III
SPECIFICATIONS OF FRAME GRABBER

Model	Matrox Meteor 2+
Manufacturer	Matrox Imaging
Interface	PC/104 +
Video Source	NTSC, PAL, RS-170, CCIR
Channel	Up to 12 video inputs
Pixel Format	RGB 8:8:8 or YUV 4:2:2
Dimension	11.56cm Length, 9.6cm Width

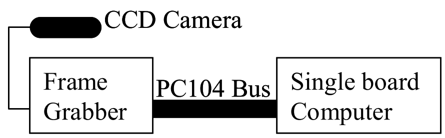

Fig. 4. Block diagram of the hardware part of the optical terminal guidance system

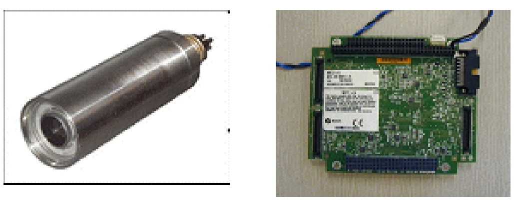

Fig. 5. CCD Camera (left) and frame grabber (right)

B. Software Part

The software part is composed of an image process and a final approach algorithm.

1) Image Process: In this paper, the image process has 4 stages. (1) Image grab, (2) Binarization of the grabbed images, (3) Elimination of noisy luminaries and discrimination of the dock lights and (4) Estimation of a position and a distance of the dock center which is a final approach target point.

Stage (1): Raw images are grabbed.

Stage (2): To discriminate the lights installed around the dock entrance, ISiMI classifies each pixel of raw images to two groups using a pre-specified threshold value; a bright group and a dark group.

Stage (3): In the underwater, there are noisy luminaries that must be eliminated. They are shown in [Fig 6]. Some objects may emit light which has a similar intensity with the dock lights. In this case, ISiMI can be confused. Especially, several lamps exist outside of the basin, and the dock lights are reflected so they make their mirror image on the water surface. These luminaries are eliminated in this stage. Stage (2) and Stage (3) are executed in the same time. Only the dock lights are discriminated and remain.

Stage (4): From positions of the discriminated lights in the camera coordinate, ISiMI estimates a position and a distance of the dock center. How to estimate the relative position and the distance was proposed in [6]. The proposed method is to derive the relative position and pose from geometric arrangement of the dock lights. Disadvantages of this method are a large amount of calculation and a difficult and complicated realization. Though it is not easy to estimate a 3-dimensional distance using 2-dimensional image data, the distance data makes contacts of ISiMI and the dock more precise. Numbers of pixels that were classified as the bright group determines a distance between ISiMI and the dock.

[Fig. 7] is a binarized image. You can see some noisy luminaries in the upper portion of [Fig. 7]. Five white points in the lower portion are the dock lights. Refer [Fig. 3]. It is seen from [Fig. 8] that noisy luminaries were eliminated and the dock lights were discriminated by this series of the image process. Estimated center of the dock is marked.

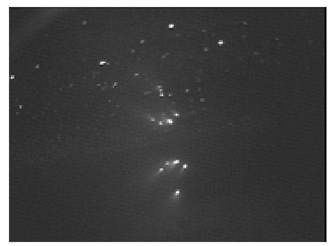

Fig. 6. Dock lights and noisy luminaries: Several lamps exist outside of the basin, and the dock lights are reflected so they make their mirror image on the water surface.

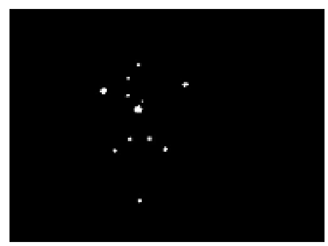

Fig. 7. Binarized image: Some noisy luminaries remain.

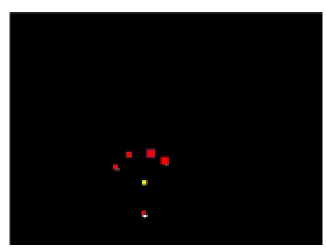

Fig. 8. Elimination of noisy luminaries and discrimination of the dock lights

2) Final Approach Algorithm: The final approach algorithm guides ISiMI to the dock. This algorithm consists of a visual servo control and an attitude keeping control.

-*Visual Servo Control*: The visual servo control guides ISiMI to the dock when all lights of the dock are positioned in the viewing range of the CCD camera. The visual servo control generates a reference yaw and a reference pitch using the estimated position of the dock. A discrepancy between the estimated dock center and the origin in the camera coordinate is used as an error input of the controller. A method of PI

(Proportional-Integrate) control is used to calculate the reference yaw and pitch from the error. ISiMI follows these reference attitudes (i.e. yaw and pitch) using a method of PD (Proportional-Derivative) control. [Fig.9] shows a block diagram of the visual servo control. Yaw motion and pitch motion are decoupled and controlled. Each values of PI, PD gains were obtained by simulations and previous underwater experiments.

-*Attitude Keeping Control*: When a distance between ISiMI and the dock is less than 1.40m, the dock lights are out of the viewing range of the camera [Fig.10]. In this area, the visual servo control is not valid and must be stopped. The distance estimated by the image process determines when the visual servo control should be stopped. The attitude keeping control is applied when ISiMI pass this boundary. This controller stops the visual servo control and fixes the reference yaw and pitch at this moment. ISiMI becomes blind and just follow these fixed reference attitudes until she contacts the dock. The attitude keeping controller has a role as one of auxiliary methods to reinforce the final approach algorithm.

This final approach algorithm process is shown in [Fig.11]

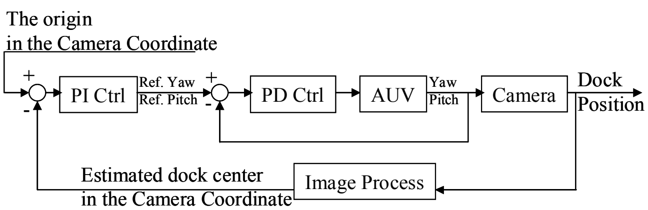

Fig. 9. Block diagram of visual servo control

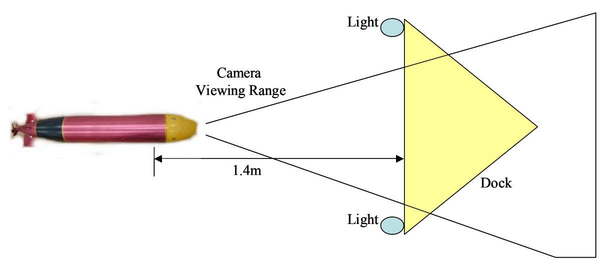

Fig. 10. The lights are out of the viewing range of the Camera

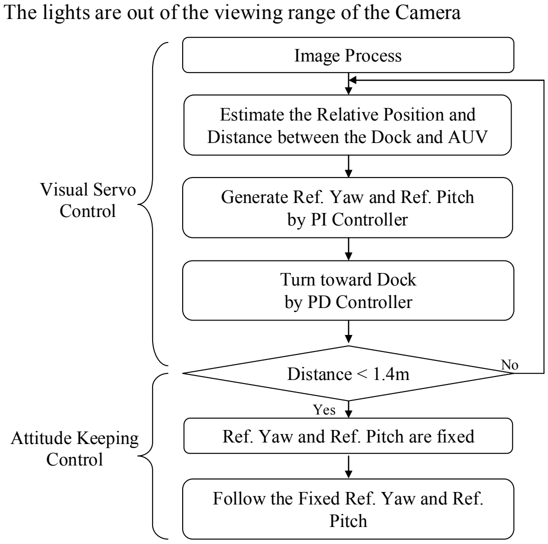

Fig. 11. Block diagram of the final approach algorithm for docking

IV. UNDERWATER DOCKING EXPERIMENTS

We conducted underwater docking experiments to verify the developed system, i.e. the optical terminal guidance system. The environmental conditions of the water basin were no current and no wave. The dock was fixed on the basin floor. [Fig.12a] and [Fig.12b] are a top view and a side view, respectively. They depict the initial start condition. The dock was placed in the viewing range of the camera. The start point of ISiMI was apart from the dock about 10m-15m. The center of the dock was placed in 1.5m depth. The water was clean. We operated ISiMI using the wired LAN communication to get image data easily for recording. R.P.M. of the thrust propeller was invariant and her speed was about 1.0m/s.

We will show two experimental stages. (1)First Stage: Only the visual servo control was executed without distance estimation, i.e. only position information was considered and the attitude keeping control was not applied. (2)Second Stage: We considered both the position and the distance for the final approach. The attitude keeping control was also applied to compensate the visual servo control. Comparing results of two kinds of the stages, we will describe that the distance estimation and the use of the attitude keeping control as well as the visual servo control make docking performance more precise and be improved.

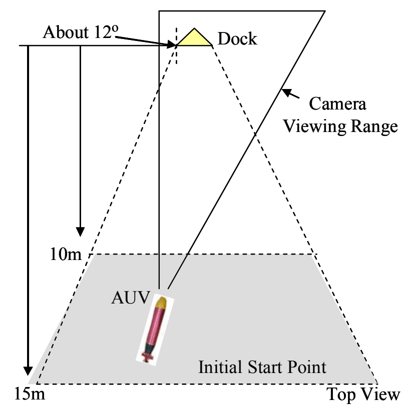

Fig. 12a. Initial start point: Top view

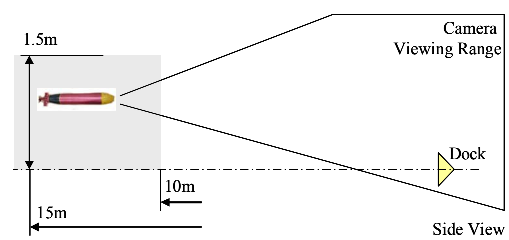

Fig. 12b. Initial start point: Side view

(1)First Stage

In the final approach guidance, the distance was not estimated. Only the visual servo control was applied. In [Fig.13], pixel errors are plotted against time. The pixel errors are deviations between the origin and the position of the estimated center of the dock in the camera coordinate. The pixel errors decreased and were regulated. But, between 9-10seconds, there were discontinuous oscillations. At this time, the dock lights were out of the camera range, hence, ISiMI could not see all of the dock light. For this reason, ISiMI estimated the dock center with improper images. Any auxiliary method to help the visual servo controller was necessary. Finally, she showed imprecise final approaches and collisions with the dock. [Fig. 14] is a sequence of continuously grabbed images taken by an underwater camera. (a): ISiMI starts, (b): she cruises to the dock, (c), (d): an imprecise approach near the dock, (e): after a collision, she was bounded, and (f): she could not enter the dock.

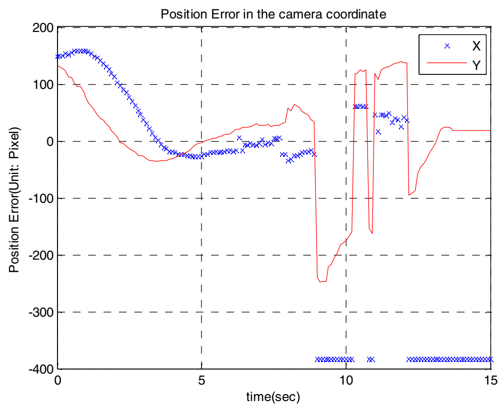

Fig. 13. Position error (unit: pixel) in the camera coordinate: The pixel errors decreased and were regulated. But, between 9-10seconds, there were discontinuities.

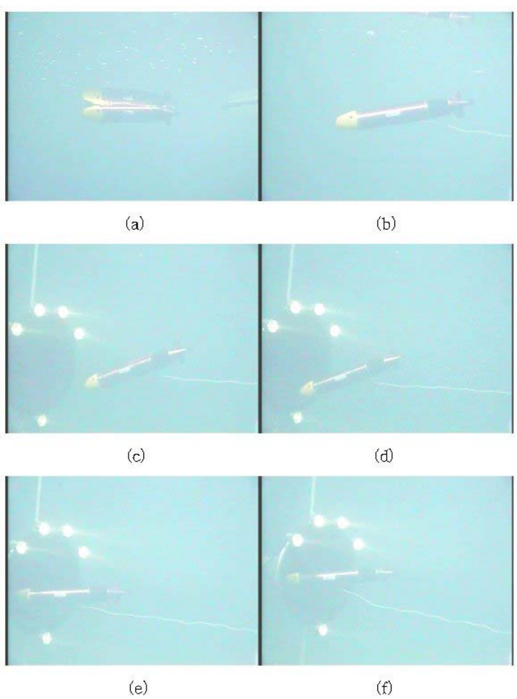

Fig. 14. Docking : Grabbed images by an underwater camera
(a): ISiMI starts, (b): she cruises to the dock, (c), (d): an imprecise approach near the dock, (e): after a collision, she was bounded, and (f): she could not enter the dock.

(2)Second Stage

In this stage, both the visual servo control and the attitude keeping control were applied for the final approach. [Fig.15] shows pixel errors. Patterns of the errors are similar to that of [Fig.13]. In the same manner, oscillations are inspected after 9 seconds. But, after this moment, the visual servo control was stopped, the reference yaw and pitch was fixed by the attitude keeping controller. In [Fig. 16], a solid line is measured attitude (yaw and pitch) by AHRS (Attitude Heading Reference System). The AHRS was installed in the inside of ISiMI. A dashed line is generated reference attitude. You can see that the reference yaw and pitch were fixed after 9 seconds. ISiMI followed the reference attitude by using PD control. [Fig.17] is a collection of grabbed images. It describes that ISiMI was going into the dock showing more precise approach.

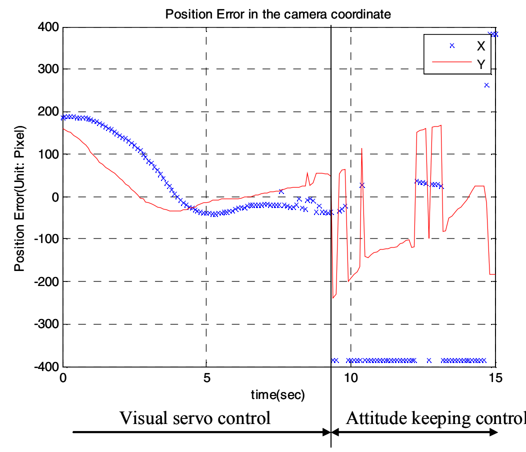

Fig. 15. Position error (unit: pixel) in the camera coordinate

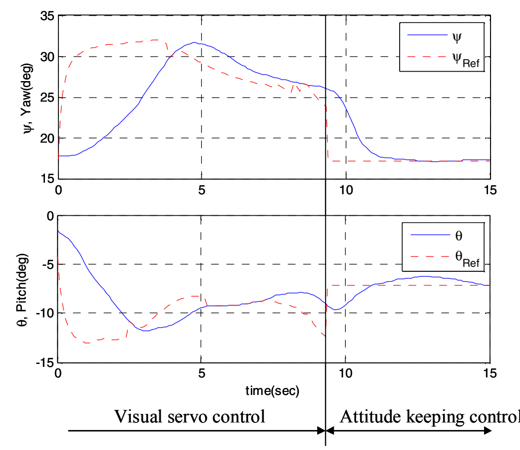

Fig. 16. Final approach: (Upper graph) Ref. Yaw and Yaw, (Lower graph) Ref. Pitch and Pitch are shown respectively. After 9 seconds, ref. yaw and ref. pitch were fixed.

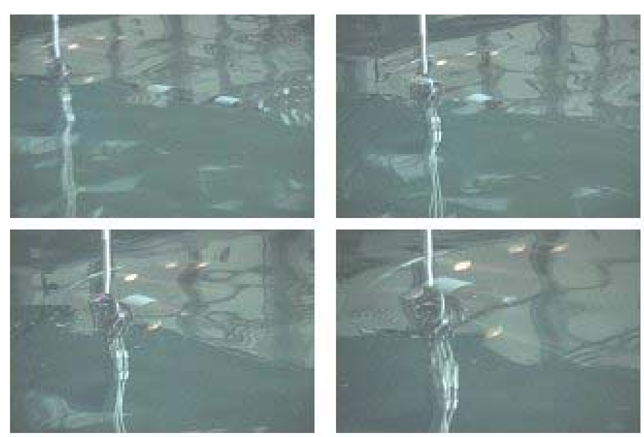

Fig. 17. Docking : Grabber images. This shows more precise approach and docking.

V. Conclusion

In this paper, we introduced ISiMI and her optical terminal guidance system. This guidance system is used for a final approach of underwater docking. Image process was also described. The image process discriminates the lights of the dock and estimates a position and a distance of the dock center which is the final approach target. To guide ISiMI into the dock, we developed the final approach algorithm. This algorithm was composed of the visual servo control and the attitude keeping control. Experiments of underwater docking were conducted to verify the developed system and control algorithms. The system showed successful underwater dockings. Also, we can conclude that the attitude keeping controller shows its efficacy as an auxiliary method to reinforce the visual servo controller. Addition of the attitude keeping control improves the performance of underwater docking. The following points are left as future problems. In a case when (1) the dock is moving, (2) the dock is placed out of the camera viewing range in the initial start point, and (3) current and wave exist. Generation of the optimized path from any initial start point to the dock is the subject for a future study.

Acknowledgment

This work was supported in part by MOMAF of Korea for the "development of a deep-sea unmanned underwater vehicle" and KORDI for the "development of smart operation technologies for exploration fleet based on ubiquitous concept"

References

[1] Michael D. Feezor, Paul R. Blankinship, James G. Bellingham and F. Yates Sorrell, "Autonomous Underwater Vehicle Homing/Docking via Electromagnetic Guidance," OCEANS '97. MTS/IEEE Conference Proceedings, Vol.2, 6-9 Oct. 1997, pp. 1137-1142

[2] Steve Cowen, Susan Briest and James Dombrowski, "Underwater Docking of Autonomous Undersea Vehicles using Optical Terminal Guidance," OCEANS '97. MTS/IEEE Conference Proceedings, Vol.2, 6-9 Oct. 1997, pp.1143-1147

[3] Ben Allen, Tom Autstin, Ned Forrester, Rob Goldsborough, Amy Kululya, Greg Packard, Mile Purcell and Roger Stokey, "Autonomous Docking Demonstrations with Enhanced REMUS Technology," OCEANS 2006. MTS/IEEE, 18-21 Sept. 2006, pp. 1-6

[4] Pan-Mook Lee, Bong-Hwan Jeon and Chong-Moo Lee, "A Docking and Control System for an Autonomous Underwater Vehicle," OCEANS 2002. MTS/IEEE, pp. 1609-1614

[5] T. Prestero, "Verification of a Six-Degree of Freedom Simulation Model for the REMUS Autonomous Underwater Vehicle," Master Thesis, Dept. of Ocean Eng. and Mech. Eng., MIT, Sept. 2001

[6] Young-Hwa Hong, Jung-Yup Kim, Pan-Mook Lee, Bong-Hwan Jeon, Kyu-Hyun Oh and Jun-ho Oh, "Development of the Homing and Docking Algorithm for AUV," ISOPE 2003. International Offshore and Polar Engineering Conference, 25-30 May. 2003, pp. 205-212

[7] Pan-Mook Lee, Bong-Hwan Jeon and Sea-Moon Kim, "Visual Servoing for Underwater Docking of an Autonomous Underwater Vehicle with One Camera," OCEAN 2003, Proceedings, Vol. 2, 22-26 Sept. 2003, pp.677-682