Visual Servoing for Underwater Docking of an Autonomous Underwater Vehicle with One Camera

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***Abstract* - Docking systems are required to increase the capability of autonomous underwater vehicles (AUVs) to recharge the batteries and to transmit data in real time in underwater. This paper presents a docking system for an AUV to dock into an underwater station with one camera installed at the nose center of the AUV. To make a visual servo controller, this paper presents an optimal control algorithm based on a state equation composed of the AUV dynamics and the optical flow equation. The control inputs of the AUV are generated with the projected target position on the CCD plane of the camera and with the AUV's motion. This paper introduces a test bed AUV for underwater docking developed in Korea Research Institute of Ships and Ocean Engineering (KRISO), KORDI of Korea. The AUV is propelled with one thruster and controlled with two horizontal planes and two vertical planes. Experiments will be performed in Ocean Engineering Basin of KRISO to demonstrate the effectiveness of the modeling and control law of the visual servoing AUV. The AUV identifies target position with processing the captured image of the lights mounted around the entrance of the dock. This paper also presents a strategy to identifier the target with lights arrays.**

I. INTRODUCTION

Autonomous underwater vehicles (AUV) have become an intense area of oceanic research because of their emerging applications, such as inspection of deep sea, long range survey, oceanographic mapping, underwater pipelines tracking, and so on. When an AUV is to be completely autonomous by itself, it must have the ability to search target area, plan homing path after conducting its mission, and come back to a surface vessel or an underwater docking station. When an AUV should be in undersea for a long time to observe the environment or to conduct a repeated mission, docking systems are required to increase the capability of the AUV to recharge the batteries and to transmit data in real time in underwater [1].

The AUV should have to track the path to a docking station exactly and its posture should be controlled near the station. In underwater, many kinds of sensors are available to know the relative position and velocity of the AUV to a docking station, such as vision sensors, inertial sensors, Doppler velocity logs, sonar tracking system and so on [2,3,4]. However, the sensors have different frequency bandwidths and some sensors are limited in application due to the size and cost of the AUV.

This paper proposes a visual docking system for an AUV that will be launched from an underwater station and come back to the station. One camera is installed at the nose's center of the AUV and visually guides the AUV to the docking station. The camera servoing AUV is similar to the hand-in-eye visual tracking problem of robotic manipulators in the control strategies [5,6,7]. In autonomous underwater vehicles, the translation of the vehicle cannot be generated directly as the case of manipulators. A coupled optical flow equation, therefore, is needed to make a visual servoing system for the AUVs.

This paper presents a docking system for an AUV to dock into an underwater station by processing the images captured with a camera installed at the nose cent of an AUV. The AUV is propelled with one thruster and controlled with two vertical planes and two horizontal planes. To make a visual servo control system, this paper derived a state equation composed of the equation of the AUV motion and an optical flow equation for the camera mounted on the AUV. The control inputs of the AUV are generated with the visual servo controller that is composed of the projected target position on the CCD plane and the desired motion of the AUV. This paper introduces a test bed AUV for underwater docking test developed in KRISO-KORDI. Two allocations of the lights are suggested in this paper to identify the location of the target with processing the light images captured on the CCD camera. The AUV identifies target position with processing the captured image of the lights mounted around the entrance of the dock. Experiments will be performed in Ocean Engineering Basin of KRISO to demonstrate the effectiveness of the visual servoing AUV. In addition, this paper proposes an alternative method to get even brightness for any direction in hemi-spherical region with a circular LED array immersed in oil inside of a circular transparent tube.

II. DESIGN OF A VISUAL SERVOING AUV

We assume one camera will be set on the nose center of the AUV and acquire successive images and feed them back to get the target position exactly when the AUV come back to an underwater station. We will make the model of the visual

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servoing AUV based on a pin-hole camera and a linearized equation of the AUV's motion. Fig. 1 depicts the coordinates of the visual servo controlled AUV, where the body fixed frame of the AUV is at the rotational center and the camera frame is at the nose's center of the AUV coincident with the AUV frame except the x-directional shift L. Since the motion of an AUV is fully nonlinear, a projected object on the camera will move in nonlinear pattern.

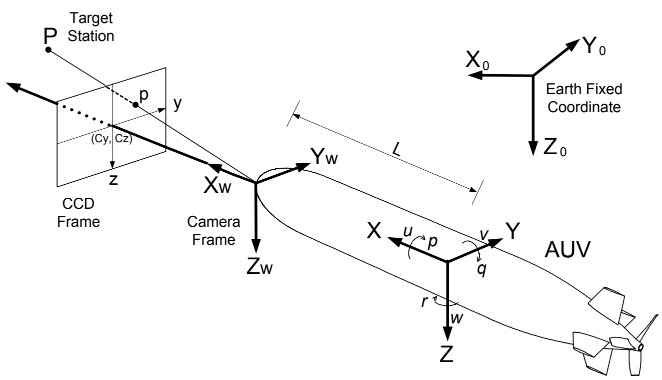


Fig. 1. Coordinate of a visual servoing AUV.

Papanikolopoulos et al. [5,6] and Smith et al. [7] developed a pin-hole camera model for the visual servo control of manipulators. Based on the Papanikolopoulos' method, we can describe the camera motion with the AUV motion because the camera is fixed at the nose center of the AUV.

Let us assume that the camera moves with a translational velocity $\mathbf{v}_W = (u_c, v_c, w_c)$ and with an angular velocity $\omega_W = (p, q, r)$. Since the velocity $\mathbf{v} = (u, v, w)$ of the AUV-fixed coordinate corresponds with that of the camera frame by $v_c = v + \omega \times r$, the flow equation of the point p on the CCD frame induced by the AUV motion, therefore, can be described as follows [8]:

$$\dot{y} = \frac{y}{X_W}u - \frac{f}{s_y X_W}v + \frac{s_z z}{s_y}p + \frac{s_z yz}{f}q - \left(\frac{f}{s_y} + \frac{s_y y^2}{f} + \frac{fL}{s_y X_W}\right)r \tag{2.1}$$

$$\dot{z} = \frac{z}{X_W}u - \frac{f}{s_z X_W}w - \frac{s_y y}{s_z}p + \left(\frac{f}{s_z} + \frac{s_z z^2}{f} + \frac{fL}{s_z X_W}\right)q - \frac{s_y yz}{f}r \, , \tag{2.2}$$

where f is the focal length of the lens, X_W is the depth information of the target during a docking process, L is the longitudinal offset distance of the camera frame as shown in Fig. 1. The two scale factors, s_y and s_z, are defined to account for camera sampling and pixel size of the CCD in vertical and horizontal dimensions, respectively.

We can represent the motion of the camera mounted at the nose center of the AUV with (2.1) and (2.2), of which the velocities are induced by the AUV motion and the perspective relations of the camera. Since the vehicle's motions of the vertical plane and the horizontal plane can be independently controlled with two dive planes and two rudders, respectively, we can introduce two linear equations of motion for the AUV in the vertical plane and in the horizontal plane.

We designed the state equation with the state variables composed of the projected position y and z, and the angular velocities of the AUV, q and r, and pitch θ and yaw ψ. By setting the fin angles, δ_s and δ_r, are the control inputs of the AUV, therefore, we can introduce a mathematical model of the visual servoing AUV as

$$\dot{\mathbf{x}}(t) = \mathbf{A}(t)\mathbf{x}(t) + \mathbf{Bu}(t) + \mathbf{d}(t)\, , \tag{2.3}$$

where

$$\mathbf{x} = \{y \; z \; q \; r \; \theta \; \psi\}^T$$

$$\mathbf{u} = \{\delta_s \; \delta_r\}^T$$

$$\mathbf{A}(t) = \begin{bmatrix} \frac{u}{X_W} & 0 & \frac{s_z yz}{f} & -\left(\frac{f}{s_y} + \frac{s_y y^2}{f} + \frac{fL}{s_y X_W}\right) & 0 & 0 \\ 0 & \frac{u}{X_W} & \left(\frac{f}{s_z} + \frac{s_z z^2}{f} + \frac{fL}{s_z X_W}\right) & -\frac{s_y yz}{f} & 0 & 0 \\ 0 & 0 & \frac{M_q}{I_{yy} - M_{\dot{q}}} & 0 & \frac{M_\theta}{I_{yy} - M_{\dot{q}}} & 0 \\ 0 & 0 & 0 & \frac{N_r}{I_{zz} - N_r} & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & M_{\delta_s} & 0 & 0 & 0 \\ 0 & 0 & 0 & N_{\delta_r} & 0 & 0 \end{bmatrix}^T$$

$$\mathbf{d}(t) = \begin{Bmatrix} -\frac{f\,v}{s_y X_W} + \frac{s_z z\,p}{s_y} \\ -\frac{f\,w}{s_z X_W} + \frac{s_y y\,p}{s_z} \\ \Delta f_q \\ \Delta f_r \\ 0 \\ 0 \end{Bmatrix}$$

where $M_{\dot{q}}$ and $N_{\dot{r}}$ are the added mass terms, M_q and N_r are linearized drag terms, M_θ is hydrostatic restoring term, M_{δ_s} and N_{δ_r} around operating speed, and Δf_q and Δf_r represent the modeling errors and the uncertainties of the AUV, respectively.

Although we suppose the projected position moves slowly, the system matrix $\mathbf{A}(t)$ is time-varying because of the change in the depth information X_W of the target during a docking process. The image motion can only be determined for successive image frames separated in time by a sampling period Δt including image processing time. We suppose that The discrete time state equation can be expressed at the k-th time step

$$\mathbf{x}(k+1) = \mathbf{\Phi}(k)\mathbf{x}(k) + \mathbf{\Gamma}\mathbf{u}(k) + \mathbf{d}(k) \quad (2.4)$$

$$\mathbf{y}(k) = \mathbf{C}\mathbf{x}(k) + \mathbf{w}(k)\ , \quad (2.5)$$

where $\Phi(k) \in R^{6\times 6}$ is the transition matrix in at the k-th time step, $\mathbf{\Gamma} \in R^{6\times 2}$ is the gain matrix, $C = \mathbf{I}^{6\times 6}$, $\mathbf{d}(k) \in R^6$ is a system disturbances vector, and $\mathbf{w}(k) \in R^6$ is a white noise vector in the k-th time step measurements.

It is necessary to adopt a method for automatic recognition of features and on-line evaluation of the target with the k-th step images. We consider that four lights around the entrance of the docking device are installed to mark the target position, where the center of the lights is the target position of the duct. One additional light is needed to identify the orientation of the target. Fig. 2 shows the light allocation for the landmark of the target in the visual servoing AUV.

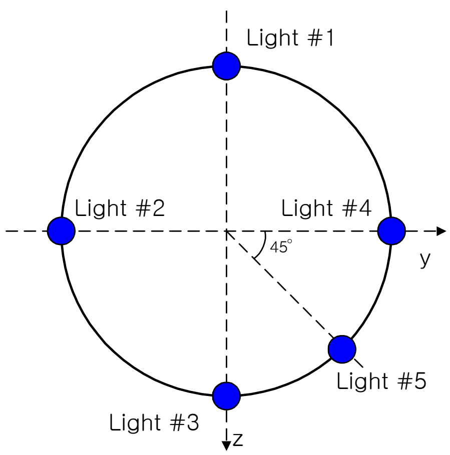


Fig. 2. Lights allocation for the landmark of the target.

The control objective is to move the AUV for the docking station in undersea holding the center of the camera to the target point. Under the assumption of slow motion of the AUV in a short sampling period Δt, we can assume that $\Phi(k)$ is time-varying but $\Phi(k) \approx \Phi(k-1)$ if the difference of the projected target's positions between successive samples is sufficiently small. Thus we can make $\Phi(k)$ with the k-th step positions, $y(k)$ and $z(k)$. In addition, $\mathbf{d}(k)$ also can be considered as a constant vector in a short sampling period.

Then we can combine (2.4) and (2.5) into a multi-input multi-output (MIMO) model

$$\begin{aligned}(\mathbf{A}_0 + \mathbf{A}_1(k)q^{-1} + \mathbf{A}_2(k)q^{-2})\mathbf{y}(k) \\ = \mathbf{\Gamma}\mathbf{u}(k-1) - \mathbf{\Gamma}\mathbf{u}(k-2) + \mathbf{n}(k)\end{aligned} \quad (2.6)$$

by subtracting the $(k-1)$-th step measurement from the k-th step measurement, where $\mathbf{A}_0 = \mathbf{I}$, $\mathbf{A}_1(k) = -\mathbf{I} - \mathbf{\Phi}(k)$, $\mathbf{A}_2(k) = \mathbf{\Phi}(k)$ and $\mathbf{n}(k)$ is the white vector corresponding to measurement noise and modeling errors. The tracking of the target's position and the AUV motion control are realized by an appropriate control of the fins with the linear model (2.6) of the visual servoing AUV.

A control law can be derived by the minimization of a cost function that aims to achieve a compromise between bringing $\mathbf{y}(k+1)$ to $\mathbf{y}_D(k+1)$ and the amount of control efforts expended, where $\mathbf{y}_D(k+1)$ is the desired position on CCD plane for an object and the attitude of the AUV in one step ahead.

The control law is derived from the minimization of the cost function [9] as follows:

$$\begin{aligned}\mathbf{u}(k) = -(\mathbf{\Gamma}^T\mathbf{Q}\mathbf{\Gamma} + \mathbf{L_u})^{-1}[\mathbf{\Gamma}^T\mathbf{Q}\{-\mathbf{A}_1(k)\mathbf{y}(k) \\ -\mathbf{A}_2(k)\mathbf{y}(k-1) - \mathbf{y}_D(k+1) - \mathbf{u}(k-1)\}]\end{aligned}\ , \quad (2.7)$$

where $\mathbf{Q}$ and $\mathbf{L_u}$ are the weighted matrixes for the servoing errors and the control inputs, respectively. We have to evaluate the depth of the target to implement the control law, because the matrixes $\mathbf{A}_1(k)$ and $\mathbf{A}_2(k)$ depend on the relative distance of the target with respect to the camera at every time step.

III. TEST BED AUV FOR VISUAL SERVOING AND EXPERIMENTAL EQUIPMENT

A. Test Bed AUV for Underwater Docking

A test bed AUV named ASUM (Advanced Small Underwater Model) was constructed to evaluate the visual servoing algorithm for docking experiments in Ocean Engineering Basin of KRISO, where 3.5m in depth, 56m in length and 30m in width. ASUM was propelled with one thruster and controlled with two vertical planes and two horizontal planes. The horizontal planes are separately movable each other and can control the roll motion of ASUM. The AUV is 1.2*m* in length and 0.17*m* in depth.

ASUM is composed of three parts: (1) a nose section made of urethane an underwater CCD camera, (2) a cylindrical pressure vessel made of aluminum embarks the image processors, main controller, batteries, motor driver, and motion sensors, (3) a rear section where the inside filled with oil is equipped with the motors, propeller, control planes and their mechanical links. The urethane nose alleviates impact when the AUV docks into a station. An angular sensor and a depth sensor were equipped to measure the AUV's motion and attitude. Fig. 3 shows the configuration of the AUV. The maximum operating depth of ASUM is 20*m*, and the maximum speed is 4 knots. The power of ASUM composed of ten lead-acid batteries is 24V 6Ah. The hull is made of aluminum except the nose cone. Table 1 shows the specification of the AUV.

Table 1. Specification of the visual sevoing AUV ASUM

Dimension (L×d)	1,200×170mm
Operating Speed	3 knots (max. 4 knots)
Max. Thrust	9.28N (50W@2.15m/s)
Batteries	Lead Acid >84Wh
Max. Working Depth	20 m
Operating Time (except hotel power)	3 hours@2knots, 2 hours@3knots, 1 hour @4knots

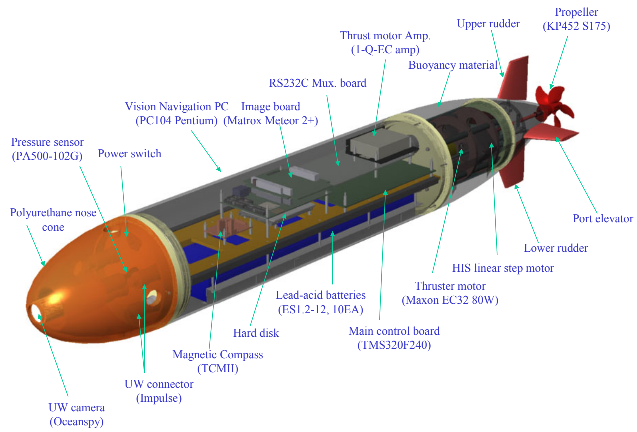


Fig. 3. 3-D allocation of the equipment of ASUM (Front-side view).

Fig. 4 shows the hull and internal electronics of ASUM. The buoyancy of ASUM is 20.12kg, and the total weight is 9.1kg in air. Payload is about 1kg. The center of mass is 7.9mm under the centerline. Fig. 5 shows ballast of ASUM excluding oil in the rear section, where the vehicle has even trim when the oil is filled in.

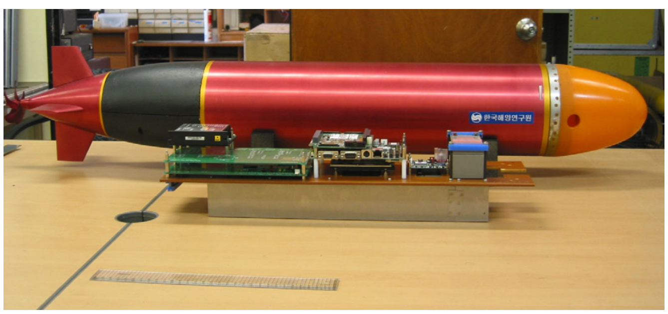


Fig. 4. The assembled hull and the embedded processors of the test bed AUV ASUM.

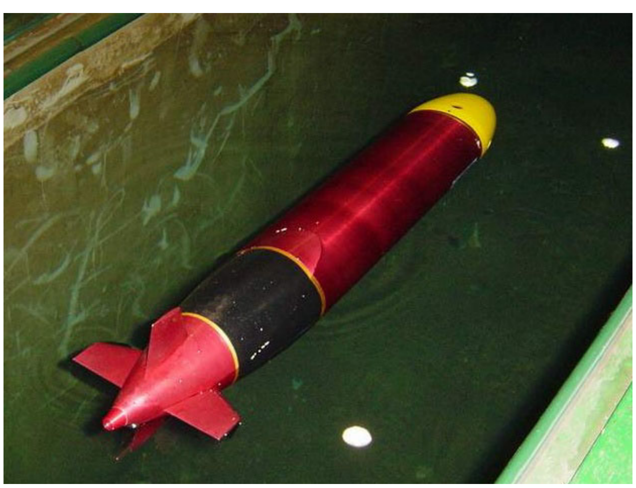


Fig. 5. Ballasting test of ASUM in a basin.

B. Controller of the Test Bed AUV

A small computer system was designed to make the visual servo controller. Fig. 4 depicts the block diagram of the ASUM controller. A main controller based on TMS320F240 DSP was designed to interface the motors and motion sensors. An image processor based on a PC104+ computer accompanying an image capture board was installed to process the images from the camera. Operating system of the computer is Microsoft Windows 98, and the software of ASUM can be downloaded via Ethernet from external computers. The PC104+ processor and the image capture board are PCM-3350 of Geode GX1-300MHz and Matrox Meteor2+/4, respectively. The main controller generates the command signals based on the visual servo algorithm with the vehicle's attitude and the projected target position, where the target position is calculated from the image processor.

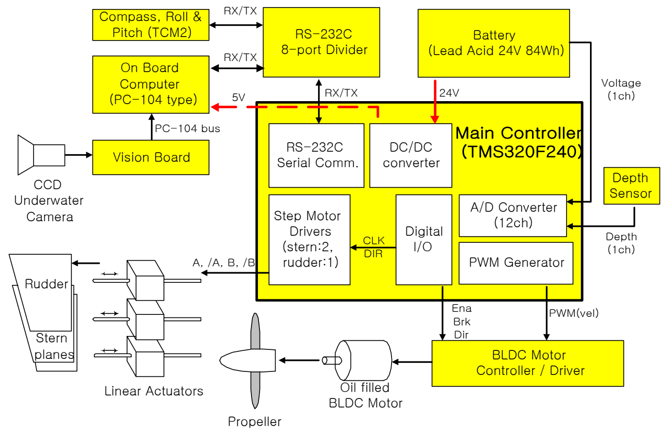


Fig. 6. Block diagram of the ASUM controller.

C. Position Tracking in Ocean Engineering Basin

A local area short baseline tracking system was configured in Ocean Engineering Basin with one pinger and four hydrophones as depicted in Fig. 7. The pinger was mounted at nose cone of ASUM is B&K 8103V model and its cable was 20m to minimize the disturbance due to the pinger cable. The hydrophones are B&K 8103 models, where one hydrophone is set on 3.0*m* in depth under waterline and the others are installed at 0.5*m* in depth under the waterline. The hydrophones were located at the axes and center of a rectangular coordinate.

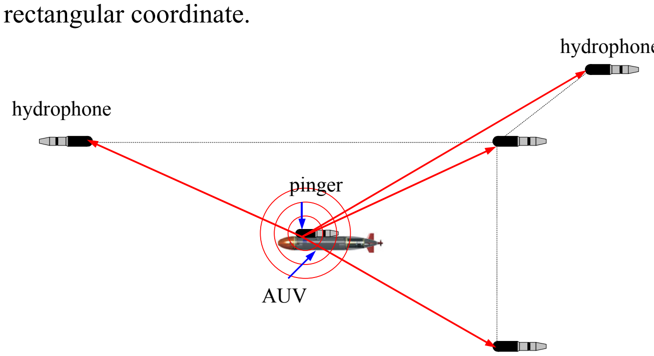


Fig. 7. Conceptual picture of a local area acoustic navigation system in Ocean Engineering Basin.

Fig. 8 shows the configuration of the local area SBL tracking system for the ASUM. The wave form generator, Agillent 33250A, makes pulse waves with 0.1 seconds interval, where the width is 10μm and the shape is Hanning window type. The signal was amplified with power amplifier, B&K 2713, and released through the pinger. The signal processing of the tracking system is the same as the conventional SBL systems. The received signal was amplified with the charge amplifier, NEXUS, and acquired with the four-channel data acquisition equipment, NI PXI-6115, connected to the computer, NI 8176. The sampling frequency is 1MHz, and the controller triggered by the waveform generator acquires the signal for 20 milliseconds. The position of ASUM was calculated with the delay of the received signal.

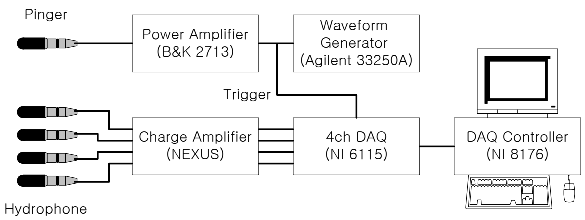


Fig. 8. Configuration of acoustic navigation system for the local area in Ocean Engineering Basin.

D. Docking Device and Target Recognition

A docking device was manufactured to conduct AUV docking test with the visual servo controller. The docking device has conical shape at the entrance of the dock that guides the AUV to enter into the funnel. Five lights were installed around the rim of the entrance as shown in Fig. 9, where the location of the lights are adjustable. The brightness of the light is adjustable to get optimal threshold level.

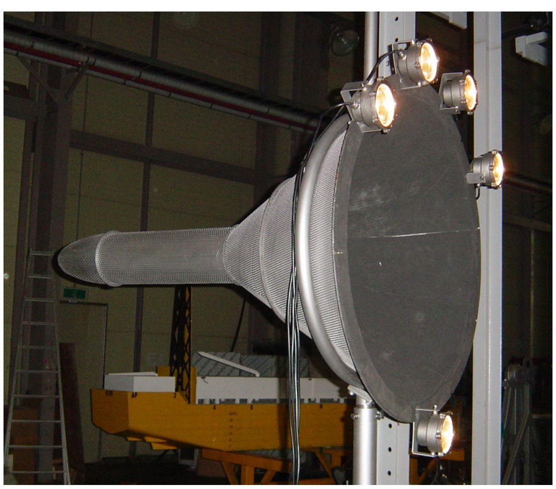
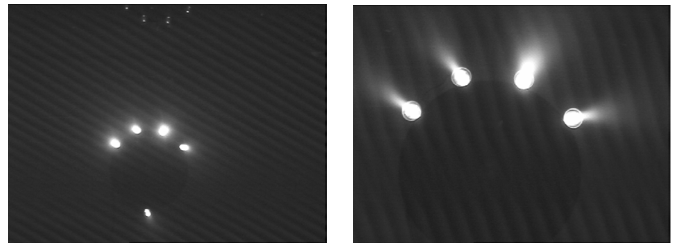


Fig. 9. The docking device of ASUM with five lights around the rim of entrance.

Authors are studying several methods to get the best allocation of the lights and the brightness. Fig. 10 showed examples of the light images acquired with the underwater camera from 5*m* and 2*m* distances between the duct and the AUV. This arrangement of the lights can be fitted to a circle for all direction to the target.



(a) 5 m (b) 2m

Fig. 10. Light images captured with the camera.

In case of the light allocation in Fig. 2, we can easily find the center of the target by searching the cross point of the two horizontal and vertical lines passing the center of the two horizontal lights and the two vertical lights. The trim and heading angles of the target also can be calculated with the length of the arms from the center of the target to the lights. The fifth light is the reference to identify the orientation of the target.

A point light with reflector is directional and distorts the center of the light due to dispersion characteristics. The dispersion phenomena shown in Fig. 10 (b) induce errors in processing the images to find the light's locations. An alternative method is suggested to get even brightness in any direction in hemi-spherical region with a circular LED array immersed in oil inside of a circular transparent tube. Fig. 11 depicts the conceptual drawings of the LED light array. The light system made of the LED array can improve the directional variation of the light scattering and reduce the errors in target identification. We can fit a circle to the light image, get the target center, and calculate the radius of the entrance and the target distance. The five discontinuities are the dark points to identify the orientation of the target.

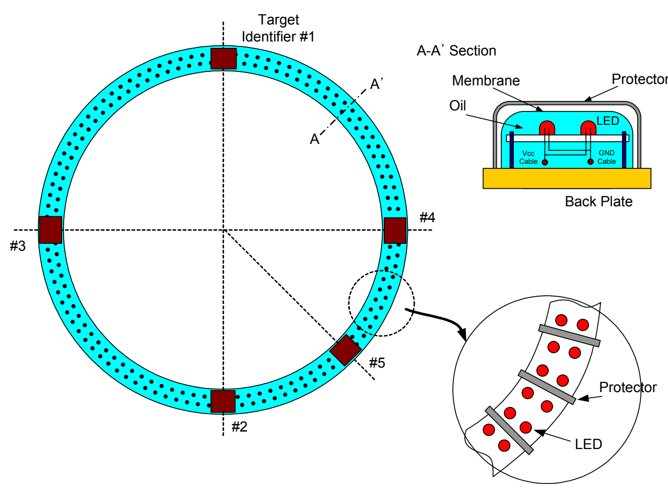


Fig. 11. A LED light array to identify the target station.

Experiments will be conducted to demonstrate the effectiveness of the visual servo controller of the AUV. Unfortunately, experiments are not performed until this article is written because the system integration of the AUV with the visual servo controller takes time more than we expected. Experimental results will be given at the presentation.

IV. CONCLUSIONS

This paper presents a visual servoing AUV for the docking to an underwater station. A CCD camera is installed at the nose center of the AUV, and the control inputs of the AUV are generated with the visual servo controller that is composed of the projected target position on the CCD plane and the desired motion of the AUV. A test bed AUV equipped with one CCD camera at the nose center of the vehicle was developed to conduct the docking test to a target. This paper suggested two allocation methods of the lights to identify the location of the target with processing the light images captured on the CCD camera. In addition, this paper proposed an alternative method to get even brightness for any direction in hemi-spherical region with a circular LED array immersed in oil inside of a circular transparent tube. Experiments will be conducted to demonstrate the effectiveness of the visual servoing AUV near future.

ACKNOWLEDGMENT

This work is the results of “Development of an advanced deep-sea unmanned underwater vehicle (2)” supported by the Ministry of Maritime Affairs and Fisheries of Korea.

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