A Docking and Control System for an Autonomous Underwater Vehicle

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Abstract- Autonomous underwater vehicles are unmanned underwater vessels to investigate sea environments, oceanography and deep-sea resources autonomously. Docking systems are required to increase the capability of the 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 a camera. To make a visual servo control system, this paper derives an optical flow model of a camera mounted on AUV, where a CCD camera is installed at the nose center of the AUV to monitor the docking condition. This paper combines the optical flow equation of the camera with the AUV's equation of motion, and derives a state equation for the visual servoing AUV. This paper also proposes a MIMO controller minimizing a cost function. The control inputs of the AUV are automatically generated with the projected target position on the CCD plane and with the AUV's motion. To demonstrate the effectiveness of the modeling and the control law of the visual servoing AUV, simulations on docking the AUV to a target station are performed with the 6-dof nonlinear equations of REMUS of WHOI and a CCD camera.

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 [1,2].

The AUV should have to track the path to a docking station exactly and its posture also 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, sonar sensors and so on. However, the sensors have different frequency bandwidths and some sensors are limited in application due to the size and cost of the AUV.

Singh, Bellingham, Hover, and et al. [2] presented a docking system for Odyssey vehicle. They used USBL system for AUV to approach the dock from any direction by determining the range and bearing to the transponder mounted on the dock. After the vehicle reached the dock, an appendage mounted on the front of the vehicle latched on to a pole mounted on the dock. The power and data connections between AUV and dock were made using inductive cores. The advantage of the system is robustness to the errors from presence of the currents and magnetic anomalies because it is omni-directional. Stokey, Allen, Austin, and et al. [3,4,5,6] developed a low cost AUV REMUS (Remote Environmental Monitoring UnitS) and its docking system based on SSBL tracking system. A fixed cone leading into a tube was used as a dock to provide protective garage for a vehicle and the direct electrical connection technique was used for the data and power transfer. The main advantage of this system is that it minimizes the external modifications to the vehicle and provides a shelter to vehicle from the grave risk of wave surge. However, it needs more precise navigation performance, since the vehicle must orient itself on a proper glide path but merely head toward the dock.

Feezor, Blankinship, Bellingham and Sorrel [7] presented an electromagnetic guidance system (EM system) as a terminal guidance of homing system for cone type of docking system. It obtained the bearing and orientation relative to the dock entrance with magnetic sensing coils installed in the AUV by detecting the electromagnetic field generated at the dock. At typical seawater salinity and temperatures, the range of the system was to approximately 25-30*cm* and the accuracy was less than 20*cm*. The advantage of the system is that the performance is not affected by the common oceanographic phenomena such that turbidity, bubbles, floating organic materials, fouling, and boundaries at the surface of bottom.

An optical guidance system which tracks the light source on the dock was proposed as another approach to the terminal guidance system for AUV docking by Cowen, Briest, and Dombrowski [8]. The range of the system was significantly related to the turbidity of water. They obtained reliable acquisition range of 10~28m according to the rate of turbidity.

We are interested in a visual docking system for an AUV, which will be launched from an underwater station and come back to the station. A camera will be 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. We briefly review the visual servoing tracking tasks of robotic manipulators.

Visual servo controls intensively have been studied in robotic manipulators. Hutchinson, Hager, and Corke [9] reviewed and classified the visual servo controls of manipulators. Papanikolopoulos and Khosla [10,11] proposed an adaptive visual tracking with one camera mounted on the end-effector of a manipulator, of which the control algorithm is based on the estimation of the relative distance of the target with respect to the camera. Smith,

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Brandt, and Papanonikolopoulos [12, 13] presented robust tracking techniques of hand-in-eye tasks for the derivation of depth from feature points on the target's surface. They showed grasping static and dynamic objects in uncalibrated environments using the vision-based control approach. Kragic and Christensen [14] proposed the fusion of multiple features facilitates robust detection and tracking of objects, which estimates a robot's end-effector position in a sequence images.

This paper presents a docking system for an AUV to dock into an underwater station with a camera. To make a visual servo control system, this paper developed an optical flow equation for a camera mounted on AUV. This paper combines the optical flow equation of the camera with the AUV's linearized equation of motion, and derives a state equation for the visual servoing AUV. The control objective is to move the AUV for the docking station in undersea holding the center of the camera to the target point. A control law is designed on the basis of an optimal one-step ahead predictive controller by minimizing a cost function. The control inputs of the AUV are automatically generated with the projected target position on the CCD plane and with the AUV's motion. To demonstrate the effectiveness of the modeling and the controller of the visual servoing AUV, simulations on docking the AUV to a target station are performed with the 6-dof nonlinear equations of REMUS [15] of WHOI and a CCD camera.

II. MODEL 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. A mathematical model, therefore, is required to make a control system with the camera. Since the motion of an AUV is fully nonlinear, a projected object on the camera will move in nonlinear pattern.

In order to make a model of the visual servoing AUV, we first define the coordinates system of the AUV. Figure 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. In this section, we will make the model of the visual servoing AUV based on a pin-hole camera and a linearized equation of the AUV's motion.

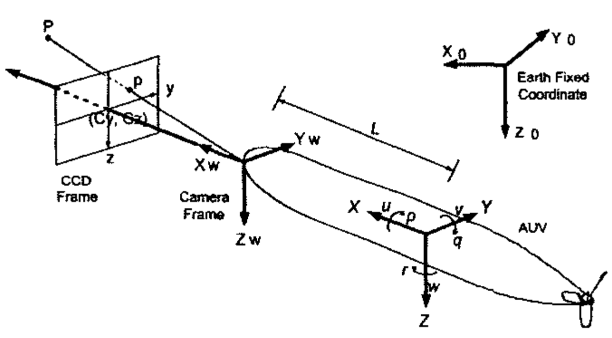


Fig. 1 Coordinate of a visual servoing AUV.

A. Camera Model

Papanonikolopoulos [10,11] and Smith [12,13] well developed a pin-hole camera model for the visual servo control of manipulators. This subsection just reviews the camera model to derive the visual servo controlled AUV.

We assume the object is in static or quasi-static compared with the motion of a camera. An object point P with coordinate (X_W, Y_W, Z_W) in the camera frame - with coordinate (X_0, Y_0, Z_0) in global coordinate frame - projects onto a point p in the image plane with image coordinate (y_i, z_i), where

$$y_i = \frac{f Y_W}{X_W} \tag{1}$$

$$z_i = \frac{f Z_W}{X_W} \tag{2}$$

and f is the focal length of the lens. If the optical axis on the CCD array is at (c_y, c_z), we can describe the actual coordinate on the CCD frame (y_A, z_A) with the two scale factors, s_y and s_z, as $y_A = y_i / s_y + c_y$ and $z_A = z_i / s_z + c_z$. The scale factors are defined to account for camera sampling and pixel size of the CCD in vertical and horizontal dimensions, respectively.

Then the point p can be expressed with the actual image position (y, z), where $y = y_A - c_y$ and $z = z_A - c_z$ are

$$y = \frac{f Y_W}{s_y X_W} \tag{3}$$

$$z = \frac{f Z_W}{s_z X_W}, \tag{4}$$

respectively. When we can describe the displacement of a rigid object on the CCD plane, the velocity of the projected point p on the CCD plane is equivalent to the camera-induced motion of the object P.

Let us assume that the camera moves in a static environment with a translational velocity $\mathbf{v}_W = (u_c, v_c, w_c)$ and with an angular velocity $\omega_W = (p, q, r)$. The velocity of the point P with respect to the camera frame can be expressed as

$$\dot{P} = -v_W - \omega_W \times P. \tag{5}$$

By taking the derivatives of (3) and (4), and substituting to (5), we can derive the optical flow equation of the point p on the CCD frame induced by the camera motion as follows:

$$\dot{y} = \frac{y u_c}{X_W} - \frac{f v_c}{s_y X_W} + \frac{s_z z}{s_y} p + \frac{s_z yz}{f} q - (\frac{f}{s_y} + \frac{s_y y^2}{f}) r \tag{6}$$

$$\dot{z} = \frac{z u_c}{X_W} - \frac{f w_c}{s_z X_W} - \frac{s_y y}{s_z} p + (\frac{f}{s_z} + \frac{s_z z^2}{f}) q - \frac{s_y yz}{f} r. \tag{7}$$

B. Camera Model Mounted on an AUV

We can describe the camera motion with the AUV motion because the camera is fixed at the nose center of the AUV. Since a traslational 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 camera motion induced by the AUV is expressed as

$$u_c = u$$
$$v_c = v + rL \quad (8)$$
$$w_c = w - qL,$$

where $r = (L,0,0)$ and L is the longitudinal offset distance of the camera frame as shown in Figure 1.

The flow equation of the point p on the CCD frame induced by the AUV motion, therefore, can be described as follows:

$$\dot{y} = \frac{y}{X_W}u - \frac{f}{s_y X_W}v + \frac{s_z z}{s_y}p + \frac{s_z yz}{f}q - \left(\frac{f}{s_y} + \frac{s_y y^2}{f} + \frac{fL}{s_y X_W}\right)r \quad (9)$$

$$\dot{z} = \frac{z}{X_W}u - \frac{f}{s_z X_W}w - \frac{s_y y}{s_z}p + \left(\frac{f}{s_z} + \frac{s_z z^2}{f} + \frac{fL}{s_z X_W}\right)q - \frac{s_y yz}{f}r \quad (10)$$

We can represent the motion of with (9) and (10), of which the velocities are induced by the AUV motion and the perspective relations of the camera.

C. System Model of the Visual Servoing AUV

The equation of motion is fully nonlinear in 6 degree-of-freedom and it is inconvenient to derive a controller with the mathematical model. We assume the vehicle will be similar to REMUS AUV of WHOI, of which two vertical planes and two horizontal planes control the AUV. Since the vehicle's motions of the vertical plane and the horizontal plane can be independently controlled with the dive planes and the rudders, respectively, we can introduce two linear equations of motion for the AUV in the vertical plane and in the horizontal plane. The linear equations of motion are reduced to

$$(I_{yy} - M_{\dot{q}})\dot{q} = M_q q + M_\theta \theta + M_{\delta_s}\delta_s + \Delta f_q \quad (11)$$

$$\dot{\theta} = q \quad (12)$$

$$(I_{zz} - N_{\dot{r}})\dot{r} = N_r r + N_{\delta_r}\delta_r + \Delta f_r \quad (13)$$

$$\dot{\psi} = r, \quad (14)$$

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.

The fin angles, δ_s and δ_r, are the control inputs of the AUV in (11) and (13), and the angular velocities of the AUV that are the outputs of (11) and (13) are the inputs of the optical flow equations (9) and (10). The optical flow equations are dependent on the AUV motion, we combined these equations, (9) ~ (14), to one state equation. We suppose the lateral velocity of the vehicle is unknown and the roll motion is not controlled with the control planes. In addition, we suppose the projected position y and z are slowly varying in a short time interval between the processing of the acquired images.

We designed the state equation with the state variables composed of the projected position y and z, and the angular components of the AUV, q, r, θ and ψ. Thus we can introduce a mathematical model of the visual servoing AUV as

$$\dot{\mathbf{x}}(t) = \mathbf{A}(t)\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{d}(t), \quad (15)$$

where

$$\mathbf{x} = \{y\ z\ q\ r\ \theta\ \psi\}^T \quad (16)$$

$$\mathbf{u} = \{\delta_s\ \delta_r\}^T \quad (17)$$

$$\mathbf{A}(t) = \begin{bmatrix} \frac{u}{X_W} & 0 & \frac{s_z yz}{f} & -\left(\frac{f}{s_y} + \frac{s_y y^2}{f} + \frac{fL}{s_y X_W}\right) & 0 & 0 \\ 0 & \frac{u}{X_W} & \left(\frac{f}{s_z} + \frac{s_z z^2}{f} + \frac{fL}{s_z X_W}\right) & -\frac{s_y yz}{f} & 0 & 0 \\ 0 & 0 & \frac{M_q}{I_{yy} - M_{\dot{q}}} & 0 & \frac{M_\theta}{I_{yy} - M_{\dot{q}}} & 0 \\ 0 & 0 & 0 & \frac{N_r}{I_{zz} - N_{\dot{r}}} & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad (18)$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & M_{\delta_s} & 0 & 0 & 0 \\ 0 & 0 & 0 & N_{\delta_r} & 0 & 0 \end{bmatrix}^T \quad (19)$$

$$\mathbf{d}(t) = \begin{Bmatrix} -\frac{fv}{s_y X_W} + \frac{s_z z p}{s_y} \\ -\frac{fw}{s_z X_W} + \frac{s_y y p}{s_z} \\ \Delta f_q \\ \Delta f_r \\ 0 \\ 0 \end{Bmatrix} \quad (20)$$

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.

III. CONTROL LAW DESIGN

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

$$\mathbf{x}(k+1) = \mathbf{\Phi}(k)\mathbf{x}(k) + \mathbf{\Gamma}\mathbf{u}(k) + \mathbf{d}(k) \quad (21)$$

$$\mathbf{y}(k) = \mathbf{C}\mathbf{x}(k) + \mathbf{w}(k), \quad (22)$$

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. Four lights around the entrance of a docking device will be installed to mark the target position, where the center of the lights is the target position.

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 (21) and (22) into a multi-input multioutput (MIMO) model

$$(\mathbf{A}_0+\mathbf{A}_1(k)q^{-1}+\mathbf{A}_2(k)q^{-2})\mathbf{y}(k)=\mathbf{\Gamma u}(k-1)-\mathbf{\Gamma u}(k-2)+\mathbf{n}(k) \quad (23)$$

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 (24) of the visual servoing AUV.

A simple control law can be derived by the minimization of a cost function [16] given below, which aims to achieve a compromise between bringing $\mathbf{y}(k+1)$ to $\mathbf{y}_D(k+1)$ and the amount of control efforts expended

$$J(k+1)=\{[\mathbf{y}(k+1)-\mathbf{y}_D(k+1)]^T\mathbf{Q}[\mathbf{y}(k+1)-\mathbf{y}_D(k+1)] + \mathbf{u}(k)^T\mathbf{L}_u\mathbf{u}(k)\}, \quad (24)$$

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, and $\mathbf{Q}$ and $\mathbf{L}_u$ are the weighted matrixes for the servoing errors and the control inputs, respectively.

The control law is derived from the minimization of the cost function (24) by taking the derivative of $J(k+1)$ with respect to the control vector $\mathbf{u}(k)$ and setting the derivative of $J(k+1)$ to zero. Combing the results with the MIMO model (23) and solving for $\mathbf{u}(k)$, the control law reduces to

$$\mathbf{u}(k)=-(\mathbf{\Gamma}^T\mathbf{Q\Gamma}+\mathbf{L}_u)^{-1}[\mathbf{\Gamma}^T\mathbf{Q}\{-\mathbf{A}_1(k)\mathbf{y}(k)-\mathbf{A}_2(k)\mathbf{y}(k-1) - \mathbf{y}_D(k+1)-\mathbf{u}(k-1)\}]. \quad (25)$$

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. One can measure or estimate the depth with various methods. A simple method for the depth estimation is applied by using the four lights installed around the entrance of the dock with square distribution. If we previously know the distance L_m between the lights, we can estimate the depth using the perspective relation of the camera given below

$$\hat{X}_W(k)=\frac{fL_m}{l_m(k)}, \quad (26)$$

where the $l_m(k)$ is the measured physical distance between the lights.

Thus the control law can be obtained as follows:

$$\mathbf{u}(k)=-(\mathbf{\Gamma}^T\mathbf{Q\Gamma}+\mathbf{L}_u)^{-1}[\mathbf{\Gamma}^T\mathbf{Q}\{-\hat{\mathbf{A}}_1(k)\mathbf{y}(k)-\hat{\mathbf{A}}_2(k)\mathbf{y}(k-1) - \mathbf{y}_D(k+1)-\mathbf{u}(k-1)\}] \quad (27)$$

where the matrix $\hat{\mathbf{A}}_1(k)$ and $\hat{\mathbf{A}}_2(k)$ are determined with the estimated depth (26) of the target point.

When we estimate the depth with (26), the control law will give large fluctuating motion of the fins in the case of the target being in a long relative distance with respect to the camera, because the measured $l_m(k)$ is very small and even hard to be detected in undersea environment. Other methods, such as using a range sonar, can compensate the error of the depth estimation when the target is in long relative distance.

IV. SIMULATION AND DISCUSSIONS

In this section, simulations on the target tracking control of a visual servoing AUV are performed to demonstrate the effectiveness of the proposed modeling and the control law of the AUV. Numerical simulation of an AUV was conducted with the 6-degree-of-freedom nonlinear equations of motion of REMUS AUV reported by Prestero [15]. We suppose that a CCD camera is installed at the nose part of REMUS AUV.

The camera used in simulation is 6*mm* in the focal length f, and the horizontal and vertical scale factors are $s_y=s_z=0.009mm$. The pixels of the CCD camera is 640×480. The camera is installed at the nose center of the AUV with the longitudinal offset $L=0.611\ m$ from the rotational center of the AUV. We assume that the images are captured and processed within 0.1 seconds successively, thus, the sampling period Δt is selected as 0.1 seconds.

The static and hydrodynamic coefficients of the linear AUV model (12) and (14) are given by Prestero [15] as follows:

$I_{yy}=3.45\text{e+}0$, $M_{\dot{q}}=-4.88\text{e+}0$, $M_q=-6.87\text{e+}0$,
$M_\theta=-5.77\text{e+}0$, and $M_{\delta_s}=-3.46\text{e+}1$ in pitch motion,
$I_{zz}=3.45\text{e+}0$, $N_{\dot{r}}=-4.88\text{e+}0$, $N_r=-3.44\text{e+}0$, and
$N_{\delta_r}=-3.46\text{e+}1$ in yaw motion.

We determine the linear yaw-directional hydrodynamic coefficients from the nonlinear pitch components of the AUV described in [15].

Numerical simulation of the projected target on the CCD plane is conducted with the relative position between the target and the camera. The simulated relative position of the target is obtained as below

$$(X_W,Y_W,Z_W)=\vec{CP}=\vec{OP}-\vec{OC}=J_1^{-1}\vec{OP}_{global}-\vec{OC},$$

where J_1 indicates the transformation matrix related with the Euler angle. The projected position (y,z) are obtained from (3) and (4). The distance between the lights is $L=1.0m$ and the truncation error in measuring the depth of the target is included in the simulation.

On the other hand, we suppose that the directional velocity u is constant in calculating the matrix $\Phi(k)$.

The roll motion of the AUV generates additional horizontal and vertical velocities of the projected point, however, we neglect the roll-induced velocities in this simulation. In experimental application with the visual servoing AUV, we can compensate the roll components by measuring the roll angle and subtracting the roll-induced velocities from the captured image feed-forwardly.

The weighting matrixes of the control law are selected as

$$\mathbf{Q}=\text{diag}[1.0\ \ 1.0\ \ 1.0\text{e+}3\ \ 1.0\text{e+}3\ \ 1.0\ \ 1.0]$$
$$\mathbf{L}_u=\text{diag}[100\ \ 20].$$

The initial conditions of the AUV in simulation are $u_0=1.54\ m/s$, $v_0=w_0=0$, $p_0=q_0=r_0=0$ in velocities. The target P is located at $(X_0,Y_0,Z_0)=(20,3,2)$ meters. The AUV is located at the origin of the global coordinate initially, and the initial angles are $\psi_0=-5^\circ$ and $\phi_0=\theta_0=0$. The desired states are all zeros except the heading angle, where the desired heading is calculated and fixed at the initial stage as

$$\psi_D = \tan^{-1}(Y_W(0)/(X_W(0)+L)).$$

Numerical integration is conducted with the Euler method and the time steps is 0.01 seconds for the full nonlinear equation of motion.

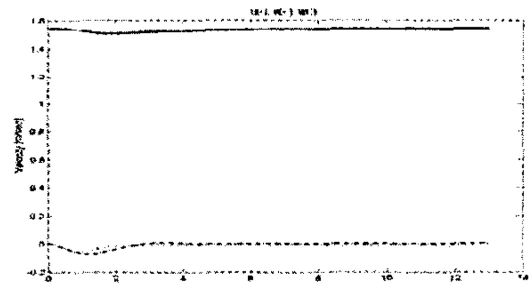
Figure 2 shows the simulated results of docking the visual servoing AUV to the target station, of which (a) the translational velocities (u, v, w), (b) the position of the AUV (X, Y, Z), (c) the angular velocities (p, q, r), and (d) the Euler angle of the AUV (ϕ, θ, ψ). Figure 3 show the simulated results, of which (a) the angles of the control fins δ_a and δ_r, (b) the forces acting on the AUV (F_x, F_y, F_z), and (c) the moments (M_x, M_y, M_z). Figure 4 shows the projected target position (y, z) on the CCD plane in pixel units. The controller can regulate the AUV to track the docking path into the target within 5 seconds. The control inputs are obtained with (27), and the fin angles are updated after Δt =0.1 seconds corresponding to the time delay of the image process. The maximum angle of the horizontal and vertical fins is set to 10 degrees.

The AUV goes well to the target in x, y, z position, and the angular motions decay to zero after converging to the desired angles. The pitch angle shows small oscillation when the AUV approaches near to the docking device. This phenomenon is caused by the increment of the visual errors, where the errors in (y, z) on CCD plane are enlarged as the AUV shortens the depth of the target. Since the equation of the pitch motion has the restoring term, the pitch motion is more sensitive than the yaw motion.

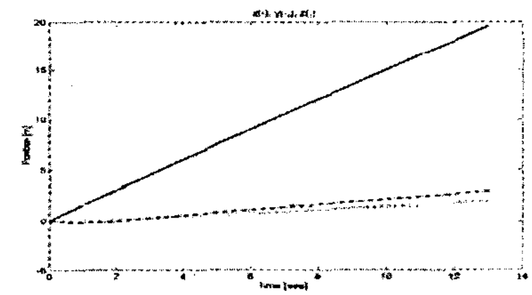
When the AUV is in long relative distance from the target, we cannot neglect the roll-induced velocity of the target on the CCD plane. Thus it is required to compensate the roll-induced motion in experiment. We suppose that the roll-induced velocity is exactly compensated in the simulation.

As the AUV approaches to the target, the location of the lights set around the entrance keep departing from the center of the CCD frame. When the AUV is within 1.39*m* from the entrance of the docking device, the light is outside of the CCD plane. In this simulation, we set the angle of the control fins to zeroes when the AUV is within 1.0*m*. Figure 3 shows that the fin angles are zeros at the final stage of the docking simulation, and the pitch moment are induced at the final stage.

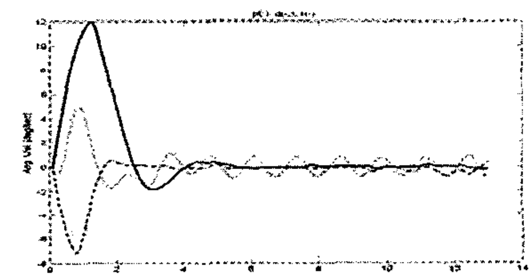
In general, the simulated results depict the effectiveness of the modeling and the control law for the visual servoing AUV. Experiments on the docking control of the visual servoing AUV will be conducted in near future.



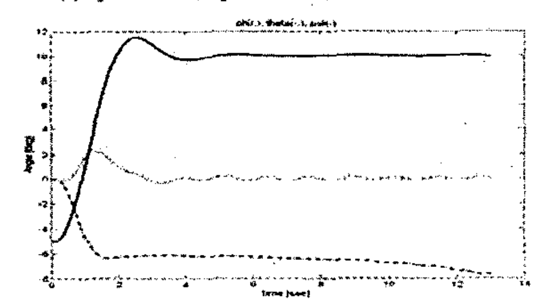
(a) u : solid line, v : dash-dot line, w : dot line



(b) x : solid line, y : dash-dot line, z : dot line



(c) p : dot line, q : dash-dot line, r : solid line



(d) ϕ : dot line, θ : dash-dot line, ψ : solid line

Fig. 2 Simulated motion of the visual servoing AUV.

V. CONCLUSIONS

This paper presents the model and the control law of 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 automatically generated with the projected target position on the CCD plane and with the desired motion of the AUV. The optical flow equation of the camera mounted on the AUV is obtained, and the optical flow equation of the camera and a linearized equation of motion of the AUV are combined to a state equation for the visual servoing AUV. The controller is designed on the basis of an optimal one-step ahead predictive controller by minimizing a cost function. Simulations on docking the AUV to a target station are performed with the 6-dof nonlinear equations of REMUS of WHOI and a CCD camera. The results illustrate the effectiveness of the modeling and the controller of the visual servoing AUV.

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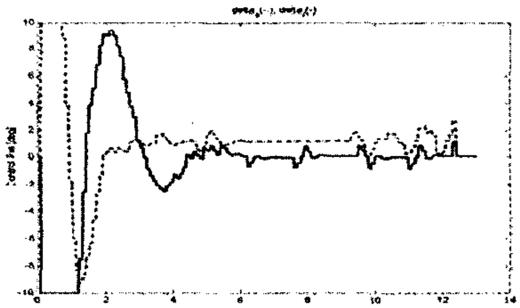
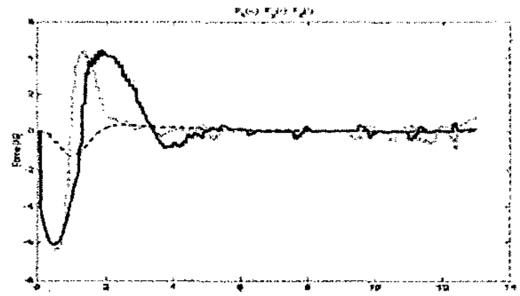
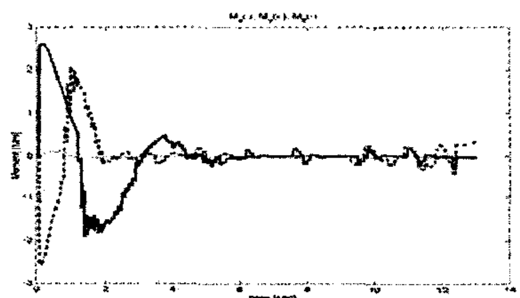


(a) δ_s : dash line, δ_r : solid line



(b) F_x : dash-dot line, F_y : solid line, F_z : dot line



(c) M_x : dot line, M_y : dash-dot line, M_z : solid line

Fig. 3 Simulated ontrol inputs, forces, and moments of the visual servoing AUV.

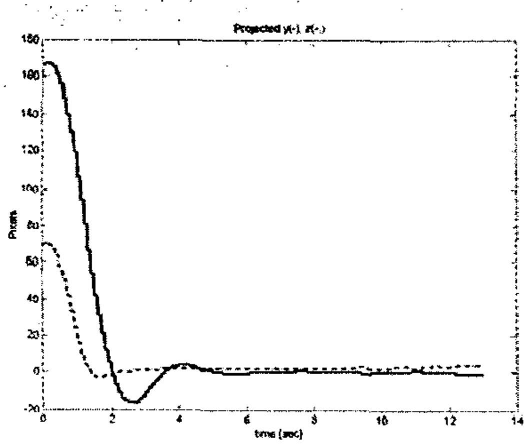


Fig. 4 Projected position of the target on CCD plane – y : solid line, z : dash-dot line.

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