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Adaptive depth controller design for a submerged body moving near free surface

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ABSTRACT

A submerged body that moves near a free surface needs to keep its attitude and position to accomplish its missions, which are required to validate the performance of a designed controller before sea trial. Hydrodynamic maneuvering coefficients are generally obtained by experiments or computational fluid dynamics, but these coefficients suffer from uncertainty. Environmental loads such as wave excitation, current, and suction forces act on the submerged body when it moves near the free surface. Therefore, a controller for the submerged body should be robust to parameter uncertainty and environmental loads. In this paper, six-degree-of-freedom equations of motion for the submerged body are constructed. An adaptive control method based on the neural network and proportional–integral–derivative controller is used for the depth controller. Simulations are performed under various depth and environmental conditions, and the results show the effectiveness of the designed controller.

1. Introduction

A submerged body mainly operates in deep environment, but some cases occur where it must move near a free surface depending on its missions. Submarine moves to periscope depth to explore a target ship or periodically travels at snorkeling depth to charge its batteries. A torpedo moves near the free surface during its terminal phase when it strikes a surface vessel. An underwater exploration robot moves near the free surface when it needs to communicate outside or receive Global Positioning System signals. In such cases, environmental loads such as wave, current, and suction forces act on the submerged body. Depth controller is needed for the submersible to perform its mission under environmental loads. Verifying the designed controller performance based on simulations is essential before the trial. Dynamic modeling used in simulations is usually performed through model test and computational fluid dynamics, but these methods suffer from uncertainty. A depth controller should be able to handle the uncertainty in dynamic model and under environmental loads.

Studies to construct the equation of motion and deduce the hydrodynamic coefficients have been actively conducted since the 1960s. Gertler and Hagen [1] proposed a dynamic model by decomposing the hydrodynamic force into a combination of nonlinear coefficients. The model was revised by Feldman [2], which considered nonlinear effects such as cross-flow drag and sail vortex. Dumlu and Istefanopulos [3] established a motion equation that considered the auxiliary tank of a submarine. Prestero [4] obtained the hydrodynamic coefficients using free-running and captive-model tests to develop a simulator for the Remote Environmental Monitoring UnitS autonomous underwater vehicle, and the controller was designed based on these coefficients. Research activities on depth control for a submerged body moving near the free surface are mainly performed using the proportional–integral–derivative (PID), linear quadratic regulator (LQR), and fuzzy controls. Hao et al. [5] designed a depth controller of a submarine in waves using fuzzy theory. J.H Choi et al. [6] and J.W. Choi et al. [7] proposed a mathematical model of the wave exciting force and performed depth control simulation using the PID method. Kim et al. [8] analyzed the limitations of PID control in depth control of a submarine and designed a depth controller using the LQR control method. Shao et al. [9] designed a depth control for a small cylindrical submerged body based on the works of Richards and Stoten [10]. Lee and Singh [11] designed the L_1 adaptive autopilot for trajectory control of the depth and pitch angle using hydroplanes. Rezazadegan et al. [12]

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proposed a novel approach to a six-degree of freedom (DOF) adaptive trajectory tracking control of an unmanned underwater vehicle in the presence of parameter uncertainties.

The limitations of the previous studies on depth control of a submerged body that moves near a free surface are as follows: first, previous research works only considered a three-DOF movement such as surge–heave–pitch; thus, applying the controller to a real submerged body proved difficult. The vertical directions of body-fixed and space-fixed coordinates do not coincide when the roll angle is disturbed by waves; thus, error in depth can increase without roll control. Second, no previous research was conducted in which the suction force is considered. A modeling research on the suction force was performed by Yoon and Trung [13], but a controller design that considers the suction force has not yet been reported in the literature.

To mitigate the drawbacks of the previous research, the present study designs a depth controller for a submerged body that moves near a free surface by considering the wave, current, and suction effects. The amplitude of regular waves is derived using the wave spectrum presented in the International Towing Tank Conference (ITTC), and irregular waves are generated using a linear theory. The double Rankine body is used to calculate the suction force under various speed and depth conditions, and a suction-force formula is constructed using the calculation results. A six-DOF equation of motion is used to simulate the maneuvering motion of the submerged body, and a roll–pitch–yaw controller is designed. The controller consists of inner and outer loops. The outer-loop controller generates the reference Euler angle by feeding back the position error of the submerged body. The inner-loop controller makes the submerged body follow the output of the outer loop. A PID controller is used in the outer loop, and an adaptive controller based on Neural Networks (NNs) is used in the inner loop for robustness to modeling uncertainty. Control simulations under various operating conditions are conducted to validate the controller performance.

2. Mathematical model

2.1. Kinematics

Fig. 1 shows the coordinate system used in this study, which consists of the body- and space-fixed coordinates.

The origin of the space-fixed coordinate $O-xyz$ is located at an arbitrary position on a free surface, and the positive direction of depth z is downward. The position and orientation of the submerged body can be defined in the space-fixed coordinate. In the figure, u, v, and w are respectively the surge, sway, and heave velocities; p, q, and r are respectively the roll, pitch, and yaw rates. The orientation can be defined by the Euler angle; and φ, θ, and ψ represent the roll, pitch, and yaw angles, respectively. The origin of the body-fixed coordinate $O-x_oy_oz_o$ is located at the center of buoyancy. δ_r, δ_{el}, and δ_{er} represent the rudder, portside-elevator, and starboard-side-elevator angles, respectively. Translational velocities between body-fixed and space-fixed coordinates are related with the following coordinate transform:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = J_1(\phi,\theta,\psi)\begin{bmatrix} u \\ v \\ w \end{bmatrix} \tag{1}$$

where

$$J_1(\phi,\theta,\psi)=\begin{bmatrix} \cos\psi\cos\theta & -\sin\psi\cos\phi+\cos\psi\sin\theta\sin\phi & \sin\psi\sin\phi+\cos\psi\sin\theta\cos\phi \\ \sin\psi\cos\theta & \cos\psi\cos\phi+\sin\psi\sin\theta\sin\phi & -\cos\psi\sin\phi+\sin\psi\sin\theta\cos\phi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix} \tag{2}$$

The second coordinate transform relates rotational velocities between body-fixed and space-fixed coordinates:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = J_2(\phi,\theta,\psi)\begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{3}$$

where

$$J_2(\phi,\theta,\psi)=\begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix} \tag{4}$$

2.2. Equation of motion

The subject submerged body is symmetrical in the x–z and x–y planes. The submerged body is equipped with a cruciform control surface in the stern. The linear hydrodynamic forces and moments are used for the submerged body because it has a good course-keeping ability. The six-DOF equation of motion can be expressed as follows:

$$\begin{aligned}
&m\left[\dot{u}-vr+wq-x_g(q^2+r^2)+z_g(pr+\dot{q})\right]=X_{\dot{u}}\dot{u}+X_u u+\{\rho(n_p/60)^2d_p^4\}X_T(1-t)-(W-B)\sin\theta+X_W\\
&m\left[\dot{v}-wp+ur+x_g(qp+\dot{r})+z_g(qr-\dot{p})\right]=Y_{\dot{v}}\dot{v}+Y_{\dot{p}}\dot{p}+Y_{\dot{r}}\dot{r}+Y_v v+Y_p p+Y_r r+(W-B)\cos\theta\sin\phi+Y_{\delta_r}\delta_r+Y_W\\
&m\left[\dot{w}-uq+vp+x_g(rp-\dot{q})-z_g(p^2+q^2)\right]=Z_{\dot{w}}\dot{w}+Z_{\dot{q}}\dot{q}+Z_w w+Z_q q+(W-B)\cos\theta\cos\phi+Z_{\delta_e}\left(\delta_{el}+\delta_{er}\right)+Z_W+Z_{suc}\\
&I_{xx}\dot{p}+\left(I_{zz}-I_{yy}\right)qr+m\left[-z_g(\dot{v}-wp+ur)\right]=K_{\dot{v}}\dot{v}+K_{\dot{p}}\dot{p}+K_{\dot{r}}\dot{r}+K_v v+K_p p+K_r r-z_g W\sin\phi\cos\theta\\
&+\{\rho(n_p/60)^2d_p^5\}K_0+K_{\delta_{el}}(\delta_{er}-\delta_{el})+K_W\\
&I_{yy}\dot{q}+(I_{xx}-I_{zz})rp+m\left[z_g(\dot{u}-vr+wq)-x_g(\dot{w}-uq+vp)\right]=M_{\dot{w}}\dot{w}+M_{\dot{q}}\dot{q}+M_w w+M_q q+M_p p+M_r r\\
&-x_g W\cos\theta\cos\phi-z_g W\sin\theta+M_{\delta_e}(\delta_{er}+\delta_{el})+M_W\\
&I_{zz}\dot{r}+\left(I_{yy}-I_{xx}\right)pq+m\left[x_g(\dot{v}-wp+ur)\right]=N_{\dot{v}}\dot{v}+N_{\dot{p}}\dot{p}+N_{\dot{r}}\dot{r}+N_v v+N_p p+N_r r+x_g W\cos\theta\sin\phi+N_{\delta_r}\delta_r+N_W
\end{aligned} \tag{5}$$

where W and B are the weight and buoyancy of the submerged body, respectively. x_g and z_g are the coordinates of the longitudinal and vertical center of gravity. The lateral center of gravity is assumed to be small. X_T is the propeller thrust, t is the propeller thrust deduction coefficient, and K_0 is the imbalance moment induced by propeller rotation. Subscript W denotes a wave, and subscript suc denotes suction.