Autopilot Design of an Autonomous Underwater Vehicle Using Robust Control

Keum Young Jung, In Soo Kim, Seung Yun Yang, and Man Hyung Lee

Abstract: In this paper, H_∞ depth and course controller of an AUV(Autonomous Underwater Vehicle) using H_∞ servo control is proposed. The H_∞ servo problem is formulated to design the controllers satisfying a robust tracking property with modeling errors and disturbances. The solution of the H_∞ servo problem is as follows: first, this problem is modified as an H_∞ control problem for the generalized plant that includes a reference input mode, and then a sub-optimal solution that satisfies a given performance criteria is calculated by LMI(Linear Matrix Inequality) approach. The H_∞ depth and course controller are designed to satisfy with the robust stability about the modeling error generated from the perturbation of the hydrodynamic coefficients and the robust tracking property under disturbances(wave force, wave moment, tide). The performances of the designed controllers are evaluated with computer simulations, and finally these simulation results show the usefulness and application of the proposed H_∞ depth and course control system.

Keywords: autonomous underwater vehicle, autopilot, path tracker, depth controller, H_∞ servo control

I. Introduction

The study on an AUV(autonomous underwater vehicle) has been initiated in the 1960s, and is progressing recently for military purposes with the latest technical developments, such as a fast operation system, a navigation system, a high-performance actuator. It is most important for an AUV system to make an autonomous control system to perform its duties autonomously without manipulation of a human being. The autopilot, which composed of path tracker and depth controller, for the guidance system is the central system in the autonomous control system of an AUV.

It is very important to keep a constant depth and heading angle of the AUV at shallow depth. But, it is very difficult to carry out for the path tracking and depth keeping control by hand at shallow depth because of the effect of the disturbances, such as the wave, tide, and so on. Therefore, it is necessary to design a robust controller for the path tracking and depth keeping voyage of the AUV under the wave disturbances. A robust multivariable control that considers complex AUV dynamics and sea wave characteristics is needed for the path tracking and depth control under the disturbances, the uncertainties of fluid parameters, approximation errors of a linearized AUV model, and so forth[1]-[3].

The objective of this paper is to design of an H_∞ path tracker and depth controller that satisfy robust path and depth tracking performances with wave disturbance attenuation. Moreover, it must be designed to be robustly stable under modeling errors occurring from uncertain variations of system parameters. To design the H_∞ path tracker and depth controller that satisfy the depth tracking performance of the AUV, an H_∞ servo problem[4] is formulated instead of extending with a mixed sensitivity problem in the H_∞ control. A generalized plant for the H_∞ servo problem is reconstructed by the internal model principle into a modified generalized plant that includes a reference mode. Since the H_∞ control problem for the modified generalized plant does not satisfied some assumptions[5] required for solving the H_∞ control, it is solved by LMI-based technique[6][7] and finally the H_∞ servo controller is designed from the solution of the H_∞ control problem. The designed H_∞ servo controllers are assessed in computer simulations. Consequently, the simulation results of the proposed H_∞ path tracker and depth controller, which satisfy the robust stability for the uncertain variation of fluid parameters, disturbances attenuation and robust path and depth tracking property under the wave disturbances show the usefulness and the applicability of this study.

II. AUV dynamics

1. AUV linear model

The equations of motion in six degrees of freedom[8] are derived by summing the applicable forces and moments in surge(x), sway(y), heave(z), roll(ϕ), pitch(θ) and yaw(ψ). The simplified linear equations of motion of an AUV are derived from the nonlinear equation of motion in six degrees of freedom with the following assumptions.

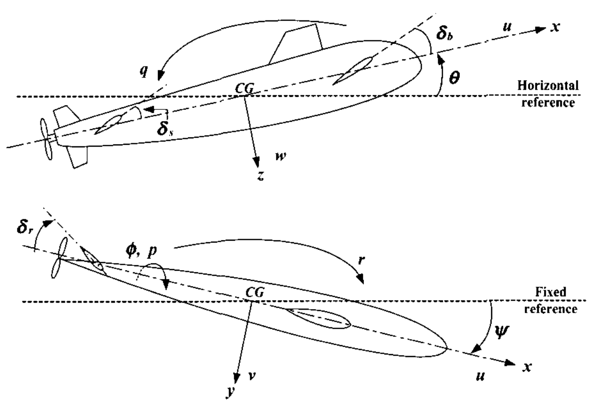

Fig. 1. The coordinate system of an AUV.

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- The forward speed can be taken as constant.
- The roll angle is assumed to be small.
- The cross-products of inertia can be neglected.
- The AUV is assumed to be in trim under the sea.

As a result of the above mentioned four assumptions, the linear equations of motion on the vertical plane are as follows.

- Equation of motion along z-axis(normal force)

$$\begin{aligned} m\dot{w} - umq &= 0.5\rho l^4 Z_{\dot{q}}\dot{q} \\ &+ 0.5\rho l^3(Z_{\dot{w}}\dot{w} + Z_q uq) \\ &+ 0.5\rho l^2(Z_w uw + u^2(Z_{\delta s}\delta s + Z_{\delta b}\delta b)) \end{aligned} \quad (1)$$

- Equation of motion about y-axis(pitch moment)

$$\begin{aligned} I_y\dot{q} &= 0.5\rho l^5 M_{\dot{q}}\dot{q} \\ &+ 0.5\rho l^4(M_q uq + M_{\dot{w}}\dot{w}) \\ &+ 0.5\rho l^3(M_w uw + u^2(M_{\delta s}\delta s + M_{\delta b}\delta b)) + Bz_B\theta \end{aligned} \quad (2)$$

where m, B, z_B, ρ and l are the AUV mass, the buoyancy, the center of buoyancy about z-axis, the density and the AUV length, respectively.

The state space model on the vertical is derived with the following state variables.

$$\dot{X}_d = A_d X_d + B_d U_d \quad (3)$$

where $X_d = [\,w\ q\ z\ \theta\,]^T$, $U_d = [\,\delta_b\ \delta_s\,]^T$,

$$A_d = \begin{bmatrix} \alpha_{11} & \alpha_{12} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 & \alpha_{24} \\ 1 & 0 & 0 & -u \\ 0 & 1 & 0 & 0 \end{bmatrix}, \quad B_d = \begin{bmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

w, q, z and θ are the heave velocity, the pitch rate, the AUV depth and the pitch angle, respectively, δ_b and δ_s are the bow and stern hydroplane angle. u is the AUV forward speed, α_{ij} and β_{ij} are the hydraulic coefficients.

The linearized form of the equations on the horizontal plane are derived as follows.

- Equation of motion along y-axis(lateral force)

$$\begin{aligned} m\dot{v} - \mu r &= 0.5\rho l^4 Y_{\dot{r}}\dot{r} \\ &+ 0.5\rho l^3(Y_{\dot{v}}\dot{v} + Y_r ur) \\ &+ 0.5\rho l^2(Y_v uv + u^2 Y_{\delta r}\delta r) \end{aligned} \quad (4)$$

- Equation of motion about z-axis(yaw moment)

$$\begin{aligned} I_z\dot{r} &= 0.5\rho l^5 N_{\dot{r}}\dot{r} \\ &+ 0.5\rho l^4(N_r ur + N_{\dot{v}}\dot{v}) \\ &+ 0.5\rho l^3(N_v uv + u^2 N_{\delta r}\delta r) \end{aligned} \quad (5)$$

where m, B, z_B, ρ and l are the AUV mass, the buoyancy, the center of buoyancy about z-axis, the density and the AUV length, respectively.

The state space model on the horizontal plane is given by

$$C_A\dot{X}_c = C_B X_c + C_C U_c \quad (6)$$

where $X_c = [\,v\ r\ \psi\,]^T$, $U_c = \delta_r$,

$$C_A = \begin{bmatrix} a_{11} & a_{12} & 0 \\ a_{21} & a_{22} & 0 \\ 0 & 0 & 1 \end{bmatrix}, C_B = \begin{bmatrix} b_{11} & b_{12} & 0 \\ b_{21} & b_{22} & 0 \\ 0 & 1 & 0 \end{bmatrix}, C_C = \begin{bmatrix} c_{11} \\ c_{21} \\ 0 \end{bmatrix}$$

v, r, ψ and δ_r are the sway velocity, the yaw rate, the yaw angle and the rudder hydroplane, respectively, and a_{ij}, b_{ij} and c_{ij} are the hydraulic coefficients.

2. Sea wave model

The sea waves have very complex forms because the waves generated at sea are superimposed on each other. The data of these complex and irregular waves are enormous, so they are used in the spectral form instead of a time series. The energy spectrum is calculated by multiplying the wave spectrum by the sea density(ρ) and the acceleration due to gravity(g), and the energy of a wave per unit area is computed by integrating the energy spectrum from 0 to ∞ at a frequency domain. The most useful wave spectrum is the ITTC(International Towing Tank Conference) wave spectrum[1] given by (7)

$$S(\omega) = \frac{A}{\omega^5}\exp\left(-\frac{B}{\omega^4}\right) \quad (7)$$

where $S(\omega)$ is the wave spectral density, $A = 8.1\times 10^{-3}g^2$, $B = 3.11/h_3^2$, ω is the wave frequency, h_3 is the significant wave height.

However, the ITTC wave spectrum is not pertinent for applying to the H_∞ controller design, because the wave forces and moments reproduced from the ITTC spectrum are very complex. Therefore, it requires that the ITTC spectrum be modified to a simplified representation such as a linear filter using white noise, which is the approximation of a wave spectrum. In this paper, the fourth-order filter that determined by the central frequency M(this frequency is where the magnitude of $S(\omega)$ reaches its maximum) of its passband was applied to represent the wave forces and moments[1]. This filter is given by

$$\frac{\eta}{\xi} = \frac{K(s/\omega_M)^2}{[\,(s/\omega_M)^2 + s/\omega_M + 1\,]^2} \quad (8)$$

where η is the approximated wave elevation, ξ is white noise, K is a filter gain.

The simplified wave force and moment equations Z_w and M_w are as follows.

$$Z_w = a\cdot\eta(t) + b,\quad M_w = c\cdot\eta(t) + d \quad (9)$$

where a, b, c and d are the hydraulic constants.

III. Controller design

1. LMI-based H∞ servo control

In the design of the H_∞ controller that satisfies the robust stability, the robust tracking property of a closed loop system, can generally be designed by applying the mixed-sensitivity approach. Hozumi *et al.*[4] solved the H_∞ servo problem for the robust tracking property of a plant by using an LMI-based solution to the H_∞ control problem. One of the significances of the LMI-based solution is that it does not require additional conditions for the H_∞ control problem proposed by Doyle *et al.*[5].

The H_∞ servo problem that considered a two degree of freedom control system described in Fig. 2 is formulated as the problem to find a controller K satisfying the following three specifications, for a given generalized plant G and a reference model.

$$G=\begin{bmatrix} A & B_1 & B_2 \\ C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{bmatrix} \tag{10}$$

S1) K internally stabilizes G

S2) $\| T_{zw} \|_\infty < \gamma$

S3) K achieves a robust tracking property

where T_{zw} is the transfer function from w to z, K is the H_∞ servo controller, $w \in R^{m_1}$ is the disturbance, $u \in R^{m_2}$ is the control input, $z \in R^{p_1}$ is the controlled output, $y \in R^{p_2}$ is the measured output, $r \in R^{p_2}$ is the reference input, respectively.

To obtain the conditions for the existence of a solution of the H_∞ servo problem, the closed loop system that is removed the feedforward controller is considered. In case the reference input is considered a step-type input, $\phi_r(s) \in RH_\infty$ defined as the largest invariant factor of $\hat{D}_r(s)$ is given by

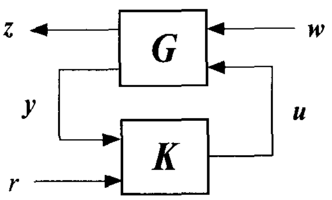


Fig. 2. H_∞ servo problem.

$$\phi_r(s)=\frac{s}{s+1} \tag{11}$$

and the controller $K_2(s)$ is obtained by

$$K_2(s)=K_r(s)\phi_r^{-1}(s)I \tag{12}$$

In conclusion, the H_∞ servo problem for the generalized plant G can be modified the H_∞ problem for the generalized plant $\hat{G}$, which is defined as

$$\hat{G}(s)=\begin{bmatrix} A & 0 & B_1 & B_2 \\ C_2 & 0 & D_{21} & 0 \\ C_1 & 0 & D_{11} & D_{12} \\ C_2 & 0 & D_{21} & 0 \\ 0 & I_{p_2} & 0 & 0 \end{bmatrix} \tag{13}$$

where p_2 denotes the number of the reference input, I_{p_2} is the $p_2 \times p_2$ identity matrix, and a reference model Σ including a reference input mode is given by

$$\Sigma(s)=\begin{bmatrix} 0 & I_{p_2} \\ I_{p_2} & 0 \end{bmatrix} \tag{14}$$

The state-space model of (13) is denoted by

$$\hat{G}(s)=\begin{bmatrix} \hat{G}_{11}(s) & \hat{G}_{12}(s) \\ \hat{G}_{21}(s) & \hat{G}_{22}(s) \end{bmatrix}=\begin{bmatrix} \hat{A} & \hat{B}_1 & \hat{B}_2 \\ \hat{C}_1 & \hat{D}_{11} & \hat{D}_{12} \\ \hat{C}_2 & \hat{D}_{21} & 0 \end{bmatrix} \tag{15}$$

The H_∞ control problem that is equivalent to the H_∞ servo problem is formulated as follows(Fig. 3).

H_∞ control problem: for the modified generalized plant (11) constructed from a given generalized plant G and a reference input r, find a controller $\hat{K}$ satisfying the following specifications,

S1)′ $\hat{K}$ internally stabilizes $\hat{G}$

S2)′ $\| T_{zw} \|_\infty < \gamma$

In the H_∞ control problem for the modified generalized plant $\hat{G}$, $\hat{G}_{12}$ has an imaginary axis zero and D_{12} dose not have a full row-rank, it can not be solved by the solution proposed by Doyle *et al.*[5]. Therefore, H_∞ the control problem is solved by an LMI-based solution proposed by Gahinet[6][7]. The suboptimal H_∞ control problem for the given performance γ is solvable if and only if there exist two symmetric matrices R and S satisfying the following system of LMIs.

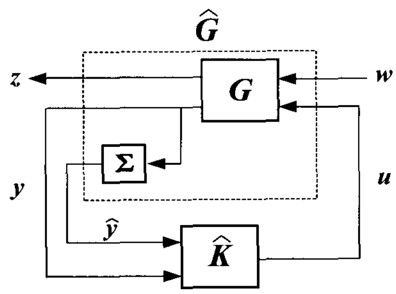


Fig. 3. H_∞ control problem.

$$\begin{pmatrix} N_R & 0 \\ 0 & I \end{pmatrix}^T \begin{pmatrix} \hat{A}R+R\hat{A}^T & R\hat{C}_1^T & \hat{B}_1 \\ \hat{C}_1 R & -\gamma I & \hat{D}_{11} \\ \hat{B}_1^T & \hat{D}_{11}^T & -\gamma I \end{pmatrix} \begin{pmatrix} N_R & 0 \\ 0 & I \end{pmatrix} < 0 \tag{16}$$

$$\begin{pmatrix} N_S & 0 \\ 0 & I \end{pmatrix}^T \begin{pmatrix} \hat{A}^T S+S\hat{A} & S\hat{B}_1 & \hat{C}_1^T \\ \hat{B}_1^T S & -\gamma I & \hat{D}_{11}^T \\ \hat{C}_1 & \hat{D}_{11} & -\gamma I \end{pmatrix} \begin{pmatrix} N_S & 0 \\ 0 & I \end{pmatrix} < 0 \tag{17}$$

$$\begin{pmatrix} R & I \\ I & S \end{pmatrix} < 0 \tag{18}$$

where $(\hat{A}, \hat{B}_2)$ is stabilizable and $(\hat{A}, \hat{C}_2)$ is detectable. N_R and N_S are orthonomal bases of the null spaces of $(\hat{B}_2^T, \hat{D}_{12}^T)$ and $(\hat{C}_2, \hat{D}_{21})$, respectively.

2. H_∞ path tracker and depth controller

The path tracker and depth controller require that the AUV should maintain constant course and depth under the sea wave disturbances. There are forces and moments as the effects of the wave to the AUV : the forces to the AUV heave and the moments to the AUV pitch. When the AUV comes nearer to the sea surface, the effects of the hyperplanes decrease whereas it is greatly affected by the wave disturbances. Thus it should be considered these characteristics of the wave for designing the path tracker and depth controller. In this paper, the H_∞ path tracker and depth controller satisfying the following specifications are designed.

1) robust stability of a closed loop system under the modeling error that occurred from the uncertain variations of system parameters.

2) robust tracking property of the AUV course and depth under the sea wave disturbances.

The variations of the AUV system parameters that considered in this paper are shown in Table 1. The state-space model for path tracker design is as follows.

$$\begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} -0.2944 & -0.5492 & 0 \\ -0.3104 & -0.7120 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v \\ r \\ \psi \end{bmatrix} + \begin{bmatrix} 0.1121 \\ -0.1335 \\ 0 \end{bmatrix} \delta_r \quad (19)$$

Table 1. The variations of the AUV parameters.

parameters	variation	parameters	variation
$X_{\delta r\delta r}$	30 %	Y_{wp}	30 %
$X_{\delta b\delta b}$	30 %	Z_{wp}	30 %
$X_{\delta s\delta s}$	30 %	Z_{vp}	30 %
$Z_{\delta b}$	30 %	K_{qr}	30 %
$Z_{\delta s}$	30 %	M_{vr}	30 %
Z_q	30 %	N_{pq}	30 %
M_q	30 %	W	1.0 %
X_{vr}	30 %	B	0.5 %

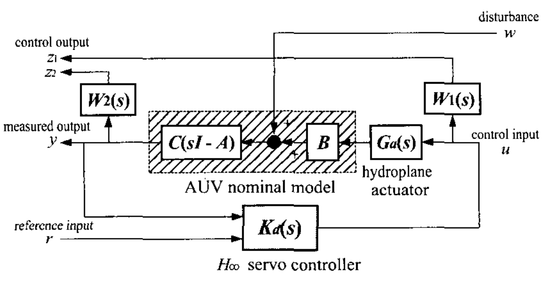


Fig. 4. The H_∞ servo controller for the AUV.

For designing the path tracker, the tide with a constant velocity is considered as the disturbance affecting on the AUV yaw angle. The generalized plant for the H_∞ path tracker has the same structure shown in Fig. 4, and the determined weighting functions $W_1(s)$ and $W_2(s)$ are as follows.

$$W_1(s) = \frac{525s}{s+3.5}, \quad W_2(s) = \frac{7.5}{s+0.125} \quad (20)$$

Since the wave forces and moments act on the AUV heave and pitch, they are considered as the disturbance w shown in Fig. 4. For the robust path-tracking performance under these disturbances, the AUV yaw angle was selected for the controlled output z_1, the AUV rudder hyperplane angle was selected for the controlled output z_2 to limit the hyperplane deflection and rate of change. y is the measured output, r is the reference input, $W_1(s)$ and $W_2(s)$ are the weighting functions at plant input and output, respectively, the controller $K(s)$ is constructed by the feedback controller satisfying robust stability, disturbance attenuation and robust tracking property. To have the robust stability of the closed-loop system and be decreased the effect of the uncertainties to the hyperplanes at high frequencies. The state-space model of the AUV for depth controller design is as follows.

$$\begin{bmatrix} \dot{w} \\ \dot{q} \\ \dot{z} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -0.3391 & 0.5506 & 0 & 0 \\ 0.1580 & -0.7314 & 0 & -0.021 \\ 1 & 0 & 0 & -2.056 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} w \\ q \\ z \\ \theta \end{bmatrix} + \begin{bmatrix} -0.1254 & -0.1016 \\ 0.0451 & -0.1090 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_b \\ \delta_s \end{bmatrix} \quad (21)$$

The H_∞ depth controller structure including the generalized plant and weighting functions is shown in Fig. 4. The AUV depth and pitch angle were selected for the controlled output z_1, the AUV bow and stern hyperplane angles were selected for the controlled output z_2 to limit the hyperplane deflection and rate of change, in the same way as the path tracker design. $W_1(s)$ was determined as a stable rational function that has large magnitude at high frequencies, and $W_2(s)$ has small magnitude at other frequencies except the wave frequency band. The determined $W_1(s)$ and $W_2(s)$ for the H_∞ depth controller are as follows.

$$W_1(s) = \frac{200s}{s+5}, \quad W_2(s) = \frac{6}{s+1.5} \quad (22)$$

3. Simulation results

The designed H_∞ path tracker and depth controller were assessed in computer simulations with the AUV nonlinear equation of motion in six degrees of freedom. The nonlinear simulation for path tracking and depth keeping is shown in Fig. 5. The performance of the designed H_∞ path tracker and depth controller under the variation of AUV system parameters, which given by Table 1, the disturbances is shown in Fig. 6. Simulations were carried out for 500-second periods and the disturbances with significant wave height of 1.0m(sea state 3) and the tide with 0.5m/s are considered.

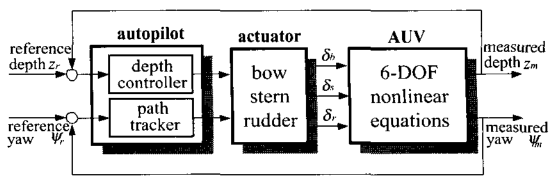
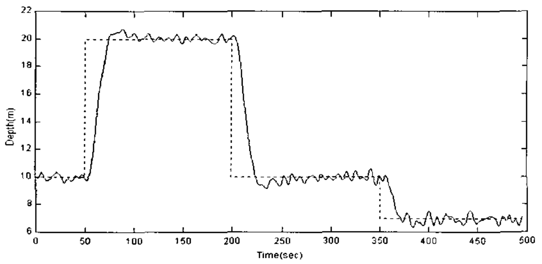


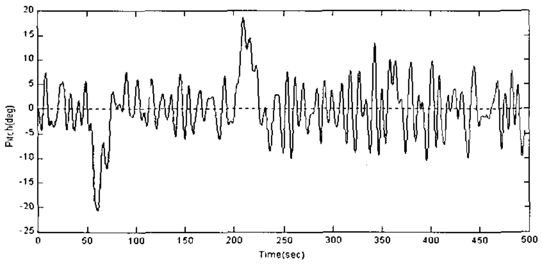
Fig. 5. The nonlinear simulation with the H_∞ path tracker

and depth controller.

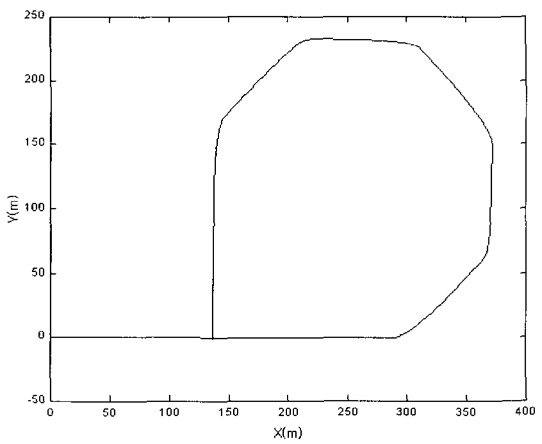
In Fig. 6(a) and Fig. 6(b), a dotted line represents a reference depth and pitch angle and a solid line is the AUV depth and pitch response, respectively. The AUV path tracking, X(surge) and Y(sway) direction, performance under the tide is shown in Fig. 6(c). The wave disturbances, the wave forces, moments, and the tide, affected greatly on the AUV depth, pitch and yaw angle at initial time, whereas the effect slowly decreased in the steady-state. The maximum deflection of the pitch angle is 20 degrees and the scope of the bow, stern and rudder hyperplanes is within 40 degrees.



(a) AUV depth



(b) AUV pitch angle



(c) AUV path(X-Y)

Fig. 6. AUV path tracking and depth keeping under the modeling error and wave disturbances.

IV. Conclusions

In this paper, the H_∞ servo controllers satisfying path tracking and depth keeping autopilots of the AUV are proposed. For the robust path and depth control of the AUV under the modeling error and disturbances, we applied the H_∞ servo problem to the linearized AUV models on vertical and horizontal plane, and the path tracker and depth controller were constructed in the form of the H_∞ servo controller. The H_∞ servo problem was developed to the H_∞ control problem with the modified generalized plant including an internal model that has the reference mode. This reformulated H_∞ control problem was solved by LMI-based solution. The weighting functions in the H_∞ servo problem were selected in the form of stable rational functions based on the AUV dynamics. Finally, simulations show that the designed H_∞ path tracker and depth controller were satisfied robust stability about the uncertain variation of fluid parameters and robust path tracking and depth keeping performances under the wave disturbances.

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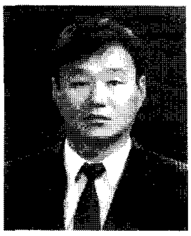

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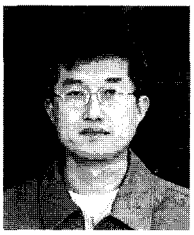

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