Design of Adaptive Fuzzy Sliding Mode Controller based on Fuzzy Basis Function Expansion for UFV Depth Control

Hyun-Sik Kim and Yong-Ku Shin

Abstract: Generally, the underwater flight vehicle (UFV) depth control system operates with the following problems: it is a multi-input multi-output (MIMO) system because the UFV contains both pitch and depth angle variables as well as multiple control planes, it requires robustness because of the possibility that it may encounter uncertainties such as parameter variations and disturbances, it requires a continuous control input because the system that has reduced power consumption and acoustic noise is more practical, and further, it has the speed dependency of controller parameters because the control forces of control planes depend on the operating speed. To solve these problems, an adaptive fuzzy sliding mode controller (AFSMC), which is based on the decomposition method using expert knowledge in the UFV depth control and utilizes a fuzzy basis function expansion (FBFE) and a proportional integral augmented sliding signal, is proposed. To verify the performance of the AFSMC, UFV depth control is performed. Simulation results show that the AFSMC solves all problems experienced in the UFV depth control system online.

Keywords: Adaptive fuzzy sliding mode controller, fuzzy basis function expansion, integral augmented sliding signal, underwater flight vehicle.

1. INTRODUCTION

Among the various types of modern underwater vehicles, the underwater flight vehicle (UFV) [1] has the lowest hydrodynamic drag, although it needs to move forward in order to maneuver because it has a propulsion unit and control planes rather than a multitude of thrusters. However, control of the UFV is well known as a difficult problem because it has a small control force due to the fact that the size of the control planes are much smaller compared to the body. In particular, UFV depth control is more difficult to achieve than other controls such as course control and speed control because it has dynamic behaviors related with the vertically non-symmetric hull force and restoring force.

Generally, the UFV depth control system operates with the following problems: it is a multi-input multi-output (MIMO) system because the UFV contains both pitch and depth angle variables as well as multiple control planes, it requires robustness because it may encounter uncertainties such as parameter variations and disturbances, it requires a continuous control input because the system that has reduced power consumption and acoustic noise is more practical, and further, it has the speed dependency of controller parameters because the control forces of control planes depend on the operating speed.

To solve these problems, various controllers have been suggested. Jalving [2] proposed the controller that has a simplified dynamic equation and a practical PID controller. Castro and Cristi [3,4] proposed the controller that has a nominal dynamic equation around the operating speed and a robust controller, and Castro [5] proposed the controller that has a gain scheduling method. Although all of these have good performances, the problems mentioned above have not yet been solved completely. Kim [6] proposed the controller that has a fuzzy sliding mode controller and a neural network interpolator. Although this did solve the above mentioned problems completely, off-line training of the interpolator was required.

To resolve these problems experienced by the conventional controllers, an adaptive fuzzy sliding mode controller (AFSMC), which is based on the decomposition method using expert knowledge in UFV depth control and utilizes a fuzzy basis function expansion (FBFE) and a proportional integral augmented sliding signal, is proposed.

The design procedure of the AFSMC encompasses the following contents: the practical generation method of the pitch command considering the depth changing rate; the convenient decomposition method

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using expert knowledge in UFV depth control; and the detailed AFSMC design method utilizing FBFEs and proportional integral augmented sliding signals.

The proposed controller has four major advantages: 1) it has a convenient decomposition method for the UFV depth control system as a MIMO system 2) it has a robustness able to overcome the uncertainties such as parameter variations and disturbances 3) it has a continuous control input that has a reduced power consumption and acoustic noise for practical application, and 4) it has an adaptive method that can solve the speed dependency of the controller parameters and improve the robustness online.

The mathematical model of the UFV is introduced in Section 2. The design of the AFSMC is described in Section 3, and the simulation results of the AFSMC in the UFV depth control are presented in Section 4. Finally, the conclusions are summarized in Section 5.

2. MATHEMATICAL MODEL OF UFV

Generally, the UFV can be divided into two types: a submarine type UFV having a vertically non-symmetric hull shape and a torpedo type UFV having a vertically symmetric hull shape. The hull shape of a submarine type UFV, which is considered in this paper, is shown in Fig. 1. It has two horizontal control planes of a stern plane δ_s and a bow plane δ_b, and has a vertical control plane of a rudder δ_r, and it employs the right-handed coordinate system.

The motion of the UFV involves six degrees of freedom (DOF) motion because six independent coordinates are required to define the position and orientation of a rigid body in three dimensions, i.e., it is described by the components of translations x, y, z and rotations ϕ, θ, φ, and forces X, Y, Z and moments K, M, N, and velocities u, v, w (surge, sway, heave) and angular velocities p, q, r (roll, pitch, yaw), and accelerations $\dot{u}, \dot{v}, \dot{w}$ and angular accelerations $\dot{p}, \dot{q}, \dot{r}$.

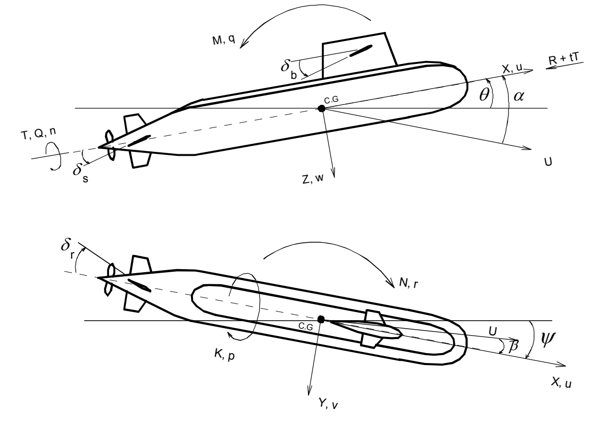

Fig. 1. Hull shape and notation of UFV.

According to this description, the dynamic equation based on Gertler's equation [7] is defined as

$$\left[\boldsymbol{m}+\boldsymbol{m}_a\right]\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{w}\\ \dot{p}\\ \dot{q}\\ \dot{r}\end{bmatrix}=-\begin{bmatrix}X_1\\ Y_1\\ Z_1\\ K_1\\ M_1\\ N_1\end{bmatrix}+\begin{bmatrix}X_2\\ Y_2\\ Z_2\\ K_2\\ M_2\\ N_2\end{bmatrix}+\begin{bmatrix}X_3\\ Y_3\\ Z_3\\ K_3\\ M_3\\ N_3\end{bmatrix}+\begin{bmatrix}X_4\\ Y_4\\ Z_4\\ K_4\\ M_4\\ N_4\end{bmatrix}, \tag{1}$$

where $\boldsymbol{m}$ is a mass, and $\boldsymbol{m}_a$ is an added mass, and $[X_1 \ \ Y_1 \ \ Z_1 \ \ K_1 \ \ M_1 \ \ N_1]^T$ is an inertia force, and $[X_2 \ \ Y_2 \ \ Z_2 \ \ K_2 \ \ M_2 \ \ N_2]^T$ is the hull force related to the body shape of the UFV, and $[X_3 \ \ Y_3 \ \ Z_3 \ \ K_3 \ \ M_3 \ \ N_3]^T$ is the restoring force related to the weight and buoyancy, and $[X_4 \ \ Y_4 \ \ Z_4 \ \ K_4 \ \ M_4 \ \ N_4]^T$ is the force generated by the control plane and propulsion unit.

Among forces and moments of hull force in (1), Z_2 is the dominant force in the steady state of depth control because it includes the hydrodynamic coefficient $Z_*^{'}$ which generates the vertically non-symmetric hull force due to vertically non-symmetric hull shape in the steady state. It is defined as

$$\begin{aligned} Z_2 = {} & \frac{\rho}{2} l^4 \left[Z_{pp}^{'} p^2 + Z_{rr}^{'} r^2 + Z_{rp}^{'} rp \right] \\ & + \frac{\rho}{2} l^3 \left[Z_{vr}^{'} vr + Z_{vp}^{'} vp \right] \\ & + \frac{\rho}{2} l^3 \left[Z_{q}^{'} uq + Z_{w|q|}^{'} \frac{w}{|w|} \left| \sqrt{(v^2+w^2)} \right| |q| \right] \\ & + \frac{\rho}{2} l^2 \left[Z_{*}^{'} u^2 + Z_{w}^{'} uw + Z_{w|w|}^{'} \left| \sqrt{(v^2+w^2)} \right| \right] \\ & + \frac{\rho}{2} l^2 \left[Z_{|w|}^{'} u |w| + Z_{ww}^{'} \left| w \sqrt{(v^2+w^2)} \right| + Z_{vv}^{'} v^2 \right], \end{aligned} \tag{2}$$

where the standard notation of [7] is adopted. To meet neutral level flight (NLF) condition, which lets the UFV perform a straight-line motion at a constant depth with q=0, in the steady state of a depth control, the effect of $Z_*^{'}$ can be eliminated by the control plane deflection. However, the deflection value depends on the operating speed.

And Z_3 is the dominant force in the uncertainties of a depth control because it includes the hydrodynamic forces B and W that generate the vertically non-symmetric restoring force due to the non-neutral buoyancy. It is defined as

$$Z_3 = (B - W)\cos\phi\cos\theta, \tag{3}$$

where B is buoyancy and W is weight of the UFV. Generally, B can be changed by disturbances and W can be changed by payloads.

(2) and (3) represent that the submarine type UFV has dynamic behaviors related with the vertically non-symmetric hull force as well as the restoring force. Alternatively, the torpedo type UFV has dynamic behaviors related with the vertically non-symmetric restoring force although it does not have behaviors related with the vertically non-symmetric hull force. Therefore, the general UFV has dynamic behaviors related with the vertically non-symmetric hull force and restoring force.

3. DESIGN OF AFSMC

In this section, an AFSMC, which is based on the decomposition method using expert knowledge in UFV depth control and utilizes FBFEs and proportional integral augmented sliding signals, is designed.

The design procedure of the AFSMC is divided into three phases: In the first phase of the design, the practical generation method of the pitch command considering the depth changing rate is described as follows:

Generally, the UFV has the depth changing rate $T_{sec/m}$, which is a required time for unit depth change, as a maneuvering specification. Therefore, it can be used in the generation method of the pitch command, i.e., if the depth command is changed from $Z_{com_{old}}$ to Z_{com}, the pitch command $\theta_{\max}$ can be determined by $T_{sec/m}$. The relation that represents the practical generation method of the pitch command is expressed by

$$\theta_{\max} = \sin^{-1}\left(\frac{Z_{com} - Z_{com_{old}}}{u \cdot T_{\sec/m} \cdot \left| Z_{com} - Z_{com_{old}} \right|} \right), \tag{4}$$

where u is the operating speed in (1). The pitch command depends on the operating speed, i.e., as u is increasing, $\theta_{\max}$ is decreasing. Note that it can prevent the UFV from losing controllability according to the increase of the operating speed while satisfying the maneuvering specifications.

In the second phase of the design, the convenient decomposition method using the expert knowledge in UFV depth control is described as follows:

As the UFV depth control system is a MIMO system because the UFV has both pitch and depth angle variables as well as multiple control planes, it is convenient to decouple the system into subsystems in terms of controller design. However, the control planes perform the same function in terms of kinematics although they have different positions and polarities. Therefore, they can be interpreted as a single control plane of a stern plane δ_s. In UFV depth control by a human operator, if depth command Z_{com} occurs, the control procedure is executed as in Fig. 2.

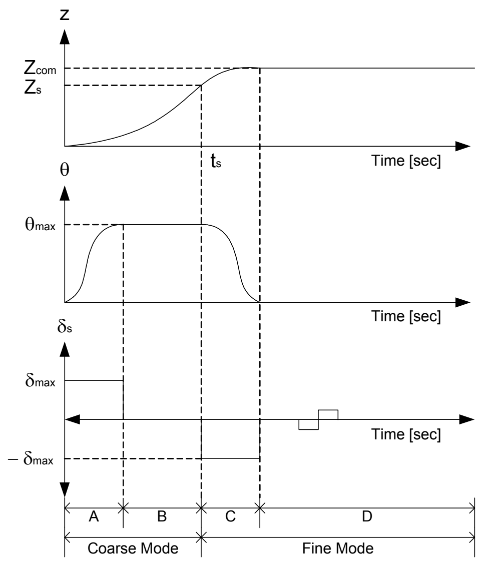

Fig. 2. UFV depth control procedure by expert.

In phase A, the operator actuates δ_s by a maximum angle $\delta_{\max}$ until a pitch θ reaches $\theta_{\max}$. In phase B, the operator actuates δ_s by a zero angle until depth z reaches the switching depth Z_s which is determined by considering the dynamic response of the UFV. In phase C, the operator actuates δ_s by a negative maximum angel $-\delta_{\max}$ until z reaches Z_{com}. And in phase D, the operator actuates δ_s properly until the control errors are minimized.

According to the analysis of the above mentioned procedure, it has two types of control modes, known as a coarse mode and a fine mode. In the coarse mode of phases A and B, it is considered as a single-input single-output (SISO) system because it has a single variable of θ as well as a single control plane of δ_s. In the fine mode of phases C and D, it is considered as a single-input multi-output (SIMO) system because it has both variables of θ and z as well as a single control plane of δ_s, which has the following kinetic relation [4].

$$\begin{aligned} \dot{z} &= -u\sin\theta + w\cos\theta, \\ \dot{\theta} &= q. \end{aligned} \tag{5}$$

However, in phase D, (5) can be approximated to $\dot{z} \approx -U_0\theta$ under the condition that w and θ are very small and the UFV is operating at $u = U_0$. Therefore, it is reconsidered as a SISO system because it nearly has a single variable of z as well as a single control plane of δ_s. These mean that the system can be decoupled into two subsystems, a depth control system and a pitch control system, using expert knowledge in the UFV depth control. Note that it solves the problem of the MIMO system in the UFV depth control system. In the final phase of design, the detailed AFSMC design method utilizing FBFEs and proportional integral augmented sliding signals is described as follows:

The AFSMC has two sub-controllers, the pitch controller and the depth controller, which are based on the decomposition method. Each sub-controller has a parallel structure that consists of the FBFE using both an integral augmented sliding signal and its derivative as a fuzzy input and a proportional integral augmented sliding signal.

A general FBFE as a fuzzy adaptive technique for nonlinear systems can be used in the function approximation [8]. And it is equivalent to the following fuzzy system with a singleton fuzzifier, a product inference, and Gaussian membership functions:

$$\hat{f}(\mathbf{x}) = \frac{\sum_{j=1}^{N} w^j \left(\prod_{i=1}^{n} \mu_{A_i^j}(\ x_i\ ) \right)}{\sum_{j=1}^{N} \left(\prod_{i=1}^{n} \mu_{A_i^j}(\ x_i\ ) \right)}, \tag{6}$$

where $\mathbf{x} = [x_1 \quad x_2 \quad \cdots \quad x_n]$ is an input vector, N is the number of fuzzy rules, w^j denotes the output of j-th fuzzy rule, and n is the number of fuzzy input variables. The membership function value is defined as

$$\mu_{A_i^j}(\ x_i\ ) = \exp\left[-\left(\frac{x_i - \xi_i^j}{\sigma^j} \right)^2 \right], \tag{7}$$

where ξ_i^j is the i-th centre and σ^j is the width of a Gaussian membership function.

Therefore, the output in (6) is re-expressed as a weighted sum or weighted average of a family of FBF with different scaling and translations:

$$\hat{f}(\mathbf{x}) = \frac{\sum_{j=1}^{N} w^j g^j \left(\frac{\left\| \mathbf{x} - \boldsymbol{\xi}^j \right\|}{\sigma^j} \right)}{\sum_{j=1}^{N} g^j \left(\frac{\left\| \mathbf{x} - \boldsymbol{\xi}^j \right\|}{\sigma^j} \right)}, \tag{8}$$

where g^j denotes a FBF, and $\boldsymbol{\xi}^j = [\xi_1^j \quad \xi_2^j \quad \cdots \quad \xi_n^j]$ is the center.

The inference method for the proposed FBFE employs the simplified method [9]. The related rule, which has the form of a fuzzy sliding rule, is expressed by

$$R^j : f\ \ S \textit{ is } A_1^j \textit{ and } \dot{S} \textit{ is } A_2^j \textit{ then } \hat{f} = w^j, \tag{9}$$

Table 1. Proposed fuzzy sliding rule for FBFE.

S \ $\dot{S}$	NB	NM	ZO	PM	PB
NB	-1.0	-0.7	-0.5	-0.3	0.0
NM	-0.7	-0.5	-0.3	0.0	0.3
ZO	-0.5	-0.3	0.0	0.3	0.5
PM	-0.3	0.0	0.3	0.5	0.7
PB	0.0	0.3	0.5	0.7	1.0

where S and $\dot{S}$ are respectively the normalized values of an integral augmented sliding signal s and its derivative $\dot{s}$, and A_1^j and A_2^j are the membership functions, and the integral augmented sliding signal is defined as

$$s = \dot{e} + c_1 e + c_0 d \int e - \dot{e}(0) - c_1 e(0), \tag{10}$$

where e and $\dot{e}$ are respectively a control error and its derivative, c_0 and c_1 are the constants. The integral augmented sliding mode controller (ISMC), which uses s in (10), has a small and continuous control input because it has a reduced reaching phase [10]. Note that it solves the problems of both the robustness and the continuous control input in the UFV depth control system. Table 1 shows the proposed fuzzy sliding rule.

The table includes the following rules: if $S(k) > 0$, the output of FBFE is assigned in order to satisfy $\dot{S}(k+1) < 0$; otherwise, the output of FBFE is assigned in order to satisfy $\dot{S}(k+1) > 0$. It guarantees the stability of the FBFE because it satisfies the sliding mode existence condition $S(k)\dot{S}(k+1) < 0$ that drives the sliding mode phenomenon.

The adaptation rule for the proposed FBFE employs the idea of deciding the centers in (8) according to u and $s\dot{s}$. Among the centers and widths of the membership functions in Table 1, the centers of NM and PM are practical parameters because they are easily ranged by the normalization and the FBFE output is sensitive to their values, i.e., if u is increased, they should be far from the centre of ZO in order to decrease the gain effect, and if $s\dot{s}$ is increased by the existence of uncertainties, they should be close to it in order to increase the gain effect. Then, only a parameter is needed to determine them because they are symmetric. The related rule is expressed by

$$R^j : \textit{if } U \textit{ is } B_1^j \textit{ and } S\dot{S} \textit{ is } B_2^j \textit{ then } \xi = W^j, \tag{11}$$

where U and $S\dot{S}$ are respectively the normalized values of u and $s\dot{s}$, B_1^j and B_2^j are the membership functions, ξ is the centre of PM, and W_j is the output. Note that it solves the problems of robustness as well

Table 2. Proposed fuzzy adaptation rule.

U \ $S\dot{S}$	NB	NM	ZO	PM	PB
LL	0.50	0.40	0.30	0.20	0.10
L	0.60	0.48	0.35	0.22	0.10
M	0.70	0.55	0.40	0.25	0.10
H	0.80	0.62	0.45	0.28	0.10
HH	0.90	0.70	0.50	0.30	0.10

as the speed dependency of controller parameters in the UFV depth control system. Table 2 shows the proposed fuzzy adaptation rule. It improves the stability of the FBFE although it has the sub-optimal output of the FBFE, which only tunes the centers of the NM and PM membership functions.

The above mentioned FBFE is applied to each sub-controller. Therefore, the outputs of the sub-controllers are defined as

$$\begin{aligned}\delta_\theta &= C_\theta \hat{f}_\theta(\mathbf{x}_\theta) + K_\theta s_\theta, \\ \delta_z &= C_z \hat{f}_z(\mathbf{x}_z) + K_z s_z,\end{aligned} \tag{12}$$

where C_θ and C_z are respectively the scale constants of the pitch controller and the depth controller, $\mathbf{x}_\theta = [S_\theta \quad \dot{S}_\theta]$ and $\mathbf{x}_z = [S_z \quad \dot{S}_z]$ are the input vectors, $\hat{f}_\theta$ and $\hat{f}_z$ are the FBFEs, K_θ and K_z are the sliding mode gains, and s_θ and s_z are the integral augmented sliding signals.

The output of the AFSMC, which is based on the control procedure in Fig. 2, can be expressed as

$$\delta = \left(ratio\delta_z + (1-ratio)\delta_\theta\right)\cdot R2D, \tag{13}$$

where $R2D$ is a constant, and the composition ratio is expressed by

$$ratio = \begin{cases} 0.0, & |e_z| > Z_s \\ C_{ratio}, & |e_z| \le Z_s, \end{cases} \tag{14}$$

where C_{ratio} is a composition ratio constant.

However, the UFV has multiple control planes and the output in (13) is applied to each control plane. Therefore, the outputs of the control planes of the UFV is expressed by

$$\begin{aligned}\delta_s &= \delta + \delta_{NLF}, \\ \delta_b &= -(L_b/L_s)\delta,\end{aligned} \tag{15}$$

where δ_{NLF} is a deflection value for the NLF condition at a low operating speed, and L_b and L_s are respectively maximum angles of δ_b and δ_s. δ_{NLF} is only applied to the stern plane because it has a dominant effect in terms of kinematics. As well, it is only used in the case of the submarine type UFV because it has $Z_*^{'}$ in (2) and is set to zero in the case of the torpedo type UFV. Although δ_{NLF} cannot completely eliminate the effect of $Z_*^{'}$ overall operating speed because the deflection value depends on the operating speed, the FBFEs of the AFSMC can help in solving this problem.

From the above mentioned procedure, the AFSMC, which is based on the decomposition method using expert knowledge in the UFV depth control and utilizes the FBFEs and proportional integral augmented sliding signals, has been designed. The block diagram of the proposed UFV depth control system is presented in Fig. 3.

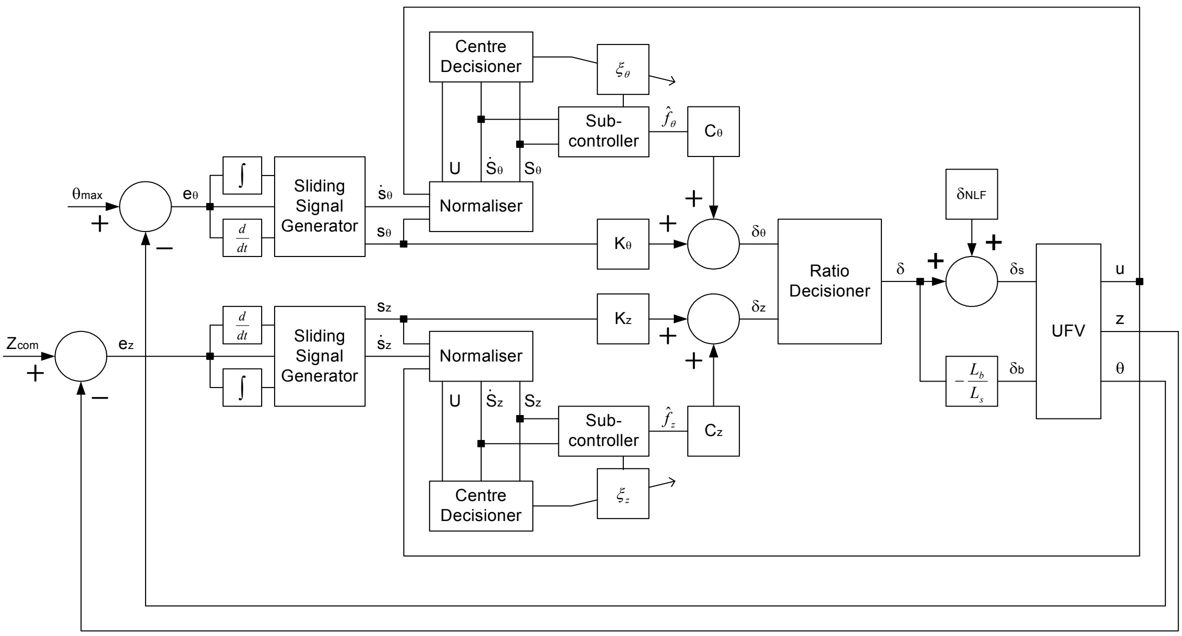

Fig. 3. Block diagram of UFV depth control system.

4. SIMULATION RESULTS

The performance of the AFSMC is tested with the depth control problem of a submarine type UFV in the vertical plane without course change in the horizontal plane. The simulation scenario for the UFV maneuvering, which is not considering the sea wave effect, is designed as follows: A speed change during time 1 to 74 with a reference speed of 4 knots (a maneuvering below the critical speed); a depth change during time 74 to 274 with a reference depth of 20 m; a depth change during time 274 to 474 with a reference depth of 5m; a speed change during time 474 to 560 with a reference speed of 8 knots; a depth change during time 560 to 760 with a reference depth of 20 m; a depth change during time 760 to 960 with a reference depth of 5 m; an under disturbance during time 960 to 1080 with weight W decreased by 0.5% of standard displace-ment; finally, no disturbance during time 1080 to 1200.

In order to compare the proposed AFSMC with conventional controllers, a PID with δ_{NLF} and an ISMC with δ_{NLF} are considered. The sampling period is determined by T=0.02. The depth changing rate in (4) is determined by $T_{sec/m}$=3. The switching depth is determined by $Z_s = 3.5$. The neutral level flight value in (15) is determined by $\delta_{NLF} = 0.37$. The composition ratio constant is determined by C_{ratio}=0.7.

The above parameters are equally applied to all controllers. The other parameters are given in Table 3. The initial parameters of the membership functions in Table 1 and the parameters of the membership functions in Table 2 are same determined by

$$[\xi_{NB} = -1.0 \quad \xi_{NM} = -0.5 \quad \xi_{ZO} = 0.0 \quad \xi_{PM} = 0.5 \quad \xi_{PB} = 1.0]$$

and

$$[\sigma_{NB} = 0.5 \quad \sigma_{NM} = 0.5 \quad \sigma_{ZO} = 0.5 \quad \sigma_{PM} = 0.5 \quad \sigma_{PB} = 0.5]$$

Figs. 4 and 5 indicate that the AFSMC has the most robustness and is not speed dependent on controller parameters because it has the FBFEs and proportional integral augmented sliding signals. In the case of the depth change at 4 knots, the performances of all controllers are not degraded because they have the switching depth Z_s. In the case of the depth change at 8 knots, the performance of the PID is considerably degraded because it has constant gains, that of the ISMC is slightly degraded because it has integral augmented sliding signals, while that of the AFSMC is not degraded because it has the FBFEs as well as proportional integral augmented sliding signals. And in the case of the disturbance, the performance of the AFSMC is slightly degraded because it has the FBFEs while those of the others are considerably degraded. W can be maximally changed by 0.5% of a standard displacement (SD) because the compensation tank, which has the capacity of 1.0% of the SD, generally has the initial state of a half fill. This can simulate both situations in which B is changed by disturbances and W is changed by payloads.

Fig. 6 shows that both AFSMC and ISMC have more continuous outputs of stern plane than the PID because they have integral augmented sliding signals. The bias values in the steady-state are those of δ_{NLF} in (15). The outputs of the bow plane are omitted because it is similar to the outputs of the stern plane with the exception of δ_{NLF}. Fig. 7 indicates that the FBFEs are adapting well to the changes of speed and disturbance. In the cases in which the speed is increasing or the disturbance is eliminated, the centers are far from the origin in order to decrease the gain effect. In the situation in which the disturbance is applied, the centers are close to the origin in order to increase the gain effect.

Table 3. Parameters of controllers.

	PID with δ_{NLF}	ISMC with δ_{NLF}	Proposed AFSMC
Pitch	$\begin{bmatrix} K_P = 0.008 \\ K_I = 0.0008 \\ K_D = 0.02 \end{bmatrix}$	$\begin{bmatrix} c_1 = 0.4 \\ c_0 = 0.04 \\ K_s = 0.03 \end{bmatrix}$	$\begin{bmatrix} c_1 = 0.4 \\ c_0 = 0.04 \\ K_\theta = 0.021 \end{bmatrix}, C_\theta = 0.08$
Depth	$\begin{bmatrix} K_P = 0.009 \\ K_I = 0.0012 \\ K_D = 0.03 \end{bmatrix}$	$\begin{bmatrix} c_1 = 0.3 \\ c_0 = 0.04 \\ K_s = 0.02 \end{bmatrix}$	$\begin{bmatrix} c_1 = 0.3 \\ c_0 = 0.04 \\ K_z = 0.014 \end{bmatrix}, C_z = 0.08$

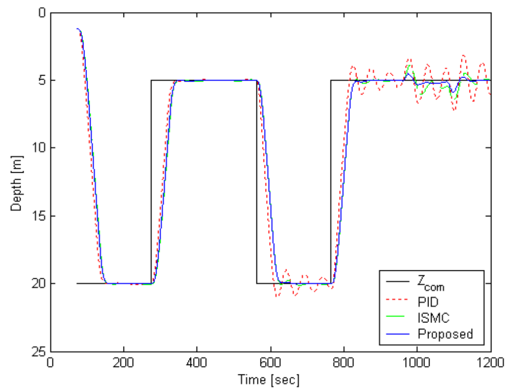

Fig. 4. Performance of depth control.

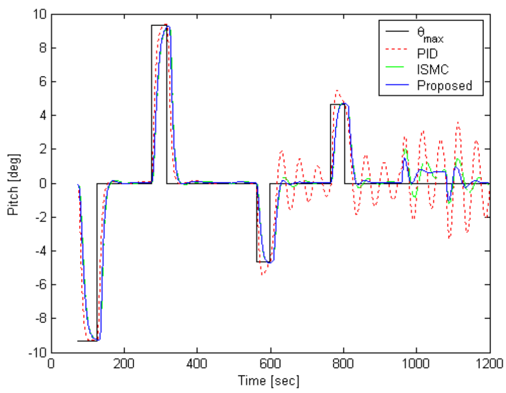

Fig. 5. Performance of pitch control.

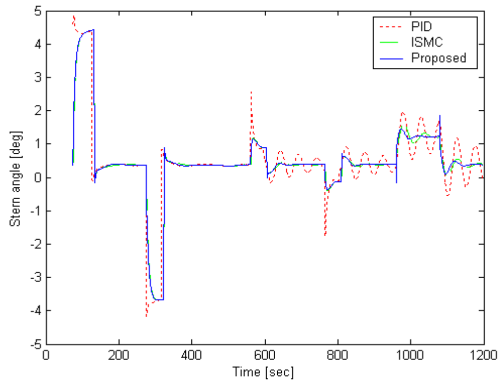

Fig. 6. Stern command angle.

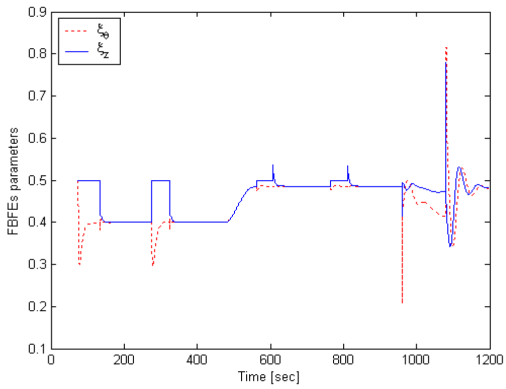

Fig. 7. Controller parameters.

Table 4. Comparison of performances.

	PID with δ_{NLF}	ISMC with δ_{NLF}	Proposed AFSMC
$\lvert e_z \rvert_{avg}$	0.5019	0.2564	0.1723
$\lvert e_\theta \rvert_{avg}$	1.0168	0.5139	0.4420
$\lvert \delta_s \rvert_{avg}$	0.4245	0.2402	0.2568

Table 4 presents the numerical comparison of the AFSMC and the conventional controllers. $\lvert e_z \rvert_{avg}$ and $\lvert e_\theta \rvert_{avg}$ are the average absolute values of the depth and the pitch control errors in the fine modes, respectively. $\lvert \delta_s \rvert_{avg}$ is the average absolute value of a stern angle in the coarse and fine modes. These values quantitatively verify the fact that the AFSMC is most effective with respect to the overall UFV maneuvering. Although the comparisons are not executed under the same conditions with respect to the controllers because there does not yet exist a controller capable of solving all the problems in the UFV depth control system online, they show well that the AFSMC has meaningful control terms.

5. CONCLUSIONS

In this paper, the adaptive fuzzy sliding mode controller, which is based on the decomposition method using expert knowledge in the UFV depth control and utilizes the FBFE and proportional integral augmented sliding signal, has been proposed. The practical generation method of the pitch command considering the depth changing rate has been described in order to prevent the UFV from losing controllability according to the increase of the operating speed while satisfying the maneuvering specifications. The convenient decomposition method using expert knowledge in UFV depth control has been described in order to solve the problem of the MIMO system. The detailed AFSMC design method utilizing FBFEs and proportional integral augmented sliding signals has been described in order to solve the problems of robustness, continuous control input, and the speed dependency of controller parameters.

The proposed controller has four major advantages: it has a convenient decomposition method for the UFV depth control system as a MIMO system, it has a robustness that can overcome uncertainties such as parameter variations and disturbances, it has a continuous control input with reduced power consumption and acoustic noise for practical application, and it has an adaptive method that can solve the speed dependency of the controller parameters and improve the robustness online. To verify the performance of the AFSMC, the UFV depth control has been performed. The simulation results have indicated that the AFSMC resolves all problems in the UFV depth control system online.

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