Integral Sliding-Mode Control for an Interlocking Unmanned Underwater and Surface Vehicle System Connected by a Cable

Bong-Han Kim¹, Hoang Quoc Dong², Jae-Kwan Ryu³, Won-Hee Lee⁴, Pyung-Mo Gu⁵, Soon-Geul Lee⁶

¹ Student, Mechanical Engineering, Kyung Hee University, Korea, bh.kim@khu.ac.kr

² Postdoctoral Researcher, Mechanical Engineering and Integrated Education Institute for Frontier Science and Technology (BK21 Four), Kyung Hee University, Korea, donghoang@khu.ac.kr

³ Researcher, LIGNex1, Korea, jaekwan.ryu@lignex1.com

⁴ Researcher, LIGNex1, Korea, wonhee.lee@lignex1.com,

⁵ Researcher, LIGNex1, Korea, pyungmo.ku@lignex1.com

⁶ Professor, Mechanical Engineering and Integrated Education Institute for Frontier Science and Technology (BK21 Four), Kyung Hee University, Korea, sglee@khu.ac.kr

Corresponding author: Soon-Geul Lee

Abstract: This paper presents modeling and control of the interlocking system connecting unmanned surface and underwater vehicles with an underwater cable. The research's primary objective is to determine the feasibility of the proposed system and designed controller, create a foundation for future studies with applications in maritime science. To complete it, the first step is to model the system's characteristics for the real system by using theories of hydrodynamics, Newton, and Lagrangian; subsequently, the algorithms of nonlinear controls, Lyapunov, and Barbalat criteria are applied for stable analyzing and designing the controller. Afterward, the simulations are carried out in the Matlab Simulink, which allows simulating the response of the system with control inputs similar to in the real-time environment and collecting the data directly to the workspace for processing and comparison using root-mean square error standard. The system is assumed to be used in marine environments. Therefore, the influences of the disturbance and uncertainties, such as tidal flows, surface waves, and winds, are the most dominant factors for control. Integral sliding mode control is proposed for the interlocking system to guarantee suitable stability and robustness of the system. Through the simulation results with the control of the motion system tracking to the given curve trajectory with impact disturbance, the effectiveness and feasibility of the proposed system and the control algorithm can be realized. Therefore, the practical application of this system for surveying and studying the marine environment shows promising potential.

Keywords: Integral Sliding Mode Control, Interlocking System, Unmanned Surface Vehicle, Unmanned Underwater Vehicle, Vehicles with Connecting Cable

1. Introduction

Missions currently performed by manned vehicle systems in the field of maritime vehicles include ocean observation and exploration, sea disaster rescue, operation in shallow or polluted seas, reconnaissance, surveillance, and mine detection and removal. These missions bring many risks and limitations to workers due to bad weather, harmful substances, and long hours of work. As trials of resolving such problems, studies on the unmanned surface vehicle (USV) and the unmanned underwater vehicle (UUV) have been investigated for assisting and replacing the work of manned vehicle systems

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[1][2].

Existing studies have often treated USVs and UUVs to operate separately[3-7]. USVs outperform UUVs considering sailing speed, communication performance, and loading capacity. However, one disadvantage lies in large waves, which may reduce the operational stability of USVs. By contrast, real-time communication in UUVs is impossible due to their underwater operation, and position errors are accumulated as the underwater driving progresses. The driving time and mileage of UUVs are also limited due to the low load capacity.

Many methods, in which USVs and UUVs work together to compensate for each other's shortcomings, have been recently devised. The USV and UUV are typically connected by an underwater cable with communication and towing functions, allowing the USV to extend the uptime, mileage, and real-time communication of UUV[8-11].

The real USV–UUV system is demonstrated by a mathematical model, which is the set of second-order differential equations. Then, this system will be regulated by a designed controller due to the influence of the same factors as the real environment. The acceptability of the control performance will confirm most of the feasibility and effectiveness of the controller, which will be applied in practice in the future. However, only a few systems were designed with the same controller, and applying one algorithm to all systems is not always possible. Therefore, before making the model and testing it in practice, a big question arises, which controller can be suitable to control the system? Is sliding mode control (SMC), a proven robust controller, feasible and able to bring good control quality to the system? Is the USV-UUV platform designed to perform well in aquatic environments even though individual systems[8][12] perform well and stably? Moreover, is there any improvement or difference in control quality of SMC and classical PID controllers? The main objective of this study is to answer those questions, thereby creating premises for building models and testing in reality. This approach also offers a proposed idea of applications in environmental research and marine survey.

The USV and UUV in the current study interact through an underwater cable compared with that in previous studies which were driven separately. Hong et al.[8] and Vu et al.[9] derived the dynamic behavioral equation of an unmanned marine vehicle system, linking USVs and UUVs with an underwater cable, and demonstrated their accuracy through simulations. In addition, Jin et al.[10] used way-point and dynamic positioning algorithms for point-to-point navigation of the USV–UUV interlocking system, and Cho et al.[11] performed interlocking system trajectory control of USV and UUV using antiwind-up[12]. However, PID controllers perform poorly under nonlinear conditions with various disturbances, such as marine environments, because the control gains are only suitable to specific operating environments.

The interlocking system comprises USV, UUV, and an underwater cable connecting USV and UUV, and its structure is shown in [Fig. 1]. Kinematic and dynamic models of the system are designed for the interlocking system controller. The integral SMC (ISMC) algorithm[13] is used to overcome various disturbances in the marine environment. Moreover, this algorithm is widely employed because of its robustness[14], finite-time convergence[15][16], and convenience to combine with other algorithms[17]. The performance of the proposed controller was verified on the basis of numerical simulation using the ocean exploration field scenario, wherein this interlocking system is expected to be used.

2. Methodology

The process of carrying out the entire work and the approaches are shown in [Fig. 1].

[Fig. 1] Research Procedure and Approach Methods

2.1 Methods for System Analysis and Modeling

This study uses several conventional theories in mechanics for Nonholonomic systems, including theories of hydrodynamics, Newton, and Lagrangian, to complete the construction of the system dynamics model. The obtained result is a system of second-order differential equations describing the physical characteristics of the system.

2.2 Approach for Controller Design

The popular theories in sliding nonlinear control are used for the controller design to ensure the sliding conditions. The convergence of the error to zero and the capability to control the trajectory precisely are respectively investigated through the Lyapunov and Barbalat stability criteria.

2.3 Matlab Simulink for Numerical Simulation and Data Processing Method

The effectiveness of the design was investigated through simulations in Simulink, a MATLAB-based graphical programming environment for modeling, simulating, and analyzing multidomain dynamical systems. Understandably, they can allow control of the system in the real-time, complex, or frequency domains. On the other hand, they can also connect to the workspace, Matlab 3D simulation, even allow control of realistic robot models.

The primary interface of Simulink is a graphical block diagramming tool and a customizable set of block libraries. Simulink offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from such an environment. The differential equations in Simulink are solved by numerical methods, such as Runge–Kutta, Bogacki–Shampine, and backward Euler. Simulink can also easily extract graphs for simulations of dynamic systems in real-time by connecting signal channels with output windows (Scope).

From Simulink, the data can be easily collected to the workspace directly for processing and analyzing. Additionally, Simulink also provides numerous available libraries or blocks for data processing, for example, filters, approximators. In addition, the root mean square error (RMSE) standard is used to

analyze the data and evaluate the accuracy of the orbital control.

3. System Modeling

3.1 Coordinate Systems and Motion

The kinematic model of the USV and the UUV was obtained on the basis of the constraint between these vehicles and their physical features. Connection point O_6 belongs to the spherical surface (O_{ca}, L_{ca}) , where O_{ca} is the cable connection point of the USV, and L_{ca} is the length of the connection cable. The kinematic model based on the global coordinate system of the USV and the UUV is as follows.

$$\begin{cases} \dot{x}_s^g = \dot{x}_s \cos(\gamma_s + \gamma_v) = \dot{x}_s (\cos \gamma_s \cos \gamma_v - \sin \gamma_s \sin \gamma_v) \\ \dot{y}_s^g = \dot{x}_s \sin(\gamma_s + \gamma_v) = \dot{x}_s (\sin \gamma_s \cos \gamma_v + \cos \gamma_s \sin \gamma_v) \\ \dot{x}_u^g = \cos \gamma_u \cos \beta_u \dot{x}_u + \cos \gamma_u \sin \beta_u \dot{z}_u \\ \dot{y}_u^g = \sin \gamma_u \cos \beta_u \dot{x}_u + \sin \gamma_u \sin \beta_u \dot{z}_u \\ \dot{z}_u^g = -\sin \beta_u \dot{x}_u + \cos \gamma_u \dot{z}_u \end{cases}, \quad (1)$$

where γ_v is the driving direction of the USV. $\dot{x}_s^g$, $\dot{y}_s^g$ represent the speed of the USV in x_g , y_g axial directions in the global coordinate system $(O_0 x_o y_o z_o) \equiv (O_g x_g y_g z_g)$ in [Fig. 2], respectively. $\dot{x}_u^g$, $\dot{y}_u^g$, and $\dot{z}_u^g$ represent the speed in each x_g , y_g , and z_g axial directions of the UUV, respectively.

3.2 System Dynamic Modeling

A dynamic model is obtained by considering action and reaction between the USV and the UUV, environmental disturbance, fluid resistance, and the resulting platform acceleration. The USV and the UUV moved on the basis of individual thrust. Mass coefficient, Coriolis force, centrifugal force, disturbance function, drag force, and control input of the USV and the UUV were modeled. The hydrodynamic model of the USV and the UUV is given as follows.

[Fig. 2] USV-UUV System

$$\mathbf{M}_s \ddot{\boldsymbol{\chi}}_{ss} + \mathbf{C}_s (\boldsymbol{\chi}_{ss}, \dot{\boldsymbol{\chi}}_{ss}) \dot{\boldsymbol{\chi}}_{ss} + \boldsymbol{\Phi}_{Ds} (t) + \mathbf{G}_s (t) = \boldsymbol{\Psi}_{Ts}, \quad (2)$$

$$\mathbf{M}_u \ddot{\boldsymbol{\chi}}_{su} + \mathbf{C}_u (\boldsymbol{\chi}_{su}, \dot{\boldsymbol{\chi}}_{su}) \dot{\boldsymbol{\chi}}_{su} + \boldsymbol{\Phi}_{Du} (t) + \mathbf{G}_u (t) = \boldsymbol{\Psi}_{Tu}, \quad (3)$$

$$\boldsymbol{\chi}_{ss} = [x_s \quad y_s \quad \gamma_s]^T, \quad (4)$$

$$\boldsymbol{\chi}_{su} = [x_u \quad z_u \quad \beta_u \quad \gamma_u]^T, \quad (5)$$

$$\mathbf{M}_s = \begin{bmatrix} m_s & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & J_{sz} \end{bmatrix}, \quad (6)$$

$$\mathbf{M}_u = \begin{bmatrix} m_u & 0 & 0 & 0 \\ 0 & m_u & 0 & 0 \\ 0 & 0 & J_{uy} & 0 \\ 0 & 0 & 0 & J_{uz} \end{bmatrix}, \quad (7)$$

$$\mathbf{C}_s (\boldsymbol{\chi}_{ss}, \dot{\boldsymbol{\chi}}_{ss}) = \begin{bmatrix} b_{sx} & m_s R_R J_{sz}^{-1} b_{sy} & 0 \\ 0 & b_{sy} & m_s R_R \dot{\gamma}_s \\ 0 & 0 & b_{s\gamma} \end{bmatrix}, \quad (8)$$

$$\mathbf{C}_u (\boldsymbol{\chi}_{su}, \dot{\boldsymbol{\chi}}_{su}) = \begin{bmatrix} b_{ux} & 0 & 0 & 0 \\ 0 & b_{uz} & 0 & 0 \\ 0 & 0 & b_{u\beta} & 0 \\ 0 & 0 & 0 & b_{u\gamma} \end{bmatrix}, \quad (9)$$

$$\boldsymbol{\Phi}_{Ds} (t) = [\Phi_{dsx} \quad \Phi_{dsy} \quad \Phi_{ds\gamma}]^T, \quad (10)$$

$$\boldsymbol{\Phi}_{Du} (t) = [\Phi_{dux} \quad \Phi_{duz} \quad \Phi_{du\beta} \quad \Phi_{du\gamma}]^T, \quad (11)$$

$$\mathbf{G}_s (t) = \begin{bmatrix} T_{enx} (t) - T_{ca} \cos \beta_{ca} m_s R_R J_{sz}^{-1} (-T_{s1} + T_{s2}) b_{sj} \\ + T_{eny} (t) - T_{scax} - T_{ca} \cos \alpha_{ca} \\ T_{ca} \sin \beta_{ca} + F_{Duz} (t) \end{bmatrix}, \quad (12)$$

$$\mathbf{G}_u (t) = \begin{bmatrix} 0 \\ -m_u g + \rho_w g \nabla_{ov} \\ + F_{Du\beta} (t) \\ + F_{Du\gamma} (t) \end{bmatrix}, \quad (13)$$

$$\Psi_{Ts}(t) = \begin{bmatrix} T_{s1} \cos \gamma_{T1} + T_{s2} \cos \gamma_{T2} \\ T_{s1} \sin \gamma_{T1} + T_{s2} \sin \gamma_{T2} \\ (-T_{s1} + T_{s2}) b_{sj} \end{bmatrix}, \quad (14)$$

$$\Psi_{Tu}(t) = \begin{bmatrix} T_{u1} - T_{u2} \\ -T_{u3} - T_{u4} \\ T_{us} L_{u3} - T_{u4} L_{u4} \\ (-T_{u1} + T_{u2}) b_{sj} \end{bmatrix}. \quad (15)$$

In equations (2)–(15), $\mathbf{M}_s$ and $\mathbf{M}_u$ represent the mass coefficients of the USV and the UUV, respectively. $\mathbf{C}_s(\chi_{ss}, \dot{\chi}_{ss})$ and $\mathbf{C}_u(\chi_{su}, \dot{\chi}_{su})$ are the Coriolis and centrifugal forces of the USV and the UUV, respectively. $\Phi_{Ds}(t)$ and $\Phi_{Du}(t)$ are the time-varying bounded disturbance functions applied to the USV and the UUV, respectively. $\mathbf{G}_s(t)$ and $\mathbf{G}_u(t)$ are the matrixes of drag force of the USV and the UUV, respectively. $\Psi_{Ts}(t)$ and $\Psi_{Tu}(t)$ are control input values of USV and UUV, respectively. T_{s1} and T_{s2} are the forces generated by the left/right thrusters of the USV. T_{u1} , T_{u2} , T_{u3} , and T_{u4} are the forces generated by the UUV thrusters, which are shown in [Fig. 3]. The angles of the line passing through the axis O_4x_4 and T_{s1} , T_{s2} are γ_{T1} and γ_{T2} . R_R is the turning radius, J_{sz} is the moment of inertia of the USV, and J_{uy} , J_{uz} are the moment of inertia of the UUV. b_{sj} is half the distance between the left/right thrusters. $T_{enx}(t)$ and $T_{eny}(t)$ are functions of external forces generated by wind and waves, respectively. b_{sx} , b_{sy} , and b_{sy} are the damping coefficients of USV, while b_{uz} , $b_{u\beta}$, and $b_{u\gamma}$ are the damping coefficients of UUV. T_{ca} is the tension of the connecting cable between the USV and the UUV. The angles between the cable and axis O_5y_5 and O_5x_5 are β_{ca} and α_{ca} , respectively. $F_{Du\beta}(t)$, $F_{Du\beta}(t)$, and $F_{Du\gamma}(t)$ are functions of the drag force which have two sources, namely the normal pressure and the skin friction.

4. Controller Design

Designing a robust controller against disturbances, such as irregular currents and winds, is necessary due to the nature of the operating environment of the USV–UUV interlocking system. Therefore, the controller of the USV–UUV interlocking system was designed using ISMC[13], a robust control method

[Fig. 3] Thrust and External Forces Acting on the System

against disturbances. The tracking error vectors of the USV and the UUV for ISMC are respectively defined as follows:

$$\tilde{\chi}_{ss} = \chi_{ss} - \chi_{ssT}, \quad (16)$$

$$\tilde{\chi}_{su} = \chi_{su} - \chi_{suT}, \quad (17)$$

where $\tilde{\chi}_{ss}$ and $\tilde{\chi}_{su}$ are the USV and UUV tracking error vectors, respectively. χ_{ssT} and χ_{suT} are the target values of χ_{ss} and χ_{su} , respectively. The sliding surface in this case is defined as follows.

$$\zeta_s(t) = \dot{\tilde{\chi}}_{ss} + \mu_{1s}\tilde{\chi}_{ss} + \mu_{2s} \int_0^t \tilde{\chi}_{ss} dt, \quad (18)$$

$$\zeta_u(t) = \dot{\tilde{\chi}}_{su} + \mu_{1u}\tilde{\chi}_{su} + \mu_{2u} \int_0^t \tilde{\chi}_{su} dt, \quad (19)$$

where $\zeta_s(t)$ and $\zeta_u(t)$ are the sliding surfaces of USV and UUV, respectively, and μ_{1s} , μ_{2s} , μ_{1u} , and μ_{2u} are respectively defined as follows:

$$\mu_{1s} = \text{diag}(\mu_{1sa}, \mu_{1sb}, \mu_{1sc}, \mu_{1sd}, \mu_{1se}, \mu_{1sf}), \quad (20)$$

$$\mu_{2s} = \text{diag}(\mu_{2sa}, \mu_{2sb}, \mu_{2sc}, \mu_{2sd}, \mu_{2se}, \mu_{2sf}), \quad (21)$$

$$\mu_{1u} = \text{diag}(\mu_{1ua}, \mu_{1ub}, \mu_{1uc}, \mu_{1ud}, \mu_{1ue}, \mu_{1uf}), \quad (22)$$

$$\mu_{2u} = \text{diag}(\mu_{2ua}, \mu_{2ub}, \mu_{2uc}, \mu_{2ud}, \mu_{2ue}, \mu_{2uf}). \quad (23)$$

In this case, μ_{1s} , μ_{2s} , μ_{1u} , and μ_{2u} comprise positive elements. The control signals in the dynamic model given to the system are defined as follows.

$$\Psi_{Ts} = +\mathbf{M}_s \begin{Bmatrix} -\lambda_{1s}\zeta_s - \lambda_{2s}\text{sign}(\zeta_s) - \mu_{1s}\dot{\tilde{\chi}}_{ss} - \mu_{2s}\tilde{\chi}_{ss} + \ddot{\chi}_{ssT} \\ -\mathbf{M}_s^{-1}[\mathbf{C}_s(\chi_{ss}, \dot{\chi}_{ss})\dot{\chi}_{ss} + \mathbf{G}_s(t)] \end{Bmatrix}, \quad (24)$$

$$\Psi_{Tu} = +\mathbf{M}_u \begin{Bmatrix} -\lambda_{1u}\zeta_u - \lambda_{2u}\text{sign}(\zeta_u) - \mu_{1u}\dot{\tilde{\chi}}_{su} - \mu_{2u}\tilde{\chi}_{su} + \ddot{\chi}_{suT} \\ -\mathbf{M}_u^{-1}[\mathbf{C}_u(\chi_{su}, \dot{\chi}_{su})\dot{\chi}_{su} + \mathbf{G}_u(t)] \end{Bmatrix}. \quad (25)$$

where Ψ_{Ts} and Ψ_{Tu} are the control inputs of the USV and UUV, respectively. λ_{1s} , λ_{2s} , λ_{1u} , and λ_{2u} are respectively defined as follows:

$$\lambda_{1s} = \text{diag}(\lambda_{1sa}, \lambda_{1sb}, \lambda_{1sc}, \lambda_{1sd}, \lambda_{1se}, \lambda_{1sf}), \quad (26)$$

$$\lambda_{2s} = \text{diag}(\lambda_{2sa}, \lambda_{2sb}, \lambda_{2sc}, \lambda_{2sd}, \lambda_{2se}, \lambda_{2sf}), \quad (27)$$

$$\lambda_{1u} = \text{diag}(\lambda_{1ua}, \lambda_{1ub}, \lambda_{1uc}, \lambda_{1ud}, \lambda_{1ue}, \lambda_{1uf}), \quad (28)$$

$$\lambda_{2u} = \text{diag}(\lambda_{2ua}, \lambda_{2ub}, \lambda_{2uc}, \lambda_{2ud}, \lambda_{2ue}, \lambda_{2uf}). \quad (29)$$

In this case, λ_{1s} , λ_{2s} , λ_{1u} , and λ_{2u} comprise positive components. The controller gains λ_{2Ds} and λ_{2Du} are respectively defined as follows:

$$\lambda_{2Ds} = [\lambda_{2sa} \quad \lambda_{2sb} \quad \lambda_{2sc} \quad \lambda_{2sd} \quad \lambda_{2se} \quad \lambda_{2sf}], \quad (30)$$

$$\lambda_{2Du} = [\lambda_{2ua} \quad \lambda_{2ub} \quad \lambda_{2uc} \quad \lambda_{2ud} \quad \lambda_{2ue} \quad \lambda_{2uf}]. \quad (31)$$

A Lyapunov candidate function is chosen as follows to analyze the system stability:

$$Y_{\Sigma}(t) = \zeta_s^T \zeta_s + \zeta_u^T \zeta_u. \quad (32)$$

For the system models (2) and (3), taking the first derivative yields the following:

$$\dot{Y}_{\Sigma}(t) = \left[-\lambda_{1s} \zeta_s - \lambda_{2s} \text{sign}(\zeta_s) + \Phi_{Ds}(t) \right]^T \zeta_s + \left[-\lambda_{1u} \zeta_u - \lambda_{2u} \text{sign}(\zeta_u) + \Phi_{Du}(t) \right]^T \zeta_u. \quad (33)$$

Thus, if the controller gains satisfy the condition that $\lambda_{2Ds} = \hat{\lambda}_{2Ds}$ and $\lambda_{2Du} = \hat{\lambda}_{2Du}$, then the sliding surfaces $\zeta_s(t)$ and $\zeta_u(t)$ are stable. Herein, $\hat{\lambda}_{2Ds} = \lambda_{2Ds}^* + \hat{\Phi}_{Ds}^T$, $\hat{\lambda}_{2Du} = \lambda_{2Du}^* + \hat{\Phi}_{Du}^T$, $0 \leq \lambda_{2Ds}^*$, $0 \leq \lambda_{2Du}^*$, and $\hat{\Phi}_{Ds}^T$, $\hat{\Phi}_{Du}^T$ are the upper boundaries of the functions $\Phi_{Ds}(t)$, $\Phi_{Du}(t)$. Thus,

$$\dot{Y}_{\Sigma}(t) \leq -(\lambda_{1s} \zeta_s)^T \zeta_s - \lambda_{2s} |\zeta_s| + \hat{\Phi}_{Ds}^T(t) |\zeta_s| - (\lambda_{1u} \zeta_u)^T \zeta_u - \lambda_{2u} |\zeta_u| + \hat{\Phi}_{Du}^T(t) |\zeta_u|.$$

The previous calculation shows the following:

$$\int_0^t \dot{Y}_{\Sigma}(t) dt \leq \int_0^t \{ \dot{Y}_1(t) + \dot{Y}_2(t) \} dt, \quad (34)$$

where $\dot{Y}_1(t) = -(\lambda_{1s} \zeta_s)^T \zeta_s - \lambda_{2s} |\zeta_s| + \hat{\Phi}_{Ds}^T(t) |\zeta_s|$ and $\dot{Y}_2(t) = -(\lambda_{1u} \zeta_u)^T \zeta_u - \lambda_{2u} |\zeta_u| + \hat{\Phi}_{Du}^T(t) |\zeta_u|$.

Consequently, $\zeta_{is} \in L_1$, $\zeta_{is} \in L_2$, $\zeta_{iu} \in L_1$, and $\zeta_{iu} \in L_2$ ($i = 1, 2, \dots, 6$). Herein, ζ_{is} and ζ_{iu} are the respective components of the vectors $\zeta_s(t)$ and $\zeta_u(t)$.

Furthermore,

$$Y_1(t) \leq Y_1(0) - \int_0^t \{ (\lambda_{1s} \zeta_s)^T \zeta_s + \lambda_{2s}^* |\zeta_s| \} dt \leq Y_1(0) \leq \infty \quad (35)$$

and

$$Y_2(t) \leq Y_2(0) - \int_0^t \{ (\lambda_{1u} \zeta_u)^T \zeta_u + \lambda_{2u}^* |\zeta_u| \} dt \leq Y_2(0) \leq \infty. \quad (36)$$

The system is asymptotically stable with the control law controller (24), (25) based on the Babarlat Lemma, and the tracking errors are converged to zero. Thus, the tracking conditions are satisfied.

5. Numerical Simulation Results

Assuming a scenario in the ocean exploration field in which the interlocking system is expected to be used, numerical simulations using MATLAB/Simulink were performed to verify the performance of the USV-UUV interlocking system trajectory tracking controller. The scenario used is as follows. First, when this USV-UUV interlocking system searches for a specific area underwater in the ocean, the USV is responsible for the main thrust until the target area of the ocean is reached due to its superior trust and fuel loading to that of the UUV. The USV movement is similar to towing the UUV.

[Fig. 4] Disturbance Function Impact on the System

(a) Control of $\dot{x}_s$

(b) Control of $\dot{y}_s$

(c) Control of γ_s

[Fig. 5] Control results of USV

The UUV is controlled at this time to track the trajectory of the USV and prevent excessive tension on the underwater cable. Second, the UUV becomes the main vehicle after reaching the ocean search target area and follows the underwater trajectory of the area to perform the search, and the USV is controlled to assist the movement of the UUV.

In addition, different disturbances may be applied to the USV and UUV considering complex disturbance factors, such as waves and currents in the marine environment, due to the positional difference between the surface and the water. The case of a calm sea may express a disturbance function based on white noise, and that of a sudden change of current may express a disturbance function of a step input. Therefore, white noise- and step input-based disturbance functions were applied in this simulation, as shown in [Fig. 4].

The reference trajectory representing the scenario is shown in [Fig. 7]. After the start of the simulation, the USV and the UUV run for approximately 8 s in a semicircle with a radius of 5 m from the origin of

(a) Control of z_u

(b) Control of β_u

(c) Control of γ_u

[Fig. 6] Control results of UUV

[Fig. 7] Trajectory of USV and UUV following the scenario

the global coordinate system, indicating the driving led by the USV to the target area of the ocean search. Afterward, the USV stops, and the UUV travels in a circular trajectory with a radius of 0.75 m for approximately 5 s from 12 s after the start of control, indicating that the ocean search operation of the UUV has reached the target area.

The simulations are performed along with comparisons with traditional PID controllers as shown in [Fig. 5–7] to evaluate the effectiveness of the ISMC controller. [Fig. 5] (a) and (b) show that the speeds of the USV in all directions $\dot{x}_s$ and $\dot{y}_s$ are controlled roughly precisely with the reference trajectories. Similarly, the yawing angle γ_s of the USV is also precisely controlled, reaching a fixed value of 16° in approximately 8 seconds. However, the tracking error is considerably smaller than that of PID when controlled by ISMC. Accumulated tracking errors will lead to errors during the movement on the half-circle of the USV from the position with coordinates (0,0) to that with coordinates (0, 10), as shown in [Fig. 7]. The difference between the control quality of PID and ISMC is insignificant (as shown in Fig. 4). Thus, the USV trajectory when controlled by PID deviates from the desired trajectory, which can be compared with the ISMC controller in [Fig. 7. b].

USV and UUV are affected by interference; thus, the impact of noise on UUV is substantial because the UUV attaches to the USV via the towing cable. The difference between the control quality of the traditional PID and the ISMC is pronounced in this case. Specifically, the PID controller shows the separation between the control trajectory (red line) and the reference trajectory (green line) when controlling the trajectories of z_u , γ_u , and β_u . Static deviation cannot be eliminated until the end of simulation time (20 s), as shown in [Fig. 6]. The oscillations of UUVs around the desired trajectories are

also relatively large due to disturbance. These limited properties do not occur with the ISMC controller due to its robustness to noise, which has been demonstrated in part III. The tracking errors of UUV are also accumulated and impact the accuracy of the trajectory tracking, as illustrated in [Fig. 7].

6. Discussion

The RMSE between the tracking and reference trajectories, which is defined as shown below, is applied for a quantitative comparison.

$$\text{RMSE}(\tilde{\mathbf{x}}) = \frac{1}{\sqrt{K}} \|\tilde{\mathbf{x}}\|_2, \quad (37)$$

where $\tilde{\mathbf{x}}$ denotes the tracking error vector, and K is the entire number of simulation samples.

The RMSEs of tracking control implemented by PID and ISMC are given in Table 1 as follows.

[Table 1] Comparison between ISMC and PID Control with Respect to RMSE of Tracking Error

RMSEs	$\dot{\tilde{x}}_s$	$\dot{\tilde{y}}_s$	$\tilde{\gamma}_s$	$\tilde{z}_u$	$\tilde{\beta}_u$	$\tilde{\gamma}_u$
PID	0.107	0.810	0.071	0.032	0.042	2.282
ISMC	0.055	0.277	0.008	0.005	0.021	0.591

The difference between PID and ISMC control can be observed through the data presented in the table. The effects of external disturbance can be easily eliminated by robustness and strong convergence through Lyapunov stabilization. Consequently, the control error is minimized, and the capability of the system to track the trajectory is considerably improved. This finding not only confirms the effectiveness of applying ISMC to the USV-UUV system but also confirms and strengthens the theory of robustness of the ISMC controller[16][17].

The accuracy of tracking control is significantly affected by the disturbance factors outside. Small errors during control gradually accumulate and lead to inaccuracies in the final position of the USV-UUV system.

Many interference factors that can affect the system, which can include the influence of water waves, wind, tides, and changes in flow resistance, are found on the actual system of unmanned ships. These disturbances are modeled in the following two common forms: sinusoidal waves and pulses. In the simulation, the disturbance affects the system; on the other hand, the system is controlled by ISMC. Evaluating the effectiveness of this controller with relative accuracy is possible through this approach. The results show that ISMC can significantly eliminate the effects of interference while still ensuring the orbital tracking capability of the USV-UUV system.

In addition to the ability to robustly control when the system is subjected to external perturbation, it can be found that ISMC is quite effective in suppressing the oscillations of UUV undergoing variable effects of water waves, as can be observed in [Fig. 7]. Consequently, it promises to improve control quality when applied to real systems[8][18].

7. Conclusions

In this study, the kinematic and dynamical models for the interlocking system connecting the USV and UUV with an underwater cable were proposed. With conventional controllers, such as PID, the precision of orbital tracking is severely affected by the impacts of external disturbance, which is similar to the real working environment. To address this issue, a robust ISMC was designed to drive the system based on reference trajectories verified by simulations based on the expected application of this interlocking

system. The precise tracking with the ISMC control is guaranteed by the stability and robustness based on Lyapunov and Barbalat criteria. The superior properties of control law were also analyzed through the simulation and analysis results given respectively in Sections 5 and 6.

The major limitation of the study lies in the absence of experimental implementations[18]. Furthermore, the assumptions in dynamic modeling can slightly affect the accuracy of the system model, although they are also based on actual working conditions. Therefore, the future works based on this project will be applying the designed control law in the practical system with applications in marine science and developing some adaptive algorithms to enhance the control performance.

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