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ABSTRACT
This paper proposes a new hybrid robust control method for control of an autonomous underwater vehicle. Fractional sliding mode control (FSMC) is robust against external disturbances. The main drawback of the FSMC method is creating a chattering phenomenon. Therefore, a compound control method is applied, which benefits in both robustness of the FSMC method and chattering elimination by the new control algorithm. A random noise is applied in order to verify the robustness of the proposed control method. The stability of FSMC and proposed compound control method has been verified by Lyapunov theory. The effectiveness of the proposed control method is compared with FSMC, which numerical simulation results confirm the best performance of the proposed control method.

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KEYWORDS
AUV; fractional sliding mode control; chattering elimination; compound control; robust control

1. Introduction

Autonomous underwater vehicles (AUVs) have been widely used in different applications such as pipeline inspection, seabed mosaic, shipwreck search, and surveillance. Therefore, an accurate control method is necessary for altitude and position control of the AUV (Li et al., 2007; Santos et al., 2018). Zhang et al. (2014) proposed a sliding mode prediction control method for AUVs to track a desired 3D path under time-varying current disturbances. In order to compensate for the effect of the hydrodynamic damping coupling, a sliding mode approach combined with predictive control method is used. Numerical simulations demonstrated the excellent path following the performance of the AUV in 3D under the proposed control method. Zhou et al. (2018) used backstepping-based control for the un-smoothness of tracking trajectory. By using backstepping techniques, the problem of parameter skip at inflection point existing in backstepping tracking control method has been solved. In addition, the proposed control method can effectively solve the singularity problem in backstepping control of virtual velocity error. The stability of the proposed control method was verified by Lyapunov theory. Miao et al. (2017) considered the problem of curvilinear path following control of under-actuated AUVs with multiple uncertainties. Zhang et al. (2015) proposed fault tolerant control for underwater vehicles in time varying ocean environments. By using adaptive terminal sliding mode, a fault tolerant control method for AUV with thruster fault is proposed. In order to estimate on-line the upper bounds of the lumped uncertainties, an adaptive approach is incorporated into terminal sliding mode. The proposed method is independent of fault detection and diagnosis module, which both can be taken into consideration the advantages of that method. Simulations and experiments of AUVs verified the feasibility and effectiveness of the proposed method. Sarkar et al. (2016) proposed a convenient controller to obtain optimal energy consumption when tracking a commanded path accurately for some envisaged applications. In addition, the proposed control method is robust against external disturbances which AUVs encounter. Cui et al. (2016) proposed a control method for AUVs with input nonlinearities and unknown disturbances. An adaptive sliding mode control is proposed for the case without any input nonlinearities. An adaptive sliding mode control method combined with a nonlinear disturbance observer for the dead-zone nonlinearity and unknown disturbances. Simulations and experimental results verified the effectiveness of the proposed control method. Elmokadem et al. (2017) proposed a new robust terminal sliding mode control method for the lateral motion of underactuated AUVs. The goal of the proposed control method was to solve the trajectory tracking problem of AUVs. Cao et al. (2018) in order to improve search efficiency and reduce tracking error, proposed a compound Glasius bio-inspired neural network and bio-inspired cascaded tracking control method. This control method deals with several conditions such as search for static or dynamic targets, and tracking of different trajectories in underwater environments with obstacles. Yan and Yu (2018) proposed a trajectory tracking control law for AUVs with the effect of states and control input quantisation. By introducing the bound of quantisation error into the switching term of the sliding mode control, a sliding mode control method is proposed to conquer the quantisation effect. Guo et al. (2003) investigated the feasibility of applying a sliding mode fuzzy controller to motion control and line of sight guidance of an AUV. Zhang et al. (2018) proposed an adaptive nonlinear second order sliding mode controller to eliminate the chattering phenomenon, which is created by sliding mode control. Millán et al. (2014) investigated the formation control problem for fleets of AUVs. In order to allow the controller to deal with delays and packets dropouts, a control method consists of a feedback H_2/H_∞ controller in combination with a feedforward controller is proposed. Kim et al. (2016)

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proposed an enhanced time delay controller for position control of AUV under disturbances. Qiao and Zhang (2017) proposed an adaptive non-singular integral terminal sliding mode control method for trajectory tracking of AUVs with dynamic uncertainties and time-varying external disturbances. It guarantees that the velocity tracking errors locally converge to zero in finite time and after that, the position tracking errors locally converge to zero exponentially. Based on all above researches, sliding mode control is a convenient tool to control an AUV system, but chattering phenomenon is its main drawback. A compound control method should be designed in order to solve this problem. Therefore, a new hybrid control technique is proposed which benefits both high trajectory tracking by fractional sliding mode control (FSMC), and chattering reductions by that controller with a new controller.

In this paper, a new robust compound control method for AUV is proposed. The main motivations in the paper are highlighted as follows:

(1) A FSMC is designed to enhance the robustness of the control system.
(2) By using a new compound control system, chattering phenomenon which is not proper for a system is eliminated.

Therefore, in order to verify the robustness of the proposed control system, a random noise is applied. In addition, the performance of the new robust control system is compared with FSMC. The main contribution is the proposed new compound robust control system.

The rest of this paper is arranged as follows. In Section 2, the dynamic modelling of the AUV is described. In Section 3, the new FSMC is presented. In Section 4, robust compound control system has been delineated. Section 5: presents the type of fractional order operator. Section 6: presents simulation results. Finally, the paper ends with the conclusion and contributions of the work.

2. Dynamics of AUV

By neglecting the motions in heave, roll and pitch, the conventional dynamic mode of the AUV in the horizontal plane can be defined by the motion components in the surge, sway and yaw directions (Figure 1). The kinematic and dynamic model of the AUV can be defined as follows (Yan & Yu, 2018):

$$\dot{\eta} = R(\psi)\upsilon \tag{1}$$

$$M\dot{\upsilon} = -C(\upsilon)\upsilon - D(\upsilon)\upsilon + \tau + E(t) \tag{2}$$

where $\eta = [x, y, \psi]^T$ is the position vector in the earth-fixed frame, x is the surge position, y is the sway position, $\psi \in [0, 2\pi]$ is the heading of the ship. Also, $\upsilon = [u, v, r]^T$is the velocity vector in the body fixed frame, u is the surge velocity, v is the sway velocity and r the yaw rate of the ship. Control inputs are denoted by $\tau = [\tau_1, \tau_2, \tau_3]^T$, where τ_1 is control forces in surge and τ_2 in sway, and τ_3 is moment in yaw. Disturbance vector can be indicated by $E(t) = [E_1(t), E_2(t), E_3(t)]^T$, where $E_1(t)$ and $E_2(t)$ are the disturbance forces in swage and sway, and $E_3(t)$ is the disturbance moment in yaw direction. The rotation matrix

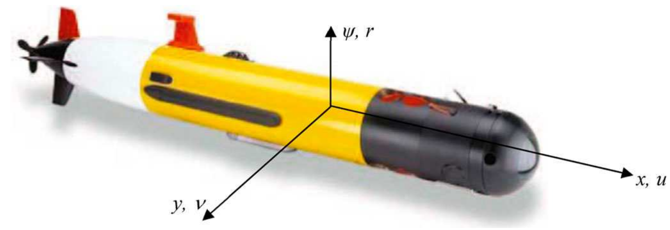

Figure 1. Body-referenced coordinate system on an AUV.

can be shown as follows:

$$R(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

It can be taken into consideration that $||R||$ and $||.||$ describe the two-norm of a vector or a matrix. $C(\upsilon)$ is the Coriolis and centripetal forces. $D(\upsilon)$ is the restoring force vector. M is the inertia matrix. Where,

$$R(\psi) = \begin{bmatrix} 0 & 0 & -m_v v \\ 0 & 0 & m_u u \\ m_v v & -m_u u & 0 \end{bmatrix} \tag{4}$$

$D(\upsilon) = \mathrm{diag}\{d_u, d_v, d_r\}$, $d_u = -X_u - X_{|u|u}|u|$, $d_v = -Y_v - Y_{|v|v}|v|$, $d_r = -N_r - N_{|r|r}|r|$, $M = \mathrm{diag}\{m_u, m_v, m_r\}$, $m_u = m - X_{\dot{u}}$, $m_v = m - Y_{\dot{v}}$, $m_r = I_z - N_{\dot{r}}$, where m is the AUV mass, $X_{(.)}, Y_{(.)}, N_{(.)}$ are hydrodynamic derivatives of the system, and $d_{(.)}$ is hydrodynamic damping effect.

By derivating of Equation (1), and replacing Equation (2) in Equation (1), the dynamic equation can be denoted as follows:

$$\begin{aligned} \ddot{\eta} = \dot{R}(\psi)\upsilon - M^{-1}R(\psi)C(\upsilon)\upsilon - M^{-1}R(\psi)D(\upsilon)\upsilon \\ + M^{-1}R(\psi)\tau + M^{-1}R(\psi)E(t) \end{aligned} \tag{5}$$

According to Equation (1), By replacing $\upsilon = \dot{\eta}/R(\psi)$ into Equation (5), then:

$$\begin{aligned} \ddot{\eta} = \left(\frac{\dot{R}(\psi)}{R(\psi)} - M^{-1}C(\upsilon) - M^{-1}D(\upsilon)\right)\dot{\eta} \\ + (M^{-1}R(\psi))\tau + (M^{-1}R(\psi))E(t) \end{aligned} \tag{6}$$

Equation (6) can be shown as follows:

$$\ddot{\eta} = P\dot{\eta} + Q\tau + NE(t) \tag{7}$$

where $P = \left(\frac{\dot{R}(\psi)}{R(\psi)} - M^{-1}C(\upsilon) - M^{-1}D(\upsilon)\right), Q = (M^{-1}R(\psi))$, and $N = (M^{-1}R(\psi))$. $\Delta P, \Delta Q$, and ΔN describe some uncertainties of parameter variations. As a result of this, Equation (7) can be defined as:

$$\ddot{\eta} = (P + \Delta P)\dot{\eta} + (Q + \Delta Q)\tau + (N + \Delta N)E(t) \tag{8}$$

By definition of l, u as lower and upper uncertainty values, the uncertainties can be bounded as:

$$\Delta P_l \le |\Delta P| \le \Delta P_u, \text{ and } \Delta Q_l \le |\Delta Q| \le \Delta Q_u$$

As well as, $\tau(t) = u(t)$, which dynamic Equation (8) can be written as follows:

$$\ddot{\eta} = (P + \Delta P)\dot{\eta} + (Q + \Delta Q)u(t) + E(t) \tag{9}$$

3. Fractional sliding mode control

FSMC is popular because of its robustness against external disturbances. The tracking error can be defined as:

$$e(t) = \eta_d - \eta \tag{10}$$

The fractional-order sliding mode surface can be defined as follows:

$$s(t) = \dot{e}(t) + \alpha D^{\mu} e(t) \tag{11}$$

where α is positive constant and μ is fractional order operator. The equivalent FSMC is obtained by taking derivative of Equation(11) and using Equation(9) as follows:

$$\begin{aligned} \dot{s}(t) &= \ddot{e}(t) + \alpha\mu D^{\mu-1}e(t) = \ddot{\eta} - \ddot{\eta}_d + \alpha\mu D^{\mu-1}e(t) \\ &= \ddot{\eta}_d - (P + \Delta P)\dot{\eta} - (Q + \Delta Q)u(t) \\ &\quad - E(t) + \alpha\mu D^{\mu-1}e(t) \end{aligned} \tag{12}$$

Therefore, the equivalent control can be defined without considering uncertainty ($E(t)$) as follows:

$$u_{eq}(t) = Q^{-1}[\ddot{\eta}_d - P\dot{\eta} + \alpha\mu D^{\mu-1}e(t)] \tag{13}$$

When external disturbances apply on a system, the equivalent control cannot ensure the effectiveness of the control performance. As a result of this, auxiliary control effort needs to be designed in order to compensate for the effect of the external disturbances. The Lyapunov function can be chosen for this task as follows (Rahmani et al., 2016a, 2016b, 2016c):

$$V(t) = \frac{1}{2}s^T(t)s(t) \tag{14}$$

In order to guarantee the stability of the control method, an appropriate condition should be selected as follows:

$$\dot{V}(t) = s^T(t)s(t) < 0, \quad s(t) \neq 0 \tag{15}$$

In order to satisfy the reaching condition, the equivalent control $u_{eq}(t)$ given in Equation (13) is completed by a control term.

$$u(t) = u_{eq}(t) + u_s(t) \tag{16}$$

By using Equation (12), Equation (15) can be denoted as follows:

$$\begin{aligned} \dot{V}(t) &= s^T(\ddot{\eta}_d - (P + \Delta P)\dot{\eta} - (Q + \Delta Q)u(t) \\ &\quad - E(t) + \alpha\mu D^{\mu-1}e(t)) \end{aligned} \tag{17}$$

According to Equation (16), Equation(17) can be rewritten as follows:

$$\begin{aligned} \dot{V}(t) &= s^T(\ddot{\eta}_d - (P + \Delta P)\dot{\eta} - (Q + \Delta Q)u_{eq}(t) \\ &\quad - (Q + \Delta Q)u_s(t) - E(t) + \alpha\mu D^{\mu-1}e(t)) \end{aligned} \tag{18}$$

By substituting Equation(13) into Equation(18), it can be shown as:

$$\begin{aligned} \dot{V}(t) &= s^T(\ddot{\eta}_d - (P + \Delta P)\dot{\eta} - (Q + \Delta Q)(Q^{-1}\ddot{\eta}_d \\ &\quad - Q^{-1}P\dot{\eta} + Q^{-1}\alpha\mu D^{\mu-1}e(t)) \\ &\quad - (Q + \Delta Q)u_s(t) - E(t) + \alpha\mu D^{\mu-1}e(t)) \end{aligned} \tag{19}$$

Simplifying Equation (19) results in

$$\begin{aligned} \dot{V}(t) &= s^T((-\Delta P + Q^{-1}\Delta QP)\dot{\eta} - Q^{-1}\Delta Q\ddot{\eta}_d \\ &\quad + (Q + \Delta Q)u_s(t) - E(t) - Q^{-1}\Delta Q\alpha\mu D^{\mu-1}e(t)) \\ &\le s^T(|-\Delta P + Q^{-1}\Delta QP||\dot{\eta}| - |Q^{-1}\Delta Q||\ddot{\eta}_d| - |E(t)| \\ &\quad - |Q^{-1}\Delta Q\alpha\mu D^{\mu-1}e(t)| - (Q + \Delta Q)u_s(t)) \end{aligned} \tag{20}$$

In order to verify that Equation (20) is less than zero, the reaching control law should be chosen as follows:

$$\begin{aligned} u_s(t) &= \mathrm{sign}(s)(Q + \Delta Q)(|-\Delta P_l + Q^{-1}\Delta Q_l P||\dot{\eta}| \\ &\quad - |Q^{-1}\Delta Q_l||\ddot{\eta}_d| - |E(t)| - |Q^{-1}\Delta Q_l\alpha\mu D^{\mu-1}e(t)|) \end{aligned} \tag{21}$$

Therefore, it can be clearly observed that by substituting Equation (21) into Equation (20), $\dot{V}(t)$ will be less than zero.

4. New hybrid control method

FSMC can be taken into consideration as one of the most convenient control methods for AUV systems because it is robust against external disturbances, but chattering phenomenon is its main drawback. Therefore, by introducing a new hybrid control law, an appropriate control method for AUV systems can be defined as follows:

$$u(t) = u_{\mathrm{FSMC}}(t) - u_h(t) \tag{22}$$

The proposed control block diagram has been shown in Figure 2. Where $u_h(t)$ can be defined as follows:

$$u_h(t) = k_1 e(t) + k_2\dot{e}(t) + k_3 e^{1/2}(t) \tag{23}$$

where k_1, k_2 and k_3 are positive constant.

In order to verify the stability of the proposed control method, Lyapunov theory can be defined as follows:

$$V(t) = \frac{1}{2}s^T(t)s(t) \tag{24}$$

By substituting Equations (22) and (16) into Equation (17), it can be denoted as follows:

$$\begin{aligned} \dot{V}(t) &= s^T(\ddot{\eta}_d - (P + \Delta P)\dot{\eta} - (Q + \Delta Q)u_{eq}(t) \\ &\quad - (Q + \Delta Q)u_s(t) - (Q + \Delta Q)u_h(t) \\ &\quad - E(t) + \alpha\mu D^{\mu-1}e(t)) \end{aligned} \tag{25}$$

By substituting Equations (13) and (23) into Equation (25), it can be demonstrated as:

$$\begin{aligned} \dot{V}(t) &= s^T(\ddot{\eta}_d - (P + \Delta P)\dot{\eta} - (Q + \Delta Q)(Q^{-1}\ddot{\eta}_d \\ &\quad - Q^{-1}P\dot{\eta} + Q^{-1}\alpha\mu D^{\mu-1}e(t)) - (Q + \Delta Q)u_s(t) \\ &\quad - (Q + \Delta Q)(k_1 e(t) + k_2\dot{e}(t) + k_3 e^{1/2}(t)) \\ &\quad - E(t) + \alpha\mu D^{\mu-1}e(t)) \end{aligned} \tag{26}$$

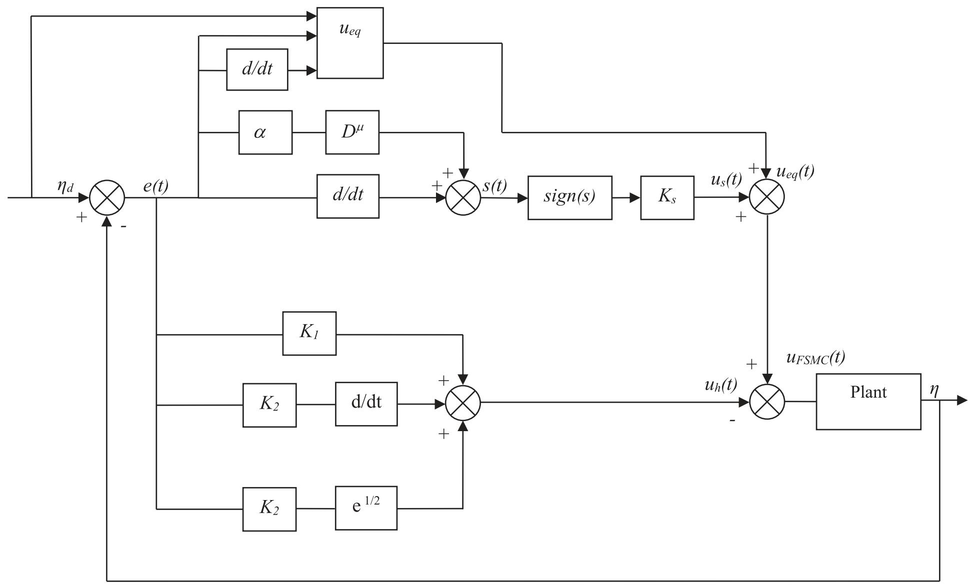

Figure 2. Block diagram of new hybrid control system.

Simplifying Equation (26) results in

$$\begin{aligned}\dot{V}(t) &= s^T((-\Delta P + Q^{-1}\Delta QP)\dot{\eta} - Q^{-1}\Delta Q\ddot{\eta}_d \\ &\quad - (Q+\Delta Q)u_s(t) - (Q+\Delta Q)(k_1 e(t) + k_2\dot{e}(t) \\ &\quad + k_3 e^{1/2}(t)) \\ &\quad - E(t) - Q^{-1}\Delta Q\alpha\mu D^{\mu-1}e(t))\end{aligned} \tag{27}$$

It can be taken into consideration that tracking error will tend to zero ($e(t) \to 0$) when time goes to infinity ($t \to \infty$), then

$$\begin{aligned}\dot{V}(t) &\le s^{\mathrm{T}}(|-\Delta P + Q^{-1}\Delta QP||\dot{\eta}| \\ &\quad - |Q^{-1}\Delta Q||\ddot{\eta}_d| - |E(t)| - (Q+\Delta Q)u_s(t))\end{aligned} \tag{28}$$

In order to verify that Equation (28) is less than zero, the reaching control law should be chosen as follows:

$$\begin{aligned}u_s(t) &= \mathrm{sign}(s)(Q+\Delta Q)(|-\Delta P_l + Q^{-1}\Delta Q_l P||\dot{\eta}| \\ &\quad - |Q^{-1}\Delta Q_l||\ddot{\eta}_d| - |E(t)|)\end{aligned} \tag{29}$$

Therefore, it can be clearly observed that by substituting Equation (29) into Equation (28), $\dot{V}(t)$ will be less than zero.

5. Implementation of fractional order operator

Scientists have been widely used in fractional calculus in engineering structures, which is why they have been applied in control system engineering. Fractional order calculus has been divided into different types: the Grunwald-Letnikov is one of fractional order calculus types which can be defined as follows (Rahmani M, 2018):

$$_aD_t^{\mu} \lim_{h\to 0} \frac{1}{h^{\mu}} \sum_{r=0}^{[(t-a)/h]} (-1)^r \binom{n}{r} f(t-rh) \tag{30}$$

where a and t are the limits of the operator and $[t - a/h]$ is the integer part. n is the integer value which satisfies the condition $n{-}1 < \mu < n$.

The value of the binomial coefficient can be denoted as follows:

$$\binom{n}{r} = \frac{\Gamma(n+1)}{\Gamma(r+1)\Gamma(n-r+1)} \tag{31}$$

The Gamma function used in Equation (31) can be defined as follows:

$$\Gamma(x) = \int_0^{\infty} t^{x-1}e^{-t}\mathrm{d}t, \quad R(z) > 0 \tag{32}$$

In order to obtain a numerical solution of fractional differential equations, this definition is noticeably convenient.

6. Simulation results

The proposed new control methods are implemented to the model of lateral dynamics for an AUV system. The initial states are chosen as follows:

$$\begin{aligned} x(0) = 0, &\quad u(0) = 0 \\ y(0) = 0, &\quad v(0) = 0 \\ \psi(0) = 0, &\quad r(0) = 0 \end{aligned}$$

In order to consider the effectiveness of the proposed control method, reference trajectories are selected as follows:

$$x_d(t) = 8\sin(0.01t), \quad y_d(t) = 10\sin(0.01t)$$

Table 1. Parameters of AUV dynamics model.

$m = 185\,\mathrm{kg}$	$I_z = 50\,\mathrm{kgm}^2$	
$X_u = -70\,\mathrm{kg/s}$	$Y_v = -100\,\mathrm{kg/s}$	$N_r = -50\,\mathrm{kgm}^2/\mathrm{s}$
$X_{\dot{u}} = -30\,\mathrm{kg}$	$Y_{\dot{v}} = -80\,\mathrm{kg}$	$N_{\dot{r}} = -30\,\mathrm{kgm}^2$
$X_{u\|u\|} = -100\,\mathrm{kg/m}$	$Y_{v\|v\|} = -200\,\mathrm{kg/m}$	$N_{r\|r\|} = -100\,\mathrm{kgm}^2$

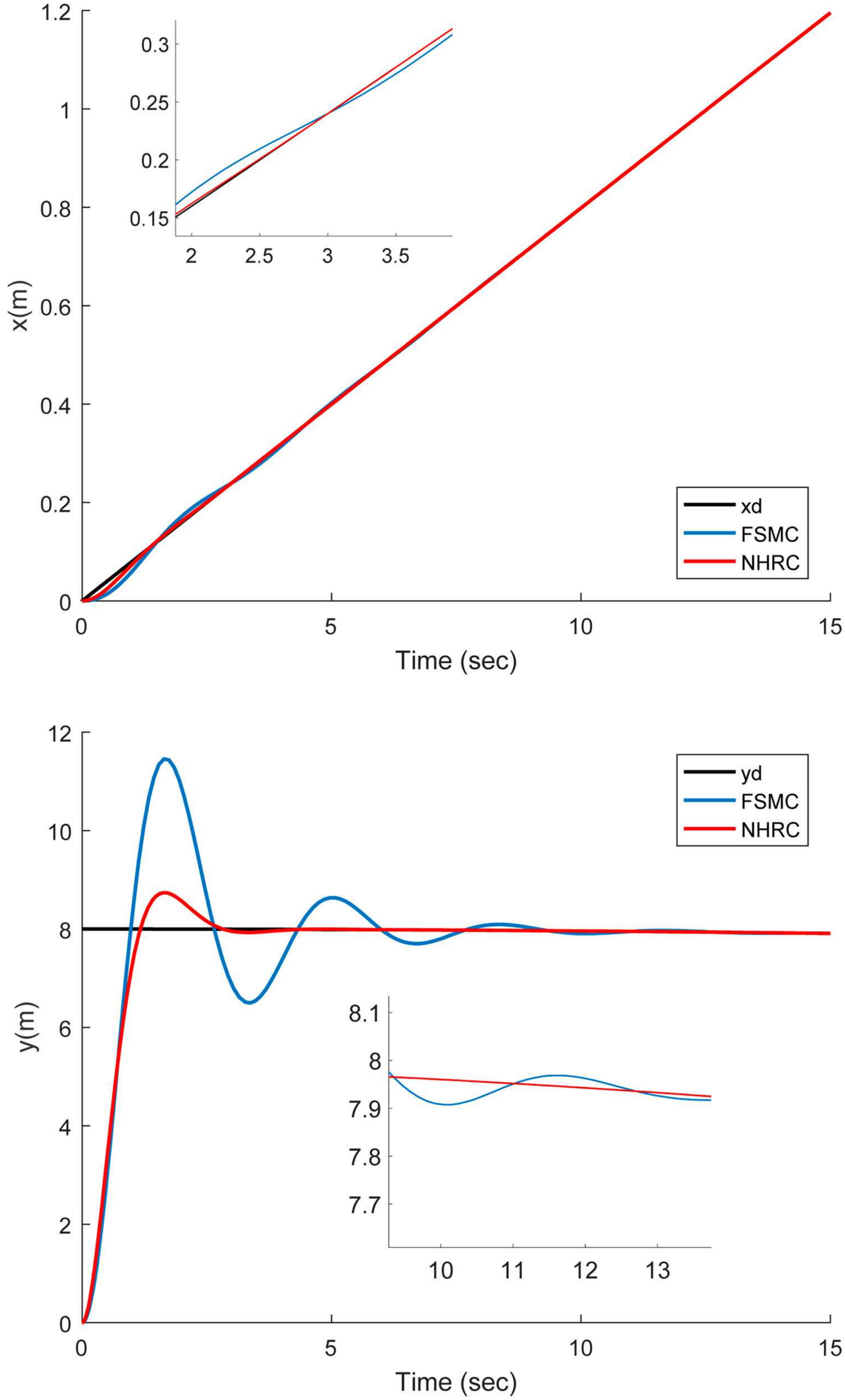

Figure 3. Position tracking of x and y under FSMC and proposed control method.

The design parameters for the proposed control method are selected as:

$$\alpha = 10, \mu = 1.5, K_s = \text{diag}\{1000, 1000\}, K_1 = \text{diag}\{400, 400\},$$
$$K_2 = \text{diag}\{500, 500\}, K_3 = \text{diag}\{20, 20\}$$

The model parameters of an AUV system are tabulated in Table 1.

Figure 3 shows position tracking of x and y under FSMC and proposed control method. By using FSMC, chattering phenomenon occurs. Therefore, by applying and designing a new

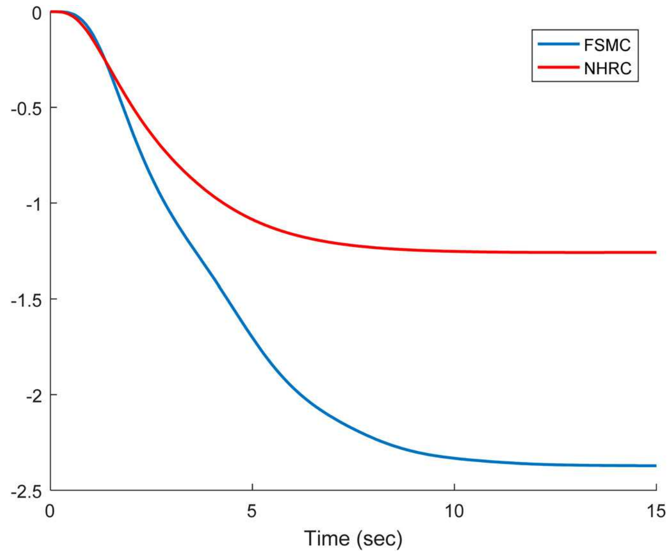

Figure 4. Position tracking of ψ (rad) under FSMC and proposed control method.

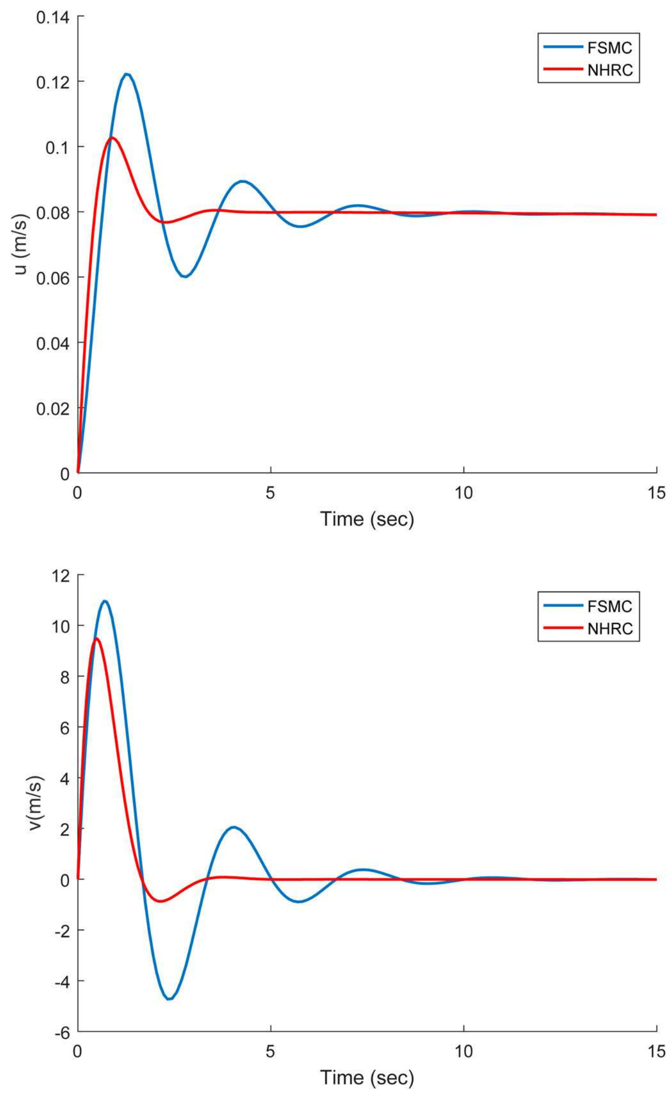

Figure 5. Position tracking error of x and y under FSMC and proposed control method.

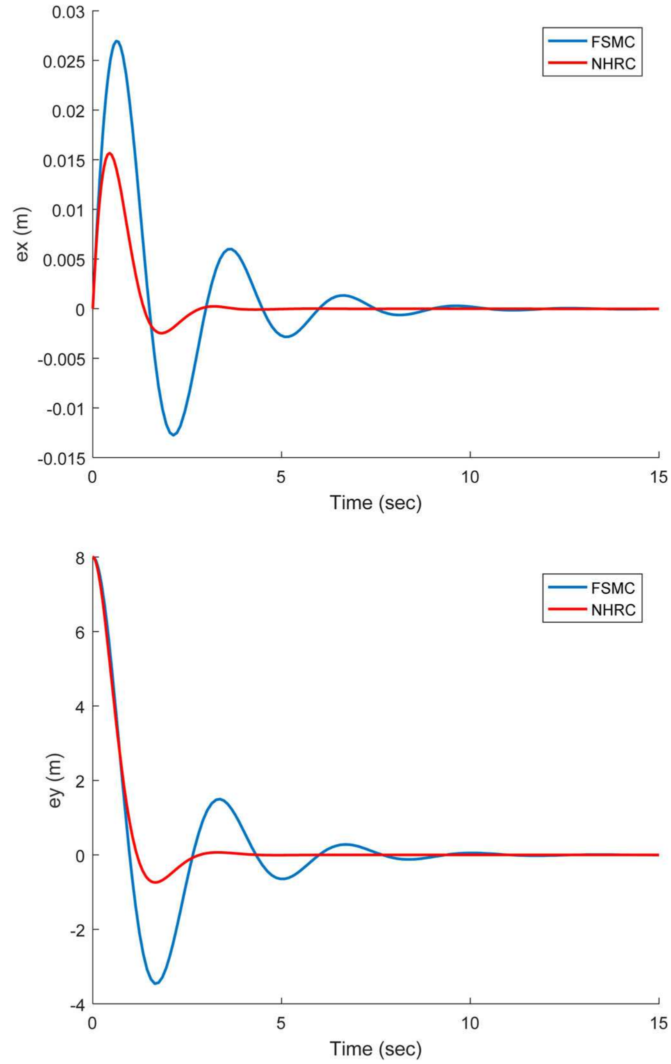

Figure 6. Velocity tracking of AUV versus time using FSMC and proposed control method.

compound control method, chattering phenomenon will be eliminated. The proposed control method ($uh(t)$) continuously calculates an error value $e(t)$ and applies a correction based $K_1e(t), K_2\dot{e}(t)$ and $K_3e^{1/2}(t)$ terms. This issue can eliminate chattering phenomenon which is created by FSMC. In addition, the maximum overshoot is reduced by proposing the new control method according to Figure 3. The underactuated ψ control is illustrated in Figure 4. Moreover, Figure 5 shows the position tracking error of x and y under FSMC and the proposed control method. According to Figure 5, maximum overshoot reduced from 0.027 under FSMC to 0.016 under proposed compound control law in the x direction. The maximum undershoot is reduced from 0.013 under FSMC to 0.0025 under new controller in the x direction. As well as, maximum overshoot and undershoot reduced from 1.5 to 0 and 3.46 to 0.74 under FSMC and proposed control method in the y direction, respectively. Figure 6 demonstrates velocity tracking of AUV versus time under FSMC and proposed control method.

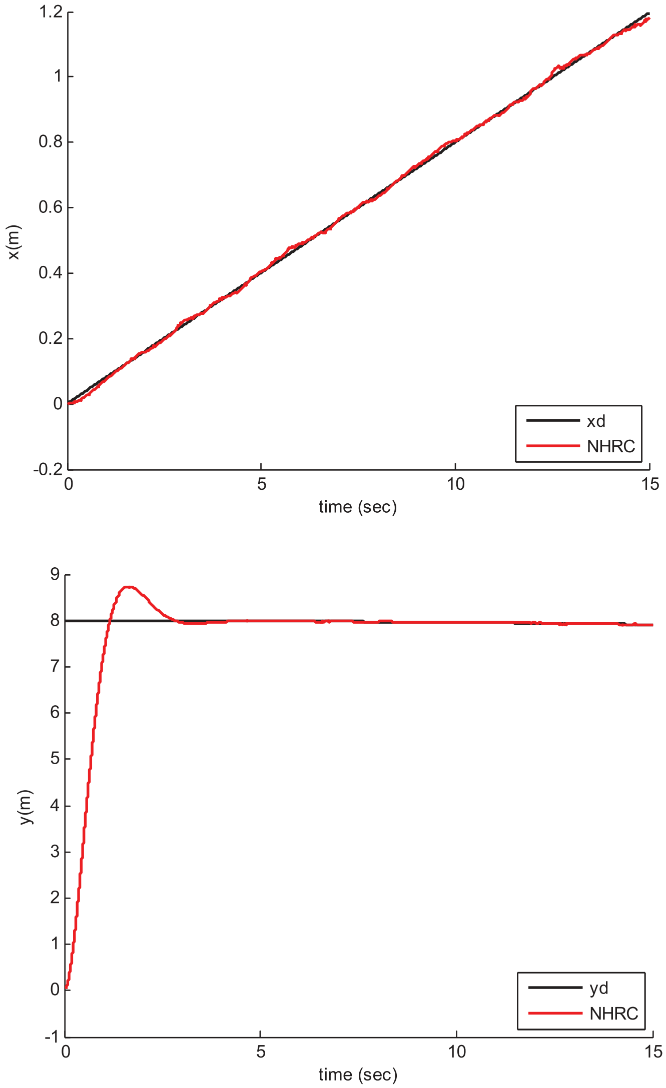

Figure 7. Position tracking of *x* and *y* under random noise.

6.1 Robustness studies

An AUV system permanently encountered with external disturbances when it moves in the water. Therefore, a robust control method should be designed in order to be robust against disturbances. Random noise with standard deviation 0.1 is applied in order to verify robustness and noise suppression of the proposed control method as follows:

$$E(t) = 0.1 * \mathrm{randn}(1, 1) \tag{33}$$

Figure 7 shows simulation results. It can be clearly observed that novel compound proposed control method conveniently suppresses the noise.

7. Conclusion

In this research, a new compound control method was proposed for an AUV system. An AUV system constantly encounters external disturbances. By knowing this problem, a FSMC is designed to enhance the robustness of the controller against disturbances. However, the main drawback of FSMC is the chattering phenomenon. By designing a new compound control law, the chattering phenomenon is eliminated. In addition, maximum overshoot and undershoot highly decreased. Simulation results verified the proposed control method.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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