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SLIDING MODE CONTROL OF AN X4-AUV

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ABSTRACT
This paper presents a design method for attitude control of an autonomous underwater vehicle(X4-AUV) based sliding mode control. We are interested in the dynamic modeling of X4-AUV because of its complexity. The dynamic model is used to design a stable and accurate controller to perform the best tracking and attitude results. To stabilize the overall systems, each sliding mode controller is designed based on the Lyapunov stability theory. The advantage of sliding mode control is it's not being sensitive to model errors, parametric uncertainties and other disturbances. Lastly, we show that the control law has a good robust and good stability through simulation.

Keywords: X4-AUV, sliding mode control, nonlinear.

INTRODUCTION
In recent years, underwater vehicles have been widely used for scientific inspection of deep sea, long range survey, oceanographic mapping, underwater pipeline tracking, exploitation of underwater resources and so on [1-2]. Underwater vehicles are difficult to control, due to nonlinearity, time variance, unpredictable external disturbances such as the environmental force generated by the sea current fluctuation and the difficulty in accurately modeling the hydrodynamic effect [3]. The well-developed linear controllers may fail in satisfying performance requirements, especially when changes in the system and environment occur during the AUV operation. Therefore, it is highly desirable to have a robust control system that has the capacities of learning and adopting to the unknown nonlinear hydrodynamic effects, parameter uncertainties, internal and external perturbations such as water current or sideslip effect. In order to deal with parametric uncertainty and highly nonlinearity in the AUV's dynamics, many researchers concentrated their interests on the applications of robust control for underwater vehicles [4].

Sliding mode control (SMC) is a type of robust control design, has been successfully applied for dynamic positioning and motion control of underwater vehicles, because of its performance insensitivity to model mismatches and disturbances. Yoerger and Slotine [5] introduced the basic methodology of using sliding mode control for AUV application, and later Yoerger and Slotine [6] developed an adaptive sliding mode control scheme in which a nonlinear system model is used. They have investigated the effects of uncertainty of the hydrodynamic coefficients and negligence of cross coupling terms. Goheen *et al.* [7] have proposed multivariable self tuning controllers as an autopilot for underwater vehicles to overcome model uncertainties while performing auto positioning and station-keeping. Cristi *et al.* [8] proposed an adaptive sliding mode controller for AUV's based on the dominant linear model and the bounds of the nonlinear dynamic perturbations. Fossen and Satagun [9] designed a hybrid controller combining an adaptive scheme and a sliding mode term for the motion control of a remotely operated vehicle (ROV).

An X4-AUV is fourthrusters AUV as shown in Figure-1.The control of the X4-AUV motion can be achieved by varying the speed of each thruster to change the thrust and torque produced by them. Each thruster produces both thrust and torque about its center of rotation, as well as a drag force opposite to the vehicle's direction of travel. Driving the two pairs of thrusters in opposite directions removes the need for tail rudders. Consequently, longitudinal rotation is achieved by creating an angular speed difference between the two pairs of thrusters. Increasing or decreasing the speed of the four thrusters simultaneously permits forward acceleration. Rotation about the vertical and the lateral axis and consequently horizontal or vertical motion is achieved by tilting the vehicle. This is possible by conversely changing the thruster speed of one pair of thrusters as described in Figure-1. In spite of the four thrusters, an X4-AUV remains an under actuated and dynamically unstable system.

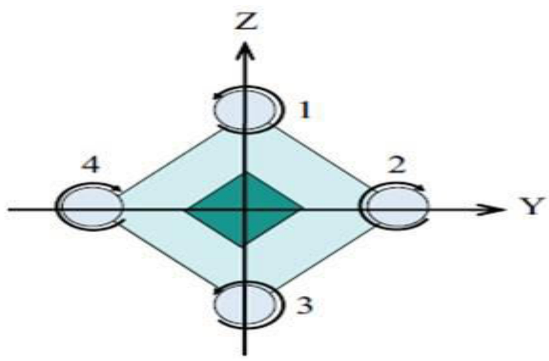

Figure-1. X4-AUV thrusters (back view).

This concept offers better payload and is simpler to build and control, which is a decisive advantage [10].If all thrusters are spinning at the same speed, with thrusters

1 and 3 rotating counterclockwise and thrusters 2 and 4 clockwise, the net hydrodynamic torque, and hence the angular acceleration about the roll axis is exactly zero, which implies that any roll stabilizing rudders of conventional vehicles are not needed. Angular accelerations about the pitch and yaw axis can be caused separately without impacting the roll axis. Each pair of thrusters rotating in the same direction controls one axis, either yaw or pitch, and increasing thrust for one thruster while decreasing thrust for the other will maintain the torque balance needed for roll stability and induce a net torque about the yaw or pitch axis.

In this paper, we present X4-AUV attitude control with sliding mode control method. The paper is organized as follows: the X4-AUV dynamic model, the proposed controller design, simulation results and conclusion.

DYNAMIC MODEL OF AN X4-AUV

There are 2 main reference frames: the earth fixed frame $\{E\}$ attached to the earth, relative to the fixed origin and the body fixed frame $\{B\}$ attached to the center of mass. Figure-2 shows the coordinate systems of an AUV, which consist of a right-hand inertial frame $\{E\}$ in which the downward vertical direction is to be positive, and a right-hand body frame $\{B\}$.

Letting $\boldsymbol{\xi} = [x \quad y \quad z]^T$ denote the centre of mass of the body in the inertial frame, and defining the rotational angles of the X, Y, and Z axes as $\boldsymbol{\eta} = [\phi \quad \theta \quad \psi]^T$, the rotational matrix R from the body frame $\{B\}$ to the inertial frame $\{E\}$ is reduced as:

$$R = \begin{bmatrix} c\theta c\psi & s\phi s\theta c\psi - c\phi s\psi & c\phi s\theta c\psi + s\phi s\psi \\ c\theta s\psi & s\phi s\theta s\psi + c\phi c\psi & c\phi s\theta s\psi - s\phi c\psi \\ -s\theta & s\phi c\theta & c\phi c\theta \end{bmatrix} \tag{1}$$

where $c\alpha$ denotes cos α and $s\alpha$ is sin α.

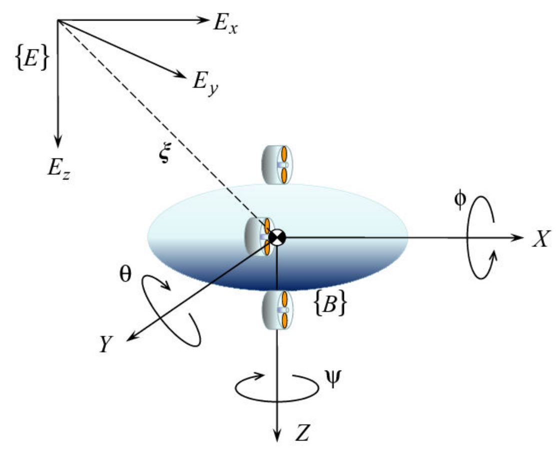

Figure-2. Coordinate systems of AUV.

Following a Lagrangian method, this section describes the dynamic model of the X4-AUV with the assumption of balance between buoyancy and gravity. The kinetic energy formula is:

$$T = T_{trans} + T_{rot} \tag{2}$$

where T_{trans} and T_{rot} are the translational kinetic energy and the rotational kinetic energy is defined by:

$$T_{trans} = \frac{1}{2}\dot{\boldsymbol{\xi}}^T M \dot{\boldsymbol{\xi}} \tag{3}$$

$$T_{rot} = \frac{1}{2}\dot{\boldsymbol{\eta}}^T J \dot{\boldsymbol{\eta}} \tag{4}$$

in which M is the total mass matrix of the body, and J is the total inertia matrix of the body. From the characteristics of added mass, it can be written as:

$$M = \text{diag}\,(m_1, m_2, m_3) = m_b I + M_f \tag{5}$$

$$J = \text{diag}\,(I_x, I_y, I_z) = J_b + J_f \tag{6}$$

Here, m_b is a mass of the vehicle, J_b is an inertia matrix of the vehicle and I is a 3×3 identity matrix.

Letting ρ denote a density of the fluid and using the formulation of the added mass and inertia under the assumption of $r_1 = 5r_2$ and $r_2 = r_3 = r$, where r_1, r_2 and r_3 the added mass matrix M_f and the added inertia matrix J_f are:

$$M_f = \text{diag}\,(0.394\rho\pi r^3, 5.96\rho\pi r^3, 5.96\rho\pi r^3) \tag{7}$$

$$J_f = \text{diag}\,(0, 24.2648\rho\pi r^5, 24.2648\rho\pi r^5) \tag{8}$$

From the assumption of the balance between the buoyancy and the gravity, i.e., the potential energy $U = 0$, the Lagrangian can be written as:

$$\begin{aligned} L &= T - U \\ &= T_{trans} + T_{rot} \end{aligned} \tag{9}$$

The dynamic model of X4-AUV summarized as:

$$\begin{aligned} m_1\ddot{x} &= \cos\theta \, \cos\psi \, u_1 \\ m_2\ddot{y} &= \cos\theta \, \sin\psi \, u_1 \\ m_3\ddot{z} &= -\sin\theta \, u_1 \\ I_x\ddot{\phi} &= \dot{\theta}\dot{\psi}(I_y - I_z) + u_2 \\ I_y\ddot{\theta} &= \dot{\phi}\dot{\psi}(I_z - I_x) - J_t\dot{\psi}\Omega + lu_3 \\ I_z\ddot{\psi} &= \dot{\phi}\dot{\theta}(I_x - I_y) + J_t\dot{\theta}\Omega + lu_4 \end{aligned} \tag{10}$$

where $u_1, u_2, u_3, and\ u_4$ are the control inputs for the translational (x, y, and z-axis) motion, the roll (ϕ-axis) motion, the pitch (θ-axis) motion, and yaw (ψ-axis) motion, respectively. A detailed derivation for dynamics model (10) given in [11].

Defining that b is a thrust factor, d is a drag factor, taken from $\tau_{Mi} = d\omega_i^2$ then $\Omega, u_1, u_2, u_3, and\ u_4$ are given by:

$$\begin{aligned}
\Omega &= (\omega_2 + \omega_4 - \omega_1 - \omega_3)\\
u_1 &= f_1 + f_2 + f_3 + f_4\\
&= b(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2)\\
u_2 &= d(-\omega_2^2 - \omega_4^2 + \omega_1^2 + \omega_3^3)\\
u_3 &= f_1 - f_3 = b(\omega_1^2 - \omega_3^2)\\
u_4 &= f_2 - f_4 = b(\omega_2^2 - \omega_4^2)
\end{aligned} \tag{11}$$

This X4-AUV dynamic model has 6 outputs, while the number of inputs is four. We are unable to control all states at the same time. Then, in order to track a desired position the controller outputs x, y, z and ψ are needed. This means we need to control the attitude, which is ϕ, θ, and ψ for smooth and stabilize the motions.

SLIDING MODE CONTROL

Nonlinear model may have impression or inaccuracies due to parametric uncertainties or choice of a simplification of the systems dynamic. One of the most approached methods to deal with the model uncertainties is to use robust control, and sliding mode control is one of it.

A Sliding mode control is a Variable Structure Control (VSC). Basically, VSC includes several different continuous functions that map plant state to a control surface. The switching among these functions is determined by plant state which is represented by a switching function.

Sliding mode control used switching control law to drive the nonlinear system trajectory on to a chosen surface and to maintain the state trajectory on the surface. When system state trajectory is above or below the surface, the switching control law should drive the trajectory back toward the surface as shown in Figure-3.

This surface is called sliding surface or sliding manifold. Lyapunov theorem is used to determine the motion of state trajectory onto sliding surface. By using the Lyapunov function bound a chosen gain of switching control law so that the derivative of Lyapunov function must be negative definite for guarantee motion of state trajectory and system stability.

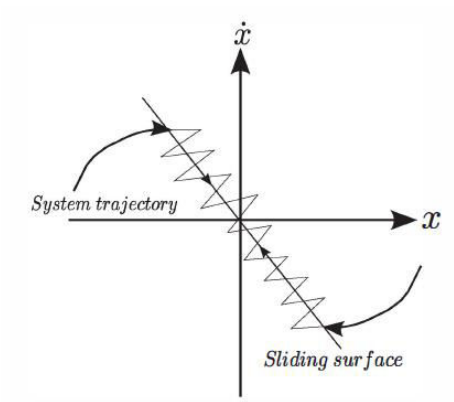

Figure-3. Possible trajectories around sliding surface.

CONTROLLER DESIGN

The model (10), can be rewritten in a state-space form $\dot{X} = f(X,U)$ by introducing $X = (x_1 \cdots x_{12})^T \epsilon\, \Re^{12}$ as state vector of the system as follows:

$$\left.\begin{aligned}
x_1 &= x\\
x_2 &= \dot{x}_1 = \dot{x}\\
x_3 &= y\\
x_4 &= \dot{x}_3 = \dot{y}\\
x_5 &= z\\
x_6 &= \dot{x}_5 = \dot{z}
\end{aligned}\;\right|\;\begin{aligned}
x_7 &= \phi\\
x_8 &= \dot{x}_7 = \dot{\phi}\\
x_9 &= \theta\\
x_{10} &= \dot{x}_9 = \dot{\theta}\\
x_{11} &= \psi\\
x_{12} &= \dot{x}_{11} = \dot{\psi}
\end{aligned} \tag{12}$$

where the inputs $U = (u_1 \cdots u_4)^T \epsilon\, \Re^4$.

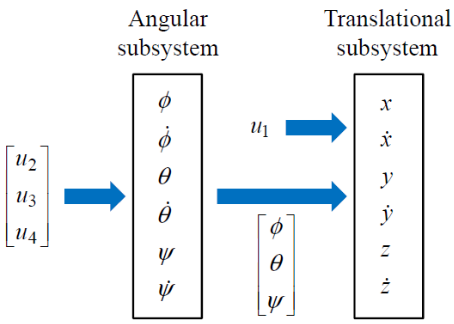

Figure-4. Connection of rotational and translational subsystems.

From (10) and (12), we obtain:

$$f(X,U) = \begin{pmatrix}
x_2\\
(\cos\theta\ \cos\psi)\frac{1}{m_1}u_1\\
x_4\\
(\cos\theta\ \sin\psi)\frac{1}{m_2}u_1\\
x_6\\
(-\sin\theta)\frac{1}{m_3}u_1\\
x_8\\
x_{10}x_{12}\left(\frac{I_y - I_z}{I_x}\right) + \frac{l}{I_x}u_2\\
x_{10}\\
x_8x_{12}\left(\frac{I_z - I_x}{I_y}\right) - \frac{J_t}{I_y}x_{12}\Omega + \frac{l}{I_y}u_3\\
x_{12}\\
x_8x_{10}\left(\frac{I_x - I_y}{I_z}\right) + \frac{J_t}{I_z}x_{10}\Omega + \frac{l}{I_z}u_4
\end{pmatrix} \tag{13}$$

with:

$$\left.\begin{aligned}
a_1 &= (I_y - I_z)/I_x\\
a_2 &= (I_z - I_x)/I_y\\
a_3 &= J_t/I_y\\
a_4 &= J_t/I_z\\
a_5 &= (I_x - I_y)/I_z
\end{aligned}\;\right|\;\begin{aligned}
b_1 &= 1/\,I_x\\
b_2 &= l/\,I_y\\
b_3 &= l/\,I_z
\end{aligned}$$

$u_y = \cos x_9 \sin x_{11}$

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$$u_z = \sin x_{11}$$

It is worthwhile to note in the latter system that the angles and their time derivatives do not depend on translation components. On the other hand, the translations depend on the angles. We can ideally imagine the overall system described by (13) as constituted of two subsystems, the angular rotations and the linear translations, see Figure-4.

The controller was splitted into 2 sections: sliding mode for attitude control, and PD controller for the altitude and position control.

Altitude control

Let us consider the simple task for the X4-AUV to be translated to a particular position $x = x^d$, $y = y^d$ and $z = z^d$. The dynamics of the x-, y- and z-positions are described by lines 1 and 2, 3 and 4, and 5 and 6 in system (13), i.e., *x-position*:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} x_2 \\ (\cos x_9 \cos x_{11}) \dfrac{u_1}{m_1} \end{pmatrix} \quad (14)$$

y-position:

$$\begin{pmatrix} \dot{x}_3 \\ \dot{x}_4 \end{pmatrix} = \begin{pmatrix} x_4 \\ (\cos x_9 \sin x_{11}) \dfrac{u_1}{m_2} \end{pmatrix} \quad (15)$$

z-position:

$$\begin{pmatrix} \dot{x}_5 \\ \dot{x}_6 \end{pmatrix} = \begin{pmatrix} x_6 \\ (-\sin x_9) \dfrac{u_1}{m_3} \end{pmatrix} \quad (16)$$

By the previous considerations in the control for the subsystem of the angular rotations in [12], we ensure that starting from an initial condition where $V(X_\alpha) < \pi/2$, the angles and their velocities are constrained in this hypersphere of $\Re^6$. In this case $\cos x_9 \cos x_{11} \neq 0$, $\cos x_9 \sin x_{11} \neq 0$ and $-\sin x_9 \neq 0$ for all the trajectories of the system under the previous control law. Systems (14), (15) and (16) can be linearized by simply compensating the weighted force by
x-position:

$$u_1 = \frac{m_1 \hat{u}_1}{\cos x_9 \cos x_{11}} \quad (17)$$

y-position:

$$u_1 = \frac{m_2 \hat{u}_2}{\cos x_9 \sin x_{11}} \quad (18)$$

z-position:

$$u_1 = \frac{-m_3 \hat{u}_3}{\sin x_9} \quad (19)$$

where $\hat{u}_1$, $\hat{u}_2$ and $\hat{u}_3$ are additional terms. By this partial feedback linearization [12], (14), (15) and (16) become
x-position:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} x_2 \\ \hat{u}_1 \end{pmatrix} \quad (20)$$

or

$$\begin{pmatrix} \dot{e}_1 \\ \dot{e}_2 \end{pmatrix} = \begin{pmatrix} e_2 \\ -\hat{u}_1 \end{pmatrix} \quad (21)$$

y-position:

$$\begin{pmatrix} \dot{x}_3 \\ \dot{x}_4 \end{pmatrix} = \begin{pmatrix} x_4 \\ \hat{u}_2 \end{pmatrix} \quad (22)$$

or

$$\begin{pmatrix} \dot{e}_3 \\ \dot{e}_4 \end{pmatrix} = \begin{pmatrix} e_4 \\ -\hat{u}_2 \end{pmatrix} \quad (23)$$

z-position:

$$\begin{pmatrix} \dot{x}_5 \\ \dot{x}_6 \end{pmatrix} = \begin{pmatrix} x_6 \\ \hat{u}_3 \end{pmatrix} \quad (24)$$

or

$$\begin{pmatrix} \dot{e}_5 \\ \dot{e}_6 \end{pmatrix} = \begin{pmatrix} e_6 \\ -\hat{u}_3 \end{pmatrix} \quad (25)$$

where $e_i \triangleq x_i^d - x_i$, $i = 1, \cdots, 6$. Adopting a simple linear state feedback stabilization law $\hat{u}_1 = k_7 e_1 + k_8 e_2$, $\hat{u}_2 = k_9 e_3 + k_{10} e_4$ and $\hat{u}_3 = k_{11} e_5 + k_{12} e_6$ we can stabilize the position by placing the poles of the subsystem in any position in the complex left half plane.

Atitude control

The mapping (13) is partially used to design the sliding-mode controller for the rotations subsystem of the X4-AUV. The first step in this design is similar to the one for the backstepping approach [13][14], except for the equation (11) were S_2 (Surface) is used instead of z_2 for more clearance.

$$s_2 = x_8 - \dot{x}_{7d} - \alpha_1 z_1 \quad (26)$$

For the second step we consider tha augmented Lyapunov function:

$$\mathrm{V}(z_1, s_2) = \tfrac{1}{2}(z_1^2 + s_2^2) \quad (27)$$

The chosen law for the attractive surface is the time derivative of (26) satisfying $(s\dot{s}) < 0)$:

$$\begin{aligned} \dot{s}_2 &= -ksign(s_2) - k_2 s_2 \\ &= \dot{x}_2 - \ddot{x_{1d}} - \alpha_1 \dot{z}_1 \quad (28) \\ &= \alpha_1 x_4 x_6 + \alpha_2 x_4 \Omega + b_1 U_2 - \ddot{x_{1d}} + \alpha_1 (z_2 + \alpha_1 z_1) \end{aligned}$$

As for the backstepping approach, the control U_2 is extracted:

$$u_2 = \frac{1}{b_1}\left(-a_1 x_{10} x_{12} - \alpha_1^2 z_2 - k_1 sign(s_2) - \mathrm{k}_2 s_2\right) \quad (29)$$

The same steps are followed to extract U_3 and U_4.

$$u_3 = \frac{1}{b_2}\left(-a_2 x_8 x_{12} - a_3 x_{12} \Omega - \alpha_2^2 z_3 - k_3 sign(s_3) - \mathrm{k}_4 s_3\right) \quad (30)$$

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ARPN Journal of Engineering and Applied Sciences

$$u_4 = \frac{1}{b_3}\left(-a_5 x_8 x_{10} - a_4 x_{10}\Omega - \alpha_3^2 z_5 - k_5 sign(s_4) - k_6 s_4\right) \quad (31)$$

with:

$$\begin{cases} z_3 = x_{9d} - x_9 \\ s_3 = x_{10} - \dot{x}_{9d} - \alpha_2 z_3 \\ z_5 = x_{11d} - x_{11} \\ s_6 = x_{12} - \dot{x}_{11d} - \alpha_3 z_5 \end{cases}$$

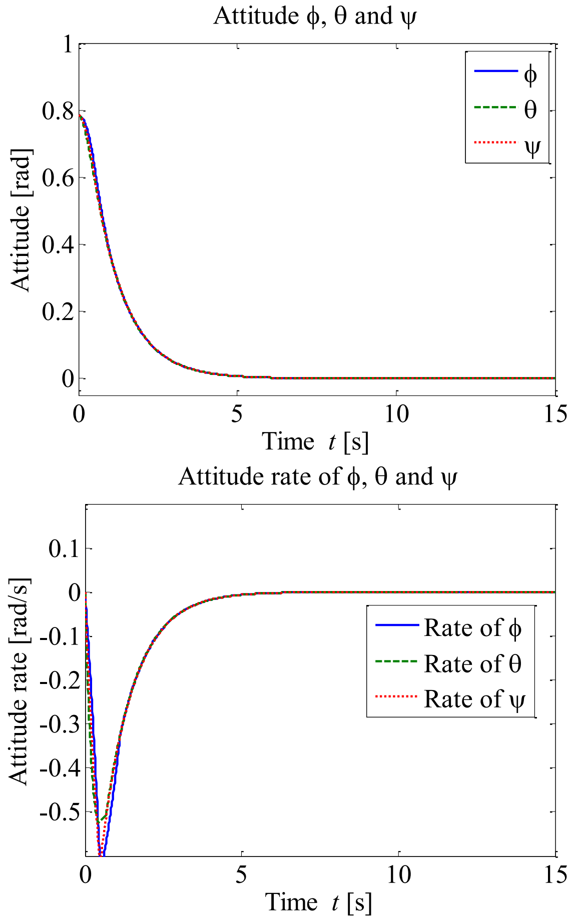
where $\alpha_2, \alpha_3, k_1, k_3, k_5$ is a positive constant.

SIMULATION RESULTS

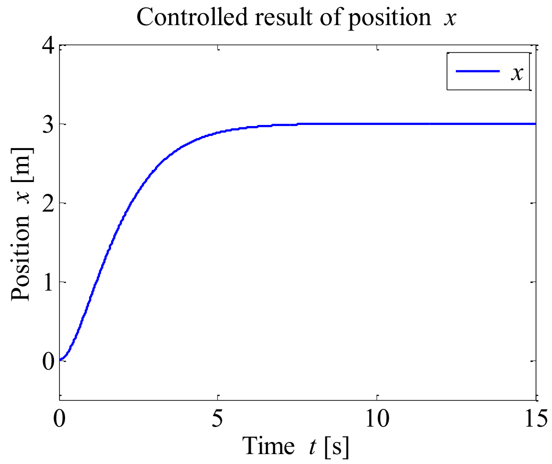
The controllers have been implemented on MATLAB and the simulation results for stabilizing an X4-AUV are shown in Figure-5. The system started with an initial state $X_0 = (0,0,0,0,0,0,\frac{\pi}{4},0,\frac{\pi}{4},0,\frac{\pi}{4},0)^T$ and we wanted the final x-positions, at 3 m with all zero orientation angles. As shown in Figure. 5, it is seen that all orientation angles, and x-positions converge to the targets, where $\alpha_1 = 1$, $\alpha_2 = 1$, $\alpha_3 = 1$, $k_1 = 1$, $k_2 = 1$, $k_3 = 1$, $k_4 = 3$, $k_5 = 1.0$, $k_6 = 2.0$, $k_7 = 1.0$, $k_8 = 2.0$. The physical parameters for X4-AUV that has been used for simulating the dynamic model presented in Table 1. Note that the simulations for stabilizing the X4-AUV in x-, y- and z-positions were implemented independently. The other results for y- and z-position are not included in this paper.

Table-1. Physical parameters for X4-AUV.

Parameter	Description	Value	Unit
m_b	Mass	21.43	Kg
ρ	Fluid density	1023.0	kg/m^3
l	Distance	0.1	M
r	Radius	0.1	m
b	Thrust factor	0.068	N·s^2
d	Drag factor	3.617e^{-4}	N·m·s^{-2}
J_{bx}	Roll inertia	0.0857	kg·m^2
J_{by}	Pitch inertia	1.1143	kg·m^2
J_{bz}	Yaw inertia	1.1143	kg·m^2
J_t	Thrust inertia	1.1941e^{-4}	N·m·s^{-2}



(a) Attitude and attitude rate control for x-position



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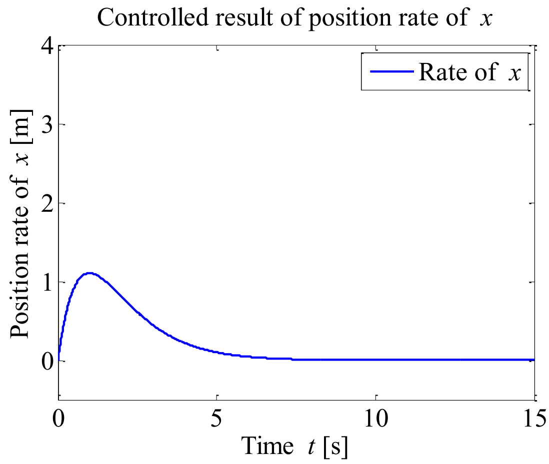
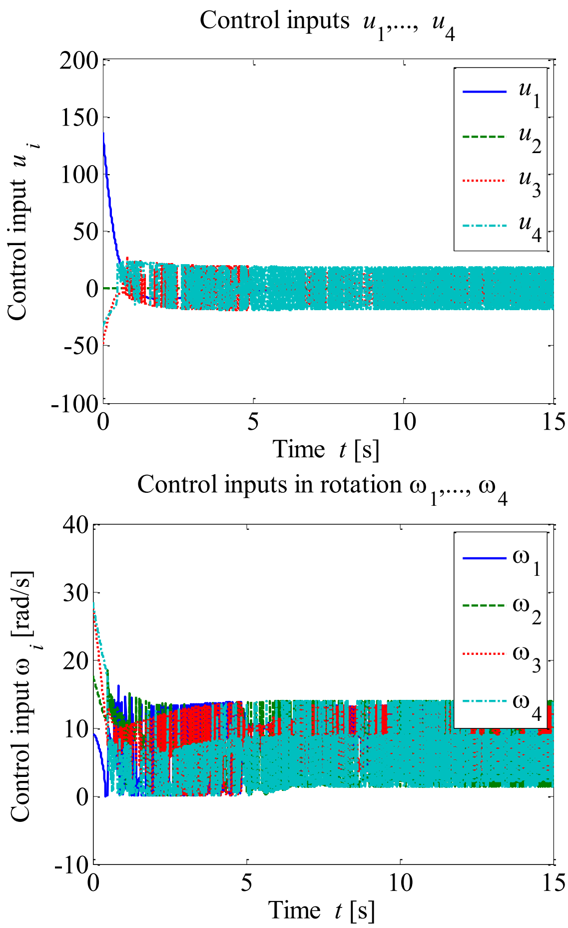


(b) A Position and position rate control for *x*-position



(c) A control inputs and control inputs in rotation

Figure-5. Sliding mode controller: A case for stabilizing the orientation angles and *x*-axis position.

CONCLUSION

This paper has considered a sliding mode control, a type of nonlinear control technique and a nonlinear unstable system, X4-AUV which has several applications. The control equations have been derived for X4-AUV dynamics. The control implementation has been exercised through simulation in MATLAB. The results have been presented here. The sliding mode control technique based on Lyapunov theory stabilize the position and angles of an X4-AUV.

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