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COMPARISON OF AN X4-AUV PERFORMANCE USING A BACKSTEPPING AND INTEGRAL BACKSTEPPING APPROACH

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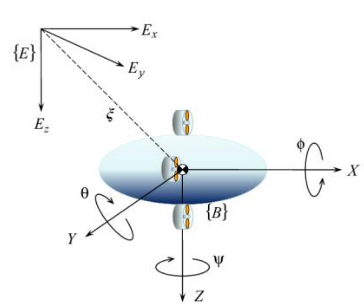
Graphical abstract



Abstract

X4-AUV is a type of an autonomous underwater vehicle (AUV) which has 4 inputs with six degrees of freedoms (6-DOFs) in motion and is classified under an underactuated system. Controlling an underactuated system is difficult tasks because of the highly nonlinear dynamic, uncertainties in hydrodynamics behaviour and mostly those systems fails to satisfy Brockett's Theorem. It usually required nonlinear control technique and this paper proposed an integral backstepping controller for stabilizing an underactuated X4-AUV. A control law is designed for the system in new state space using integral backstepping. The performance of the proposed control method is examined through simulation and results demonstrate all motion is stabilized and convergence into desired point. We also compared the results with backstepping approach to see the effectiveness of the propose control system.

Keywords: Underactuated system, X4-AUV, integral backstepping control

1.0 INTRODUCTION

Underwater robotic is an important research area due to its numerous applications: i.e., from a scientific research of ocean, surveillance, inspection of commercial undersea facilities, military operations and many more. Nevertheless, controlling such system is a challenging task because the dynamic model has nonlinearity and uncertain external disturbances besides difficulties in hydrodynamic modelling. Thus, it attracted further research and attention correlate with underactuated AUV, defined as the system with a fewer number of control inputs than a number of DOFs. Consideration for setting up a system with fewer actuators than DOFs is motivated by several reasons. The main aims to reduce the cost, less actuator will need less energy to operate and it is indirectly reducing the costs of fuel used. Besides, it is building compactly and fewer actuators make a structure become lighter. Furthermore, it also increases the reliability of a system in case actuator failures occur.

Control of nonholonomic systems is theoretically challenging and practically interesting. Brockett's Theorem [1] defined those systems cannot be stabilized to a point with pure smooth (or even continuous) state feedback control, usual smooth and time invariant. A stabilization problem consists of designing control law which guarantees equilibrium of a closed loop system is asymptotically stable or at least locally asymptotically stable. Therefore, control of underactuated systems usually required nonlinear control techniques and there are numerous control techniques such as linearization, H∞, intelligent PID, sliding mode and backstepping control for nonlinear systems [2, 3, 4].

The backstepping is a recursive Lyapunov based scheme proposed by Krstic *et al.* [5] and backstepping is one of the active research in controlling underactuated AUV [6 - 9]. The idea of backstepping is to construct a recursive controller by considering some of the state variables as "virtual controls" and designing an intermediate control laws. The imperative advantage of backstepping as it has the adaptability to avoid eliminations of helpful nonlinearities and accomplishes the objectives of stabilization and tracking. Backstepping control widely can be found in robotics areas such as for mobile robot [10], aerospace vehicles [11], and marine vehicles [12].

The idea of adding an integral into backstepping was firstly introduced by Kanellakopoulos *et al*. [13] and the combination of this control method referred as integral backstepping. In integral backstepping design, the integral of tracking error is added between the original system input and the input to be designed at a beginning of a derivation. This method has been implemented for ship control [14], industrial motion control systems [15], and largely used in UAV. The integral backstepping technique show effective and advanced result in stabilizing quadrotor helicopters which also generally falls into underactuated system [16 - 18]. X4-AUV dynamic model have similar pattern as quadrotor helicopters dynamic which have 6 states and 4 inputs and both are classed into underactuated system. Hence, an integral backstepping is proposed to stabilize the underactuated X4-AUV.

Integral presence helps the controller to deal with the disturbances existing in the systems and enhance the system transient and steady state performance. Tan *et al.* [15] compared the performance of backstepping controller with and without integral for motion control systems. The results show by added integral, steady state tracking error is eliminated from the close loop system and the fast tracking performance is preserved.

This article presented an integral backstepping controller for stabilizing all positions and attitudes of an underactuated X4-AUV with 4 inputs and 6-DOFs. The X4-AUV are executed by nonlinear control strategies by separating the system into two subsystems which are translational and rotational subsystems. The simulation results indicate the effectiveness of the control strategy for stabilizing an underactuated X4-AUV.

The remainder of this article is constructed as follows. Systems modelling of X4-AUV coordinate and dynamic model presented in Section 2. Section 3 proposed an integral backstepping control strategies for stabilizing the X4-AUV to the desired point. Simulation of proposed method illustrated in section 4 followed by concludes the paper in Section 5.

2.0 DEFINITION OF COORDINATE SYSTEM

In order to describe the underwater vehicle's motion, a special reference frame must be established. There have two coordinate systems: i.e., inertial coordinate system (or fixed coordinate system) and motion coordinate system (or body-fixed coordinate system). The coordinate frame $\{E\}$ is composed of the orthogonal axes $\{E_x\ E_y\ E_z\}$ and is called as an inertial frame. This frame is commonly placed at a fixed place on Earth. The axes E_x and E_y form a horizontal plane and E_z has the direction of the gravity field. The body fixed frame $\{B\}$ is composed of the orthonormal axes $\{X, Y, Z\}$ and attached to the vehicle. The body axes, two of which coincide with principle axes of inertia of the vehicles, are defined in Fossen [19] as follows:

X is the longitudinal axis (directed from aft to fore)
Y is the transverse axis (directed to starboard)
Z is the normal axis (directed from top to bottom)

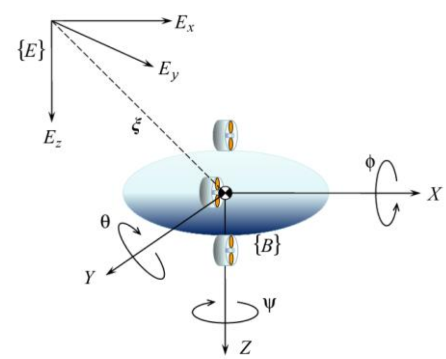


Figure 1 Coordinate systems of AUV

Figure 1 show the coordinate systems of AUV, which consist of a right-hand inertial frame $\{E\}$ in which the downward vertical direction is to be positive and right-hand body frame $\{B\}$.

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

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

where cα denotes cos α and sα is *sin* α.

Following a Lagrangian method, the dynamic model of X4-AUV is summarized by (2) and detailed derivation given in [20]:

$$
\begin{aligned}
m_1\ddot{x} &= \cos\theta\cos\psi u_1 \\
m_2\ddot{y} &= \cos\theta\sin\psi u_1 \\
m_3\ddot{z} &= -\sin\theta u_1 \\
I_x\ddot{\phi} &= \dot{\theta}\dot{\psi}\left(I_y - I_Z\right) + u_2 \\
I_y\ddot{\theta} &= \dot{\phi}\dot{\psi}\left(I_z - I_x\right) - J_t\dot{\psi}\Omega + lu_3 \\
I_z\ddot{\psi} &= \dot{\phi}\dot{\theta}\left(I_x - I_y\right) - J_t\dot{\theta}\Omega + lu_4
\end{aligned} \tag{2}
$$

3.0 CONTROL STRATEGY OF AN X4-AUV

The model (2) can be rewritten in a state space form $\dot{X} = f(X,U)$ by introducing $X = (x_1 \cdots x_{12})^T \in \Re^{12}$ as state vector of the system as follows:

$$
\begin{array}{l|l}
x_1 = x & x_7 = \phi \\
x_2 = \dot{x}_1 = \dot{x} & x_8 = \dot{x}_7 = \dot{\phi} \\
x_3 = y & x_9 = \theta \\
x_4 = \dot{x}_3 = \dot{y} & x_{10} = \dot{x}_9 = \dot{\theta} \\
x_5 = z & x_{11} = \psi \\
x_6 = \dot{x}_5 = \dot{z} & x_{12} = \dot{x}_{11} = \dot{\psi}
\end{array} \tag{3}
$$

where the inputs $U = (u_1 \cdots u_4)^T \in \Re^4$.
From (2) and (3), we obtain:

$$
f(X,U) = \begin{pmatrix}
x_2 \\
\cos\theta\cos\psi \dfrac{1}{m_1} u_1 \\
x_4 \\
u_y \dfrac{1}{m_2} u_1 \\
x_6 \\
u_z \dfrac{1}{m_3} u_1 \\
x_8 \\
x_{10}x_{12}a_1 + b_1 u_2 \\
x_{10} \\
x_8 x_{12} a_2 - a_3 x_{12}\Omega + b_2 u_3 \\
x_{12} \\
x_8 x_{10} a_5 + a_4 x_{10}\Omega + b_3 u_4
\end{pmatrix} \tag{4}
$$

with:

$$
\begin{array}{l|l}
a_1 = I_y - I_z / I_x & b_1 = 1 / I_x \\
a_2 = I_z - I_x / I_y & b_2 = l / I_y \\
a_3 = J_t / I_y & b_3 = l / I_z \\
a_4 = J_t / I_z & u_y = \cos\theta\sin\psi \\
a_5 = I_x - I_y / I_z & u_z = -\sin\theta
\end{array}
$$

It is to be noted 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. The complete system described by (4) composed of two subsystems which are the angular rotations and linear translations as illustrate in Figure 2.

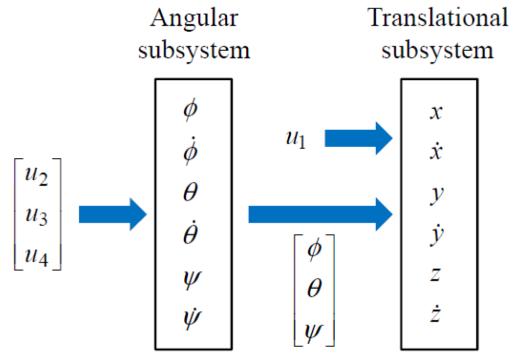


Figure 2 Connection of rotational and translational subsystems

3.1 Control of the Rotations Subsystem

The control of rotational subsystem is considered first due to its complete independence compare than translational. For the first step, consider the roll tracking error $e_1 = \phi_d - \phi$ and its dynamics:

$$\dot{e}_1 = \dot{\phi}_d - \omega_x \tag{5}$$

The angular speed ω_x is not an input and has its own dynamics. So, set desired behaviour and consider it as virtual control.

$$\omega_{xd} = c_1 e_1 + \dot{\phi}_d + \lambda_1 X_1 \tag{6}$$

with c_1 and λ_1 a positive constant and $X_1 = \int_0^t e_1(\tau) d_t$ is an integral of the roll tracking error.

Since ω_x has its own error e_2, compute its dynamic (6) as follows:

$$\dot{e}_2 = c_1\left(\dot{\phi}_d - \omega_x\right) + \ddot{\phi}_d + \lambda_1 e_1 - \ddot{\phi} \tag{7}$$

where the angular velocity tracking error, e_2 defined by:

$$e_2 = \omega_{xd} - \omega_x \tag{8}$$

Using (5) and (7), rewrite the roll tracking error dynamics as:

$$\dot{e}_1 = -c_1 e_1 - \lambda_1 X_1 + e_2 \tag{9}$$

By substitute $\ddot{\phi}$ in (6) by its corresponding expression dynamic model (2), control input u_2 appears as follows:

$$\dot{e}_2 = c_1(\dot{\phi}_d - \omega_x) + \ddot{\phi}_d + \lambda_1 e_1 - x_{10}x_{12}\alpha_1 + b_1 u_2 \quad (10)$$

The desirable dynamics for the angular speed tracking error is:

$$\dot{e}_2 = -c_2 e_2 - e_1 \quad (11)$$

By combining (6) and dynamics model (2), control input u_2 given by:

$$u_2 = \frac{1}{b_1}(1 - c_1^2 + \lambda_1)e_1 + (c_1 + c_2)e_2 - c_1\lambda_1\chi_1 \quad (12)$$

where c_2 is a positive constant.
Similarly, the same steps are followed to extract u_3 and u_4.

$$u_3 = \frac{1}{b_2}(1 - c_3^2 + \lambda_2)e_3 + (c_3 + c_4)e_4 - c_3\lambda_2\chi_2 + \ddot{\theta}_d - x_9 x_{12}\alpha_2 - \alpha_3 x_{12}\Omega \quad (13)$$

$$u_4 = \frac{1}{b_3}(1 - c_5^2 + \lambda_3)e_5 + (c_5 + c_6)e_6 - c_5\lambda_3\chi_3 + \ddot{\psi}_d - x_9 x_{10}\alpha_5 - \alpha_4 x_{10}\Omega \quad (14)$$

with:

$$\begin{cases} e_3 = \theta_d - \theta \\ e_4 = c_2 e_2 + \dot{\theta}_d + \lambda_2 X_2 - \dot{\theta} \\ e_5 = \psi_d - \psi \\ e_6 = c_3 e_3 + \dot{\psi}_d + \lambda_3 X_3 - \dot{\psi} \end{cases} \quad (15)$$

where $(c_3, c_4, c_5, c_6, \lambda_2, \lambda_3) > 0$, is a positive constant while X_2, X_3 is an integral tracking error of e_2 and e_3.

3.2 Control of the Linear Translations Subsystem

Longitudinal (x-axis) keeps the X4-AUV stabilized in desired point. Used the same approach described in subsection rotational control, the control law for controller is:

$$u_1 = \frac{1}{\cos\theta\cos\psi}(1 - c_7^2 + \lambda_4)e_7 + (c_7 + c_9)e_9 - c_7\lambda_4\chi_4 \quad (16)$$

with:

$$\begin{cases} e_7 = x_d - x \\ e_8 = c_4 e_4 + \dot{x}_d + \lambda_4 X_4 - \dot{x} \end{cases} \quad (17)$$

where $(c_7, c_8, \lambda_4) > 0$, is a positive constant while X_4 is an integral of the tracking error for x-position.

3.3 Linear y and z Motion Control

The orientations of u_1 responsible for the motion through y and z axes. The control law can be defined as follows:

$$u_y = \frac{m_2}{u_1}\left(1 - c_9^2 + \lambda_5\right)e_9 + \left(c_9 + c_{10}\right)e_{10} - c_9\lambda_5 X_5 \quad (18)$$

$$u_z = \frac{m_3}{u_1}\left(1 - c_{11}^2 + \lambda_6\right)e_{11} + \left(c_{11} + c_{12}\right)e_{12} - c_{11}\lambda_6 X_6 \quad (19)$$

where $(c_9, c_{10}, c_{11}, c_{12}, \lambda_5, \lambda_6) > 0$, is a positive constant while X_5, X_6 is an integral tracking error of y and z position.

4.0 RESULT AND DISCUSSION

A nonlinear control strategy; integral backstepping is implemented to stabilize the position and angles of the underactuated X4-AUV. The simulation is conducted to verify the proposed control method by using u_1, u_2, u_3 and u_4 respectively as control input. 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 desired value for position is setting at x-position = 3 m, y-position = 2m, and z-position = 4m with all orientation angles is zero. Parameters values are manually tuned and as follows: $c_1 = 8, c_2 = 2, c_3 = 8, c_4 = 2, c_5 = 4, c_6 = 2,$ $c_7 = 4, c_8 = 4, c_9 = 4, c_{10} = 4, c_{11} = 4, c_{12} = 4, \lambda_1 = 0.5,$ $\lambda_2 = 0.5, \lambda_3 = 0.5, \lambda_4 = 0.5.$ Note that this integral backstepping technique also used for Unmanned Aerial Vehicles (UAV) studied in [16, 17]. The physical parameters indicated in Table 1 were used for simulating X4-AUV.

In order to compare the performance of backstepping controller with or without integral, the simulation of underactuated X4-AUV using backstepping control [9] also been presented.

Table 1 Physical parameters for X4-AUV [21]

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

A. Backstepping Control

Figure 3 and Figure 4 shows backstepping controller stabilized all attitudes and positions of an underactuated X4-AUV.

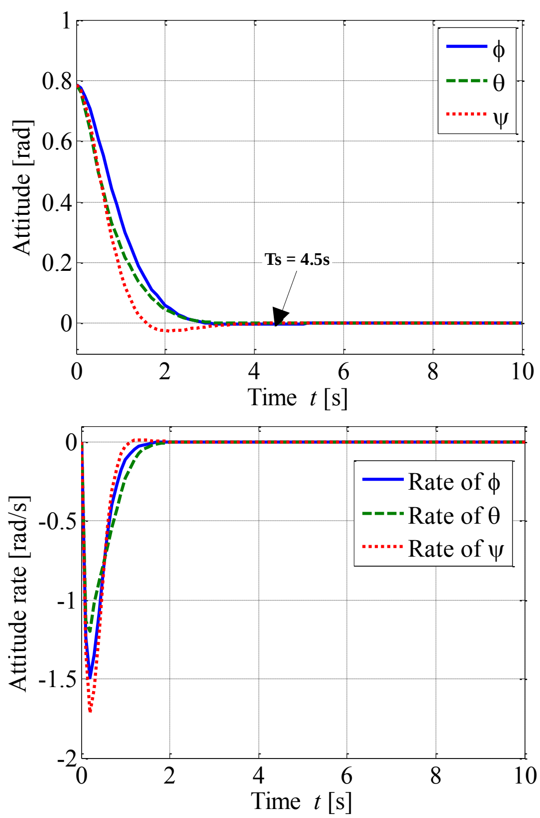


Figure 3 Backstepping control: Attitude and attitude rate control

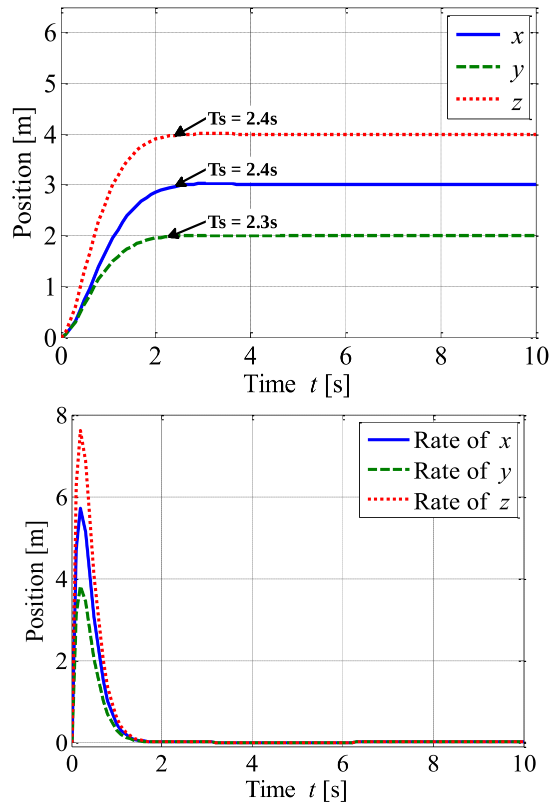


Figure 4 Backstepping control: Position and position rate control

B. Integral Backstepping Control

Figure 5 and Figure 6 indicates the response of integral backstepping controller stabilized all positions and angles into the desired point. Figure 7 illustrates inputs for controlling X4-AUV where u_1, u_2, u_3 and u_4 denote command signal and a control input in rotation.

Settling time is the time required for the response curve to reach and stay within a range of a certain percentage (usually 5% or 2%) of the final value. In this study, 2% of the desired point is used to determine the settling time. Integral backstepping control takes a faster settling time, T_s to achieve desired point compared to the backstepping control as summarized in Table 2.

Table 2 Settling Time,Ts of backstepping and integral backstepping controller

	Settling Time,T_s	
	Backstepping	**Integral Backstepping**
x-position	2.4s	1.82s
y-position	2.3s	1.98s
z-position	2.4s	1.66s
Attitude	4.5s	3.44s

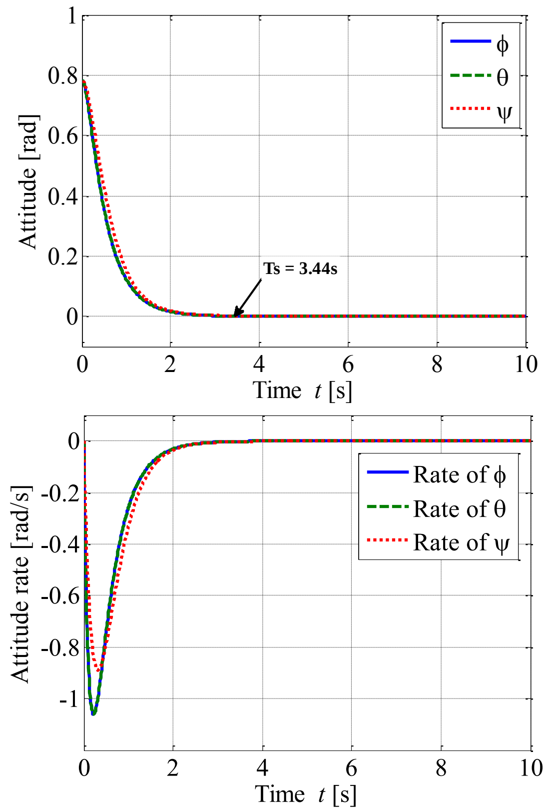


Figure 5 Integral backstepping control: Attitude and attitude rate control

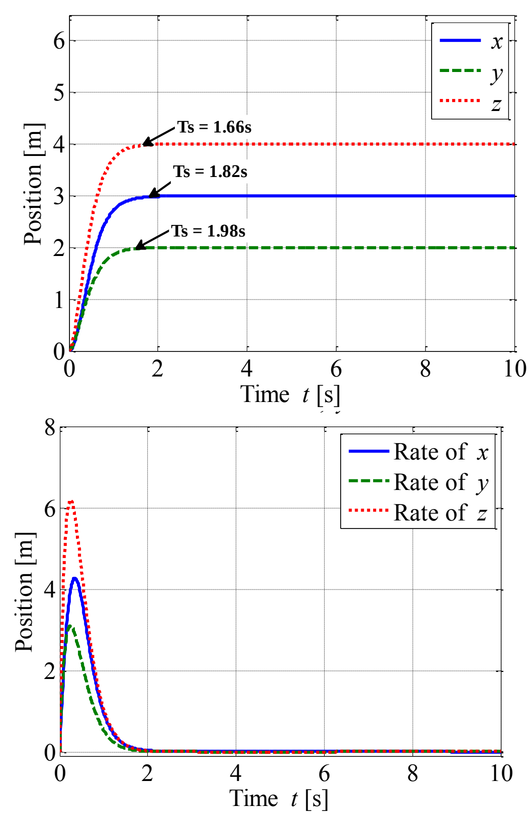


Figure 6 Integral backstepping control: Position and position rate control

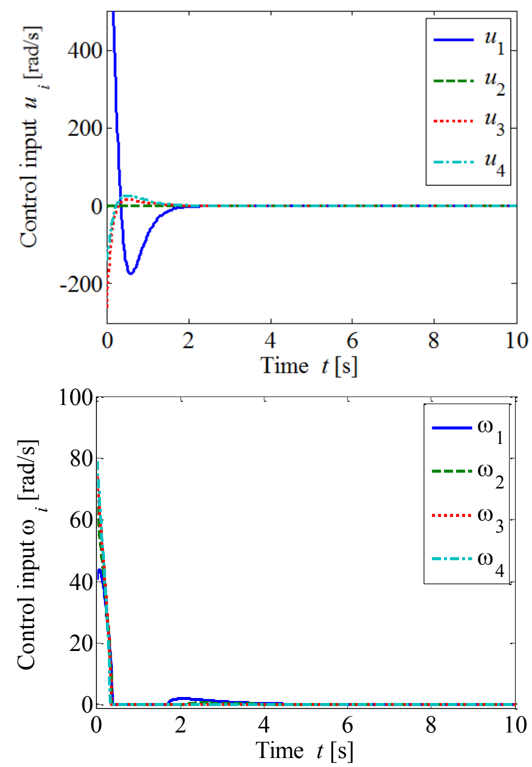


Figure 7 Integral backstepping control: A control inputs and control inputs in rotation

5.0 CONCLUSIONS

This article presented a nonlinear control method for stabilize attitudes and positions of an underactuated X4-AUV with 6-DOFs and 4 inputs. An integral backstepping is applied to the rotational and translational subsystem of the X4-AUV. Integral backstepping performance is smooth and takes a fast settling time, T_s into desired point compared to the backstepping control. Presence of integral in backstepping controller enhances the system performance by eliminating the steady state error and improves the system transient. For future work, an optimization technique will be applied to automatically tune the parameters value for controller.

Acknowledgement

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References

[1] Brockett, R. W. 1983. Asymptotic Stability and Feedback Stabilization. Differential Geometric Control Theory. 181-191.

[2] Koshkouei, A. J., Burnham, K. and Zinober, A. 2008. Flatness, Backstepping and Sliding Mode Controllers for Nonlinear Systems, Modern Sliding Mode Control Theory. Springer Berlin Heidelberg. 269-290.

[3] Kamarudin, M., Husain, A. and Ahmad, M. 2013. Stabilization of Uncertain Systems using Backstepping and Lyapunov Redesign. 160-163.

[4] Li, Y. and Song, S. 2012. A Survey Of Control Algorithms for Quadrotor Unmanned Helicopter. *Advanced Computational Intelligence (ICACI), 2012 IEEE Fifth International Conference*. 365-369.

[5] Krstić, M., Kanellakopoulos, I., and Kokotović, P. V. 1994. Nonlinear Design Of Adaptive Controllers For Linear Systems. *Automatic Control, IEEE Transactions on*. 39(4): 738-752.

[6] Han, Y., Bi, X. and Bai, T. 2010. Dynamic Inversion Control Based On Backstepping For Underwater High-Speed Vehicle. *Proceedings of the World Congress on Intelligent Control and Automation (WCICA)*. 3868-3871.

[7] Wang, Y. W. Y., Yan, W. Y. W., Gao, B. G. B. and Cui, R. C. R. 2009. Backstepping-based Path Following Control Of An Underactuated Autonomous Underwater Vehicle. *Int. Conf. Inf. Autom.*

[8] Zain, Z. M., and Harun, N. F. 2015. Backstepping Control Strategy For An Underactuated X4-AUV. *Jurnal Teknologi.* 74(9).

[9] Zain, Z. M., Pebrianti, D., and Harun, N. 2014. Stabilization Control For An X4-AUV Using Backstepping Control Method. *Australian Journal of Basic and Applied Scienes*. 8(15): 140-146.

[10] Mnif, F. 2004. Recursive Backstepping Stabilization Of A Wheeled Mobile Robot. *Control, Communications and Signal Processing. First International Symposium*. 135-139.

[11] Mian, A. A., and Daobo, W. 2008. Modeling And Backstepping-Based Nonlinear Control Strategy For A 6 DOF Quadrotor Helicopter. *Chinese Journal of Aeronautics.* 21(3): 261-268.

[12] Ji, Y., Guo, S., Wang, F., Guo, J., and Wei, W. Wang, Y. 2013. Nonlinear Path Following For Water Jet Based Spherical Underwater Vehicles. *Robotics and Biomimetic (ROBIO)*. 994-1000.

[13] Kanellakopoulos, I., and Krein, P. 1993. Integral-Action Nonlinear Control Of Induction Motors. *Proc. of the 12th IFAC World Congress on 1993, Sydney Australia.*

[14] Fossen, T. I., and Strand, J. P. 2001. Nonlinear Passive Weather Optimal Positioning Control (WOPC) System For Ships And Rigs: Experimental Results. *Automatica*. 37(5): 701-715.

[15] Tan, H., Chang, J., He J., and Tan, Y 2000. Advanced Nonlinear Control Strategy For Motion Control Systems. *Power Electronics and Motion Control Conference, 2000. Proceedings. IPEMC 2000. The Third International*. 1: 116-121.

[16] Tahar, M., Zemalache, K. M., and Omari, A. 2011. Control of an Under-Actuated X4-flyer using Integral Backstepping Controller. *Przegląd Elektrotechniczny*. 87(10): 251-256.

[17] Bouabdallah, S., and Siegwart, R. 2007. Full Control of a Quadrotor. *Intelligent Robots And System IROS 2007, IEEE/RSJ International Conference*. 153-158.

[18] Bouabdallah, S. 2007. Design And Control Of Quadrotors With Application To Autonomous Flying. Doctoral Dissertation. École Polytechnique federale de Lausanne.

[19] Fossen, T. I. 1994. *Guidance And Control Of Ocean Vehicles*. John Wiley & Sons Inc.

[20] K. Okamura. 2009. Position And Attitude Control For An Autonomous Underwater Robot Using A Manifold Theory. Master Thesis, Saga University.

[21] Zain, Z. M. 2012. Underactuated Control for an Autonomous Underwater Vehicle with Four Thrusters. Ph.D. Thesis. Okayama University.