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A BACKSTEPPING BASED PID CONTROLLER FOR STABILIZING AN UNDERACTUATED X4-AUV

NurFadzillah Harun and Zainah Md. Zain
Robotics and Unmanned Research Group, Instrument & Control Engineering Cluster, Faculty of Electrical and Electronics Engineering, Universiti Malaysia Pahang, Pekan, Pahang, Malaysia
E-Mail: nurfadz @gmail.com

ABSTRACT

The autonomous underwater vehicle (AUV) mostly has fewer control inputs than the degree of freedoms (DOFs) in motion and be classified into underactuated system. It is a difficult tasks to stabilize that system because of the highly nonlinear dynamic and model uncertainties. It is usually required nonlinear control method and this paper presents the stabilization of an underactuated X4-AUV using backstepping based PID nonlinear control techniques. The X4-AUV system is executed by separating system into two subsystems which is translational and rotational subsystems. Integral backstepping control is applied for translational subsystem and PID backstepping control for the rotational subsystem. As a results the *x*-position and all angles is stabilized into desired point. The effectiveness of the proposed control technique for an underactuated X4-AUV demonstrates through simulation.

Keywords: X4-AUV, underactuated systems, and backstepping based PID.

INTRODUCTION

Control of underactuated systems has attracted many researchers in recent years. Various applications arise in underactuated systems and typically used for mobile robots, aerospace and marine robotics. Consideration for developing a system with fewer actuators than DOFs is motivated by several reasons. The main aim is to reduce the cost where less actuator will need less energy to operate and it is indirectly reducing the costs of fuel used. Besides, fewer actuators make a structure become lighter and space saving. Furthermore, it also increases the reliability of a system in case actuator failures occur.

Research in underactuated systems has been a dragged to study another control problem which is nonholonomic systems. Nonholonomic systems frequently appear in finite mechanical systems where constraints are imposed on the motion that are not integrable, i.e. the constraints cannot be written as time derivatives of some function of the generalized coordinate [1]. Particular constraints can generally be defined in terms of nonintegrable linear velocity relationships.

The problems occur in controlling class of nonholonomics system have attracted the researchers interest. The investigation is motivated by the fact that such constraint is not responsive to linear control methods, and they cannot be converted into linear control problems in any significant way. Moreover, due to Brockett's Theorem [2], these systems cannot be stabilized to a point with pure smooth (or even continuous) state feedback control, usual smooth and time invariant. Hence, these nonlinear control problems required nonlinear control techniques. There are numerous control techniques such as linearization, H∞, intelligent PID, sliding mode and backstepping control for nonlinear systems.

The backstepping is a recursive Lyapunov based scheme proposed by Krstic et al on 1990s [3]. The concept of backstepping is to design a recursive controller by considering some of the state variables as "virtual controls" and designing an intermediate control laws. The important benefit of backstepping is that it has the flexibility to avoid eliminations of useful nonlinearities and achieves the goals of stabilization and tracking. Backstepping control widely can be found in robotics areas such as for mobile robot [4], aerospace vehicles [5], and marine vehicles [6].

Backstepping control for certainly a comprehensive combined with artificial intelligence such as artificial neural networks and fuzzy systems [7, 8]. It also can work together with another controller such as sliding mode control [9] and PID to improve robustness of the systems [5]. The combination of backstepping approach and integral from PID techniques is known as integral backstepping [10]. This method has been implemented for ship control [12], industrial motion control systems [12], and UAV [13]. Integral presence helps controller to deal with the disturbances existing in the systems and enhance the system transient and steady state performance [12].

This paper presents the backstepping based PID control strategies for stabilizing an underactuated X4-AUV. The coordinate system of X4-AUV is shown in Figure-1. The X4-AUV are executed by nonlinear control strategies by separating system into two subsystems which is translational and rotational subsystems. The integral backstepping control for translational subsystem stabilizes the position. Besides, rotational subsystem achieves the desired roll, pitch, and yaw angles using PID backstepping control. The simulation results indicate effectiveness of the control strategy for stabilizing an underactuated X4-AUV.

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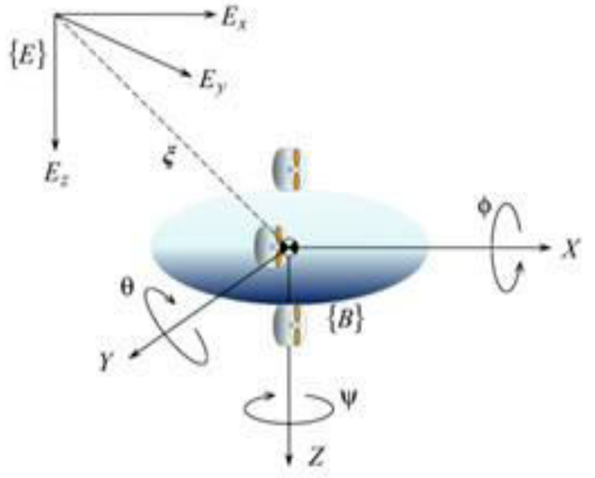

Figure-1. The coordinate system of X4-AUV.

X4-AUV DYNAMIC MODEL

The dynamic model of X4-AUV obtained via Lagrange approach is given by Equation. (1) and detailed derivation for X4-AUV dynamics model given in [14].

$$\begin{aligned} m_1\ddot{x} &= \cos\theta\cos\psi u_1 \\ m_2\ddot{y} &= \cos\theta\sin\psi u_1 \\ m_3\ddot{z} &= -\sin\theta u_1 \\ I_x\ddot{\phi} &= \dot{\theta}\dot{\psi}\left(I_y - I_Z\right) + u_2 \\ I_y\ddot{\theta} &= \dot{\phi}\dot{\psi}\left(I_z - I_x\right) - J_t\dot{\psi}\Omega + lu_3 \\ I_z\ddot{\psi} &= \dot{\phi}\dot{\theta}\left(I_x - I_y\right) - J_t\dot{\theta}\Omega + lu_4 \end{aligned} \tag{1}$$

Here u_1 is the control input for the position (x, y, z) and u_2, u_3 and u_4 is the control inputs for roll (ϕ), pitch (θ) and yaw (ψ) angles respectively.

The dynamic model in Equation. (1) 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 the state vector of the system as follows:

$$\begin{aligned} &x_1 = x && x_7 = \phi \\ &x_2 = \dot{x}_1 = \dot{x} && x_8 = \dot{x}_7 = \dot{\phi} \\ &x_3 = y && x_9 = \theta \\ &x_4 = \dot{x}_3 = \dot{y} && x_{10} = \dot{x}_9 = \dot{\theta} \\ &x_5 = z && x_{11} = \psi \\ &x_6 = \dot{x}_5 = \dot{z} && x_{12} = \dot{x}_{11} = \dot{\psi} \\ &a_y = \cos\theta\sin\psi && a_z = -\sin\theta \end{aligned} \tag{2}$$

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

From Equation. (1) and Equation. (2) above, we obtained:

$$f(X,U) = \begin{pmatrix} x_2 \\ \cos\theta\cos\psi\frac{1}{m_1}u_1 \\ x_4 \\ a_y\frac{1}{m_2}u_1 \\ x_6 \\ a_z\frac{1}{m_3}u_1 \\ x_8 \\ x_{10}x_{12}a_1 + b_1u_2 \\ x_{10} \\ x_8x_{12}a_2 - a_3x_{12}\Omega + b_2u_3 \\ x_{12} \\ x_8x_{10}a_5 + a_4x_{10}\Omega + b_3u_4 \end{pmatrix} \tag{3}$$

with,

$$a_1 = \frac{I_y - I_z}{I_x}, a_2 = \frac{I_z - I_x}{I_y}, a_3 = \frac{J_t}{I_y}, a_4 = \frac{J_t}{I_z}, a_5 = \frac{I_x - I_y}{I_z},$$

$$b_1 = \frac{1}{I_x}, b_2 = \frac{l}{I_y}, b_3 = \frac{l}{I_z}, a_y = \cos\theta\sin\psi, a_z = -\sin\theta$$

CONTROL STRATEGIES

The complete system is described by Equation. (3) is composed of two subsystems, the angular rotations and the linear translations shown in Figure-2. The rotational system and its derivatives do not depend on a translational system in contrary the translations rely on a rotational system. This section shows the design methodology for developing control law using backstepping based PID strategies. Integral backstepping control is applied for translational subsystem and PID backstepping control for the rotational subsystem. The rotational subsystem is considered first because of its independence.

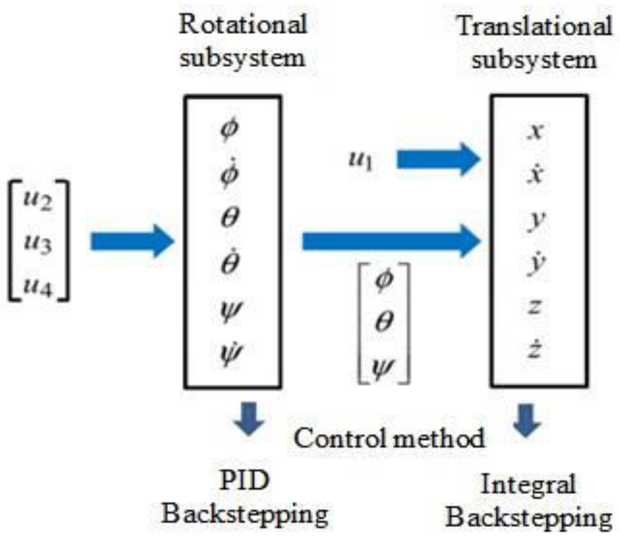

Figure-2. Connection of rotational and translational subsystem with control method.

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Rotational control

The backstepping based PID control technique is designed for rotational subsystem, which the control inputs are u_2, u_3 and u_4. Note that this technique also been used for quadrotor helicopter [5].

Let the roll tracking error be defined as:

$$e = \phi_d - \phi \tag{4}$$

The first error considered in designing the backstepping is,

$$z_1 = K_1 e + K_2 \int edt \tag{5}$$

where K_1 and K_2 is a positive constant and $\int edt$ represent integral of roll error.

Lyapunov theorem is used by considering the Lyapunov function, z_1 positive definite and it's time derivative negative semi-definite:

$$V_1 = \frac{1}{2} z_1^2 \tag{6}$$

The derivative of Equation. (6) is given by:

$$\dot{V}_1 = z_1 \dot{z}_1 = z_1\left(K_1\dot{\phi} - K_1\dot{\phi}_d + K_2 e\right) \tag{7}$$

The stabilization of z_1 can be obtained by introducing ϕ be a virtual control input, then desired virtual control $\dot{\phi}_d$ is defined as:

$$\dot{\phi}_d = \dot{\phi}_d - \frac{K_2}{K_1} e - \frac{c_1 z_1}{K_1} \tag{8}$$

with c_1 is a positive constant.
The virtual control has its own error, z_2 defined by: [5]

$$z_2 = \dot{\phi} - \dot{\phi}_d = \frac{1}{K_1}\left[\dot{z}_1 + c_1 z_1\right] \tag{9}$$

The Lyapunov function for z_2 are given by: [5]

$$V_2 = \frac{1}{2} z_1^2 + \frac{1}{2} z_2^2 \tag{10}$$

The time derivative of Equation. (10) becomes: [5]

$$\dot{V}_2 = z_1 \dot{z}_1 + z_2 \dot{z}_2 \tag{11}$$

Considering $\dot{z}_1$ and $\dot{z}_2$ in Equation. (11), the following equation can be obtained.

$$\dot{V}_2 = z_2 \begin{bmatrix} e\left(K_1^2 + \frac{c_1 K_2}{K_1}\right) + x_{10} x_{11} a_1 + \\ b_1 u_1 - \ddot{\phi}_d + \dot{e}\left(\frac{K_2}{K_1} + c_1\right) + \\ \int edt\left(K_1 K_2\right) \end{bmatrix} - z_1\left[c_1 K_1 e + c_1 K_2 \int edt\right] \tag{12}$$

The desirable dynamics for z_2 are:

$$\dot{V}_2 = -c_2 z_2 = \frac{c_2}{K_1}\left(\dot{z}_1 + c_1 z_1\right) \tag{13}$$

where c_2 is a positive constant.

By combining Equation. (12) and Equation. (1), control input u_2 is extracted as follows:

$$u_2 = \frac{1}{b_1} \begin{bmatrix} -e\left(\frac{c_2}{K_1} K_2 + c_2 c_1 + K_1^2 + \frac{K_2 c_1}{K_1}\right) - \\ \int edt\left(\frac{c_2 c_1 K_2}{K_1} + K_1 K_2\right) - \\ \dot{e}\left(c_2 + \frac{K_2}{K_1} + c_1\right) + \ddot{\phi}_d - x_{10} x_{11} a_1 \end{bmatrix} \tag{14}$$

PID of each mode in u_2, u_3 and u_4 is given by:

$$P = \frac{c_2}{K_1} K_2 + c_2 c_1 + K_1^2 + \frac{K_2 c_1}{K_1} \tag{15}$$

$$I = \frac{c_2 c_1 K_2}{K_1} + K_1 K_2 \tag{16}$$

$$D = c_2 + \frac{K_2}{K_1} + c_1 \tag{17}$$

The same steps are followed to extract u_3 and u_4.

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$$u_3 = \frac{1}{b_2}\begin{bmatrix} -e\left(\frac{c_4}{K_3}K_4 + c_4c_3 + K_3^2 + \frac{K_4c_3}{K_3}\right) - \\ \int edt\left(\frac{c_4c_3K_4}{K_3}\right) + K_3K_4 - \dot{e}(c_4 + \frac{K_4}{K_3} + c_3) \\ + \ddot{\theta}_d - x_8x_{12}a_2 - a_3a_{12}\Omega \end{bmatrix} \quad (18)$$

$$u_4 = \frac{1}{b_3}\begin{bmatrix} -e\left(\frac{c_6}{K_5}K_6 + c_6c_5 + k_5^2 + \frac{K_6c_5}{K_5}\right) - \\ \int edt\left(\frac{c_6c_5K_6}{K_5} + K_5K_6\right) - \dot{e}\left(c_6 + \frac{K_6}{K_5} + c_5\right) \\ + \ddot{\psi}_d - x_8x_{10}a_5 - a_4a_{10}\Omega \end{bmatrix} \quad (19)$$

where $c_3, c_4, c_5, c_6, K_3, K_4, K_5, K_6$ is a positive constant.

Translational control

Consider the altitude tracking error, $e_{a1} = x_d - x$ and its dynamics:

$$\dot{e}_{a1} = \dot{x}_d - w_x \quad (20)$$

There is no control input in Equation. (20) and w_x represent altitude rate. So, desired w_x, w_{xd} is considered as a virtual control.

$$w_{xd} = c_{a1}e_{a1} + \dot{x}_d + \lambda_1 X_1 \quad (21)$$

with c_{a1} and λ_1 a positive constant and $X_1 = \int e_{a1}dt$ is an integral of the altitude tracking error.
The w_x represent altitude rate and its own error given by:

$$\dot{e}_{a2} = c_{a1}\dot{e}_{a1} + \ddot{\phi}_d + \lambda_1 e_{a1} - \ddot{x} \quad (22)$$

The angular velocity tracking error, e_{a2} is defined by:

$$e_{a2} = w_{xd} - w_x \quad (23)$$

Applying Equation. (21) and Equation. (23), the dynamics of altitude tracking error is rewritten as:

$$\dot{e}_{a1} = -c_{a1}e_{a1} - \lambda_1 X_1 + e_{a2} \quad (24)$$

Followed by substituting $\ddot{x}$ in Equation. (22) by its corresponding expression model Equation. (1), control input u_1 presents as follows:

$$\dot{e}_{a2} = c_{a1}e_{a1} + \ddot{x}_d + \lambda_1 e_{a1} - \cos\theta\cos\psi\left(\frac{u_1}{m_1}\right) \quad (25)$$

The desirable dynamics for e_{a2} are:

$$\dot{e}_{a2} = -c_{a2}e_{a2} - e_{a1} \quad (26)$$

Combining Equation. (25) and dynamics model Equation. (26) control input u_1 is given by:

$$u_1 = \frac{m_1}{\cos\theta\cos\psi}\left(1 - c_{a1}^2 + \lambda_1\right)e_{a1} + \left(c_{a1} + c_{a2}\right)e_{a2} - c_{a1}\lambda_1 X_1 \quad (27)$$

with c_{a2} is a positive constant.

RESULTS AND DISCUSSION

Backstepping based PID control strategies are implemented to stabilize an underactuated X4-AUV. Integral backstepping control is applied for translational subsystem while PID backstepping control for the rotational subsystem. The simulation was performed to demonstrate the effectiveness of both nonlinear control performances by using u_1, u_2, u_3 and u_4 respectively as a control inputs.

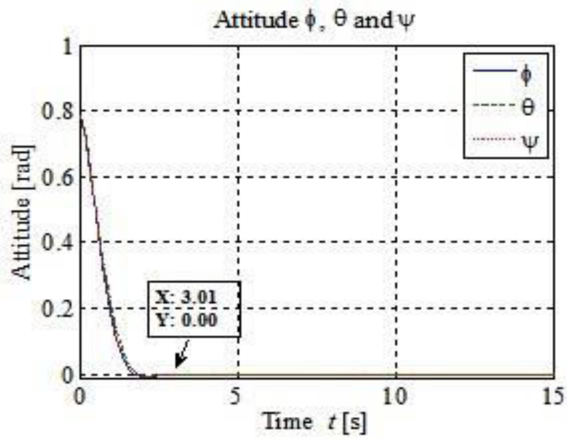
The system started with an initial state $X_0 = \left(0,0,0,0,0,0,\frac{\pi}{4},0,\frac{\pi}{4},0,\frac{\pi}{4},0\right)$ and desired value x-position is set at 3m with all zero orientation angles. The physical parameters for X4-AUV been used for simulating are shown in Table-1. The feedback control law derived in control strategies subsection have been applied to an X4-AUV. The control parameters used as follows:

$$K_1 = 0.5, K_2 = 0.5, K_3 = 0.5, K_4 = 0.5, K_5 = 0.5, K_6 = 0.5,$$

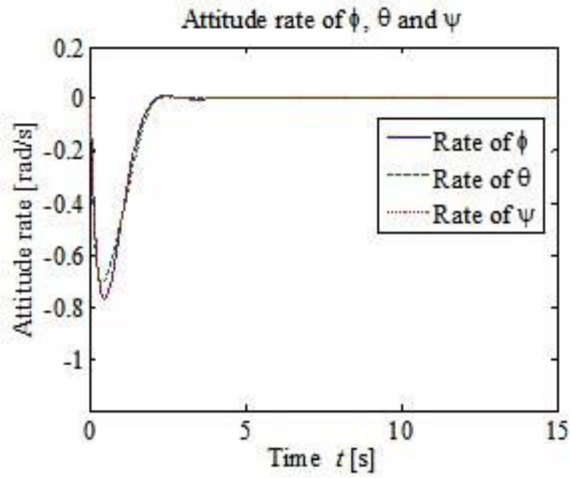
$$c_1 = 3, c_2 = 1, c_3 = 3, c_4 = 2, c_5 = 3, c_6 = 1, c_{a1} = 4, c_{a2} = 3, \lambda_1 = 0.5.$$

Note that this simulation only stabilizes x-position and all angles.

Figure-3 shows the response of backstepping controller stabilizing roll, pitch and yaw angles of X4-AUV to the desired point in 3.01s. Position control and rate response in Figure-4 show the x-position achieve zero steady state in 4.07s to the targets at 3m. Figure-5 illustrates the speed response and inputs for controlling X4-AUV where u_1, u_2, u_3 and u_4 denote command signal for position and all angles.

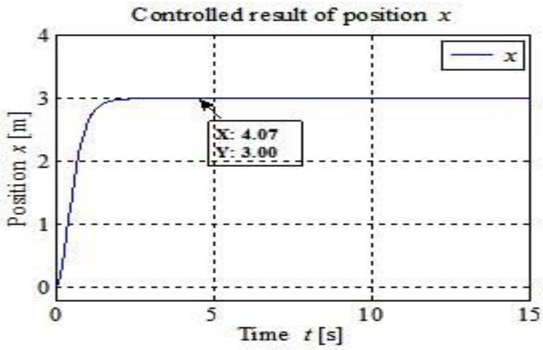


(a)

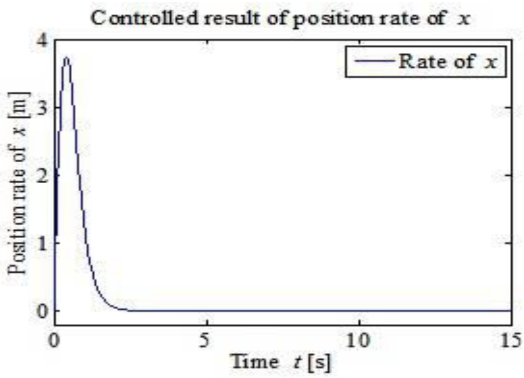


(b)

Figure-3. Attitude and attitude rate control for *x*-position.

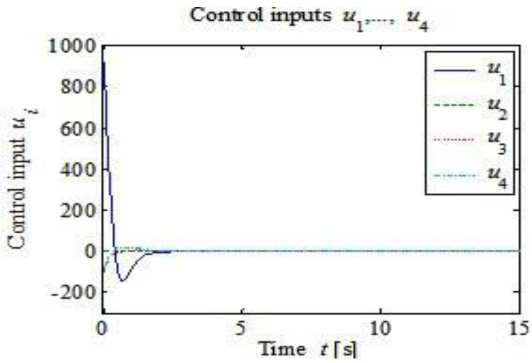


(a)

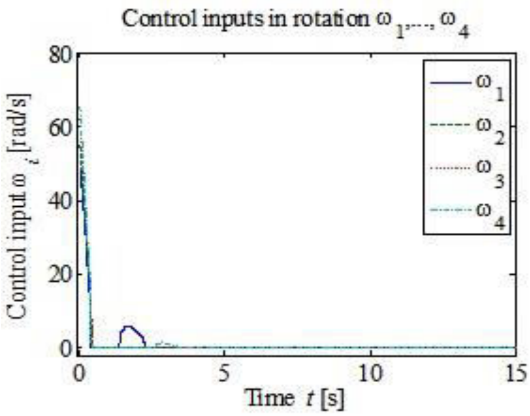


(b)

Figure-4. Position and position rate control for x-position.



(a)



(b)

Figure-5. Control inputs and control inputs in rotation.

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	$N \cdot s^2$
d	Drag factor	3.617e^{-4}	$N \cdot m \cdot s^{-2}$
J_{bx}	Roll inertia	0.0857	$kg \cdot m^2$
J_{by}	Pitch inertia	1.1143	$kg \cdot m^2$
J_{bz}	Yaw inertia	1.1143	$kg \cdot m^2$
J_t	Thruster inertia	1.1941e^{-4}	$N \cdot m \cdot s^{-2}$

CONCLUSION

This article presented a backstepping based PID control strategies in stabilizing attitudes and *x*-position for an underactuated X4-AUV with four thrusters and six DOFs. The controller designs are executed by separating the system into two subsystems which is translational and rotational subsystems. Integral backstepping control is applied for translational subsystem and PID backstepping control for the rotational subsystem. The simulation results indicate effectiveness of the control strategy for stabilizing an underactuated X4-AUV. For future work, an optimization technique will be applied to automatically tune parameters.

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REFERENCES

[1] Kolmanovsky I. and McClamroch N. H. 1995. Developments in nonholonomic control problems. Control Systems, IEEE. Vol. 15, No. 6, pp. 20-36.

[2] Brockett R. W. 1983. Asmpototic stability and feedback stabilization. Differential Geometric Control Theory. pp. 181-191.

[3] Krstić M., Kanellakopoulos I. and Kokotović P. V. 1994. Nonlinear design of adaptive controllers for linear systems. Automatic Control, IEEE Transactions on. Vol. 39, No. 4, pp. 738-752.

[4] Mnif F. 2004. Recursive backstepping stabilization of a wheeled mobile robot. In Control, Communications and Signal Processing. First International Symposium. pp. 135-139.

[5] Mian A. A., Ahmad M. I. and Wang D. 2008. Backstepping based PID Control Strategy for an Underactuated Aerial Robot. In Proceedings of the 17th World Congress, The International Federation of Automatic Control, Seoul, Korea.

[6] Ji Y., Guo S., Wang F., Guo J., Wei W. and Wang Y. 2013. Nonlinear path following for water jet based spherical underwater vehicles. In Robotics and Biomimetic (ROBIO). pp. 994-1000.

[7] Wang H. J., Chen Z. Y., Jia H. M. and Chen X. H. 2011. NN-backstepping for diving control of an underactuated AUV. In OCEANS 2011. pp. 1-6.

[8] Han S. I. and Lee J. M. 2014. Recurrent fuzzy neural network backstepping control for the prescribed output tracking performance of nonlinear dynamic systems. ISA Transactions. Vol. 53, No. 1, pp. 33-43.

[9] Moghadam A. M. and Balochian S. 2013. Design of combined sliding mode controller backstepping using genetic algorithm. Journal of Engineering, Vol. 2013.

[10] Kanellakopoulos I. and Krein P.1993. Integral-action nonlinear control of induction motors. In Proceedings of the 12th IFAC World Congress, Vol. 254. Sydney, Australia.

[11] Fossen T. I. and Strand J. P. 2001. Nonlinear passive weather optimal positioning control (WOPC) system for ships and rigs: experimental results. Automatica. Vol. 37, No. 5, pp. 701-715.

[12] Tan H., Chang J., He J. and Tan Y. 2000. Advanced nonlinear control strategy for motion control systems. In Power Electronics and Motion Control Conference, IPEMC. The Third International. Vol. 1. pp. 116-121.

[13] Tahar M., Zemalache K. M. and Omari A. 2011. Control of an underactuated X4-flyer using integral backstepping controller. Przegląd Elektrotechniczny. Vol. 87, No. 10, pp. 251-256.

[14] Zain Z. M. 2012. Underactuated control for an autonomous underwater vehicle with four thrusters. Doctoral dissertation, Okayama University.