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BACKSTEPPING CONTROLLER WITH PSO FOR AN UNDERACTUATED X4-AUV

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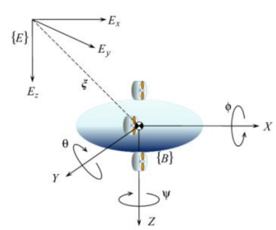
Graphical abstract



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 AUV 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 a nonlinear control approach and this paper proposed a backstepping control method with Particle Swarm Optimization (PSO) to stabilize an underactuated X4-AUV system. In backstepping controller design, accurate parameters are important in order to obtain the maximal and effective response. Hence, PSO is implemented to obtain optimal parameters for backstepping controller and its carry out by minimizing the fitness function. Comparison results illustrated the controller with PSO has a smooth and fast transient response into the desired point compared than manually tune controller parameters and also improve the system performances. The validity of the proposed control technique for an underactuated X4-AUV demonstrates through simulation.

Keywords: X4-AUV; backstepping control; particle swarm optimization

1.0 INTRODUCTION

Autonomous underwater vehicles (AUV) are programmable robotic vehicles that are driven through the water by a propulsion system, controlled and piloted by onboard computer and maneuverable in three dimensions. Regularly AUVs is classified under an underactuated system with nonholonomic constraints. Mostly those systems fail to satisfy Brockett's Theorem [1] i.e., these systems cannot be stabilized to a point with pure smooth (or even continuous) state feedback control. The dynamics of AUVs mostly are highly nonlinear systems, strong coupling, and have uncertainties in hydrodynamics parameters.

This research focuses on point stabilization for X4-AUV. It is a type of AUV which has four inputs with six DOFs in motion and class under an underactuated system and have nonholonomic constraints. Le Tu *et al.* [2] develop a small X4-AUV, however to control this system is not an easy task, the X4-AUV still uncontrollable and the experiment is not achieved as expected yet. A discontinuous control method in chained form [3] is used for stabilizing X4-AUV and the method can only realize partially underactuated control, which controls five states out of six states by using four inputs. A transformation from the dynamic model into state-space model is needed in order to design a model based controller. A direct Lyapunov theory is applied to stabilize an X4-AUV and it found that position and angles are not smoothly controllable compare than used backstepping control [4].

Research in underactuated systems has been a dragged to study another control problem which is nonholonomic system. Nonholonomic systems frequently appear in finite mechanical systems where constraints are imposed on the motion are not integrable, i.e. the constraints cannot be written as time derivatives of some function of the generalized coordinate [5]. 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 interests of researchers. 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, 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 the 1990s [6]. 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 [7], aerospace vehicles [8], and marine vehicles [9].

Despite the fact that backstepping method can provide an efficient procedure for controller design, it is difficult to get satisfactory performance because the controller parameters obtained by the backstepping method are chosen arbitrarily. It is important to select the proper parameters to obtain a good response because an improper selection of the parameters leads to inappropriate responses or may even lead to instability of the system. If the parameters are manually chosen or tune, it cannot be claimed that the optimal parameters are selected. In [10, 11], the authors applied backstepping control method for stabilized underactuated X4-AUV with manually tuned parameters. The simulation results show the controller succeeded in stabilizing the systems but it cannot be claimed that the performance is the best because the parameters is not an optimal values.

In order to overcome the problem in determining controller parameter values, particle swarm optimization (PSO) algorithm has been used. PSO is a population based stochastic optimization technique developed by Dr. Eberhart and Dr. Kennedy in 1995 [12]. The method has been inspired by the behavior of organisms, such as fish schooling and bird flocking. Generally, PSO is identified as a straightforward idea, simple to execute, computationally efficient and quick convergence. It also is under a flexible and well-balanced mechanism to enhance the global and local exploration abilities [13]. The PSO algorithm has been used effectively in a wide range of engineering such as computer science problems [14, 15], power system [16], maglev transportation system [17], and largely used in UAV [18, 19, 20]. Due to its effectiveness, PSO is applied to compute the optimal parameter values for backstepping controller of X4-AUV systems.

This article presented a backstepping controller with PSO for stabilizing $x-$position and angles of an underactuated X4-AUV with four inputs and six DOFs. The X4-AUV are executed by nonlinear control strategies by separating system into two parts subsystem which are translational and rotational subsystems. Parameters of backstepping controller determine using PSO and a set of optimal parameters selected by minimizing the fitness function. The simulation results indicate the effectiveness of the control strategy for stabilizing an underactuated X4-AUV.

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 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)

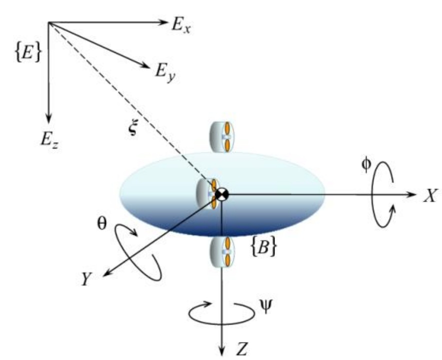


Figure 1 Coordinate systems of AUV

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

$$R = \begin{bmatrix} C\theta C\psi & S\varphi S\theta C\psi - C\varphi S\psi & C\varphi S\theta C\psi + S\varphi S\psi \\ C\theta S\psi & S\varphi S\theta S\psi + C\varphi C\psi & C\varphi S\theta S\psi - S\varphi C\psi \\ -S\theta & S\varphi C\theta & C\varphi C\theta \end{bmatrix} \quad (1)$$

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 [3]:

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

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:

$$\begin{aligned} x_1 &= x & x_7 &= \varphi \\ x_2 &= \dot{x}_1 = \dot{x} & x_8 &= \dot{x}_7 = \dot{\varphi} \\ x_3 &= y & x_9 &= \theta \\ x_4 &= \dot{x}_3 = \dot{y} & x_{10} &= \dot{x}_9 = \dot{\theta} \\ x_5 &= z & x_{11} &= \psi \\ x_6 &= \dot{x}_5 = \dot{z} & x_{12} &= \dot{x}_{11} = \dot{\psi} \end{aligned} \quad (3)$$

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

$$f(X,U) = \begin{pmatrix} x_2 \\ \cos\theta\cos\psi\frac{1}{m_1}u_1 \\ x_4 \\ u_y\frac{1}{m_2}u_1 \\ x_6 \\ u_z\frac{1}{m_3}u_1 \\ x_8 \\ x_{10}x_{12}a_1 + b_1u_2 \\ x_{10} \\ x_8x_{12}a_2 - a_3x_{12}\Omega + b_2u_3 \\ x_{12} \\ x_8x_{10}a_5 + a_4x_{10}\Omega + b_3u_4 \end{pmatrix} \quad (4)$$

with:

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

It is worthwhile to note in the latter system that the angular subsystems do not depend on translation components as show in Figure 2. On the other hand, the translational subsystems depend on the angular subsystems. We can ideally imagine the overall system described by (4) as constituted of two subsystems.

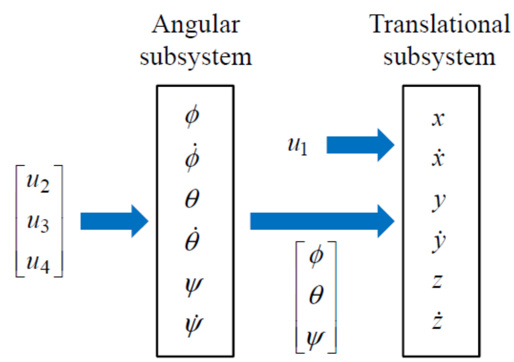


Figure 2 Connection of rotational and translational subsystems

3.1 Control of the Rotations Subsystem

Using the backstepping approach, one can synthesize the control law forcing the system to follow the desired trajectory. For the first step we consider the tracking-error:
For the first step, tracking error of roll is defined as:

$$z_1 = x_{7d} - x_7 \quad (5)$$

Then use Lyapunov theorem by considering Lyapunov function, z_1 is a positive definite:

$$V(z_1) = \frac{1}{2}z_1^2 \quad (6)$$

It follows by its time derivative:

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

The stabilization of z_1 can be obtained by introducing a virtual control input x_8 with $\alpha_1 > 0$

$$x_8 = \dot{x}_{7d} + \alpha_1 z_1 \quad (8)$$

The Equation (6) becomes:

$$\dot{V} = (z_1) = -\alpha_1 z_1^2 \quad (9)$$

Let proceed by making the variable change, z_2 defines as:

$$z_2 = x_8 - \dot{x}_{7d} - \alpha_1 z_1 \quad (10)$$

For second step, consider the augmented Lyapunov function:

$$V(z_1, z_2) = \frac{1}{2}z_1^2 + \frac{1}{2}z_2^2 \quad (11)$$

It's time derivative is formulated as:

$$\begin{aligned} \dot{V}(z_1, z_2) &= z_2\left(a_1x_{10}x_{12} + b_1u_2\right) \\ &\quad - z_2\left(\ddot{x}_{7d} - \alpha_1\left(z_2 + \alpha_1 z_1\right)\right) - z_1z_2 - \alpha_1 z_1^2 \end{aligned} \quad (12)$$

The control input u_2 is then extracted $(\ddot{x}_{1,2,3d} = 0)$, satisfying $\dot{V}(z_1z_2) < 0$:

$$u_2 = \frac{1}{b_1}z_1 - a_1x_{10}x_{12} - \alpha_1\left(z_2 + \alpha_1 z_1\right) - \alpha_2 z_2 \quad (13)$$

Similarly, same steps are followed to extract u_3 and u_4

$$u_3 = \frac{1}{b_2} z_3 - a_2 x_8 x_{12} - a_3 x_{12}\Omega - \alpha_3 \left(z_4 + \alpha_3 z_3\right) - \alpha_4 z_4 \tag{14}$$

$$u_4 = \frac{1}{b_3} z_5 - a_5 x_8 x_{10} - a_4 x_{10}\Omega - \alpha_5 \left(z_6 + \alpha_5 z_5\right) - \alpha_6 z_6 \tag{15}$$

with:

$$\begin{cases} z_3 = x_{9d} - x_9 \\ z_4 = x_{10} - \dot{x}_{9d} - \alpha_3 z_3 \\ z_5 = x_{11d} - x_{11} \\ z_6 = x_{12} - \dot{x}_{11d} - \alpha_5 z_5 \end{cases} \tag{16}$$

where $(\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6) > 0$, is a positive constant.

3.2 Control of the Linear Translations Subsystem

The altitude control keeps the X4-AUV stabilized at desired point. Used the same approach described in subsection 3.1, the control law for altitude controller is:

$$u_1 = \frac{m_1}{\cos\theta\cos\psi} z_7 - \alpha_7 \left(z_8 + \alpha_7 z_7\right) - \alpha_8 z_8 \tag{17}$$

with:

$$\begin{cases} z_7 = x_{1d} - x_1 \\ z_8 = x_2 - \dot{x}_{1d} - \alpha_7 z_7 \end{cases} \tag{18}$$

where α_7 and α_8 is a positive constant.

4.0 OPTIMIZATION OF BACKSTEPPING CONTROLLER PARAMETERS

The flowchart of PSO technique is applied to identify the optimal set of backstepping controllers parameter values is shown in Figure 3. For each iteration, each particle is updated by following two "best" values. The first is the best result (fitness) it has accomplished so far and this value is called P_{best}. Another "best" value that is followed by the PSO is the best value, obtained so far by any particle in population. This best value is a global best and called G_{best}. After finding the two best values, the particle updates its velocity and positions with three weight factors namely; inertia factor, w, self confidence factor, c_1, and swarm confidence factor, c_2 in (19) and (20);

$$v_i^{k+1} = w \cdot v_i^k + c_1 \cdot rand \cdot \left(P_{best} - x_i^k\right) + c_2 \cdot rand \cdot \left(G_{best} - x_i^k\right) \tag{19}$$

The appropriate value range for c_1 and c_2 is 1-2 but 2 are the most appropriate in many cases and *Rand* is a random number in between 1 to 5.

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{20}$$

where v_i is the particle velocity and x_i is a current particle. The following inertia weight is used:

$$w = w_{max} - \left(w_{max} - w_{min}\right) k / k_{max} \tag{21}$$

where k_{max}, k is the maximum number of iterations and the current number of iterations, w_{min} and w_{max} are the minimum and maximum weights, appropriate values are 0.4 and 0.9.

The flowchart for determining optimal parameter values showed in Figure 3. In this study, the following values are assigned for controller parameter optimization:

(a) Dimension of the search space = 8
(b) Population or swarm size = 30
(c) The number of maximum iteration = 20
(d) The self and swarm confident factor, c_1 and c_2 = 2
(e) The inertia weight factor w, w_{max} = 0.9 and w_{min} = 0.4
(f) The searching ranges for the backstepping parameters are limited to [1, 5]
(g) The simulation time, t is equal to 15s
(h) Optimization process is repeated 20 times

The fitness function is called to determine a fitness of each particle during the search for choosing the best value. The aim is to minimize this fitness function in order to improve the system response in terms of steady-state errors. Sum of Squared Error (SSE) is used as a fitness function in order to optimize parameter values. The formula of SSE is given by:

$$SSE = \sum_{i=1}^{n} \left(x_i - x_d\right)^2 \tag{22}$$

with:

SSE = Sum of squared error
I = number of iteration
x_i = system output value at i iteration
x_d = initial input

A good stabilization response will produce minimum SSE.

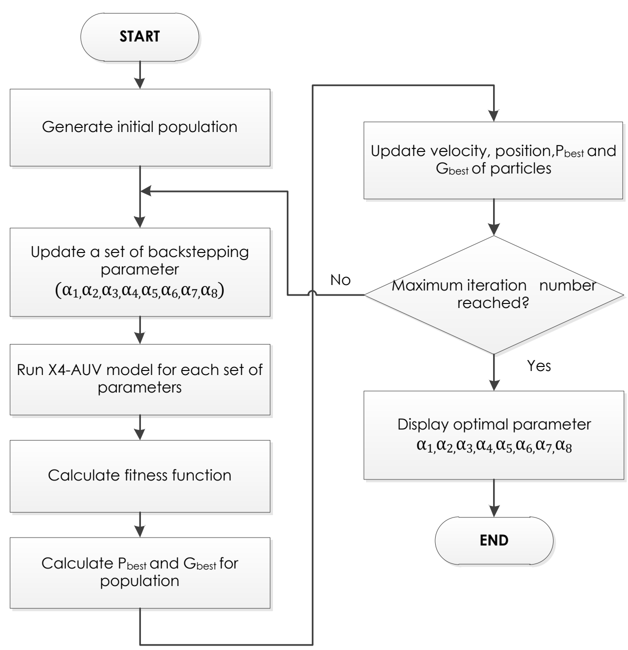


Figure 3 The flowchart of PSO for determining backstepping controller parameters

5.0 RESULT AND DISCUSSION

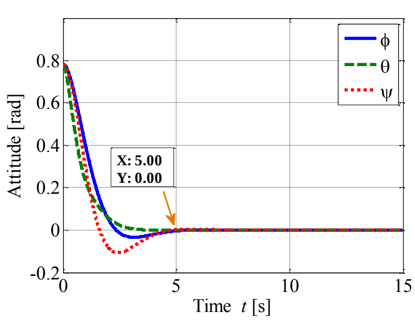
Backstepping control method with PSO is implemented to stabilize an underactuated X4-AUV. Backstepping controllers were proposed for controlling each orientation angle and the position are stabilized according to the Lyapunov stability theory. Parameters of backstepping controller determine using PSO and a set of optimal parameters selected by minimizing the fitness function. The simulation was performed to demonstrate the effectiveness of proposed control performances by using u_1, u_2, u_3 and u_4 respectively as a control input. The system started with an initial state for position $x=0$ and all angles $= \frac{\Pi}{4}$. We wanted the final $x-$position stabilized at 3 m with all zero orientation angles. The symbols used in controllers are presented in Table 1. Note that 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 Symbols used in backstepping controller

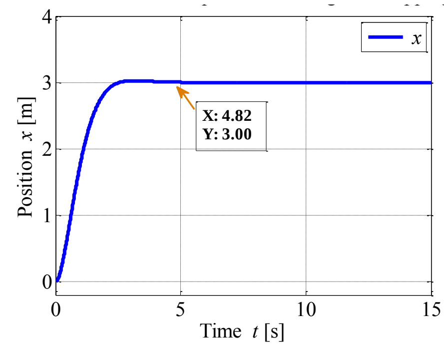
Symbol	Definition
x	$x-$position coordinates
ϕ	Roll angle
θ	Pitch angle
ψ	Yaw angle
$\alpha_1, \ldots, \alpha_{12}$	Control parameters
u_1, u_2, u_3, u_4	Control inputs

5.1. Backstepping Controller With Manual Tuned Parameters

The improper selection of parameters for backstepping controller may lead to ineffective responses of the system. X4-AUV system has eight parameters and manually tuned is not an easy task. This section carried out similar simulation as past publication [7, 8] and the parameter obtains via manual tuned as follows [8]: $\alpha_1 = 1.0, \alpha_2 = 1.0, \alpha_3 = 2.0,$ $\alpha_4 = 3.0, \alpha_5 = 1.0, \alpha_6 = 1.0, \alpha_7 = 1.6, \alpha_8 = 1.4$. Figure 4 illustrated response of backstepping controller with manual tuned.



(a)



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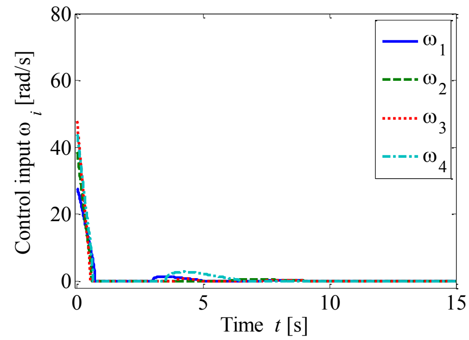
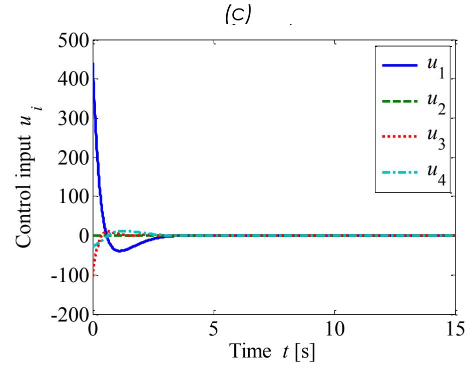


(c)



(d)

Figure 4 Manual tuned parameters: (a) Attitude control (b) $x-$position control (c) A control inputs (d) A control inputs in rotation

5.2. Backstepping Controller With Optimization (PSO)

The simulation done in several runs and the five best fitness value with optimal parameters is summarized in Table 3. The best fitness is 4E-16 and the optimal parameters are $\alpha_1 = 1.4, \alpha_2 = 2.2, \alpha_3 = 2.1, \alpha_4 = 2.2,$ $\alpha_5 = 1.9, \alpha_6 = 3.2, \alpha_7 = 3.6, \alpha_8 = 4.9$.

Figure 5(a) and Figure 5(b) indicates the response of backstepping controller stabilizing roll, pitch and yaw angles of X4-AUV into zero in T_s = 3.02s. Position control of X4-AUV in Figure 6(a) and Figure 6(b) shows the $x-$position is convergence to the targets at 3 m in T_s = 2.37s. Figure 7(a) illustrates inputs for controlling X4-AUV where u_1, u_2, u_3 and u_4 denote command signal for position and all angles and Figure 7(b) show a control input in rotation.

Table 2 Fitness value and optimal controller parameters

No.	Fitness Value	Optimal Parameters							
		α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8
1	4E-16	1.4	2.2	2.1	2.2	1.9	3.2	3.6	4.9
2	4E-16	3.3	5.0	1.5	1.2	1.1	2.2	3.4	4.8
3	9E-16	1.6	4.3	1.6	3.7	1.1	4.5	3.9	3.1
4	9E-16	1.1	2.2	4.9	4.4	1.4	1.2	4.6	3.2
5	2E-15	2.6	3.2	2.0	1.5	3.0	3.6	3.1	3.9

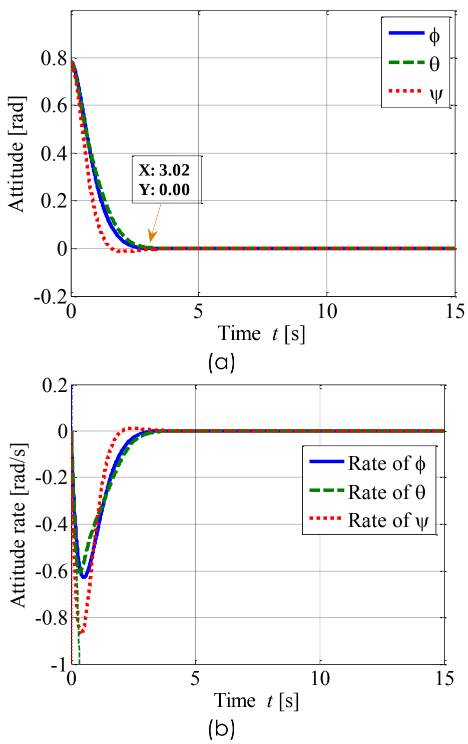
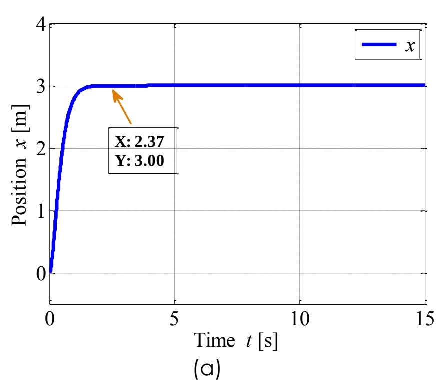


Figure 5 Optimal parameter values using PSO: (a) Attitude control (b) Attitude rate control



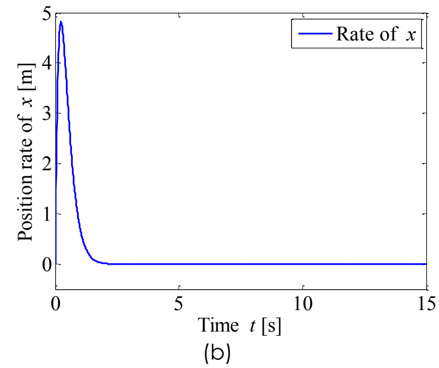


Figure 6 Optimal parameter values using PSO: (a) x – position control (b) x – position rate control

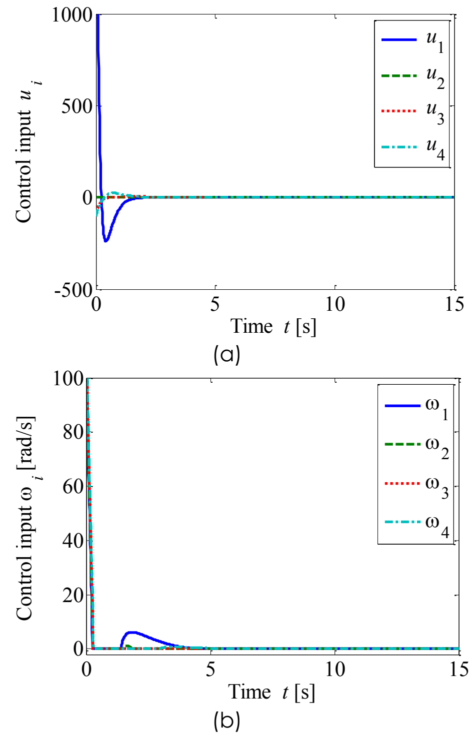


Figure 7 Optimal parameter values using PSO: (a) A control inputs (b) A control inputs in rotation

5.3. Comparison of Backstepping Controller With Manual Tuned and PSO

Both controllers with and without PSO succeeded in stabilizing x – position and all angles into desired point. In order to compare performances between the controllers, settling time, T_s is used. 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.

The controller with manual tune parameters succeeded in stabilizing x – position and all angles but has slow response. Settling time for backstepping controller with PSO is faster and has a smooth performance compared than a controller with manually tuned parameters as summarized in Table 3. Percentage change of controller with manual tuned parameters is improved to 50.8% for $x-$position while a rotation improved as much as 39.6%. By using PSO, it automatically generated optimal parameters value for X4-AUV systems and enhances the system performances.

Table 3 Settling time, T_s of PSO and manual tuned

No.	Selection of Parameters	Settling Time,Ts	
		Position $x-$	Rotations (ϕ,θ,ψ)
1	Manual tuned	4.82	5.00
2	PSO	2.37	3.02

6.0 CONCLUSIONS

This article presented a backstepping controller with PSO in stabilizing attitudes and $x-$position of an underactuated X4-AUV with four inputs and six DOFs. The backstepping controller effective in stabilized the X4-AUV system into desired point from initial point given. Accurate parameters value will give maximal results and effective response of the system while improper selection of parameters may lead to unproductive results. Parameters of backstepping controller is determine using PSO and a set of optimal parameters is selected by minimize the fitness function. Simulations results illustrate the backstepping controller with PSO shows a smooth performance and has a fast settling time into the desired point compared than controller with manually tune parameters. This study is motivated to investigate more on backstepping control and optimization technique for further improvement in controlling underactuated systems.

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