PSO Approach for a Controller Based-on Backstepping Method in Stabilizing an Underactuated X4-AUV

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***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 task to stabilize that system because of the highly nonlinear dynamic and model uncertainties, therefore it is usually required nonlinear control method to control this type of system. Conventionally, to control the system, parameters for the controller are selected by the trial-and-error method or manually chosen. It is challenging to get satisfactory responses because manual tuning is not an easy task and consuming much time, especially involve many parameters. It is necessary to select proper parameters because an improper selection of the parameters may jeopardize the system stability and leads to inappropriate responses. Thus, an optimization technique is required in selecting the optimal parameter for the controller. In this paper, the controller based on backstepping method is required for an underactuated X4-AUV system. Three types of controller based on backstepping are designed ; standard backstepping, PID backstepping and integral backstepping. Twelve optimal parameter values are generated for each controller using particle swarm optimization (PSO). All these three controllers show an improvement in term of settling time, and it has rapid responses compare than a controller with manual tuning parameters. The effectiveness of the controllers is verified in a computer simulation using MATLAB software.**

***Keywords*—PSO;backstepping;AUV**

I. Introduction

Underwater vehicles are divided into manned and unmanned underwater vehicles (UUV). UUVs consist of two types which are AUVs and remotely operated vehicles (ROV). ROV are controlled by a human operator from a cable or on wireless communication on a ship or the ground. Differently, AUVs is controlled automatically by onboard computers and can work independently without connecting to the surface. AUVs have received wider attention than ROVs due to advantages of operational efficiency, mobility, and low operational cost [1-3].

Controlling of an underactuated system is a challenging issue considering of its unstable system with highly nonlinear and model uncertainties. Some equation in the motion of the system appears as a second-order nonholonomic constraint, and they cannot be stabilized to the desired point using state feedback controllers. Therefore, nonlinear control methods are required, and controllers with the backstepping approach are proposed in solving the underactuated nonholonomic system problems.

Despite the fact that backstepping method can provide an efficient procedure for controller design, it is hard to get satisfactory performance because the controller parameters obtained are chosen using a trial-and-error approach or manual tune. It is important to select the proper parameters to get a good response because an improper selection of the parameters leads to inappropriate responses or may even result in instability of the system. Furthermore, if the parameters are manually chosen, it cannot be claimed that the optimal parameters are selected.

To overcome the problem in determining the controller parameters, an optimization technique which is particle swarm optimization (PSO) algorithm is proposed. PSO is a flexible and well-balanced mechanism to enhance the global and local exploration abilities [4]. This method also has been executing for power system [5], maglev transportation system [6], and UAV [7-9]. Different controllers have been introduced to deal with PSO for automatically selecting the controller parameters. PSO is used to generate nine optimal values for the integral backstepping controller [9]. Boubertakh *et al.* [8] proposed a control design method for the stabilization of a quadrotor and PSO be used to tune the PID controller's parameter. PSO is utilized to determine twelve values of backstepping controller parameters as presented in [10].

Controlling of the underactuated system with six DOFs is not an easy task, not to mention the difficulty in trial-and-error to identify the optimal parameters that usually have quite a lot of numbers. In simplify the task, PSO is co-operated with the backstepping controller to give the best performance and stability to the system.

II. X4-AUV System

This section presented a model of X4-AUV system with six DOFs and four control input (thrusters). It is categorized in underactuated AUV and has equations of the motion appear as second-order nonholonomic constraints. Zain [11] proposed an X4-AUV with an ellipsoidal hull shape, the slender body of ellipsoidal hull shape makes it works efficiently than conventional X4-AUV in term of drag pressure.

Following a Lagrangian method, the dynamic model of X4-AUV is summarized in (1). A dynamic model is describing the position and attitude of the vehicle and it important in controller design. Detailed derivation of a dynamic model of X4-AUV can refer in [11].

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

Here, m_1, m_2 and m_3 is a total mass in the $x-, y-$ and $z-$ direction respectively, I_x, I_y and I_z is a total inertia in the $x-, y-$ and $z-$ direction respectively, J_t is total thruster inertia, l is a horizontal distance from the propeller center to the center of gravity, Ω is an overall thruster's speed. u_1, u_2, u_3 and u_4 are control inputs for the translation $(x-\text{axes})$ motion, the roll (ϕ), and the yaw (ψ) motion respectively.

The total thruster speed (Ω) are the sum of four thruster forces F_1, F_2, F_3, and F_4. Therefore, the motion in $x-$direction is related to total forces generated. The motion in $y-$and $z-$directions occurs by changing the pitch (θ) motion and yaw (ψ) motion. Four control inputs u_1, u_2, u_3 and u_4 used to control X4-AUV are defined in (2), u_1, u_3 and u_4 related to forces while u_2 is a net of total torque generated by four thrusters of X4-AUV.

$$\left.\begin{aligned} u_1 &= F_1 + F_2 + F_3 + F_4 \\ u_2 &= T_1 + T_3 - T_2 - T_4 \\ u_3 &= F_1 - F_3 \\ u_4 &= F_2 - F_4 \end{aligned}\right\} \tag{2}$$

The dynamic model in (1) can be rewritten in a state space form. A state representation is a mathematical model of a physical system, which is a set of input, output, and state variables. These state variables are related by a set of first-order differential equations. The dynamic model can be transformed into form $\dot{X} = f(X,U)$ by introducing $X = (x_1 \ldots x_{12})^T \in \Re^{12}$ as state vector of the system as follows:

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

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

Equation (4) is obtained from (1) and (3):

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

III. Control Strategies

This section presents the design of backtepping control law and PSO tuning for stabilizing an underactuated X4-AUV. The X4-AUV controller is executed by separating the system into two subsystems which are translation and rotation as in Fig. 1.

Translation subsystem keeps longitudinal $(x-\text{axis})$ of X4-AUV stabilized into the desired point by used u_1 as control input. Rotation subsystem used u_2, u_3 and u_4 as control inputs to obtain the desired roll, pitch and yaw angles orientation of the X4-AUV.

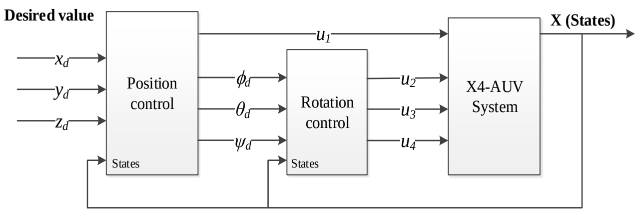

Fig. 1. The architecture of X4-AUV comprising of position and rotation controller.

A. *Backstepping Control Law*

This subsection presents the backstepping control strategies for stabilizing an underactuated X4-AUV. The control law for standard backstepping is derived first, and then others technique such as an integral and PID is added into the backstepping control forming integral backstepping and PID backstepping controller. Summary of input control generates by backstepping control as follows:

1) Standard backstepping: Standard backstepping control is applied for rotation and translation subsystems of an underactuated X4-AUV. Note that this technique is motivated from Bouabdallah and Siegwart in controlling quadrotor helicopter [12]. Detailed derivation of a backstepping control law can refer in [13].

Translation subsystems to control u_1 :

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

Rotation subsystems to control u_2, u_3 and u_4 :

$$u_2 = \frac{1}{b_1}\left[z_1 - \dot{\theta}\dot{\psi}\frac{I_y - I_z}{I_x} - \alpha_1(z_2 + \alpha_1 z_1) - \alpha_2 z_2 \right]$$

$$u_3 = \frac{1}{b_2}\left[z_3 + \dot{\theta}\dot{\psi}\frac{I_z - I_x}{I_y} - \frac{J_t}{I_y}\dot{\psi}\Omega - \alpha_3(z_4 + \alpha_3 z_3) - \alpha_4 z_4 \right]$$

$$u_4 = \frac{1}{b_3}\left[z_5 + \dot{\phi}\dot{\theta}\frac{I_x - I_y}{I_z} + \frac{J_t}{I_z}\dot{\theta}\Omega - \alpha_5(z_6 + \alpha_5 z_5) - \alpha_6 z_6 \right]$$

2) PID backstepping: PID backstepping is a combination of standard backstepping with PID control and is applied for rotation and translation subsystems of an underactuated X4-AUV. Note that this technique also been used for quadrotor helicopter [14]. Detailed derivation of a backstepping control law can refer in [15].

Translation subsystems to control u_1 :

$$u_1 = \frac{m_1}{\cos\theta\cos\psi}\left[-(P_4)e_7 - (I_4)\int e_7 dt - (D_4)\dot{e}_7 \right]$$

Rotation subsystems to control u_2, u_3 and u_4 :

$$u_2 = \frac{1}{b_1}\left[-(P_1)e_1 - (I_1)\int e_1 dt - (D_1)\dot{e}_1 + \ddot{\phi}_d - \dot{\theta}\dot{\psi}\frac{I_y - I_z}{I_x} \right]$$

$$u_3 = \frac{1}{b_2}\left[\begin{array}{l} -(P_2)e_3 - (I_2)\int e_3 dt - (D_2)\dot{e}_3 + \ddot{\theta}_d \\ -\dot{\theta}\dot{\psi}\frac{I_z - I_x}{I_y} - \frac{J_t}{I_y}\dot{\psi}\Omega \end{array} \right]$$

$$u_4 = \frac{1}{b_3}\left[\begin{array}{l} -(P_3)e_5 - (I_3)\int e_5 dt - (D_3)\dot{e}_5 + \ddot{\psi}_d \\ -\dot{\phi}\dot{\theta}\frac{I_x - I_y}{I_z} - \frac{J_t}{I_z}\dot{\theta}\Omega \end{array} \right]$$

3) Integral backstepping: Integral backstepping is a combination of standard backstepping with an integral is applied for the rotation and translation subsystems of an underactuated X4-AUV. Note that this technique also been used for quadrotor helicopter [16-17]. Detailed derivation of a backstepping control law can refer in [18].

Translation subsystems to control u_1 :

$$u_1 = \frac{m_1}{\cos\theta\cos\psi}\left[(1 - c_7^2 + \lambda_4)e_7 + (c_7 + c_8)e_8 - c_7\lambda_4\chi_4 \right]$$

Rotation subsystems to control u_2, u_3 and u_4 :

$$u_2 = \frac{1}{b_1}\left[\begin{array}{l} (1 - c_1^2 + \lambda_1)e_1 + (c_1 + c_2)e_2 - c_1\lambda_1\chi_1 \\ + \ddot{\phi}_d - \dot{\theta}\dot{\psi}\frac{I_y - I_z}{I_x} \end{array} \right]$$

$$u_3 = \frac{1}{b_2}\left[\begin{array}{l} (1 - c_3^2 + \lambda_2)e_3 + (c_3 + c_4)e_4 - c_3\lambda_2\chi_2 \\ + \ddot{\theta}_d - \dot{\theta}\dot{\psi}\frac{I_z - I_x}{I_y} - \frac{J_t}{I_y}\dot{\psi}\Omega \end{array} \right]$$

$$u_4 = \frac{1}{b_3}\left[\begin{array}{l} (1 - c_5^2 + \lambda_3)e_5 + (c_5 + c_6)e_6 - c_5\lambda_3\chi_3 \\ + \ddot{\psi}_d - \dot{\phi}\dot{\theta}\frac{I_x - I_y}{I_z} - \frac{J_t}{I_z}\dot{\theta}\Omega \end{array} \right]$$

B. Tuning of backstepping parameters using PSO

In a conventional backstepping control method, the controller parameters are usually selected by the trial-and-error method. It is also possible that the parameters are properly chosen, but it cannot be said that the optimal parameters are selected. PSO technique is used for determining the optimal value for the backstepping controller parameters. In sum, twelve control parameters need to be selected simultaneously for the X4-AUV system.

The basic PSO algorithm consists of three steps: generating particles positions and velocities, velocity update, and finally, position update. Here, a particle refers to a point in the design space that changes its position from one move (iteration) to another based on velocity updates.

First, the positions x_i^k and velocities v_i^k, of the initial swarm of particles are randomly generated as expressed in (5) and (6).

$$x_i^0 = x_{\min} + \text{rand}(n, N)(x_{\max} - x_{\min}) \quad (4)$$

$$v_i^k = x_{\min} + \text{rand}(n, N)(x_{\max} - x_{\min}) \quad (5)$$

with:

$x_{\min} =$ Minimum *rand* number

$x_{\max} =$ Maximum *rand* number

$N =$ Number of particles

$n =$ Number of dimensions (sum of parameters to be tuned)

Here, the positions and velocities are given in a vector format with the subscript and superscript denoting the *i*-th particle at iteration *k*, respectively.

The second step is to update the velocities of all particles at iteration $k+1$ using the objective or fitness values of particles, which are functions of the particle current positions in the design space at iteration *k*. The fitness function value of a particle determines which particle has the best global value in the current swarm, G_{best} and also determines the best position of each particle over iteration, P_{best}, i.e., in the current and all previous moves. After finding the two best values, the particle updates its velocity and positions in (7) and (8).

$$v_i^{k+1} = w \cdot v_i^k + c_1 \cdot \text{rand} \cdot \left(\mathrm{P_{best}} - x_i^k\right) + c_2 \cdot \text{rand} \cdot \left(G_{best} - x_i^k\right) \quad (6)$$

with:

$w =$ Inertia factor

$c_1 =$ Self-confidence factor

$c_2 =$ Swarm confidence factor

The appropriate value ranges for c_1 and c_2 is 1 or 2, but 2 are the most suitable in many cases.

Position update is the last step in each iteration. The position of each particle is updated using its velocity vector as shown in (8).

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (7)$$

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

$$w = w_{\max} - \left(w_{\max} - w_{\min}\right)k / k_{\max} \quad (8)$$

with:

$k_{\max} =$ k is the maximum number of iterations

$w_{\min} =$ Minimum weights

$w_{\max} =$ Maximum weights

The appropriate values w_{min} and w_{max} are 0.4 and 0.9 [10].

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 to improve the system response regarding steady-state errors. The sum of squared error (SSE) is used as a fitness function to optimize parameter values. The formula of SSE is given by (10) where all the output states are calculated. A good stabilization response will produce minimum SSE.

$$SSE = \sum_{i=1}^{n} \left(x_i - x_d\right)^2 \quad (9)$$

with:

$SSE =$ Sum of squared error

$i =$ Number of iteration

$x_d =$ System output value $\left(x_d, y_d, z_d, \phi_d, \theta_d, \psi_d\right)$ at i iteration

$x_i =$ Initial input value $\left(x, y, z, \phi, \theta, \psi\right)$

IV. Results and Discussion

This section will be verified the control law obtained in Section 3. Three controller based-backstepping namely standard backstepping, PID backstepping, and integral backstepping will be tested in a computer simulation using MATLAB software. For each simulation results, the controllers stabilize the positions (x, y, z) and attitude (ϕ, θ, ψ) of the system. All controllers must be able to stabilize and bring the system from initial value to a desired point of the system. After that, the controller effectiveness of controller is investigated by analyzing their settling time, T_s.

The system started with an initial value, $[x, y, z, \phi, \theta, \psi] = \left[0,0,0,\frac{\pi}{4},\frac{\pi}{4},\frac{\pi}{4}\right]$ and the desired point are set at $[3,2,4,0,0,0]$.

A. *Tuning of backstepping parameters using PSO*

Conventionally the controller parameters are variously chosen or selected by the trial-and-error approach. The X4-AUV system has twelve parameters and manually tuned is not an easy task. By utilizing PSO, it naturally generated optimal parameters value for X4-AUV systems and improved the system performances. The following values are assigned for controller parameter optimization:

- Dimension (number of parameters) = 12
- Population or swarm size = 20
- The number of maximum iteration = 10
- The self and swarm confident factor, c_1 and c_2 = 2
- The inertia weight factor w,w_{max} = 0.9 and w_{min} = 0.4
- The searching ranges for the parameters = [1,10]
- The simulation time,t is equal to 10s
- Optimization process is repeated five times

The sum of squared error (SSE) is used as a fitness function to optimize parameter values and the formula of SSE is given by (10). The smallest value of fitness function is selected as the best-optimized value for the controller.

PSO is added into X4-AUV system to generate optimal parameters for standard backstepping, PID backstepping, and integral backstepping controller. Table 1 illustrated the optimal parameters obtained using PSO for the three controllers. Parameters obtained by manual tuning that have been used in Section 4*A* also shown in Table 1. For standard backstepping, the best fitness value is 2.2653e-007 which appeared in the iteration number 8. The optimal values for standard backstepping is identified by PSO as follows: α_1 = 8, α_2 = 6, α_3 = 5, α_4 = 7, α_5 = 3, α_6 = 5, α_7 = 9, α_8 = 6, α_9 = 10, α_{10} = 9, α_{11} = 10, α_{12} = 6. The best fitness value for PID backstepping is 1.4242e-007 which shows up in the iteration number 1 and the optimal values for PID backstepping as follows: c_1 = 6, c_2 = 3, c_3 = 9, c_4 = 6, c_5 = 2, c_6 = 8, c_7 = 8, c_8 = 4, c_9 = 7, c_{10} = 7, c_{11} = 6, c_{12} = 6. Fitness value for integral backstepping is 1.2552e-005 which comes up in the iteration number 8 and the optimal values for integral backstepping as follows: : c_1 = 8, c_2 = 6, c_3 = 5, c_4 = 7, c_5 = 3, c_6 = 5, c_7 = 9, c_8 = 6, c_9 = 10, c_{10} = 9, c_{11} = 10, c_{12} = 6.

The simulation results for standard backstepping controller with trial-and-error tuning parameters and via PSO method is shown in Fig. 1 and Fig. 2. Note here that the other results for these three controllers can be seen in [13], [15] and [18].

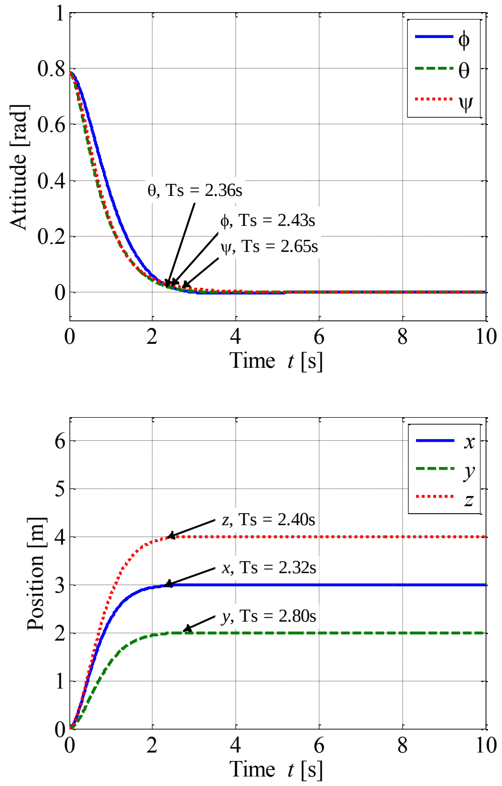

Fig. 1. Attitude and position of standard backstepping controller (parameter tuning via trial-and-error)

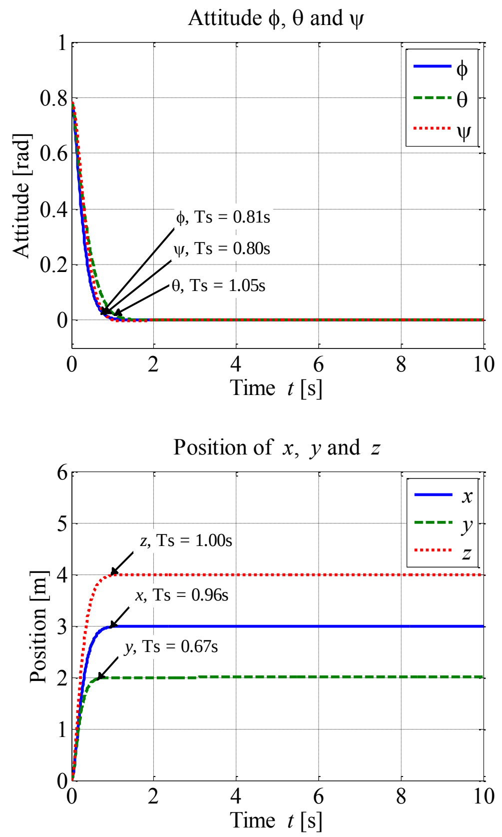

Fig. 2. Attitude and position of standard backstepping controller (parameter tuning using PSO)

TABLE I. CONTANT PARAMETERS FOR MANUAL TUNING AND BY PSO

	Standard		**PID**		**Integral**	
No.	Manual	PSO	Manual	PSO	Manual	PSO
1	1	8	3	6	8	8
2	2	6	1	3	2	6
3	3	5	3	9	8	5
4	2	7	2	6	2	7
5	1	3	3	2	4	3
6	5	5	1	8	2	5
7	2	9	3	8	3	9
8	3	6	3	4	1	6
9	2	10	3	7	4	10
10	2	9	2	7	2	9
11	2	10	3	6	4	10
12	2	6	2	6	2	6

B. Comparison of Manual Tuning and PSO

The controller effectiveness is investigated by analyzing their settling time. 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 paper, 2% of the desired point is used to determine the settling time.

Table 2 shows a settling time of standard backstepping, PID backstepping, and integral backstepping controller with parameter obtained using a trial-and-error approach. According to Table 2, PID backstepping controller has fastest settling time for position and angles compare than standard and integral backstepping controller. Settling time for $x_$position = 1.51, $y_$position = 1.54s and $z_$position = 1.58s while $\phi_$angle =1.56s, $\theta_$angle =1.64s and $\psi_$angle =1.43s. To be noted that for this section, a parameter for controllers is obtained via trial-and-error approach.

A settling time of standard backstepping, PID backstepping, and integral backstepping controller with parameter obtained using PSO is shown in Table 3. For each controller, twelve optimal values are generated using PSO. Compared to Table 2, this three controller have fastest settling time. From Table 3, it can be seen that the standard backstepping and integral backstepping have a fairly similar settling time response. The mean value is calculated to identify the fastest controller, and the results display both controllers have equal mean values. Overall, for controller's parameter tuning using PSO, standard backstepping and integral backstepping have fast response compare than PID backstepping. The percentage change as in Equation 3.85 is calculated. By using PSO, the controllers with the trial-and-error approach is improved as 62.93% for standard backstepping, 19.16% for PID backstepping and 53.29% for integral backstepping.

TABLE II. SETTLING TME, TS OF BACKSTEPPING CONTROLLERS (PARAMETER TUNING VIA TRIAL-AND-ERROR)

Subsystems		**Settling time, T_s**					
Translation	**Rotation**	**Position**			**Angles**		
		x	y	z	ϕ	θ	ψ
Standard backstepping		2.32	2.80	2.40	2.43	2.36	2.65
PID backstepping		1.51	1.54	1.58	1.56	1.64	1.43
Integral backstepping		2.62	1.65	1.90	1.89	1.89	1.96

TABLE III. SETTLING TME, TS OF BACKSTEPPING CONTROLLERS (PARAMETER TUNING USING PSO)

Subsystems		Settling time, T_s					
Translation	**Rotation**	**Position**			**Angles**		
		x	y	z	ϕ	θ	ψ
Standard backstepping		0.96	0.67	1.00	0.81	1.05	0.80
PID backstepping		1.31	1.19	1.26	1.24	1.11	1.38
Integral backstepping		0.99	0.68	1.03	0.80	0.96	1.10

V. CONCLUSION

A nonlinear control law based on backstepping control achieved the stabilization of X4-AUV system. Backstepping-based controller e.g. standard backstepping, PID backstepping, and integral backstepping maintained the position and attitude at desired point. The system started with an initial value $[x, y, z, \phi, \theta, \psi] = \left[0,0,0,\frac{\pi}{4},\frac{\pi}{4},\frac{\pi}{4}\right]$ and reached the desired values at $[3,2,4,0,0,0]$. Overall, the mean of the controller's settling time is 1.03s; it shows each controller has a fast response, excellent stability, and no overshoot. PSO is utilized in selecting optimal values of controller's parameter. Twelve optimal controller parameters are generated for standard, PID, and integral backstepping controllers. Using the optimal parameters obtained using PSO, all these three controllers show an improvement in term of settling time, and it has rapid responses compare than a controller with manual tuning parameters.

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