

Submarine control system using sliding mode controller with optimization algorithm

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Article Info

Article history:

Received Jan 5, 2022

Revised Oct 18, 2022

Accepted Oct 31, 2022

Keywords:

AUV

PID

PSO

SMC

Submarine

ABSTRACT

The purpose of this paper is to design and implement the pitch and depth control system of an autonomous underwater vehicles (AUV). This control system will determine the best pitch angle as well as the depth automatically when there are changes in speed, weight, etc. In this paper, the kinematic and dynamic equations of motion for the AUV are derived to obtain the pitch angle and depth transfer functions. The control strategies applied here, are firstly, the sliding mode controller (SMC) driven by particle swarm optimization (PSO) algorithm. Secondly, the proportional integral derivative controller (PID) tuned by PSO algorithm as a standard controller. The PSO algorithm is used as an efficient algorithm to search for the optimal controllers' parameters and hence improving the performance of the system. The findings show that the designed sliding mode control (SMC) could improve the stability and performance and provides more realistic behavior for the AUV compared to other classical controllers and according to pitch and the depth changes.

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1. INTRODUCTION

The seas and oceans that cover approximately 71 percent of earth surface still have many undiscovered areas. Therefore, different research is implemented about the ocean, such as marine territory, life of the oceans, submarine earthquakes, and as well as research of marine resources [1]. The gathering of ocean information by scanning and monitoring is essential for the researchers and the development of research. Because the ocean has little transparency and one cannot monitor the bottom of the sea in detail remotely, studies and examination using a ship is not adequate [2]. Due to water pressure, divers cannot tread into the deepest sea simply as every 1 pressure of atmosphere is incremented every 10 m of diving. Different underwater equipment like humane submersible, autonomous underwater vehicles (AUV), and so on are developed to explore and monitor the deep ocean, beginning with the invention of the Bathyscape by Prof. A. Piccard in 1948 [3], [4]. The basic target of AUVs is to explore the deepest water without the help of a driver in order to discover and gather data, which implemented by running the AUVs from the water's surface. In contrast to AUVs, ROVs are stilling connected to the host ship and are powered and controlled by a driver from a distance [5]. AUVs have a very broad range of uses, varying from military uses, study purposes, commercial applications, investigations of air damage etc. AUVs are applying to make maps with details and to scan the ocean floor for purposes such as gas and oil manufacturing before constructing infrastructures

beneath the surface of sea [6]. As technological developments in underwater vehicles increase, they applied for the study of seas and oceans as well as ocean bases. Some real applications of AUVs are analyzing light absorption and reflection as well the microscopic presence, and calculating the concentration of different elements or the intensity of compounds. AUVs can effectively use as a pair of two AUVs to deliver specific sensor packages to determine locations [7].

In the defense field, AUVs considered very reliable tools. A set of AUVs needed to keep a particular formation for collecting intelligence, observation and reconnaissance [8]. Recently, different control strategies have supposed. The following studies address the modern control techniques for AUVs as follow: Herlambang and Nurhadi [9], the design of motion control system for an AUV system was proposed considering two degree of freedom (DOF). The findings showed that the stability of the system reached where percentage errors of surge and rolling motions were about 0.002% and 0.05% respectively. Lei [10], presented a nonlinear stability analysis of an underactuated AUV system. It shown that the speed of translational dynamics is slower than that of orientation dynamics. Quiroz and Cuellar [11], focused on the design of an adaptive backstepping controller (adaptive-BSC) for direct power control (DPC) of a three-phase PWM rectifier. In the proposed system, it is desire to control both the output DC voltage of the rectifier and the reactive power simultaneously by making them track desired respective values. Seyed S., Mohsen E., show two goals, which are firstly removing any chattering by using a sliding mode controller and secondly, the allocation of thrust depending on reducing the biggest component of the manifold of thrust [12].

Gao and Guo [13], introduce a strategy of control called leader and follower in their paper. This strategy states that each vehicle named 'follower' is required to follow a feasible vehicle. The algorithm of this strategy depends on interpreting the problem of figuration control into a group of position chase problems for the AUV. Chenguang *et al.* [14], introduced a control system of micro AUV in the basis of open source hardware. The micro AUV is small in size its energy is limited. Thus, the volume and power consumption are restricted to meet the limitation of the micro AUV. Carlucho *et al.* [15], the authors presented a formula of deep reinforcement learning using the architecture of actor-critic, fundamentally utilizing on the DDPG strategy. This modified for AUV low-level control, utilizing the sensors of the board only as a system of perception that that alternately considers the entries for the algorithm of control.

Sun *et al.* [16] proposed a fuzzy control algorithm to provide optimal path through (3-D) AUV environment. Tracking the path was accomplish by two sonars placed to cover the horizontal and vertical planes. The speed and acceleration of the AUV in (3-D) were obtain based on fuzzy system. Al-Mahturi *et al.* [17] showed a strategy called adaptive fuzzy controller of type-2 for the AUVs. This controller controls the yaw, pitch and surge movements of AUV through planes of XZ and XY. The law of adaptation to this controller is dependent on the sliding mode control (SMC) strategy. Another work implemented a strategy of robust control for the dynamic tracking of the waypoint and position of under-actuated AUVs. In order to guarantee the robustness of the controller, the technique of SMC implemented in the process of design [18]. Shojaei and Dolatshahi showed how model environmental disruption as well as uncertainties could use to track the under-actuated AUV. Adaptive control, dynamic surface control and neural networks strategies utilized to implement controllers for the tracking of the AUV target in a three-dimension frame [19].

Vladimir and Dmitry proposed in their paper that robust control strategy can used as the controlling technique for the lateral movement of under-actuated AUVs. The strategy applied for the problem of trajectory chasing of AUVs based on terminal sliding mode control [20]. The control techniques of variable structure control (VSC) with SMC which invented and established at 1950s in Soviet Union by Emelyanov as well as several other researchers such as Wan *et al.* [21]. Through the last ten years, specific attention on SMC and VSC has created in the community of control study. The most distinguished property of SMC is it is fully insensitive to surroundings noises and uncertainties of parameter due to the use of sliding mode [22], [23].

Throughout the operation, the structure of the control system changes from state to state, thus gaining the term VSC. To summarize the necessity of the sliding mode role, the control also named SMC [24]. Additionally, the capability to modify performance directly makes SMC attractive from the perspective of design. System trajectories can be stabilized by SMC. When the first phase is reached, the state of the system "slides" with the line $s=0$. The specific $s=0$ surface is selected due to the eligible minimized-order dynamics that are forced to it [25], [26]. The initial step is creating a sliding surface so that the system limited to the switching surface has a required response. This means that the variables of state of the system dynamics are limited to achieving another group of equations that modify the named switching surface. The second step is building switched feedback gains that are essential to direct the trajectory of the system state into the sliding surface. These structures designed on the generalized theory of Lyapunov stability. The particle swarm optimization (PSO) method is applied to find optimal control gains and to remove the chattering effect that can produced by using a SMC.

2. METHOD (MODELLING AND CONTROL OF AUV SYSTEM)

The AUV mathematical model is composed of a static and dynamic model. The static model related to the analysis of rigid bodies in rest conditions or related to movement in a state of fixed velocity. The dynamic model is concerned with solid bodies in conditions of accelerated motion. The motion of AUV can be illustrated by six degrees of freedom (6DOF). Therefore, six coordinates are required to calculate the position and orientation of AUV as shown below in Table 1. The derivatives of the first three coordinates give the linear movement and location in three axes of x, y, and z [27]. The motion equations require two frames of coordinates: an earth-fixed frame as well as a body-fixed frame. The body-fixed frame considered the reference frame and fixed at the center of the AUV vehicle. The center (O) of the body-fixed frame generally selected to concur with the center of gravity. The movement of the body-fixed frame depicted related to a basic frame of reference. The movement of the earth-fixed frame hardly affects low-speed marine vehicles. The frame of the earth-fixed reference can thus be considered as inertial. The orientation and position of the AUV must be depicted corresponding to the basic frame of reference, while the translational and angular speeds of the AUV must be represented using the body-fixed frame system. By utilizing the symbols in these frames, the common motion equations for AUV can be illustrated as (1)-(3).

$$\eta = [\eta_1^T, \eta_2^T]^T; \eta_1 = [x, y, z]^T; \eta_2 = [\phi, \theta, \varphi]^T \tag{1}$$

$$v = [v_1^T, v_2^T]^T; v_1 = [u, v, w]^T; v_2 = [p, q, r]^T \tag{2}$$

$$\tau = [\tau_1^T, \tau_2^T]^T; \tau_1 = [X, Y, Z]^T; \tau_2 = [K, M, N]^T \tag{3}$$

Table 1. The AUV degree of freedoms

DOF	Forces and moments	Linear and angular velocities	Positions and Euler angles
Translation along x-axis (surge)	X	u	x
Translation along y-axis (sway)	Y	v	y
Translation along z-axis (heave)	Z	w	z
Rotation about x-axis (roll)	K	p	ϕ
Rotation about y-axis (pitch)	M	q	θ
Rotation about z-axis (yaw)	N	r	φ

η Depicts the orientation and position of the vehicle relative to the frame of the earth-fixed reference. v indicates linear and rotational speeds relative to the frame of the body-fixed reference, τ indicates the overall moments and forces affecting the AUV relative to the frame of the body-fixed reference. Figure 1 illustrates the earth-fixed and body-fixed frames of reference. In the guidance of marine vehicles and systems of control, orientation generally indicated using Euler angles and quaternions. The path of the vehicle's flight corresponds to the coordinate system of earth-fixed frame and given by transformations of velocity. The Euler angles must follow the order described below to prevent the singularity in transformation and circulation. The modelling of the AUV system can be divided into two parts: Pitch and Depth models.

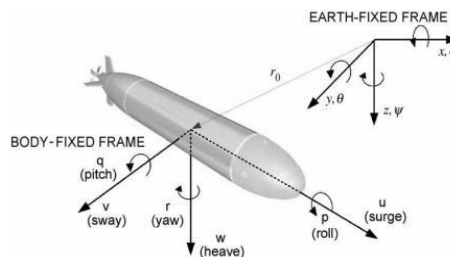


Figure 1. The AUV frames

2.1. Pitch model of the AUV system

The AUV *pitch* model will be derived in this section by determining the ranges of Euler angles as:

$$0 < \varphi < 2\pi$$

$$-\frac{\pi}{2} < \theta < \frac{\pi}{2}$$

$$-\pi < \phi < \pi$$

the six kinematic equations of motion for AUV will be:

$$\dot{\phi} = p + q\sin\phi\tan\theta + r\cos\phi\tan\theta \tag{4}$$

$$\dot{\theta} = q\cos\phi - r\sin\phi \tag{5}$$

$$\dot{\psi} = \frac{q\sin\phi + r\cos\phi}{\cos\theta} \tag{6}$$

$$\dot{x} = u(\cos\theta\cos\phi) + v(\sin\phi\sin\theta\cos\phi - \cos\phi\sin\theta) + w(\cos\phi\sin\theta\cos\phi + \sin\phi\sin\theta) \tag{7}$$

$$\dot{y} = u(\cos\theta\sin\phi) + v(\sin\phi\sin\theta\sin\phi + \cos\phi\cos\theta) + w(\cos\phi\sin\theta\sin\phi - \sin\phi\cos\theta) \tag{8}$$

$$\dot{h} = -\dot{z} = u\sin\theta + v(-\sin\phi\cos\theta) + w(-\cos\phi\cos\theta) \tag{9}$$

according to the equations of motion, the transfer function that will represent the relation between the elevator as input and the pitch angle as output is as (10).

$$G_{\theta}(s) = \frac{\frac{M_E}{I_Y - M_A}}{s^2 - \frac{M_T}{I_Y - M_A}s - \frac{M_{\theta}}{I_Y - M_A}} \tag{10}$$

where:

M_E : Elevator lift, I_Y : Moment of Inertia in Y direction, M_A : Added Mass, M_T : Total Mass, M_{θ} : Hydrostatic

Therefore, the final block diagram of the Pitch model of the AUV system can be represent as Figure 2.

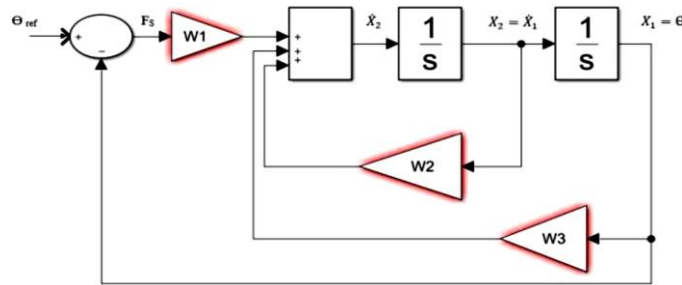


Figure 2. Block diagram of the pitch model of the AUV system

2.2. Depth model of the AUV system

According to the equations from (4) to (10), the transfer function of the depth (z) is written as (11).

$$G_z(s) = \frac{-M_1}{s} \tag{11}$$

Therefore, the block diagram of the depth model of the AUV system is represented as in Figure 3.

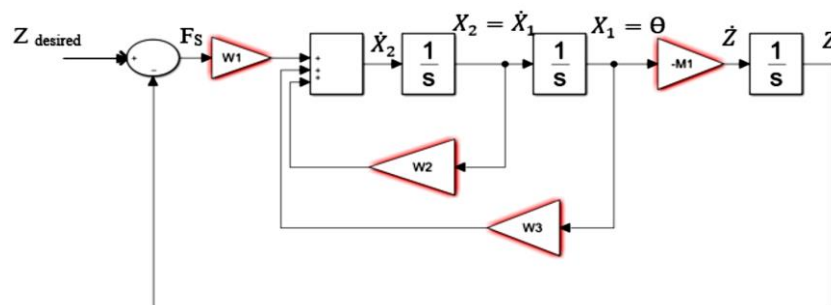


Figure 3. Block diagram of the pitch model of the AUV system

2.3. SMC AND PSO DESIGN FOR AUV

In this section, control and the optimization method has applied for the AUV model. The control method applied here is a conventional SMC approach, and then PSO used to optimize the pitch angle response of the vehicle.

2.3.1. SMC design for AUV

Assume the error (e) is the difference between the actual pitch angle ($X_1=\theta$) and the desired pitch angle ($X_{1d}=\theta_d$) as (12).

$$e = X_1 - X_{1d} \quad (12)$$

Where

$$X_1 = \theta, \dot{X}_1 = \dot{\theta} = X_2, \ddot{X}_1 = \ddot{\theta} = \dot{X}_2$$

After derivation of error equation twice and for the transfer function depicted in (10) the sliding surface (S) can be verify as (13).

$$S = c.e + \dot{e} \quad (13)$$

Then differentiate the sliding surface (S) we have control laws as (14), (15).

$$u_\theta = \frac{1}{K}(b\theta + c\dot{e} + \eta s + a\dot{\theta} + \ddot{\theta}_d) \quad (14)$$

$$u_z = \frac{1}{K}(bz + c\dot{e} + \eta s + a\dot{z} + \ddot{z}_d) \quad (15)$$

2.3.2. Parameter optimization

In order to obtain best performance, the parameters of the SMC controller must be fine-tuned to achieve better performance. Trial-and-error procedure for finding or setting these parameters is cumbersome and it does not lead to optimal solutions in terms of better dynamic performance of controlled systems. Thus, the PSO technique is being suggested to find the optimal values of these parameters that could satisfy the perfect performance of the proposed controllers. In PSO, each particle navigates around the search (solution) space by updating their position and velocity according to its own (and the other particles') searching experience; known as personal and social acceleration. Each particle must update its velocity and position according to the number of iterations [28]. In the present work, the setting of parameters for PSO algorithms are listed in Table 2. The optimized parameters used in PSO algorithm a, b, and c represent the gains of derivative of depth, depth, and error respectively.

Table 2. PSO parameters and gains

PSO Techniques Parameters	Value
POS momentum (w)	0.01
Personal acceleration (C1)	1.5
Social acceleration (C2)	1
Swarm size (n)	500
Iteration number	50
SMC gain (a)	2.6810
SMC gain (b)	-0.00964
SMC gain (c)	3.1619
PID gain (kp)	1.296
PID gain (ki)	0.316
PID gain (kd)	0.646

3. RESULTS AND DISSCUSION

3.1. Case study 1

In this case study, the results are obtained by simulating the whole model presented in Figure 4 using MATLAB. The results of the SMC controller are compared with the PID as a standard controller. The AUV has been modeled and coded in MATLAB m-functions using Simulink library blocks. The numerical value of the AUV model parameters is shown in Table 3. The transfer functions of the Pitch and Depth after substituting these parameters are shown in (26, 27). The AUV is subjected to 20 m sudden change downward in depth at time 0 sec. The response of PID is presented in black color, while the SMC response in Red. Figure 5 shows the response of the depth following the depth change. It can be seen that SMC provides smoother transition without overshoot. Figure 6 shows the response of the pitch angle following the step

change. The SMC turned the pitch angle to about 80 degrees, while PID turned it to 100 degrees. It is clear that the pitch response drawn by SMC is more realistic than PID because the pitch angle should not exceed 90 degrees. Figure 7 describes the sliding surface (S) response that supposed to be stabilized at zero level. Figure 8 represents the control law (u) drawn by the SMC. In comparison with the PID controller, the pros and cons of SMC can be discussed as:

- a) Although the response of the SMC is slower than PID, the response is smoother more realistic to the AUV application. That is, the change in pitch angle following a 20 m in depth is limited to the threshold ($-\frac{\pi}{2} < \theta < \frac{\pi}{2}$). In addition, the SMC could drive the depth with less energy consumption.
- b) For an online optimization system to optimize the PID gains in an AUV application, limiter control system must be integrated to limit the value of the PID gains within a specified level. However, there is no need for such limiter controller in SMC.
- c) Although the SMC response is accompanied with small chattering in the steady state region, this will not affect the stability of the AUV in straight movement.

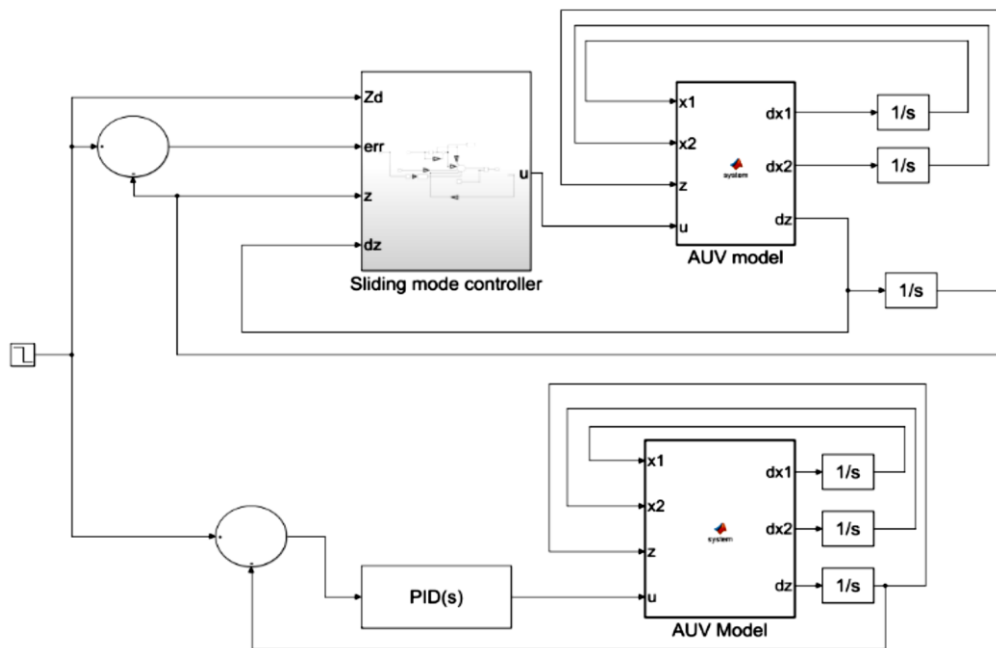


Figure 4. Block diagram of the pitch model of the AUV system

Table 3. AUV model parameters

Parameter description	Value
Elevator lift (M_E)	-1575.9 Kg.m ² /s
Moment of Inertia (I_y)	469 Kg/m ²
Added Mass (M_A)	-458 Kg.m ²
Total Mass (M_T)	9826.2 Kg.m ² /s
Hydrostatic (M_θ)	13719.6 Kg.m ² /s ²

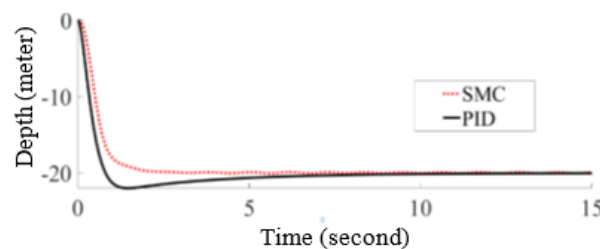


Figure 5. SMC vs PID controller depth response

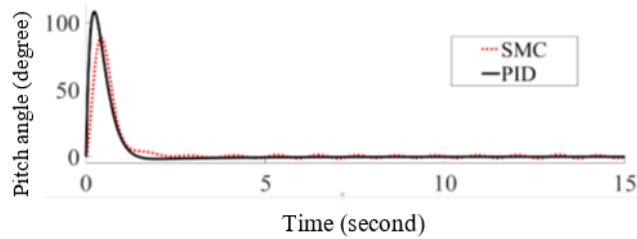


Figure 6. SMC vs PID controller pitch angle response

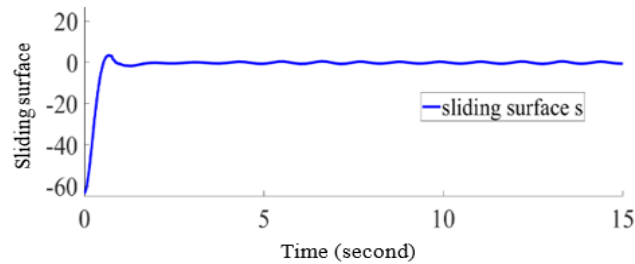


Figure 7. Response of sliding surface (s)

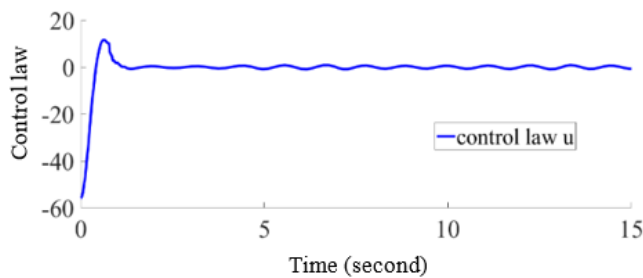


Figure 8. Response of control law (u)

3.2. Case study 2

Typically, most of system models could involve uncertainty. Hence, tuning the gains of any controller should be proper enough to cover wide-range of uncertainty. In this case study, the parameters of the AUV system are exposed to a wide range of uncertainties, ranges from 10% to 60% of their modelled values. After, the performance of both PID and SMC are examined against these uncertainties using the simulation results presented in Figure 9 to Figure 14. Figures 9(a) and 9(b) as well Figures 10(a) and 10(b) show the performance of PID and SMC when 20% of uncertainties are given to the all AUV parameters. It can be seen that, when using SMC, the depth of AUV always converges to the desired level with no overshoot. However, when using PID, the depth response converges but with overshoot. In addition, SMC has controlled the pitch angle against most uncertainties to the acceptable limit ($-\pi/2 \leq \theta \leq \pi/2$). When using PID, the pitch angle went outside the acceptable limit though most of uncertainties.

In Figures 11(a) and 11(b) to Figures 12(a) and 12(b), 40% of uncertainties are given to the AUV parameters. This time the overshoot has increased slightly (about 1 m) when using SMC and to about 4m when using the PID. Unfortunately, the rate of change in pitch angle has increased more as for the increase in uncertainties, but still superior to PID.

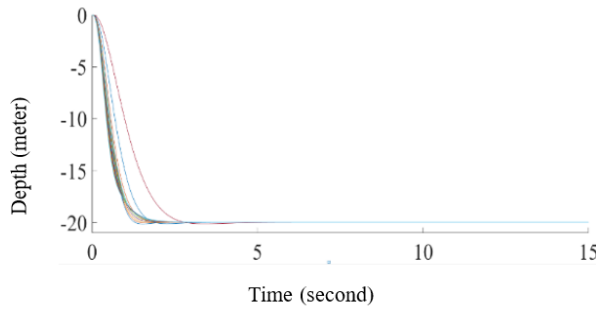
The simulation results presented in Figures 13(a) and 13(b) as well Figures 14(a) and 14(b) represents the most excessive scenario where 60% of uncertainties are considered. Although the overshoot of depth has increased to about 4meter when using SMC and 8m when using PID, the SMC maintained the stability of the system. But, the system is oscillatory and tends to loss its stability when using PID.

Table 4. Depth responses with uncertainties

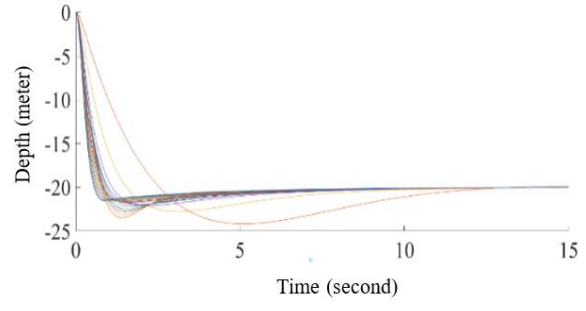
Parameters	SMC controller	PID controller
20% uncertainties		
Max Overshoot (m)	0	4
Settling time (s)	5	13
40% uncertainties		
Overshoot (m)	1	5
Settling time (s)	5	13
60% uncertainties		
Overshoot (m)	4	8
Settling time (s)	6	25

Table 5. Pitch angle responses with

Parameters	SMC controller	PID controller
20% uncertainties		
Overshoot (degree)	10	60
Settling time (s)	5	13
40% uncertainties		
Overshoot (degree)	20	60
Settling time (s)	5	15
60% uncertainties		
Overshoot (degree)	50	110
Settling time (s)	7	20

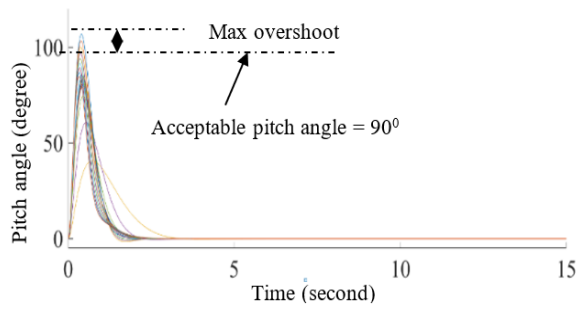


(a)

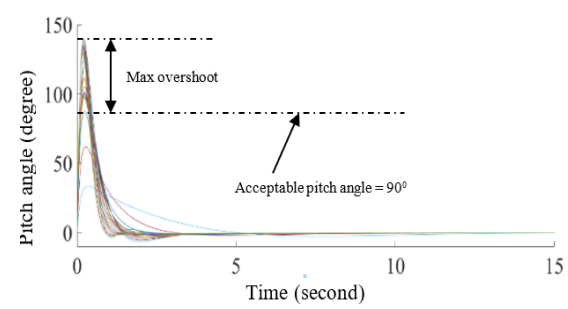


(b)

Figure 9. Effects of 20% uncertainties (a) depth response for SMC and (b) depth response for PID

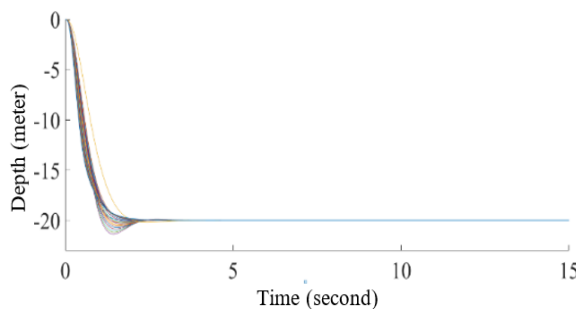


(a)

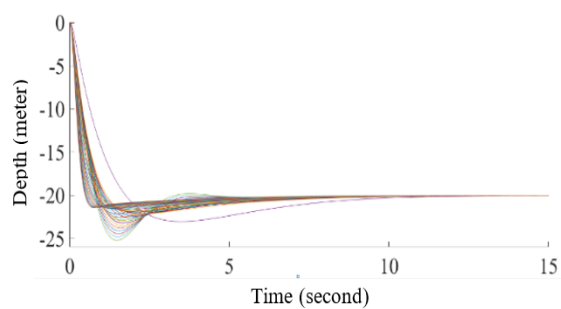


(b)

Figure 10. Effects of 20% uncertainties (a) pitch angle response for SMC and (b) pitch angle response for PID



(a)



(b)

Figure 11. Effects of 40% uncertainties (a) depth response for SMC and (b) depth response for PID

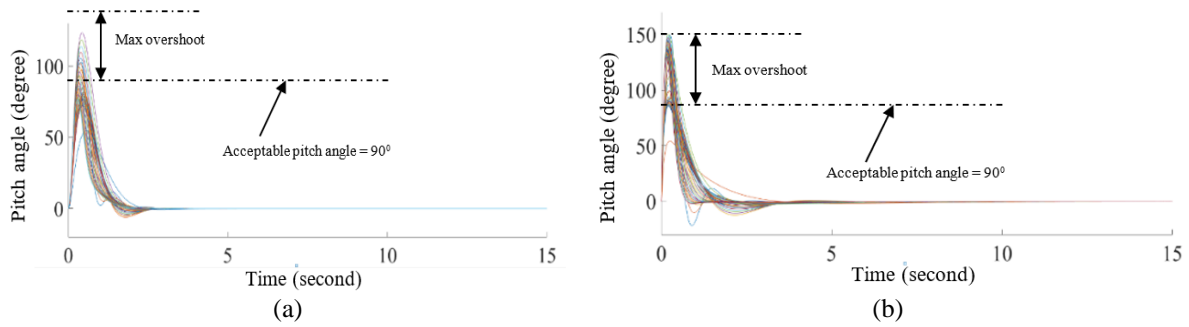


Figure 12. Effects of 40% uncertainties (a) pitch angle response for SMC and (b) pitch angle response for PID

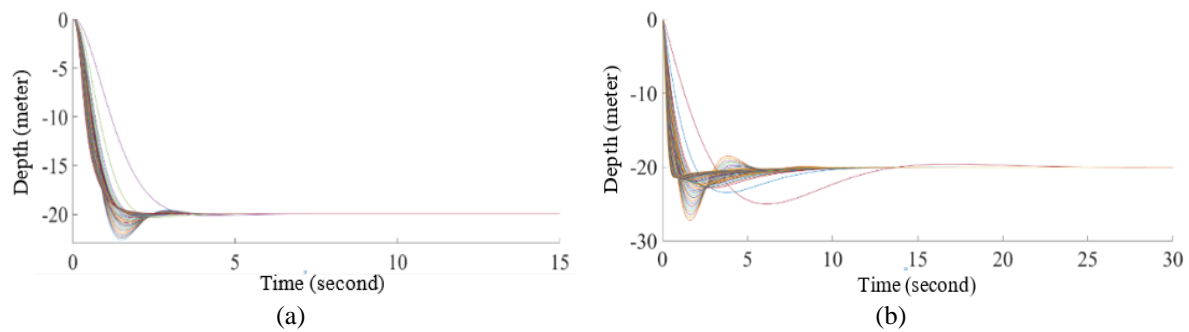


Figure 13. Effects of 60% uncertainties (a) depth response for SMC and (b) depth response for PID

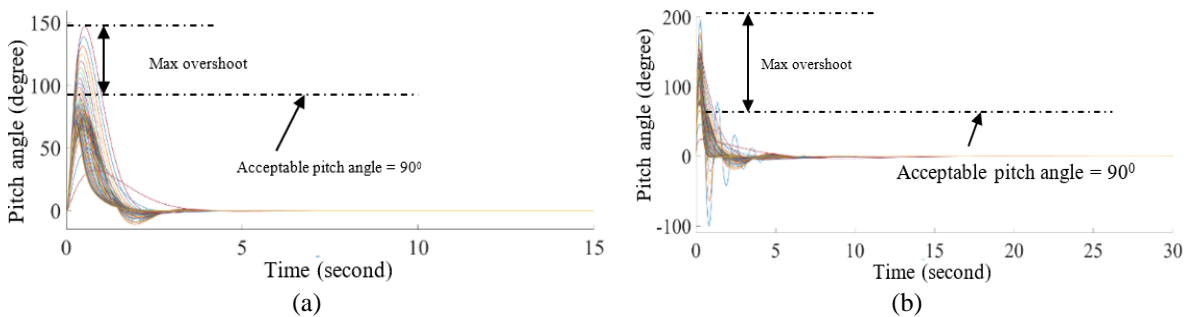


Figure 14. Effects of 60% uncertainties (a) pitch angle response for SMC and (b) pitch angle response for PID

4. CONCLUSION

SMC to control the pitch and depth of AUV system was investigated. The optimality of the controller was persisted by considering an optimization method to tune the parameters according to depth change. That is, PSO algorithm was conducted as an efficient method to tune the SMC' parameters against pitch and depth changes. To investigate the robustness and performance of the system, the results obtained by SMC were compared with results obtained by standard optimized PID controller. In addition, the robustness of PID and SMC were examined against wide-range of system uncertainties. Simulation results showed that the SMC controller achieved smoother performance and more realistic behavior for the AUV application.




In SMC, the optimization of controller's parameters led to a stable pitch angle and depth with no overshoot, while in PID, the optimization led to pitch angle outside the realistic range. When considering wide-range of uncertainties, the SMC maintained the stability of the system. This study could provide a new scope for improved SMC controller design to improve the performance of AUV with the presence of system complex uncertainties.

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