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ADAPTIVE CONTROL OF A SUBMARINE FOR VARIOUS DIVING DEPTHS USING AN EXPONENTIAL FUNCTION

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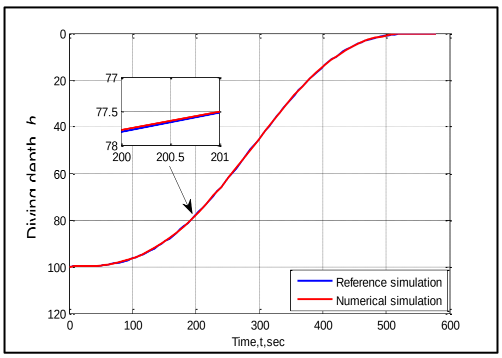
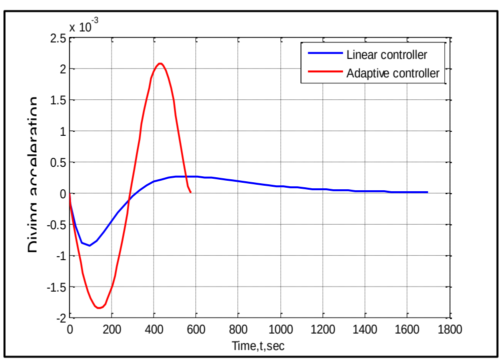
Graphical abstract





Abstract

Due to the progress of deep submergence capabilities, a submarine is extensively employed on many sides of marine science. For that reason, it has become necessary to design an effective submarine position controller while achieving a fast and stable mission. An adaptive analytical scheme for the underwater submarine was developed. The main purpose of the adaptive analytical scheme is to provide a powerful analytical controller that can successfully steer the submarine from the current state under the water to the surface of water in a short time. To achieve that, a seventh-term exponential function was proposed to reshape the reference diving depth while maintaining the control variable limitation and satisfying initial and final boundary conditions. The direct search method with two cascade loops was employed to achieve a minimum cost function by determining an appropriate constant of the function and minimum final time. However, using the direct search method can be time-consuming since a number of algebraic operations are executed inside these two loops. Therefore, the curve fitting method was used to fit the set of direct search method data using power functions. Then, at a certain diving depth, the function coefficients were computed based on the final settling time and function constant using the Gaussian elimination method. A nominal numerical simulation of the submarine's model was implemented using both adaptive analytical and linear controllers. The results show that the proposed scheme can safely guide the watercraft from the diving depth (100) meters to the surface of water in 580 seconds compared to the linear controller that needs 1359 seconds to steer the vehicle at the same initial depth. Eventually, numerical simulations with various initial diving depths are presented and the results illustrate the validity of the new algorithm to command the system from the current state to the surface of water in a short time.

Keywords: Adaptive control, analytical controller, Monte Carlo simulation

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1.0 INTRODUCTION

Submarines may dive by adjusting the depth rudder during travel while traveling in order to generate a downward force. In this way, the submarine can move regardless of the ratio of its weight compared to the weight of the displaced water. Another way of diving is by inserting water into it or expelling water out of it to move it downwards or upwards respectively. Designing a control system that is capable of achieving precise maneuvers is an important issue for a successful accomplishment of the required tasks. Considerable efforts have been made to explore the nonlinear dynamics of submarines. Linear and nonlinear control techniques have been proposed to achieve accurate tracking.

In [1], six degrees of freedom model was used and a multivariable sliding mode control was designed. The results showed reasonable tracking characteristics with remarkable robustness. In [2] a nonlinear system was represented by linear sub-models and an sliding surface was created. Transforming the time varying system into a higher order sub-systems leads to an optimal and robust sliding surface which improves the system performance. A sliding mode-multimodel controller was introduced in [3] to reduce the chattering effect. In [4], a linearized error space model was used to design a static output feedback controller. The desired vehicle orientation was determined from the reference frame that was generated based on the kinematics of the vhiecle. A dynamic recurrent fuzzy neural network was used in [5] to design an adaptive output feedback controller that requires only locational information. The results showed that the proposed control techniques exhibits better performance characterisitics than traditional neural network technique due to the reduction in the number of inputs and the memory enhancement. A virtual guidance method and back-stepping-based design strategy was used in [6] for the purpose of controlling the underactuated unmanned underwater vehicles. The effectiveness of the control strategy was assessed using simulation

In [7], Bode and Nyquist plots were used for the control design of a Multivariable submarine in the frequency-domain under low-depth conditions in the presence of wave disturbances. The system robustness was studied in terms of gain and phase margins. The resulting low order controller is easier to be impimented and tuned and provides better stability. H-infinity control design was proposed in [8] for the robust autonomous underwater vehicles control. In [9], an adaptive control strategy for the dive-plane of multi-input multi-output submarines with uncertain model was introduced. $\mathcal{L}1$ adaptive control theory was implemented and simulation results were presented. Model Predictive control for submarine was used in [10]. The system nonlinearities were taken into account in order to for the model to be representative of the actual system. Auto disturbance rejection controller was designed in [11] for the purpose of controlling the depth and pitch of a submarine separately. The simulation showed that the control strategy achieves good trajectory tracking. In [12] utilized Bode and Nyquist methods to control a low-depth watercraft under a wide range of operations. The controller was tested using several nonlinear simulations and the results demonstrated the performance of the proposed algorithm while involving the speed nonlinearity.

Analytical control strategy provides excellent performance [13]. In this method, a profile for the reference signal is given in the time domain and a solution that gives an accurate signal is determined. In [14], an analytical position control system was designed for a hydraulic actuator. The actuator position profile was created and the actuator velocity and pressure as well as the rotational speed were solved analytically. The results showed that the proposed control strategy provides great performance even in the presence of external disturbance and system uncertainties. An analytical control technique for a nonlinear single rotary inverted pendulum was presented in [15]. The velocity profile and the pendulum angle were determined using a single analytical function. The results proved the effectiveness of the analytical control algorithm. It is essential to design an effective controller to steer underwater vehicles while including the effect of water waves. In [16], the guidance and control problems of submarines have been copied by using multi-level control methodologies. During the motion, the algorithm captured the vehicle to follow a planned three-dimensional trajectory while dealing with depth dispersions and wave disturbances. The simulated results were validated using computational fluid dynamics [17] presented a robust depth control strategy while involving system uncertainties. The model was greatly able to stabilize the submarine under time and frequency variations.

In this paper, an adaptive analytical algorithm to enable the submarine to capture the surface of water is proposed. Firstly, the introduced scheme utilizes a seventh-term exponential function to produce the reference diving depth profile from the current depth to the surface of water. Secondly, the initial boundary conditions, final boundary conditions, and constant function are satisfied while sustaining the control variable constraint. Then, the direct search method is employed to iterate on the final settling time and constant function achieving a minimum final settling time. Eventually, various initial diving depths are initiated to perform the proposed algorithm using the Monte-Carlo Method

2.0 SYSTEM MODEL

A system dynamics model of submarine, shown in Figure 1 is presented by the following governing differential equation [16].

$$\dddot{h} + a\ddot{h} = u \tag{1}$$

The state space representation model of the submarine can be represented as follows

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 \\ \dot{x}_3 &= -ax_3 + u \end{aligned} \tag{2}$$

where x_1, x_2, and x_3 are the diving depth, velocity, and acceleration, respectively. A Swedish submarine has been studied with the parameter a =0. 005 [19], [20]. The diving depth can be measured using a depth gauge so that y = x1. Moreover, the control variable (u) is designed so that the maximum absolute input should never be exceeded 2.5(10^{-5}) [19]. Figure (1) shows the submarine underwater [18].

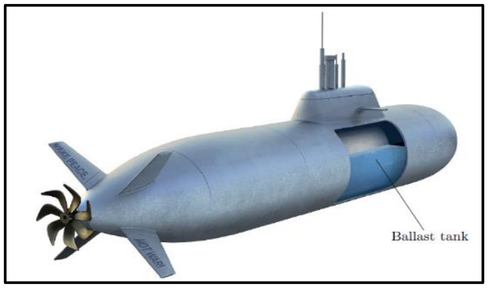


Figure 1 Submarine underwater

3.0 ADAPTIVE ANALYTICAL MODELING

Commonly, the essential aim of converting the system differential equations to the state space representation model is to compute the system eigenvalues that determines whether the system is stable or unstable. Afterward, either linear or nonlinear control methods can be proposed to design a feedback control that ensures a high stability, good damping, and insured tracking performance. However, the proposed algorithm describes a new technique that controls the diving depth without relying on any feedback control methods. In order to fully reach that, an adaptive analytical control approach is exploited to steer the watercraft from the current state to the top of the water. The submarine uses a series of exponential functions of time to reshape the reference diving depth, velocity, and acceleration as shown in Eqs. (3), (4), and (5), respectively.

$$x_{1\text{ref}} = k\sum_{m=1}^{7} C_m \exp(mt) \tag{3}$$

The vehicle velocity is the time derivative of the diving depth

$$x_{2\text{ref}} = k\sum_{m=1}^{7} mC_m \exp(mt) \tag{4}$$

The vehicle acceleration is the time derivative of the diving velocity

$$x_{3\text{ref}} = k\sum_{m=1}^{7} m^2 C_m \exp(mt) \tag{5}$$

Substituting Eq. (5) and the time derivative of Eq. (5) into Eq. (1) and solving the resultant equation for u, the reference control variable is obtained as follows

$$u_{\text{ref}} = \left(k\sum_{m=1}^{7} m^3 C_m \exp(mt)\right) + a\left(k\sum_{m=1}^{7} m^2 C_m \exp(mt)\right) \tag{6}$$

Seven boundary conditions are required to evaluate the seven function coefficients Cm. In this case, we applied one pair of depth, $(h_0, 0)$,velocity $(\dot{h}_0, 0)$, acceleration$(\ddot{h}_0, 0)$ at the initial state, one pair of depth$(0, t_f)$, velocity$(0, t_f)$, acceleration$(0, t_f)$ at the desired state (over the water), and one pair of the time derivative of the acceleration $(0, t_f)$ at the desired state. Ultimately, the system of linear equations with seven variables was solved based on Gaussian elimination method and the function coefficients can be computed as follows

$$\begin{pmatrix} C_1 = \dfrac{Num_1}{Den}, & C_2 = \dfrac{Num_2}{Den}, & C_3 = \dfrac{Num_3}{Den}, \\ C_4 = \dfrac{Num_4}{Den}, & C_5 = \dfrac{Num_5}{Den}, & C_6 = \dfrac{Num_6}{Den}, \\ C_7 = \dfrac{Num_7}{Den} & & \end{pmatrix} \tag{7}$$

where

$$Den = \begin{vmatrix} \exp(10kt_f) - 12\exp(11kt_f) + \\ 66\exp(12kt_f) - 220\exp(13kt_f) + \\ 495\exp(14kt_f) - 792\exp(15kt_f) + \\ 924\exp(16kt_f) - 792\exp(17kt_f) + \\ 495\exp(18kt_f) - 220\exp(19kt_f) + \\ 66\exp(20kt_f) - 12\exp(21kt_f) + \\ \exp(22kt_f) \end{vmatrix} \tag{8}$$

$$Num_1 = \begin{vmatrix} 21h_0\exp(14kt_f) - 140h_0\exp(15kt_f) + \\ 402h_0\exp(16kt_f) - 648h_0\exp(17kt_f) + \\ 640h_0\exp(18kt_f) - 396h_0\exp(19kt_f) + \\ 150h_0\exp(20kt_f) - 32h_0\exp(21kt_f) + \\ 3h_0\exp(22kt_f) \end{vmatrix} \tag{9}$$

$$Num_2 = -\begin{vmatrix} 28h_0\exp(13kt_f) - 175h_0\exp(14kt_f) + \\ 460h_0\exp(15kt_f) - 652h_0\exp(16kt_f) + \\ 524h_0\exp(17kt_f) - 218h_0\exp(18kt_f) + \\ 20h_0\exp(19kt_f) + 20h_0\exp(20kt_f) - \\ 8h_0\exp(21kt_f) + h_0\exp(22kt_f) \end{vmatrix} \tag{10}$$

$$Num_3 = -3\begin{pmatrix} 126h_0 \exp(12k\,t_f) - 700h_0 \exp(13k\,t_f) + \\ 1515h_0 \exp(14k\,t_f) - 1440h_0 \exp(15k\,t_f) + \\ 150h_0 \exp(16k\,t_f) + 948h_0 \exp(17k\,t_f) - \\ 900h_0 \exp(18k\,t_f) + 360h_0 \exp(19k\,t_f) - \\ 60h_0 \exp(20k\,t_f) + h_0 \exp(22k\,t_f) \end{pmatrix} \quad (11)$$

$$Num_4 = -2\begin{pmatrix} 42h_0 \exp(11k\,t_f) - 175h_0 \exp(12k\,t_f) + \\ 150h_0 \exp(13k\,t_f) + 420h_0 \exp(14k\,t_f) - \\ 1160h_0 \exp(15k\,t_f) + 1206h_0 \exp(16k\,t_f) - \\ 600h_0 \exp(17k\,t_f) + 100h_0 \exp(18k\,t_f) + \\ 30h_0 \exp(19k\,t_f) - 15h_0 \exp(20k\,t_f) + \\ 2h_0 \exp(21k\,t_f) \end{pmatrix} \quad (12)$$

$$Num_5 = 3\begin{pmatrix} 7h_0 \exp(10k\,t_f) - 140h_0 \exp(12k\,t_f) + \\ 440h_0 \exp(13k\,t_f) - 580h_0 \exp(14k\,t_f) + \\ 316h_0 \exp(15k\,t_f) + 506h_0 \exp(16k\,t_f) - \\ 160h_0 \exp(17k\,t_f) + 85h_0 \exp(18k\,t_f) + \\ 20h_0 \exp(19k\,t_f) + 2h_0 \exp(20k\,t_f) \end{pmatrix} \quad (13)$$

$$Num_6 = -\begin{pmatrix} 35h_0 \exp(10k\,t_f) - 168h_0 \exp(11k\,t_f) + \\ 252h_0 \exp(12k\,t_f) + 60h_0 \exp(13k\,t_f) - \\ 654h_0 \exp(14k\,t_f) + 900h_0 \exp(15k\,t_f) - \\ 612h_0 \exp(16k\,t_f) + 228h_0 \exp(17k\,t_f) - \\ 45h_0 \exp(18k\,t_f) + 4h_0 \exp(19k\,t_f) \end{pmatrix} \quad (14)$$

$$Num_7 = -\begin{pmatrix} 15h_0 \exp(10k\,t_f) - 96h_0 \exp(11k\,t_f) + \\ 262h_0 \exp(12k\,t_f) - 396h_0 \exp(13k\,t_f) + \\ 360h_0 \exp(14k\,t_f) - 200h_0 \exp(15k\,t_f) + \\ 66h_0 \exp(16k\,t_f) - 12h_0 \exp(17k\,t_f) + \\ h_0 \exp(18k\,t_f) \end{pmatrix} \quad (15)$$

By substituting Eqs. (7-15) into Eq. (6), we end up with one equation that has the control variable confined on the left side of the equation while the other system boundary conditions (h_0, k, and t_f) isolated on the right side. At a certain diving depth, a direct search method is applied to find the minimum final time (t_f) and function constant (k) such that the control variable profile does not exceed the maximum control variable (u_{max}= 2.5(10^{-5})) from the initial state to the desired state. Figure 2 presents the adaptive analytical controller. As we can see from Figure (2), the analytical controller is computed while solving the system of seventh-linear equations without employing any feedback techniques.

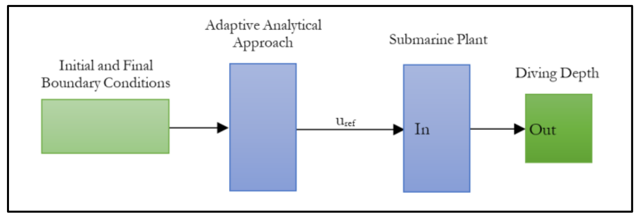


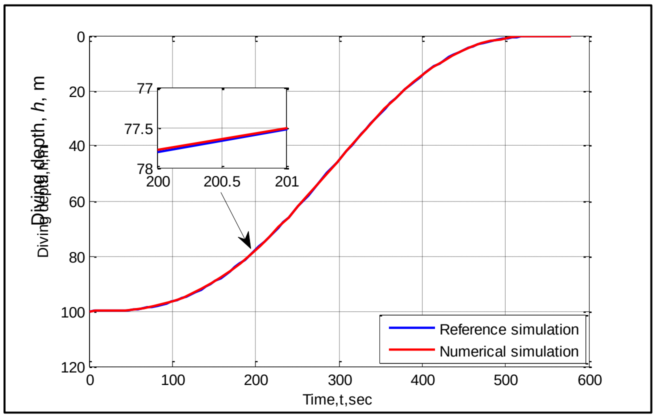
Figure 2 Adaptive analytical block diagram

4.0 NOMINAL NUMERICAL SIMULATION

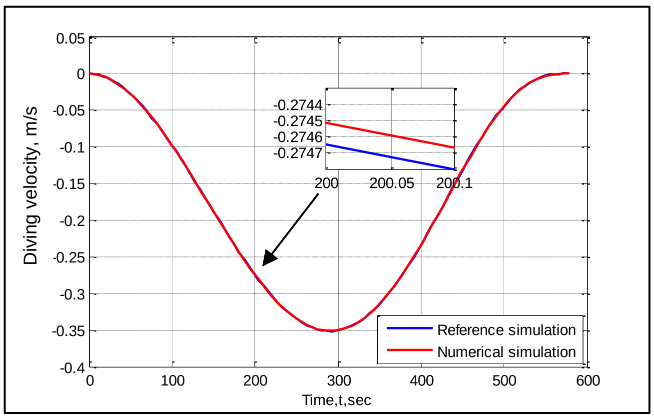
The essential objective of submarine depth-control algorithms is to steer the underwater vehicle to capture the surface of water while involving control variable constraints. Typically, these algorithms depend on two concepts: propagating a reference trajectory, and then planning a linear or nonlinear control to pursue the shaped reference path. Differently, as previously mentioned, our work proposed a new analytical approach that can successfully guide the system to the desired state without providing any feedback effort. So, to exam the performance of the proposed controller, the submarine model is numerically simulated under the nominal conditions.

In summary, Eq. (6) is the required controller command to track the reference diving depth, velocity, and acceleration profiles defined by Eqs. (3), (4), and (5), respectively.

Figures 3(a)-3(c), show the diving depth, velocity, and acceleration profiles vs. time, respectively. With applying the adaptive controller, these figures show that the submarine is greatly able to track reference states without requiring feedback loop. These results indicate the effectiveness of the analytical control to direct the underwater vehicle smoothly with in a very short final time (t_f =580 s).



(a)



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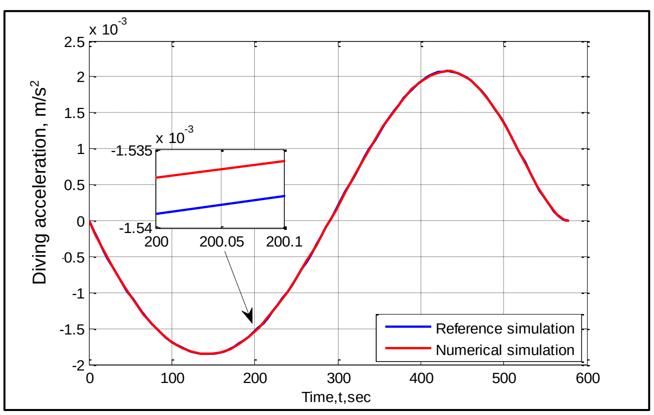
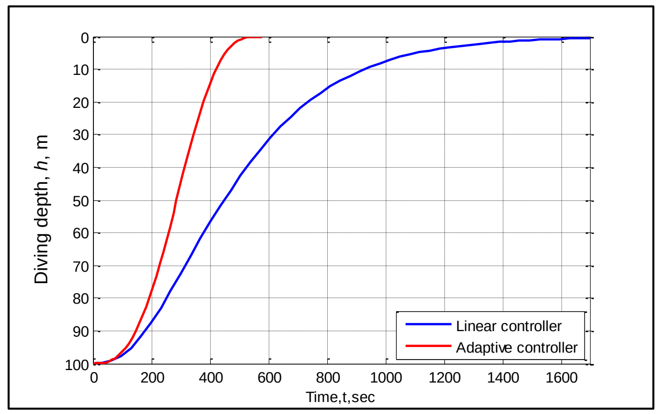


(c)

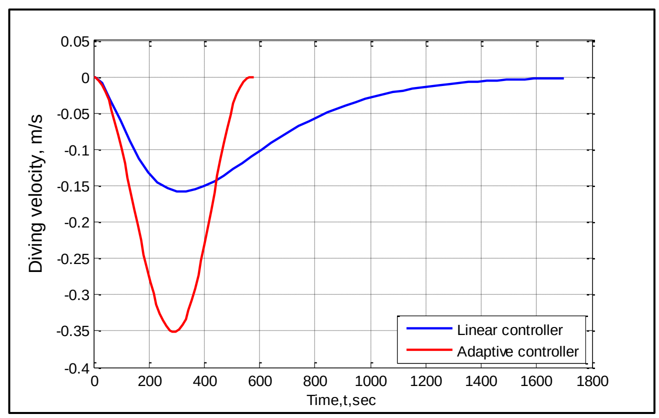
Figure 3 Submarine's reference and numerical simulations vs. time using adaptive controller under nominal conditions; (a) diving depth vs. time; (b) diving velocity vs. time; (c) diving acceleration vs. time.

To compare the current work with other control methods, Figures 4(a)-4(d) present the numerical diving depth, velocity, acceleration, and control variable, respectively, based on a linear controller (blue lines) and the proposed adaptive controller (red lines) under nominal conditions ($h_0 = 100\text{ m}, \dot{h}_0 = 0, \text{and } \ddot{h}_0 = 0$. It can be seen from Figures 4a-4c that the submarine handles the surface of water in a very short final time (t_f =580 s) with using the new adaptive controller while it needs around (t_f = 1652 s) to reach the same state with using a very good feedback linear controller.

Furthermore, Figure (4d) shows that the effort required to control the system does not exceed the maximum control variable with the proposed controller, however, it surpasses the allowable control variable with the linear controller. Hence, the new designed controller is successfully able to guide the submarine in a short settling time while adhering the control variable constraint.



(a)



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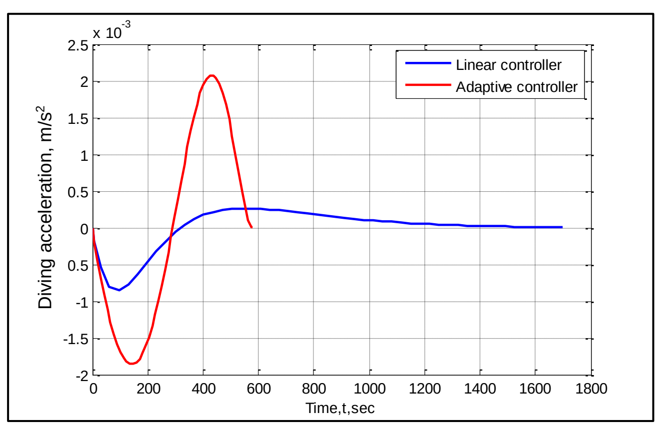


(c)

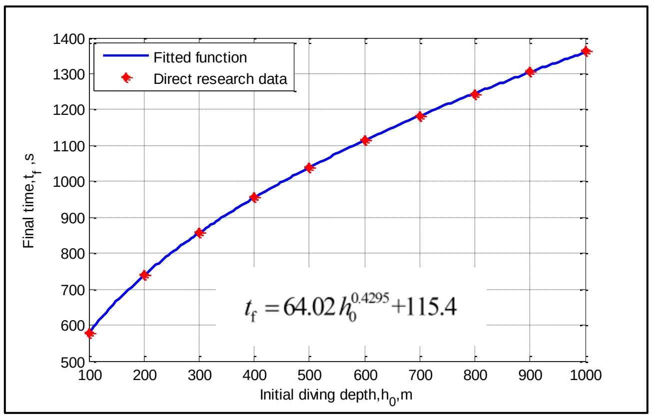
Figure 4 Submarine's states vs. time using linear and adaptive controllers;(a) diving depth vs. time; (b) diving velocity vs. time; (c) diving acceleration vs. time; (d) control variable vs. time

5.0 CURVE FITTING TECHNIQUE

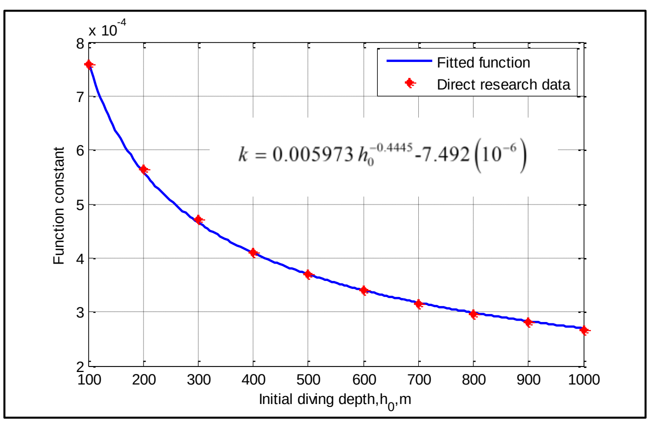
Even the direct search method is a simple effective strategy that commonly uses to find out the best solutions, it takes a lot of time since its calculations rely on using two cascade loops (the final time and function constant loops). Therefore, analytical functions are also proposed based on curve fitting with power functions for modelling the final time and function constant with the initial diving depth.

To be more specific, ten initial depths (100-1000) m are implemented to get the fitted functions on condition of minimizing the final time and exhibiting the control variable limitation.

Figures (5a) and (5b) present the direct search method data and fitted functions for the final time and function constant, respectively. As It can be seen from Figures (5a) and (5b), when the watercraft is initiated, the algorithm will be readily available to compute the minimum final time and function constant, which are then used to determine the needful control variable [Eq. (6)].



(a)



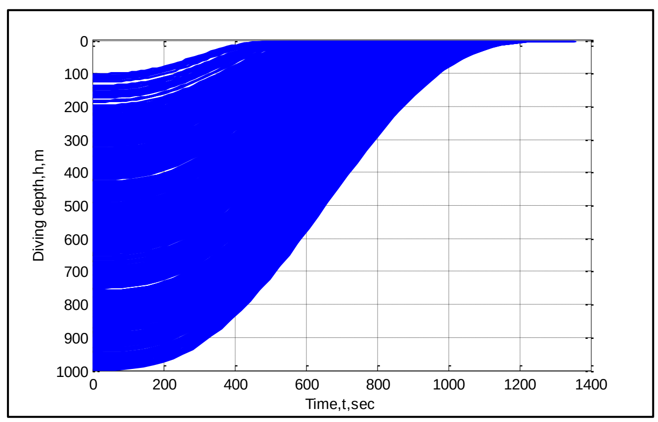
(b)

Figure 5 Fitted functions and direct search method data vs. initial diving depth; (a) final time vs. initial depth; (b) function constant vs. initial depth

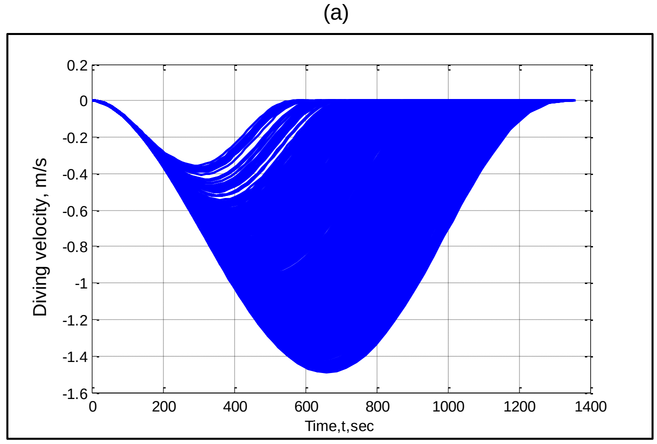
6.0 OFF-NOMINAL NUMERICAL SIMULATION

The aim of deviation simulations is to compute the performance of the adaptive analytical scheme in the presence of significant dispersions in the initial diving depth. To do that, a Monte Carlo simulation involving 1000 adaptive analytical paths with random dissipations in the initial diving depth was implemented [21] and [22]. The Monte Carlo simulation is a multiple probability methodology that is applied to assess possible output values under dissipated state values. This method utilizes a probability distribution for uncertain variables to re-compute the results again and again

Values for the initial diving depth dispersions were bounded between [100 1000] m. So, the proposed fitted functions can be easily used to determine the final time and function constant required to run the adaptive analytical algorithm. In figures 6(a) -6(c), histories of the diving depth, velocity, acceleration, and control variable versus time, respectively, are illustrated for 1000 dispersed adaptive analytical trajectories. Figure 6a shows that all the simulated trajectories reach the surface of water despite the wide range dispersions in the initial depth. This significantly indicates the performance of the proposed analytical scheme to steer the vehicle from the initial states to the desired state with smooth paths and minimum final times. Figures 6b and 6c illustrate that the submarine comes to rest when it captures the surface of water even it initiates with different diving depths. Finally, Figure 6d shows the control variable profiles do not exceed the maximum allowed value which indicates that the submarine can safely attain the desired goal with no chance of vehicle damage.



(a)



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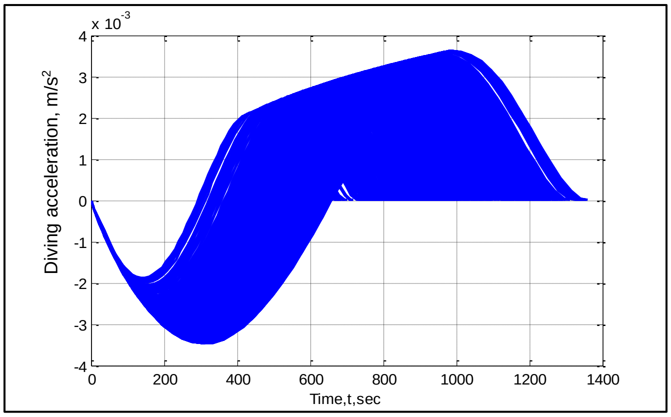

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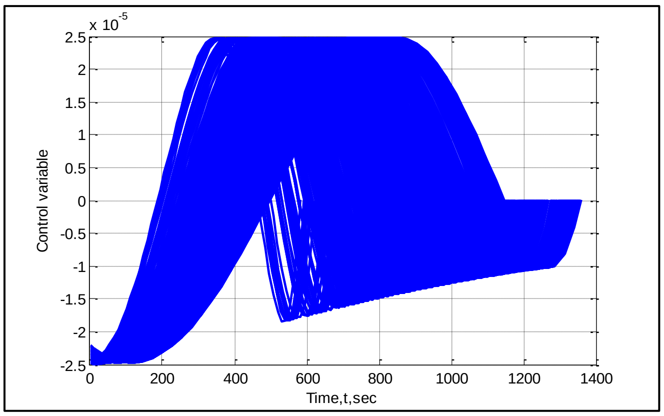

(d)

Figure 6 Submarine's histories vs. time using adaptive controller; (a) diving depth vs. time; (b) diving velocity vs. time; (c) diving acceleration vs. time; (d) control variable vs. time

Table 1 summarizes the final differences between the reference and numerical simulations for 1000 Monte-Carlo tests. All the minimum and maximum final errors are extremely small as well as the means of the final errors are close to zero. Accordingly, the submarine can effortlessly achieve short reachable times which are between (580-1359) s for all the initial operating diving depths. Furthermore, the watercraft can remarkably able to descend to 1000 m while illustrating the control variable limitation.

Table 1 Statistics for final errors

State	Mean	Minimum	Maximum
Depth (m)	-0.0293	-0.0693	-0.0035
Velocity (m/s)	-2.28e-05	-4.178e-05	-5.482e-06
Acceleration (m/s^2)	-2.597e-10	-6.399e-10	-7.18e-11

7.0 CONCLUSION

A new adaptive analytical scheme for the submarine underwater has been presented. The introduced analytical controller based on the seventh-term exponential function was successfully able to guide the submarine from the current state to the surface of water. At the initial state, the analytical algorithm adjusted the final time and function constant, so that the submarine achieved a minimum final time while exhibiting a control variable limitation. In order to reduce the program implementation time, the curve fitting was used to fit the set of direct search method data (final time and function constant) using power functions with initial depth as the independent variable. Knowing the initial diving depth, the minimum final settling time, and the function constant, the seven analytical functions were solved linearly to find the analytical control variable required to steer the submarine from the current state to the desired state. Numerical simulations with various initial depths were obtained to validate the proposed algorithm. The results indicated the capability of the submarine to capture the surface of water in a short settling time avoiding any excessive control variable.

In this work, the proposed algorithm can readily guide the submarine from the initial operating diving depths between [100 - 1000] m to the surface of the water while satisfying a control variable limitation. However, in future work, the range of initial operating diving depths can be extended to involve high depths and the initial velocity dispersions can be encompassed as well.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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