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Designing a predictive controller for an underwater robot to track certain targets using the sliding mode technique

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Abstract

In this research, the goal of designing an adaptive control system is to overcome the uncertain values of a robot underwater and to prove its asymptotic stability by using nonlinear control theory, in the design of the mode controller. Sliding After defining the sliding surface, the control law must be selected in such a way that it satisfies the sliding condition and results in the stability of the system. The results obtained through the theory of the problem that shows the stability of the closed loop system show the Lyapunov stability of the system. Also, the simulation results obtained at the end show the time characteristics obtained and the position errors of the work power in the improvement and development of the control methods used for underwater robots.

Keywords:
Underwater robot modeling, Adaptive-sliding control, Predictive control, Target tracking

1. Introduction

Due to needs for using the robot in high-tech and for safety application in industries, there is an attention for developing the robot control systems. The study of robotic systems has a history of 50 years, the initial studies in the field of dynamic modeling of these robots were investigated on simple examples with low degrees of freedom, and then in studies on controllers, uncertainties and system characteristics. Adaptations have been added to it (Herman, 2022; Bejarano et al., 2021; Nerkar et al., 2022; Nerkar et al., 2022; Li and Du, 2021).

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The underwater robot is a semi-automatic system that allows the user to control and guide this device in the depths of the water and perform the desired operations through the commands taken by the user (Hasan and Abbas, 2022; Akinyele et al., 2021). Underwater robots are used in several ways, the common type of these robots, by entering a certain point of the underwater with a built-in rake, perform the desired operation, which can include reconnaissance operations, relocation operations, or measurement operations. The second type of these robots are designed as mobile robots that can move under the water and perform specific purposes.

In (Herman, 2021) they have conducted studies on the structure and dynamics of robots and the effect of water in this modeling, they have studied the use of these robots in navigation for submarines and their exploration issues and their ability to track non-level paths. In (Manzanilla, 2021), the non-linear control method that is coupled to an underwater robot in navigating its goals is investigated and the results are shown using MATLAB. In this work, not much uncertainty has been considered and only one disturbance term has been introduced as an external force to the system to evaluate the resistance of the control system in dynamics. In (Liu et al., 2008) they designed the nonlinear control system in the condition of disturbance in the system, the design type is the feedback output linearization method and it is not considered uncertain.

In (Yang et al., 2015) used the fuzzy logic method in adapting the control system to deal with uncertainty, and this method is considered for special conditions for which global stability cannot be imagined. In (Yang et al., 2016), control laws and dynamic models have been considered for the underwater robot system, and the arguments raised in these systems have been investigated in a specific and general form of robots. The main goal in this article is to guide the underwater robot in a specific path. In the meantime, the parameters of the robot are considered uncertain, and the sliding method is used to estimate these parameters. Next, in the third part, the sliding model control method is presented and the types of structures related to this method, the conditions of the method, the statement of Lyapunov's rule in proving the stability of the method are stated as the parts related to the work. Then, the adaptive methods used in uncertain systems have been investigated, and the combined sliding-adaptive method is also investigated as the method used. In the results section, the method used in the software simulations was evaluated and the simulation results were carefully examined. Finally, in the fifth section, a summary of the findings were provided.

2. Modeling

In the investigated underwater robot system, the parameters are assumed to be uncertain, which are often used in a specific and fixed manner in similar cases such as studies (Fischer et al., 2011; Azis et al., 2014). These system parameters include parameters of mass, length, moment of inertia and especially the forces acting on the robot system, which are in the form of table (1). The basic goal of the work is to make it possible to maneuver the underwater robot in its prong in order to track different targets, which is based on the possibility of turning underwater, following different paths and overcoming different limited forces acting on it. For this purpose, it is necessary to introduce a robust method that can meet this importance for the system. The method used in this thesis is the sliding-adaptive model method, the block diagram of this method is shown in figure (2). The parameters specified in table (1) are shown in figure (1).

Table 1: Considerations for robot uncertainty

section with uncertainty	First parameter	Second parameter	Third parameter	Uncertain force
First Joint	First Link Length	the mass of the first link	The inertia moment of the first link	-
Second Joint	Second Link Length	the mass of the second link	The inertia moment of the second link	-
robot's prong	dimensions of the robot's prong	-	-	Forces due to gravity, water pressure, friction

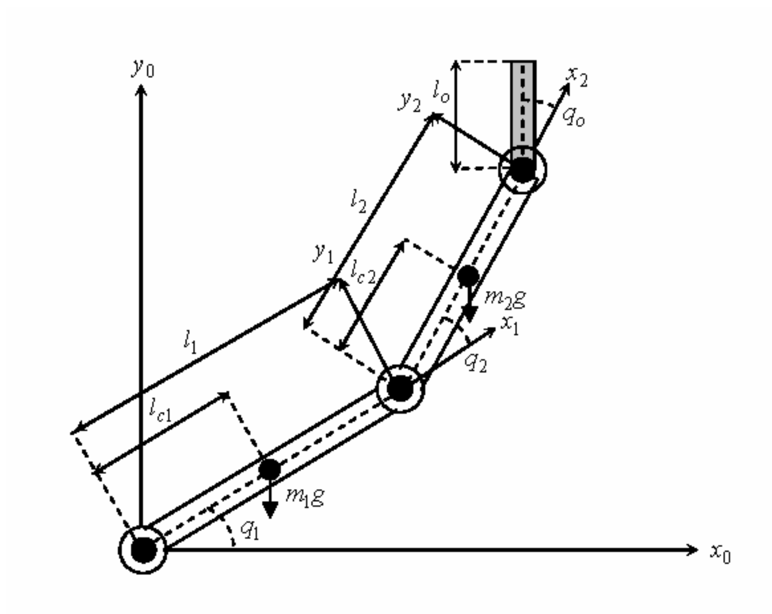

Figure 1: Schematic of the underwater robot along with the robot parameters

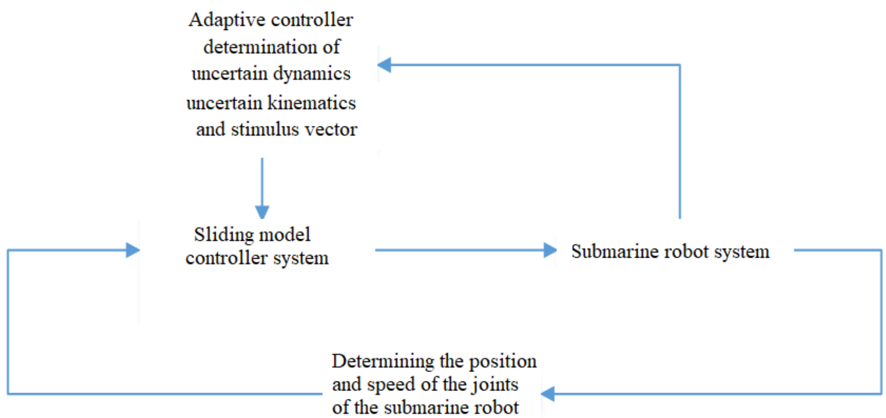

Figure 2: Block diagram of the method used in the underwater robot [5].

Based on Figure (2), the adaptive control system allows the control department to design the robust control law for the underwater robot system by estimating the uncertain values of the system at every moment, which includes uncertain dynamics, uncertain kinematics, and stimulus vector. It should be noted that all the mentioned uncertainties are derived from the basic values of the parameters specified in table (1).

2.1 Sliding model controller design process

Considering the following system, we have:

$$\dot{x} = f(x) + b(x)u + \delta(x) \quad \textbf{(1)}$$

in which $\delta(x)$ is a disturbance; Disturbance in different systems has different definitions, for example, in the inverted pendulum system, the disturbance is the additional force that enters the pendulum from the outside, in the missile and target system, it is the wind or rain disturbance that occurs along the path of the missile. The target side brings it and also an important category of disturbances is the uncertainties or uncertainties of the system parameters. For example, in the missile system and the target, the mass of the missile varies due to fuel consumption, and every moment the mass of the missile is changing, in this case, the disturbance is a function of the system state variables. It is assumed that:

$$|\delta(x)| \leq k \quad \textbf{(2)}$$

in which K is maximum disturbance; and is a positive number. This assumption should be found in the case of the problem. Of course, if the process is carried out practically, the maximum possible disturbance to the system should be measured.

2.2 Adaptive controller

The purpose of using adaptive control is that the controller designed in this way can respond appropriately to slow changes in the system as well as modeling errors in the case of non-linear systems considering that separating The stable and unstable parts of the system are not an easy task, generally, intelligent methods such as neural networks are used to estimate the model and controller design. Real systems are always accompanied by uncertainty and changes, and in principle, it is not possible to obtain an accurate model of the system. For this reason, we need to use a method that can obtain the exact model of the system, because the control of the internal model requires an accurate model of the system. So this is where the idea of adaptive control comes into play. As seen in figure (3), a matching law adjusts the parameters of the model in such a way that the error caused by the model and the real system becomes zero.

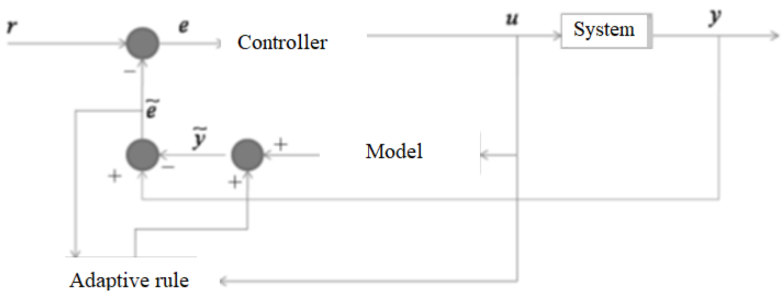

Figure 3: Adaptive control model

2.2.1 Reference model adaptive controller

In the reference model adaptive control method, the ideal response to the input signal is defined as a reference model. By using this control method, the error between the system output and the model output becomes zero by applying mechanisms. The MRAC method has advantages, among which the fast adaptation process and less complexity of the adaptation algorithm can be mentioned. The conventional MRAC model is shown in Figure (4).

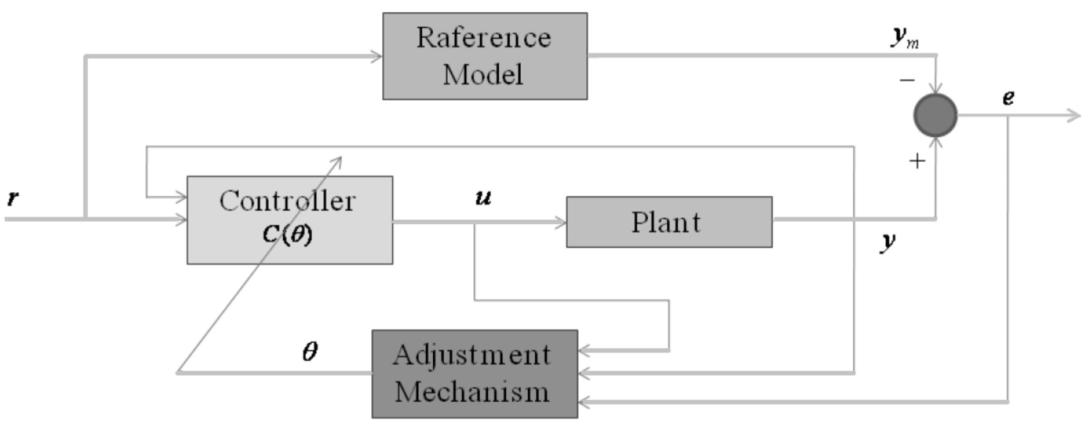

Figure 4: Block diagram of the reference model adaptive controller method [6].

The desired behavior of the system is determined by a reference model. ey is the difference between the output of the model ym and the output of the system yp, which is used to adjust the controller parameters based on an adaptive law. This law is defined so that the behavior of the closed loop system tends towards the reference model.

2.2.2 Adaptive control based on sliding mode

The adaptive control method based on the sliding mode can be checked in three modes (Azis et al., 2012). First case) Consider the following nonlinear single-input-single-output system.

$$\begin{cases} x^{(n)} = f(x, \dot{x}, \dots, x^{(n-1)}) + b(x)u \\ y = x \end{cases} \quad (3)$$

Assumptions:

It is assumed that in $b(x) = b_0(x) + \tilde{b}(x)$ that the $b_0(x)$ is nominal quantity and $\tilde{b}(x)$ is expression of indefinite of $b(x)$, and for the nonlinear part in the same way, $f = f_0 + \tilde{f}$. It is assumed that unknown dynamics, disturbances, unmodeled dynamics, $\tilde{b}(x)u$ and $\tilde{f}$ all are collected in the nonlinear function $g(x, \dot{x}, \dots, x^{(n-1)})$, and there is an unknown, constant and positive parameter η, that $|g| < \eta$. As a result, the nonlinear system will become as follows.

$$\begin{cases} x^{(n)} = \hat{f} + b_0(x)u + g(x, \dot{x}, \dots, x^{(n-1)}) \\ y = x \end{cases} \quad (4)$$

By defining the error vector, the sliding mode surface and the following Lyapunov function:

$$e = [x - x_d, \dot{x} - \dot{x}_d, \dots, x^{(n-1)} - x_d^{(n-1)}]^T = [e_1, e_2, \dots, e_n]^T \quad (5)$$

$$\lambda > 0\ ,\ \Lambda = [\lambda^{n-1}, (n-1)\lambda^{n-2}, \dots, (n-1)\lambda]^T \quad (6)$$

$$V = \frac{1}{2} S^2 \quad (7)$$

It can be shown that with the following control law, the system error will go to zero.

$$u = b_0^{-1}(-\hat{f} + q - \bar{g} - k\ \mathrm{sgn}(S)) \quad (8)$$

$$\bar{g} = \begin{cases} \eta \dfrac{S}{|S|}\ , & |S| > \varepsilon \\ \eta \dfrac{S}{\varepsilon}\ , & |S| \le \varepsilon \end{cases} \quad (9)$$

The same relations can be extended to multi-input-multi-output systems. In this case, all the previous relations will be converted into vector, the control law will be as follows, and that's mean

$$q = x_d^{(n)} - e^T \Gamma^T \in R^m\ , e \in R^{n \times m}, S \in R^m\ , k = diag\{k_1, k_2, \dots, k_m\} \quad (10)$$

$$u = b_0^{-1}(-\hat{f} + q - \bar{g} - k \frac{S}{\|S\|}) \quad (11)$$

$$\bar{g} = \begin{cases} \eta \dfrac{S}{\|S\|} & , \|S\| > \varepsilon \\ \eta \dfrac{S}{\varepsilon} & , \|S\| \le \varepsilon \end{cases} \tag{12}$$

The second case) the following non-linear and multi-input-multi-output system is considered:

$$\dot{X} = f(X,t) + \Delta f(X,t) + d(t) + u \tag{13}$$

where $\Delta f\ (X\ ,t)$ is represented of Uncertainty expression of the system, and $d\,(t)$ is disturbance (It is assumed that both are bounded $\|\Delta f\ (X\ ,t)\|_\infty \le \alpha\ ,\|d\,(t)\| \le \beta$). By defining the surface of the sliding mode as follows:

$$\begin{aligned} S &= E(t) \\ E(t) &= X(t) - X_d(t) \end{aligned} \tag{14}$$

and Lyapunov as

$$V = \frac{1}{2} S^T S + \frac{1}{2\gamma}(k_{as} - \hat{k})^2 \tag{15}$$

It can be shown that the following control law is a stabilizing control law.

$$\begin{aligned} & u_{eq} = -f\ (X\ ,t) + \dot{X}_d \quad , \ u_r = k_{as} u_s \\ & u = u_{eq} + u_r = -f\ (X\ ,t) + \dot{X}_d + k_{as} u_s \end{aligned} \tag{16}$$

which can be found in the above relations that:

$$\dot{k}_{as} = -\gamma \|S\|_1 \quad and \quad u_s = sign(S) = [sign(s_1),\dots,sign(s_n)]^T \tag{17}$$

and $\hat{k}$ is chosen as $\alpha + \beta + \hat{k}$ to be negative. The block diagram of the closed loop system is also shown in Figure (5):

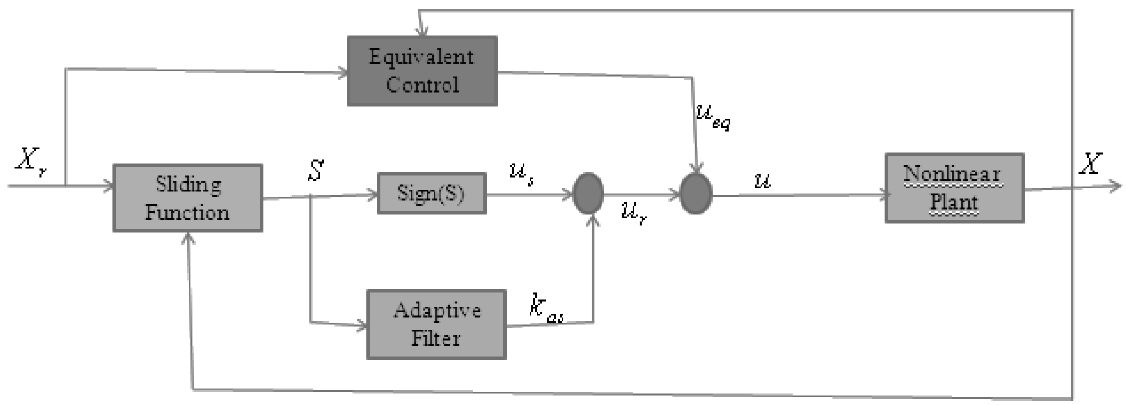

Figure 5: Block diagram of closed loop system

Third mode) In this part, a non-linear system with Dead Zone feature is investigated. This property exists in most practical systems that use drivers.

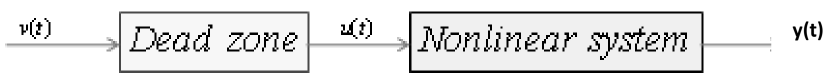

Figure 6: Nonlinear system in presence of dead zone

Consider the following nonlinear system

$$\begin{cases} \dot{x} = Mx + h\left[u + f^T(x)\theta + Z^T g(x)\theta\right] \\ \dot{Z} = a(x) + b(x)Z \end{cases} \quad \textbf{(18)}$$

Here, the vector x is the vector of states that can be measured, and the vector z states that cannot be measured. M and h are definite and fixed vectors and $f(x), g(x), a(x), b(x)$ all are non-linear and definite functions, and θ as the system parameter is also indeterminate. The Dead Zone model is as follows:

$$u(t) = mv(t) + d(v(t))$$

$$d(v(t)) = \begin{cases} -mb_r & for \quad v(t) \geq b_r \\ -mv(t) & for \quad b_l < v(t) < b_r \\ -mb_l & for \quad v(t) \leq b_l \end{cases} \quad \textbf{(19)}$$

Assumption : Dead Zone parameters b_r, b_l, m are all unknown but their sign is known and its output i.e. u(t) cannot be measured. Dead Zone parameters b_r, b_l, m mean that they all have limits, but their limits are not known. Pairs (M, h) are controllable. There are positive definite matrices, P_z , Q_z such that

$$B^T(x)P_z + P_z B(x) \le -Q_z \tag{20}$$

The uncertain parameters of the system θ_i are all bounded. By defining the following Lyapunov function:

$$V = \frac{1}{2}\left[\frac{\phi}{w}s^2 + \tilde{\Psi}^T \Gamma \tilde{\Psi} + \frac{1}{\eta}\tilde{\phi}^2 + \tilde{Z}^T \Lambda_{|\Psi|} P_z \tilde{Z} + \tilde{b}^2\right] \tag{21}$$

$$\Lambda_{|\Psi|} = diag\left(|\theta_1|, |\theta_2|, \ldots, |\theta_p|\right) \tag{22}$$

And the surface of the sliding mode is defined as follows.

$$s(t) = \Lambda^T \tilde{x}(t) \ , \ \Lambda^T = \left[\lambda^{n-1}, (n-1)\lambda^{n-2}, \ldots, 1\right], \ \tilde{x} = x(t) - x_d(t) \tag{23}$$

It can be shown that the following control law will be the optimal control law.

$$v(t) = -k_d s(t) + \frac{\hat{\phi}}{w}\left\{x_d^{(n)} - \Lambda_v^T \tilde{x}\right\} - f^T(x)\hat{\Psi} - \hat{Z} g^T(x)\hat{\Psi} - \hat{b}|s| \tag{24}$$

3. Results

The simulation has been done for 10 seconds and considering the time to reach the steady state of the system, the results of the simulation are shown in figures (7) to (11).

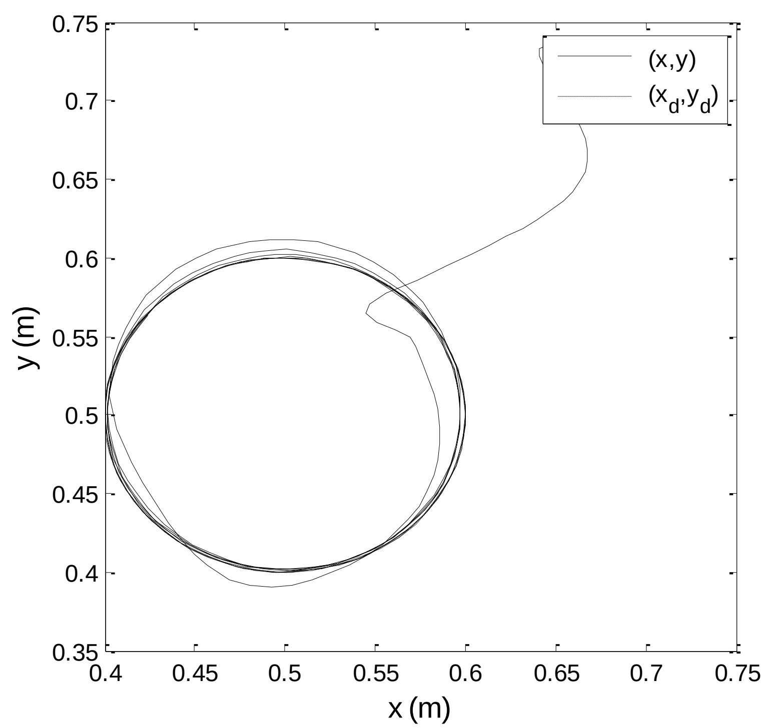

Figure 7: The circular path following by the underwater robot

In figure (7), the path traveled by the robot and the desired path in the robot's workspace are drawn. It can be seen carefully in this figure that the underwater robot stays on the circle after one lap of the circular path and travels this continuous path. The correctness of the work is appropriate, obviously the robot is following the path around its reference path with the corresponding q angles in a mapping expressed by the inverse of the integral of the Jacobian function. In figure (8), the values corresponding to location and speed for the robot are drawn in comparison with the corresponding optimal value for each. The first diagram shows how to track the x-axis, the second diagram shows the path on the y-axis, the third diagram shows the derivative along the x-axis, and the fourth diagram shows the derivative of the path along the y-axis. You can get the sitting time by looking at the waveforms carefully. The system is around 0.4 seconds and the waveforms have a low overshoot rate, on the other hand, the steady state error is in the zero range and the system quickly stabilizes in its steady state.

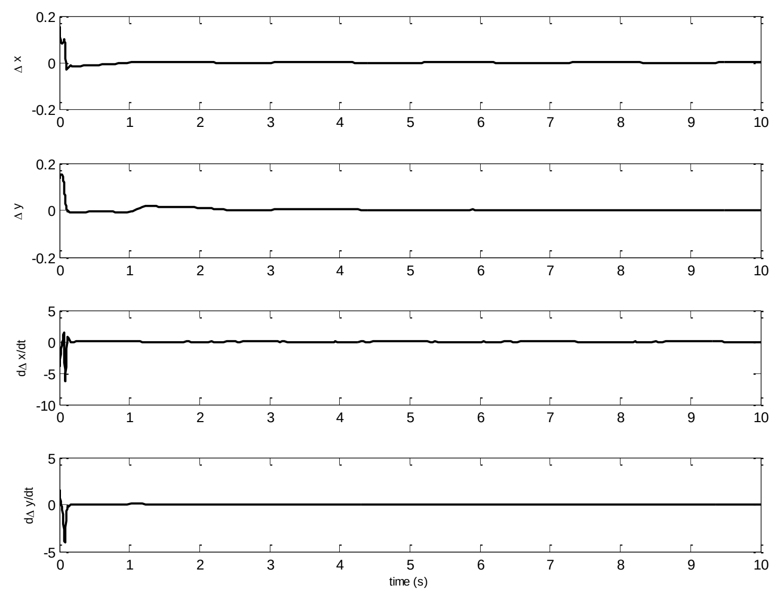

Figure 8: location and speed variables in the workspace in comparison with the corresponding desired values at each moment

In figure (9), the error value is plotted at each moment for the robot in the working space for displacement and speed, as it is known after a time of about 0.1 second, which is related to the transient state of the system and the influence of the control force caused by the initial values. The system has an error close to zero in the location and speed error variables. These graphs are actually obtained by subtracting the actual value from the corresponding desired value, the error variables have an error value that is close to 0.01 m, which changes in an oscillating manner, and this value is caused by the sliding mode parameter. In the controller equations, they are in the joint space which is represented by the Jacobian integral function to the robot's working space. In previous studies, this error has reached 0.015 in the same period of time.

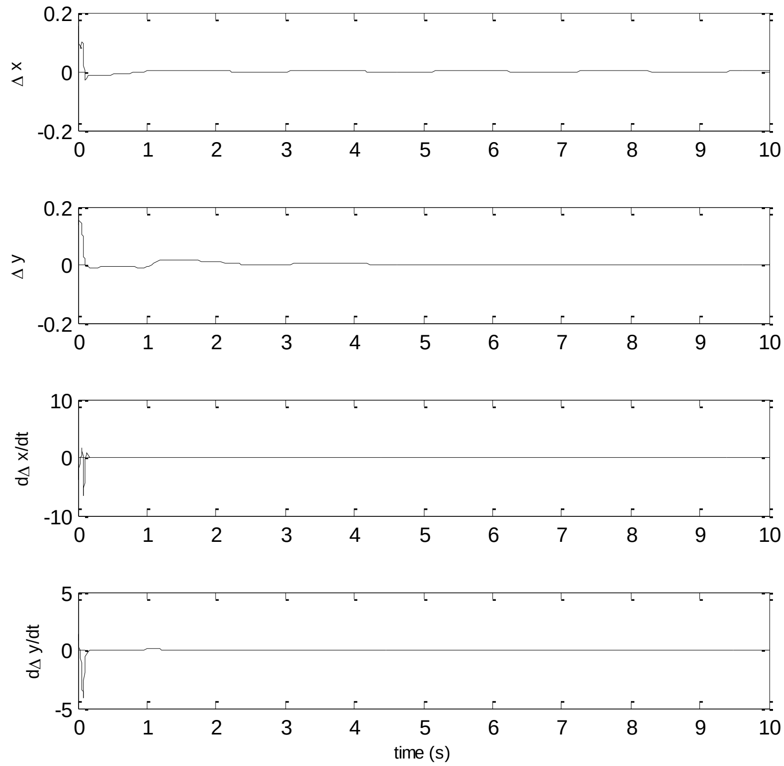

Figure 9: The error value for the robot in the workspace for location and speed variables

Figure (10) shows the diagram of the control force applied to the joints of the robot at any moment. The control force in the initial moments (transient state) has maximum values due to the initial conditions of the system, the corresponding value after the transient state always fluctuates around the zero value, which is due to the adaptation values and the sliding vector. In fact, the initial control energy is due to the initial conditions of the system, and this value disappears when the actual value is set on the desired path, and then only the forces resulting from the sliding values remain, on the other hand, the value of the control force depends on Sudden path changes and momentary disturbances also enter the system, but if the path changes are continuous and derivable, the control force will change in a limited way and we will have stability again according to Lyapunov's proof for the proposed control law. Corresponding control forces are sent to the actuators in the first and second joints, and then these actuators will be the ones that interpret the force as torque and transfer it to the joints.

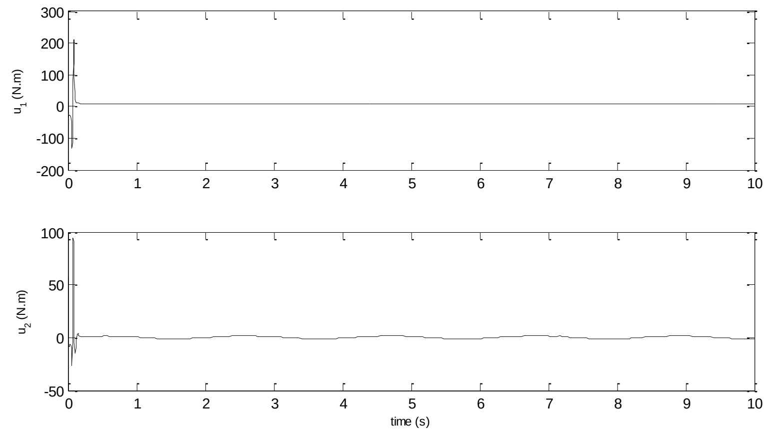

Figure 10: Control force diagram on the robot

Figure (11) shows the adaptive sliding vector in the joint space of the system. This sliding force is fluctuating, and when the error changes from positive to negative, its sign also changes, and the purpose of this sliding parameter is to control the robot's acceleration variables.

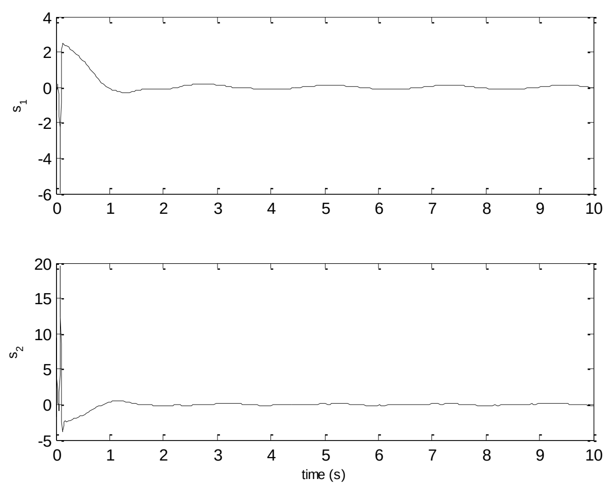

Figure 11: Adaptive slip vector in joint space

3.1 Examining the results from a numerical point of view

From the control point of view, in a desirable closed loop system, the problem is to reach the desired value in the shortest time with the least increase in the response and with the least error of the steady state. Therefore, in this section and based on the obtained results, numerical studies have been evaluated on circular routes, and these results are shown in Table (2).

Table 2: Quantitative review of the answers obtained

Route type	System settling time	Response increase rate	Response steady state error
Circular	0.1	1	0

By studying the values obtained for the time domain of the response, it can be seen that the sliding model-adaptive controller was able to obtain the standard conditions of a closed loop system in terms of time indicators.

4. Conclusion

In this article, by examining the dynamics of the underwater robot and modeling it with the Lagrange method, we obtained a common second-order system used in robotics, with an uncertain assumption on the basic parameters of the robot, the dynamic, kinematics and actuator values in this thesis were associated with uncertainty In order to design the control system for this underwater robot, adaptive method based on sliding model was used. In the evaluation of the used method, we used various types of system paths, including circular paths and elliptical paths. All system traces in the longitudinal and horizontal axes were carefully checked, and the following results were obtained:

1- The introduced control system was able to track the desired routes with the least possible error.

2- The adaptive system provides the controller with the kinematic, dynamic and stimulus matrices used in the control section at any moment in a way that is compatible with the Lyapunov function.

3- The final control force is obtained in an optimal and limited manner, which can be implemented in practical systems.

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