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Modeling Unmanned Submarine by an Adaptive Control to Follow an Ellipse Path by Considering Disturbances on the System

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Abstract

Recent advances in the robotics industry and the design of controllers in sync with the structure of robots have made it possible to use robotic systems in exploration, information display in human-difficult environments, military, medical, and human life-saving purposes. The accuracy and robustness of the path tracking is essential for the use of robots for such purposes. In this article, the modeling of the underwater robot is done and the adaptive control system is presented to track the path of the robot. Submarine robots have a non-linear dynamic with dynamic and kinematic uncertainties and excess force terms due to the robot's entry into the sea, and the controller designed for the system must be able to overcome these forces and be able to estimate the terms It is required to control the robot so that the control system can use this information to eliminate the effects of the stated uncertain terms. The results showed that the designed control system was able to predict and travel the target path with an error of less than 5% despite the presence of unconventional forces and external disturbances in the model.

Keywords: Underwater robot modeling, Routing, predictive control, Kinematic analysis, Disturbance

1. Introduction

In general, the performance of the robot as well as the submarine robot directly depends on the technology used in it. In a proper operation, the submarine robot must be able to travel the predicted routes in a robust manner and with minimal errors. From a dynamic point of view, this system should be able to overcome the tensions under the water and bear the pressure caused by the adjacent engine

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systems (Rath and Subudhi, 2022; Rober et al., 2021). On the other hand, sensor systems for determining the situation must be able to perform properly under water. These sensor systems include position, speed, force and distance sensors, which need to be resistant to water and resistant to certain threshold forces.

1.1 Underwater robot components

The Underwater robot, like other robots, has two mechanical and electrical parts. The mechanical part includes the two main parts of the mechanical and moving arm, and the electrical part includes the sensor and controller. The mechanical arm is a tool for moving and performing operations. Submarine robots equipped with arms have a very good efficiency in moving and crossing obstacles. Also, by moving the arm, they can move their center of gravity, which is very suitable for climbing stairs and steep slopes. The motion part includes components such as wheel drive and thrust system that help the robot navigate the path. The electronic systems of submarine robots can be divided into the following sections: Telecommunication communication system with operator and control system; casualty detection sensor systems; robot control and electronic system; motor drive systems and mechanical devices; Mapping and navigation systems. The functional mechanism of the robot with the integrated combination of mechanical and control parts in navigation and stability has been investigated in various research (Peng et al., 2018; Qu et al., 2021; Ul'yanov and Maksimkin, 2019). In Lapierre and Jouvencel (2008) have studied the optimization of path tracking for a submarine robot, this problem has been studied in the form of piecewise paths and piece-by-piece optimization. In Wang et al., 2020 used the adaptive law based on the velocity gradient to control the system, in this study, the viewer was used to estimate the uncertainties, and the closed loop system including the viewer was used to prove the stability.

In Miao et al., 2022 have used the linearization of the nonlinear equations of the submarine robot system and a Lyapunov-based method that uses the positive square function has been used to prove stability. In Wang, et al., (2021), in a study on path tracking for a submarine robot, considered a nonlinear holonomic path for it and designed a robust nonlinear control system for it. In Qu et al., (2021) has used the neural network method online to control the submarine robot. In this method, network training is done using experimental data. In this article, the movement kinematics of submarine robots and its dynamic structure and the uncertainties raised in submarine robotic systems are examined. For this perspective, firstly, the background of research conducted in the field of robots, especially submarine robots, was stated. Then modeling and design of predictive controller for robot routing is presented. Finally, the performance of the controller in tracking the desired path of the robot is evaluated by considering the disturbances on the system during the elliptical path, and the kinematic and dynamic variables of the system are checked for stability.

2. Method

In this section, underwater robot modeling and predictive controller design are presented. In this chapter, first, we will model the submarine robot with two degrees of freedom by expressing the Lagrangian method, and then we will express the uncertainties of the system. In the following, we will design the control system for the submarine robot using the sliding-adaptive method. The described method is based on Lyapunov and the stability of the closed loop system of the robot is measured in the presence of the controller. The parametric uncertainties in the submarine robot system, as well as the uncertain forces acting on it, made it use robust methods to control it. In this section, the robust predictive control method is presented, which also has the property of being compatible with adaptive methods based on Lyapunov.

2.1 Adaptive control based on passivity theory

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. To check this method, first some definitions are provided. Definition (1): The transformation function $G(s)$ is called positive real if $\mathrm{Re}G(s) \geq 0 \quad for \quad s \geq 0$

Definition (2): The transformation function $G(s)$ is called positive real if $G(s-\varepsilon)$ $is \quad PR \quad for \quad \varepsilon \geq 0$

Definition (3): A system with a transformation function $G(s)$ is called negative if the real is positive.

Definition (4): A system with a transformation function $G(s)$ is called strictly negative if it is positive real.

2.2 Passivity Theorem

The closed loop system is considered as Figure (1).

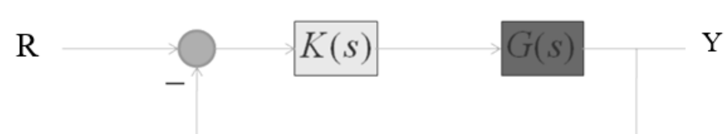

Figure 1: Closed loop system

If $G(s)$ is strictly passive and $K(s)$ is passive, then the closed loop system will be asymptotically stable in the sense that the values of the system states will reach their desired values in a limited time Miao et al., (2022). Now, if $G(s)$ is not passive, then we will use the ring shift idea, which is as follows in Figure 2:

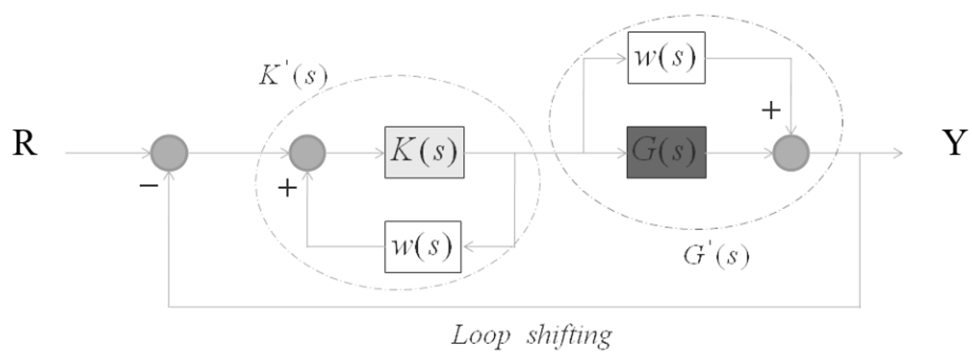

Figure 2: Loop Shifting Method

In fact, we should choose W(s) in such a way that $G'(s)$ becomes strictly passive, in this case, we can make the closed loop system asymptotically stable by designing a passive controller $K'(s)$.

2.3 Adaptive controller design for submarine robot

A submarine arm type robot with two degrees of freedom (the object is locked at the end point, that holds an object in its hand) is considered. m_1 .and m_2 are the mass of the first and second interfaces respectively, and the moment of inertia of the first and second arms respectively, and the length of the first and second arms respectively, l_1 and l_2 are the distance of the center of mass of the first arm from the first joint and l_{c1} and l_{c2} are the distance of the center of mass of the second arm from the second joint, l_0 is the length of the object in the hand of the robot, q_0, q_1 and q_2 respectively are the angle between the horizon surface and the first interface, the angle between the first and second arm and the angle between the second arm and the object, and finally G is the acceleration of the earth's gravity and the corresponding numerical values used for them is provided in the Table 1.

Table 1: Numerical values of simulation parameters

Parameter	Value
m_1	1 kg
m_2	1 kg
I_1	0
I_2	0
l_1	0.5 m
l_2	0.5 m
l_{c1}	0.25 m
l_{c2}	0.25 m
B	Diag{1,1}
K	Diag{1,1}
l_0	0.06 m
q_0	rad$\pi/4$
$\widehat{K}$	Diag{1.2,}

The linear and angular velocities for the i-th interface are:

$$v_i = J_{vi}(q)\dot{q} \quad , \quad w_i = J_{wi}(q)\dot{q} \tag{1-1}$$

which is the linear velocity for calculating the kinetic energy caused by linear movements and the angular velocity is used to calculate the kinetic energy caused by the angular movement. In this case we will have:

$$K = \frac{1}{2}\dot{q}^T[\sum_{i=1}^{m}\{m_i J_{vi}(q)^T J_{vi}(q) + J_{wi}(q)^T R_i(q) I_i R_i(q)^T J_{wi}(q)\}]\dot{q} = \frac{1}{2}\dot{q}^T D(q)\dot{q} \tag{2-1}$$

where m_i is the mass of the i-th interface, I_i is the inertia tensor of the i-th interface and K is the kinetic energy of the system. D(q) is the inertia matrix or mass and inertia matrix.

The potential energy of the robot is due to its placement in the earth's gravitational field. The potential energy of the i-th interface is:

$$P_i = m_i g^T r_{ci} \tag{3-1}$$

where $g=[0 .\cdots.g_0]$ and r_{ci} is the coordinate of the center of mass of the i-th interface relative to the ground frame, the potential energy of the entire robot with n interfaces is equal to the sum of the potential energies of its interfaces, that is:

$$P_i = m_i g^T r_{ci} \tag{4-1}$$

The difference between kinetic and potential energy (Lagrange's function) will be:

$$L = K - P = \frac{1}{2}\dot{q}^T D(q)\dot{q} - P(q) = \frac{1}{2}\sum_{i=1}^{n}\sum_{i=1}^{n} d_{ij}(q)\dot{q}_i\dot{q}_j - P(q) \tag{5-1}$$

$$\frac{\partial L}{\partial q_k} = e_k^T D(q)\dot{q} = \sum_{j=1}^{n} d_{kj}(q)\dot{q}_j \tag{6-1}$$

where $e_k=[0.\cdots.1.\cdots.0]$ is the unit vector whose kth component is 1, so:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_k}\right) = \frac{d}{dt}\sum_{j=1}^{n} d_{kj}(q)\dot{q}_j = \sum_{j=1}^{n} d_{kj}(q)\ddot{q}_j + \sum_{j=1}^{n}\frac{d}{dt}\left(d_{kj}(q)\right)\dot{q}_j = \sum_{j=1}^{n} d_{kj}(q)\ddot{q}_j + \sum_{j=1}^{n}\sum_{i=1}^{n}\frac{\partial d_{kj}}{\partial q_i}(q)\,\dot{q}_i\dot{q}_j \tag{7-1}$$

Also

$$\frac{\partial L}{\partial q_k} = \frac{1}{2}\dot{q}^T\frac{\partial D}{\partial q_k}(q)\dot{q} - \frac{\partial P}{\partial q_k} = \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{\partial d_{ij}}{\partial q_k}(q)\dot{q}_i\dot{q}_j - \frac{\partial P}{\partial q_k}(q) \tag{8-1}$$

As a result, according to the Lagrange relation, we will have:

$$\sum_{j=1}^{n} d_{kj}(q)\ddot{q}_j + \sum_{i=1}^{n}\sum_{j=1}^{n}\left\{\frac{\partial d_{kj}}{\partial q_i}(q) - 0.5 * \frac{\partial d_{ij}}{\partial q_k}(q)\right\}\dot{q}_i\dot{q}_j + \frac{\partial P}{\partial q_k}(q) = \tau_k \tag{9-1}$$

$$k = 1:n$$

It can be rewritten as follows:

$$\sum_{i=1}^{n}\sum_{j=1}^{n}\left\{\frac{\partial d_{kj}}{\partial q_i}(q) - 0.5 * \frac{\partial d_{ij}}{\partial q_k}(q)\right\} = \sum_{i=1}^{n}\sum_{j=1}^{n} 0.5 * \left\{\frac{\partial d_{kj}}{\partial q_i} + \frac{\partial d_{ki}}{\partial q_j} - \frac{\partial d_{ij}}{\partial q_k}\right\}(\dot{q}_i\dot{q}_j) = \sum_{i=1}^{n}\sum_{j=1}^{n} c_{ijk}\dot{q}_i\dot{q}_k \tag{10-1}$$

where c_{ijk} are Christopher's coefficients. Now we consider the G_k as follows:

$$G_k(q) = \frac{\partial P}{\partial q_k}(q) \tag{11-1}$$

So it can be resulted in

$$\sum_{j=1}^{n} d_{kj}(q)\ddot{q}_j + \sum_{i=1}^{n}\sum_{j=1}^{n}\{c_{ijk}\}\dot{q}_i\dot{q}_j + G_k(q) = \tau_k \quad (12\text{-}1)$$

where τ is the vector of torques on the joints, and by simplifying we will have the above relationship:

$$M(q)\ddot{q} + C(q,\dot{q})\,\dot{q} + G(q) = \tau \quad (13\text{-}1)$$

and for 2 DoF robot we have:

$$G(q) = [G_1 \; G_2] \quad (14\text{-}1)$$

$$G_1(q_1,q_2) = (m_1 * l_{c1} + m_2 * l_1) * g. * \cos(q_1) + m_2 * l_{c2} * g. * \cos(q_1 + q_2) \quad (15\text{-}1)$$

$$G_2(q_1,q_2) = m_2 * l_{c2} * g. * \cos(q_1 + q_2)$$

$$C(q,\dot{q}) = \begin{bmatrix} h\dot{q}_2 & h(\dot{q}_1 + \dot{q}_2) \\ -h\dot{q}_1 & 0 \end{bmatrix} \quad (16\text{-}1)$$

$$M(q) = \begin{bmatrix} m_1 l_{c1}^2 + m_2\left(l_1^2 + l_{c2}^2 + 2 l_1 * l_{c2}^2 \cos(q_2)\right) + I_1 + I_2 & m_2\left(l_{c2}^2 + l_1 l_{c2}\cos(q_2)\right) + I_2 \\ m_2\left(l_{c2}^2 + l_1 l_{c2}\cos(q_2)\right) + I_2 & m_2 l_{c2}^2 + I_2 \end{bmatrix} \quad (17\text{-}1)$$

As we know, in changing the joint space to the working space, we need the Jacobian matrix, which is obtained through the robot's transfer equations, and according to the descriptions given in the section of the interaction of sea water and the robot, and also considering Uncertainty for the submarine robot, the kinematics of the robot will have uncertainty, on the other hand, this uncertainty in the driver gain vector will also be uncertain due to the unknown (uncertainty) of the forces introduced by the sea water, and finally, the dynamic equations will also be used to use The Jacobian matrix and the derivative of this matrix are also considered uncertain, the set of these uncertainties leads us to use the adaptive process in the control law in order to estimate these terms and to establish the stability of the closed loop by mentioning the state space laws for Express the system. According to this problem and using the robot transfer equation, the Jacobian matrix is:

$$J(q) = \begin{bmatrix} -(l_1\sin(q_1) + l_2\sin(q_1+q_2) + l_0\sin(q_1+q_2+q_0)) & -(l_2\sin(q_1+q_2) + l_0\sin(q_1+q_2+q_0)) \\ l_1 * \cos(q_1) + l_2\cos(q_1+q_2) + l_0 * \cos(q_1+q_2+q_0) & l_2 * \cos(q_1+q_2) + l_0 * \cos(q_1+q_2+q_0) \end{bmatrix} \quad (18\text{-}1)$$

2.4 Controller Design

In the design of the controller, the goal is to create a system that can continuously guide the object carried by the robot in the desired direction for indefinite and bounded dimensions of the submarine robot, as well as indefinite values in length and angle, this robot should be able to estimate the selected dynamic parameters at any moment, provide kinematics and stimuli so that its goals can be achieved, the figure 3 schematic shows a general block diagram of the control:

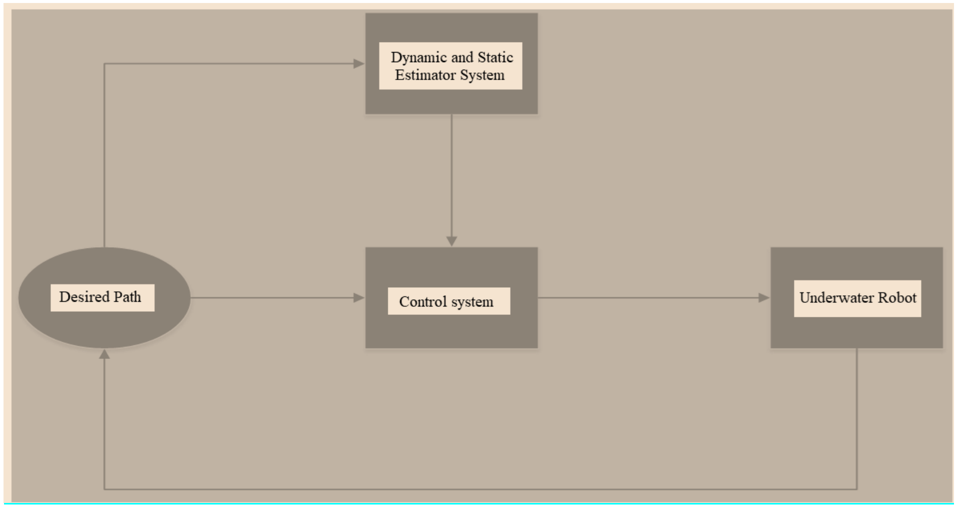

Figure 3. Schematic of the used adaptive control method

According to the dynamic relationship obtained in the previous section and the dynamic equation, we have n=2:

$$M(q)\ddot{q} + \left(B + S(q,\dot{q}) + \frac{1}{2}\dot{M}(q) \right)\dot{q} + G(q) = Ku \tag{19-1}$$

where: M(q)∈R^(n×n): symmetric and positive definite matrix of mass and inertia; B∈R^(n×n): the matrix of damping coefficients resulting from the interaction of sea water, which is obtained on the right side and is transferred to the left side because it is multiplied in the expression of the joint derivative; K∈R^(n×n): matrix for transferring voltage inputs to torque; G(q)∈R^n: gravitational vector; And on the other hand:

$$S(q,\dot{q}) = C(q,\dot{q}) - \frac{1}{2}\dot{M}(q) \tag{20-1}$$

where, $C(q.\dot{q}) \in R^{n\times n}$ is Coriolis and centrifugal matrix. And the vector u is equivalent to the control force applied on the first and second joints, which is multiplied by an indeterminate k resulting from the sum of the interaction of sea water and the equivalent driving force and appears as torque in the equation. In the process of designing these control rules, the values of the dynamic parameters with the vector $\theta_d = (\theta_{d1}.\theta_{d2}.\theta_{d3}.\theta_{d4}.\theta_{d5}.\theta_{d6}.\theta_{d7})^T$ where:

$$\theta_{d1} = m_1 l_{c1}^2 + m_2(l_1^2 + l_{c2}^2) + I_1 + I_2 \tag{21-1}$$

$$\theta_{d2} = m_2 l_1 l_{c2} \tag{22-1}$$

$$\theta_{d3} = m_2 l_{c2}^2 + I_2 \tag{23-1}$$

$$\theta_{d4} = m_1 l_{c1} + m_2 I_1 \tag{24-1}$$

$$\theta_{d5} = m_2 l_{c2} \tag{25-1}$$

$$\theta_{d6} = b_1 \tag{26-1}$$

$$\theta_{d7} = b_2 \tag{27-1}$$

Above equations are considered as uncertain dynamic parameters, as well as kinematic parameters with vector $\theta_k = (\theta_{k1}.\theta_{k2}.\theta_{k3})^T$ where:

$$\theta_{k1} = l_1 \tag{28-1}$$

$$\theta_{k2} = l_2 + l_0 \cos(q_0) \tag{29-1}$$

$$\theta_{k3} = l_0 \sin(q_0) \tag{30-1}$$

They are considered as indeterminate kinematic parameters, and finally the driving parameters with the vector $\theta_a = (\theta_{a1}.\theta_{a2})^T$ which are force and numerical are considered as indeterminate parameters. Therefore, the system has 4 state equations that correspond to the design of two control components and 12 matching laws corresponding to the 12 uncertain parameters introduced above. By using the following relationships that express the relationship between the working space and the joint, we can say:

$$\boldsymbol{X} = h(q) \tag{31-1}$$

$$\dot{\boldsymbol{x}}(\mathbf{q}) = J(q)\dot{q} \tag{32-1}$$

Now, by inserting the equations (1-31) and (1-32) and expressing the equations based on the regressor matrix, we can write:

$$M(q)J^{-1}(q)\ddot{x} - (M(q)J^{-1}(q)\dot{J}(q) + B + S(q,\dot{q}) + \frac{1}{2}\dot{M}(q))J^{-1}(q)\dot{x} + g(q) = Ku$$

Considering that the values of the length of the robot links L_1 and L_2, the length of the portable object L_0 and also the angle of movement towards the object q_0 are considered indefinite, the value corresponding to the Jacobian matrix in equation (1-17) will be indefinite and virtual Use its estimate as follows.

$$\hat{x} = \hat{J}(q,\hat{\theta}_k)\dot{q} = Y_k(q,\dot{q})\hat{\theta}_k \tag{33-1}$$

$$Y_k(q,\dot{q}) = \begin{bmatrix} -\sin(q_1)\dot{q}_1 & -\sin(q_1+q_2)(\dot{q}_1+\dot{q}_2) & -\cos(q_1+q_2)(\dot{q}_1+\dot{q}_2) \\ \cos(q_1)\dot{q}_1 & \cos(q_1+q_2)(\dot{q}_1+\dot{q}_2) & -\sin(q_1+q_2)(\dot{q}_1+\dot{q}_2) \end{bmatrix} \tag{34-1}$$

And the estimated Jacobian matrix will be:

$$\hat{J}(q,\hat{\theta}_k) = \begin{bmatrix} -\hat{\theta}_{k1}\sin(q_1) - \hat{\theta}_{k2}\sin(q_1+q_2) - \hat{\theta}_{k3}\cos(q_1+q_2) & -\hat{\theta}_{k2}\sin(q_1+q_2) - \hat{\theta}_{k3}\cos(q_1+q_2) \\ \hat{\theta}_{k1}\cos(q_1) + \hat{\theta}_{k2}\cos(q_1+q_2) - \hat{\theta}_{k3}\sin(q_1+q_2) & \hat{\theta}_{k2}\cos(q_1+q_2) + \hat{\theta}_{k3}\sin(q_1+q_2) \end{bmatrix} \tag{35-1}$$

And the estimation values are related to the kinematic estimation values which are shown in the relation (1-27) to (1-29). Now assuming that x_d ، $\dot{x}_d$ و $\ddot{x}_d$ are the desired path, speed and acceleration in the working space, we define the following components:

$$\dot{x}_r = \dot{x}_d - \alpha(x - x_d) \tag{36-1}$$

$$\ddot{x}_r = \ddot{x}_d - \alpha(\dot{x} - \dot{x}_d) \tag{37-1}$$

With the above definitions, we can express the sliding-adaptive vector for the workspace in the form of the following equations.

$$\hat{s}_x := \hat{\dot{x}} - \dot{x}_r = \hat{J}(q, \hat{\theta}_k)\dot{q} - \dot{x}_r \tag{38-1}$$

$$\dot{\hat{s}}_x = \hat{\ddot{x}} - \ddot{x}_r = \hat{J}(q, \hat{\theta}_k)\ddot{q} + \dot{\hat{J}}(q, \hat{\theta}_k)\dot{q} - \ddot{x}_r \tag{39-1}$$

With this new expression and in the sliding space that was expressed in expressions (1-38) and (1-39), equation (1-32) can be written as follows:

$$M(q)\dot{s} + \left(B + \frac{1}{2}\dot{M}(q) + S(q, \dot{q})\right)s + Y_d\,(q, \dot{q}, \dot{q}_r, \ddot{q}_r)\theta_d = Ku \tag{40-1}$$

In which the dynamic regressor matrix fields are as follows:

$$\begin{aligned}
Y_{d11} &= \ddot{q}_{r1} \\
Y_{d12} &= \cos(q_2)\,(2\ddot{q}_{r1} + \ddot{q}_{r2}) - \sin(q_2)\,(\dot{q}_2\dot{q}_{r1} + (\dot{q}_1 + \dot{q}_2)\dot{q}_{r2}) \\
Y_{d13} &= \ddot{q}_{r2} \\
Y_{d14} &= g\cos(q_1) \\
Y_{d15} &= g\cos(q_1 + q_2) \\
Y_{d16} &= \dot{q}_{r1} \\
Y_{d17} &= 0 \\
Y_{d21} &= 0 \\
Y_{d22} &= \cos(q_2)\,\ddot{q}_{r1} + \sin(q_2)\,\dot{q}_1\dot{q}_{r1} \\
Y_{d23} &= \ddot{q}_{r1} + \ddot{q}_{r2} \\
Y_{d24} &= 0 \\
Y_{d25} &= g\cos(q_1 + q_2) \\
Y_{d26} &= 0 \\
Y_{d27} &= \dot{q}_{r2}
\end{aligned} \tag{41-1}$$

Now, according to the assumption we had before about the Jacobian matrix, the dynamic and kinematic parameters of the submarine robot were estimated values, now assuming this uncertainty in the input transfer matrix (stimulus), the matrix K in relation (1-40) will also be unknown. We will use stimulus matching to compensate. As a result, 3 matching laws for dynamic, kinematic and driving parts are needed to estimate the optimal values for each corresponding part to be used in the control law, so we have the dynamic matching law as follows:

$$\dot{\hat{\theta}}_d = -L_d Y_d^T(q,\dot{q},\dot{q}_r,\ddot{q}_r)s \tag{42-1}$$

$$L_d = diag\{\text{۰,۰۱},\text{۰,۰۰۲},\text{۰,۰۰۲},\text{۰,۰۰۲},\text{۰,۰۱۵},\text{۰,۰۱},\text{۰,۰۱}\} \tag{43-1}$$

We will have the kinematic adaptive law as follows:

$$\dot{\hat{\theta}}_k = L_k Y_k^T(q,\dot{q})\left(K_v\Delta\dot{x} + K_p\Delta x\right) \tag{44-1}$$

where $\Delta x = x - x_d$ and $\Delta\dot{x} = \dot{x} - \dot{x}_d$, so:

$$L_k = diag\{\text{۰,۱۳},\text{۰,۱۵},\text{۰,۰۱۵}\} \tag{45-1}$$

We also express the adaptive law of the stimulus as follows:

$$\dot{\hat{\theta}}_a = -L_a Y_a(\tau.)s \tag{46-1}$$

$$\dot{\hat{\theta}}_k = L_k Y_k^T(q,\dot{q})\left(K_v\Delta\dot{x} + K_p\Delta x\right) \tag{47-1}$$

$$\tau. = \hat{J}^T\left(q,\hat{\theta}_k\right)\left(K_v\Delta\dot{x} + K_p\Delta x\right) - Y_d(q,\dot{q},\dot{q}_r,\ddot{q}_r)\hat{\theta}_d \tag{48-1}$$

$$Y_a(\tau.) = diag\{\tau_{,\text{۱}},\tau_{,\text{۲}},\ldots,\tau_{,n}\} \tag{49-1}$$

$$L_a = \{\text{۰,۱۵},\text{۰,۱}\} \tag{50-1}$$

Are. According to the theorem of inverse dynamics and considering the estimated values and adaptive laws expressed in equations (1-42), (1-44) and (1-46), the formula of the general control law can be written as follows:

$$u = -\hat{K}^{-\text{۱}}\hat{J}^T\left(q,\hat{\theta}_k\right)\left(K_v\Delta\dot{x} + K_p\Delta x\right) + \hat{K}^{-\text{۱}}Y_d(q,\dot{q},\dot{q}_r,\ddot{q}_r)\hat{\theta}_d + \hat{K}^{-\text{۱}}Y_a(\tau.)\hat{\theta}_a \tag{51-1}$$

By inserting equation (3-50) into equation (3-40), we will have the closed loop equation of the system as follows:

$$M(q)\dot{s} + \left(B + \tfrac{\text{۱}}{\text{۲}}\dot{M}(q) + S(q,\dot{q})\right)s + Y_d(q,\dot{q},q_r,\dot{q}_r)\Delta\theta_d + J\left(q,\hat{\theta}_k\right)\left(K_v\Delta\dot{x} + K_p\Delta x\right) + \left(K\hat{K}^{-\text{۱}} - I\right)\tau. - K\hat{K}^{-\text{۱}}Y_a(\tau.)\hat{\theta}_a = \tag{52-1}$$

where

$$\Delta\theta_d = \theta_d - \hat{\theta}_d \tag{53-1}$$

$$\Delta\theta_k = \theta_k - \hat{\theta}_k \tag{54-1}$$

$$\bar{\theta}_a = (\bar{\theta}_{a1}, \bar{\theta}_{a2}, \ldots, \bar{\theta}_{an})^T \tag{55-1}$$

$$\Delta\bar{\theta}_a = \bar{\theta}_a - K\hat{K}^{-1}\hat{\theta}_a \tag{56-1}$$

By placing these relationships in equation (1-51), we will have:

$$M(q)\dot{s} + \left(B + \frac{1}{2}\dot{M}(q) + S(q,\dot{q})\right)s + Y_d(q,\dot{q},q_r,\dot{q}_r)\Delta\theta_d + J(q,\hat{\theta}_k)(K_v\Delta\dot{x} + K_p\Delta x) + Y_a(\tau,)\Delta\bar{\theta}_a = 0 \tag{57-1}$$

In order to prove the stability of relation (3-56) according to the adaptive laws (1-42), (1-44) and (1-46) and the control law (1-49) considering the general Lyapunov function as follows will have:

$$V = \frac{1}{2}S^T M(q)S + \frac{1}{2}\Delta\theta_d{}^T L_d{}^{-1}\Delta\theta_d + \frac{1}{2}\Delta\theta_k{}^T L_k{}^{-1}\Delta\theta_k + \frac{1}{2}\Delta\bar{\theta}_a{}^T L_a{}^{-1}K\hat{K}^{-1}\Delta\bar{\theta}_a + \frac{1}{2}\Delta x^T(K_p + \alpha K_v)\Delta x \tag{58-1}$$

where the Lyapunov function is a positive definite function, now by deriving the Lyapunov function we will have:

$$\dot{V} = -S^T BS - \Delta\dot{x}^T K_v \Delta x - \alpha\Delta x^T K_p \Delta x < 0 \tag{59-1}$$

The derivative of the Lyapunov function is a negative expression, so the closed loop system with equation (1-56) is stable and the objectives of the submarine robot system can be reached in a limited time.

3. Results

In this section, according to the design done for the submarine robot and in order to analyze and check the results of the dynamic equations, control equation and the equations related to the adaptation of the dynamics, kinematics and actuator of the robot are simulated in MATLAB software and the results are also presented and will be reviewed and analyzed. In order to simulate the closed loop system of the robot and the controller, considering an ellipse path specified by the following equations as the optimal path for the robot and considering the numerical parameters for the submarine robot system in the form of relations (60) to (63).

$$X_d \coloneqq 0.5 + 0.1\sin(0.54 + 3 * t) \tag{60-1}$$

$$Y_d \coloneqq 0.5 + 0.1\cos(0.54 + 3 * \mathrm{t}) \tag{61-1}$$

$$m_1 = m_2 = 1(kg) \;\; I_1 = I_2 = 0 \;\;\; l_1 = l_2 = 0.5(m) \;\; l_{c1} = l_{c2} = 0.25(m) \tag{62-1}$$

$$B = diag\{1,1\} \;\; K = diag\{1,1\} \;\; l_0 = 0.06(\mathrm{m}) \;\; \mathrm{q}_0 = \pi/4(\mathrm{rad}) \tag{63-1}$$

where X_d is the desired component for the X axis in the corresponding work space and Y_d is the desired component for the Y axis in the corresponding work space. In this simulation, the fixed parameters for the control system have been selected as (64) to (70), in the selection of these parameters, the conditions of the Lyapunov function have been taken into account, and the conditions of the transient state of the system are also included as a compromise with the control energy. The values are chosen based on the Lyapunov constraints.

$$\widehat{K} = \mathrm{diag}\{1.2.1\} \tag{64-1}$$

$$\alpha = 2 \tag{65-1}$$

$$K_p = \mathrm{diag}\{420,40\} \tag{66-1}$$

$$K_v = \mathrm{diag}\{5.5\} \tag{67-1}$$

$$L_d = diag\{0.01.0.002.0.002.0.002.0.015.0.01.0.01\} \tag{68-1}$$

$$L_k = diag\{0.14.0.15.0.015\} \tag{69-1}$$

$$L_a{:}= diag\{0.15,0.1\} \tag{70-1}$$

where $\widehat{K}$ is the control gain vector, α is the filter system parameter, K_p is the proportional gain vector, K_v is the derivative gain vector, $L_d$is the dynamic adaptive control system gain vector, L_k is the kinetic adaptive control system gain vector and L_a is the actuators adaptive control system gain vector. In this simulation, the initial values for the estimates are in the form of the following relations.

$$\hat{\theta}_d(0) = (0.56.0.188.0.044.1.1250.0.4750.1.50.1.50)^T \tag{71-1}$$

$$\hat{\theta}_k(0) = (0.70,0.76,0.06)^T \tag{72-1}$$

$$\hat{\theta}_a(0) = (0.150,1.50)^T \tag{73-1}$$

which respectively indicate the initial values of estimation of dynamic, kinematic and stimulus parameters. In figure (4-6) the estimated parameters for relations (1-27) to (1-29) are displayed.

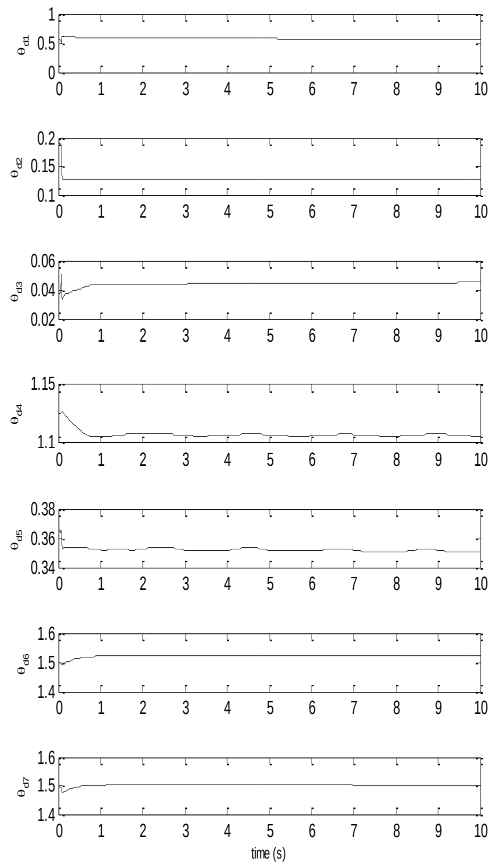

Figure 5: Estimated dynamic parameters

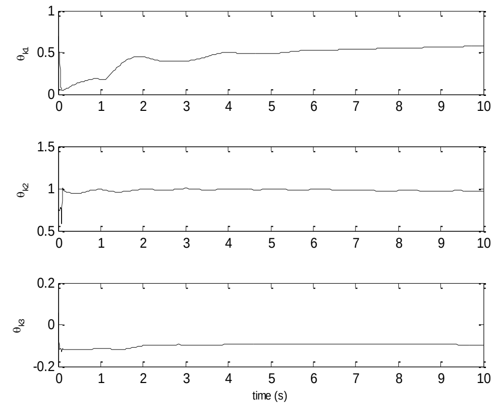

Figure 4: Estimated kinematic parameters

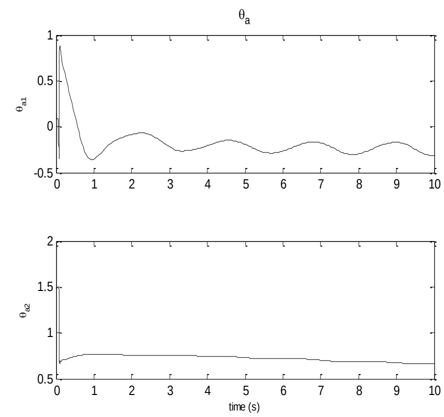

Figure 6: Estimated stimulus parameters

These parameters are shown according to the definition of relation (1-44) from the second chapter, and they are created as a result of considering the uncertainty for the kinematic parameters (Jacobin matrix fields). In fact, the control block of the system is able to form a kinematic relationship in the control force design by using the estimated values in figure (4) and multiplying the matrix formed by them in the kinematic regressor matrix, these values in robots with different dimensions and characteristics , the values will be different, but according to Lyapunov's law, there is no need to accurately estimate these parameters according to what is in the dynamic model, and only the boundedness of these values is sufficient. In Figure (5) the estimated dynamic parameters are given in the second chapter and in relation (1-42) and the control law by forming the matrix composed of these variables and multiplying it in the dynamic regressor matrix able to use the expressions The dynamics will be in the controller equation. Like the kinematic parameters, the boundedness of these values is enough to prove Lyapunov. And finally, in Figure (6) the estimated stimulus parameters are displayed, which are numerical according to the definition made in the chapter and are directly used in the controller. In order to test how the robot moves, the reference path is also used in the form of a vertical elliptical path according to Figure (7) and the way the robot moves is also obtained for it, following the reference diagram with low error and low settling time of the system indicates the path tracking. And in figure (8) this process is shown for a horizontal elliptical path, it is noted that the movement path is estimated according to the Jacobian pattern, which must always have a positive determinant, and this makes a path Choose non-linear and safe to navigate to your desired path.

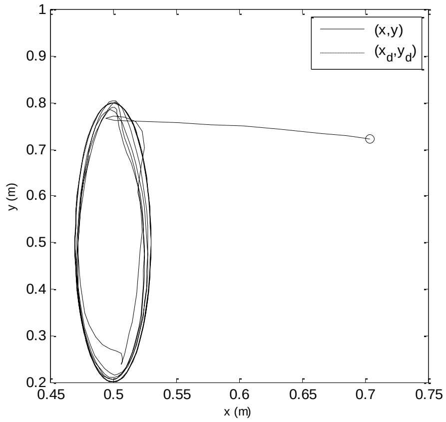

Figure 7: The path tracked by the robot arm along the X and Y axis and the optimal path of the vertical ellipse

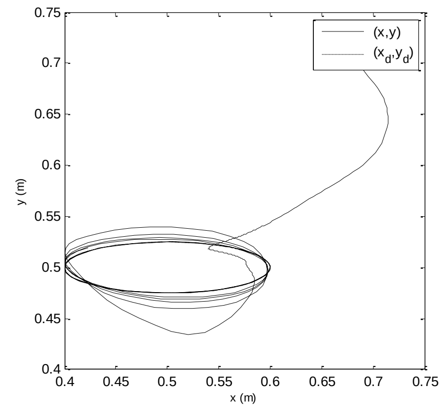

Figure 8: The path tracked by the arm along the X and Y axes and the desired horizontal ellipse path

4. Conclusion

In this paper, the problem of rotation of the submarine robot arm was considered, and accordingly, the uncertainty problem in the variables of the robot arm was considered. Also, the undetermined external forces that are bounded were also applied against the robot, and the results showed that the adaptive controller was able to travel the elliptical path with the least deviation. Also, the results showed that the time characteristics of the system such as the increase in the acceptable limit below 10%, the settling time of the system below the limit of 0.5 seconds and the steady state error below 2% of the final value have all been observed. The resistance of the controller against various disturbances on the floating system showed that the uncertainties caused by the considered friction and pressure forces have been fully stabilized in the system and the effects of these forces have been eliminated in the steady state. For the future works, the following items are suggested: (a) Designing a mobile robot system as a supplement to the described system so that transfer movement can also be considered for the robot. (b) Performing operations related to optimal control in order to save the energy consumed in the robot. For this purpose, non-linear methods such as coefficient of variation or Hamiltonian method can be used. (c) Using sea energy as a source for batteries driving the robot system. (d) The possibility of using fuzzy logic in the detection of power residuals in order to improve the control status of the underwater robot system

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