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Design of Robust Nonlinear Optimal Controller for Underwater Vehicle to Move in Depth Channel using Gradient Descent Method with Systematic Step Selection

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Abstract. This paper proposes the design of a robust nonlinear optimal controller to move the underwater vehicle in the depth channel using gradient descent method. A nonlinear model with six degrees of freedom (6-DOF) has been extracted for the underwater vehicle. To selection of the model and design of controller, conventional assumptions used for other controllers have not been considered and the developed controller can be implemented via at least assumptions. In presented control method, systematic step selection for solving of the algorithm has increased the rate of convergence significantly. The performances of the proposed robust controller for moving in depth channel with considering of parametric uncertainty for the model have been confirmed via some simulations. The results show the desirable performance of developed controller.

Introduction

Submarines currently represent considerable abilities in the field of scientific, military. Thus, modeling and determination of motion equations and applying an appropriate control method for them is very important. Different studies have already been performed in the field of modeling of the submarine. For example, according to the forces that affect on movement of the underwater vehicle, the equations of motion had been derived [1, 2]. The proposed dynamic model for Torpedo underwater vehicle by Holland is another attempt for modeling of submarine [3]. But, despite the ability of computing systems for the simulation of complex and different models, few reports have been published in field of implementation and design of controllers for the vehicle. Among the published cases can be pointed to a comparative research of robust controller and sliding mode using the linear and reduced order models [4]. Also it can be referred to design of fuzzy controller for a submarine that this task is done with a model with five degrees of freedom [5]. Another effort is the design an adaptive single input fuzzy logic controller (ASIFLC) using lots of simplifications [6]. Moreover, depth control of the vehicle based on neural network with considering four state variables and a control input has been presented in [7]. Foregoing presented control methods have advantages and disadvantages. Due to complex nature of underwater systems, it is possible to achieve the better response and more practical implementation by applying suitable nonlinear model that is developed in the current study.

Model Extraction for The Underwater Vehicle

The position and orientation of the vehicle are defined by the quantities that there are according to SNAME notation [8] using Eq. 1 as:

$$\eta_1 = (x, y, z)^T \ , \ \eta_2 = (\phi, \theta, \psi)^T \ , \ \eta = (\eta_1^T, \eta_2^T)^T. \tag{1}$$

Where η_1 denotes the position of the vehicle, and η_2 represents the orientation. Also velocity vectors of the underwater vehicle are defined in the body-fixed frame as shown in Eq. 2:

$$v_1 = (u\,, v\,, w)^T \ , \ v_2 = (p\,, q\,, r)^T \ , \ v = (v_1^T, v_2^T)^T. \tag{2}$$

Here v_1 is the vector of linear velocities and v_2 is the vector of angular velocities.

The kinematic and dynamic equations of motion of the submarine. The kinematic equations of the vehicle are described as the following vector form in Eq. 3:

$$\begin{bmatrix}\dot{\eta}_1\\ \dot{\eta}_2\end{bmatrix} = \begin{bmatrix} J_1(\eta_2) & 0_{3\times3}\\ 0_{3\times3} & J_2(\eta_2)\end{bmatrix}\begin{bmatrix}v_1\\ v_2\end{bmatrix}. \tag{3}$$

Here the matrices $J_1$and J_2 are coordinate transformation matrices [1]. The dynamic equations of submarine are presented according to the submarine forces and moments acting on the vehicle [9,10,11]. The hydrodynamic coefficients which appear in the equations of this paper are related to submarine P650 as shown in Fig.1 [10].

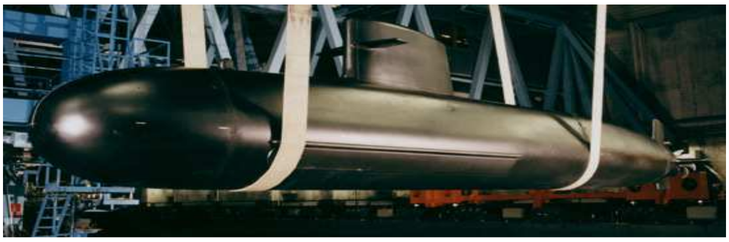

Fig. 1. Schematic of the submarine P-650

Design Of Nonlinear Optimal Controller

In general, the optimal control problem is defined as shown in Eq. 4:

$$\begin{cases} J = \Phi\,(X(T), X^T) + \int_0^T F\big(X(t), U(t)\big)dt, \qquad \dot{X}(t) = f\big(X(t), U(t)\big). \\ \Phi\,(X(T), X^T) = \sum_{j=1}^{12} \alpha_j \left(X_j(T) - X_j^T\right)^2, \quad F\big(X(t), U(t)\big) = \sum_{j=1}^{3} \beta_j \left(U_j(t)\right)^2 + \sum_{i=1}^{12} \delta_i \left(X_i(t)\right)^2. \end{cases} \tag{4}$$

Here $\Phi(X(T), X^T)$ and $F\big(X(t), U(t)\big)$ are two generic functions. There are several optimization methods to solve the mentioned optimization problem, but it seems as if it is solved with the gradient descent method, it provides the ability to achieve the desired response, because the gradient descent method is a very useful method for the large and complex models [12].

Gradient descent method. In the gradient descent method, the search begins from an initial point to find the minimum of a function using gradient descent and it continues with a reasonable step in the direction of the negative gradient to reach the optimal and suitable solution [13]. This method involves the main steps that it is mentioned in the following:

- Initialization of the control signal U^0.
- Calculation of the determined control signal by Eq. 5:

$$U^{k+1} = U^k - \lambda \nabla J(U^k), \quad \text{for } k \geq 0. \tag{5}$$

This step is repeated according to the condition of $\varepsilon|J(U^0)| \leq |J\big(U^{k+1}\big) - J\big(U^k\big)|$. Where $\lambda, \nabla J\big(U^k\big)$ and ε are respectively the step parameter, the gradient of the cost function and the accuracy of measuring. In this method, the choice of algorithm steps is the crucial issue. Using a huge step, it causes that the method would be inefficient and as a result, it cannot be achieved to a proper response. Also, selection of a very small step causes the convergence rate is much reduced [14].

Simulation With Systematic Step Selection

Now the desired optimization problem is solved using the gradient descent method to Satisfies the purpose of rising of the underwater vehicle from 100 meters depth to sea level (zero level) and the step size is systematically selected. For solving this problem, algorithm is designed in such a way that the initial step be a great choice to increases the convergence rate and reduces time. This process continues when error of the cost function to be one-tenth of its initial error, then, this value is reduced to the amount of 0.1 times the size of previous step so that the desired result is achieved. The specified assumptions are described in Eq. 6:

$$\begin{cases} \alpha_3 = 1,\ \alpha_j = 0 \ \text{ for } \ j \neq 3, \qquad \beta_j = 0 \ \text{ for } \ j = 1,2,3. \\ X(0) = (0,0,100,0,0,0,0,0,0,0,0,0), \qquad X^T = (0,0,0,0,0,0,0,0,0,0,0,0). \end{cases} \tag{6}$$

Thus the simulation results are obtained as follows:

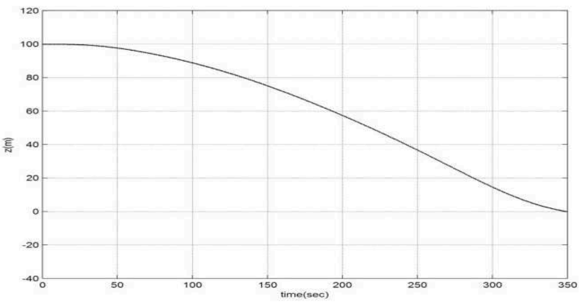

Fig. 2. Rising of the vehicle from100 meters depth to sea level in the depth channel with systematic step selection.

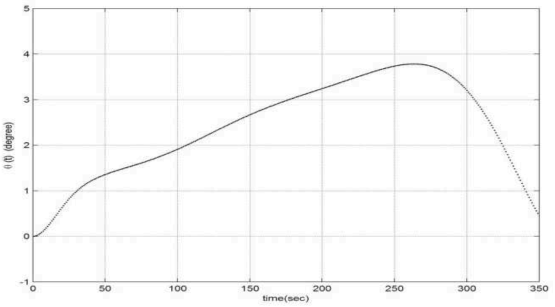

Fig. 3. Pitch Angle $\theta(t)$.

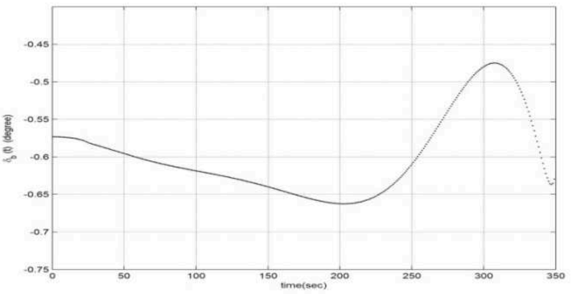

Fig. 4. Deflection of bow plane $\delta_b(t)$.

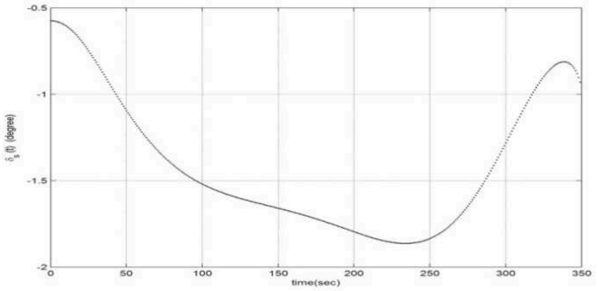

Fig. 5. Deflection of stern plane $\delta_s(t)$.

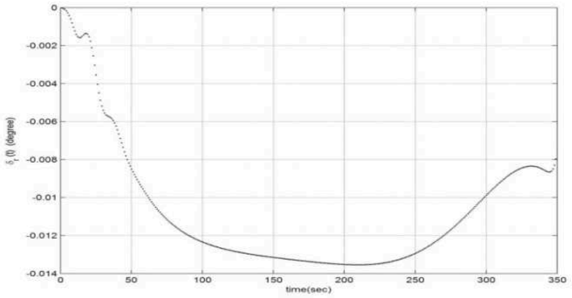

Fig. 6. Deflection of the rudder $\delta_r(t)$.

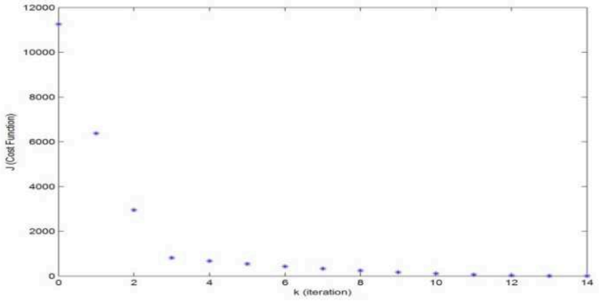

Fig. 7. Cost Function.

Fig. 2 through Fig. 6 indicates that the underwater vehicle could reach from depth of 100meters to the water level by designed controller. It has been placed at the same level at the end time of simulation. As a result, the optimization problem is attained. Also, considering the cost function in Fig.7, it is clear that the designed nonlinear optimal controller could reach to the desired result using the gradient descent method with systematic step selection.

Design Of Robust Controller by Considering Parametric Uncertainty

The change of parameters of the model during the process can Create errors and uncertain in the determination of these values. Hence in this section, the real uncertainty is considered for the mass of submarine that is a very important parameter and it is applied in the objective function and the robust nonlinear optimal controller is simulated in MATLAB to ensure stability and optimal performance in the mentioned conditions [15].

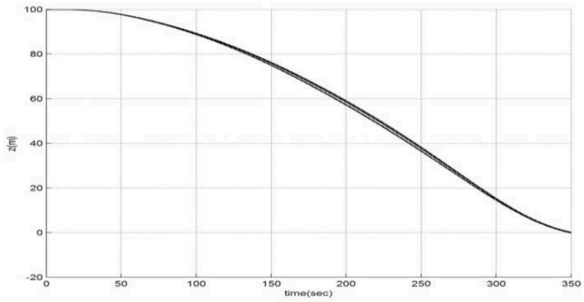

Fig. 8. Rising of the vehicle from 100 meters depth to sea level using the robust nonlinear optimal controller

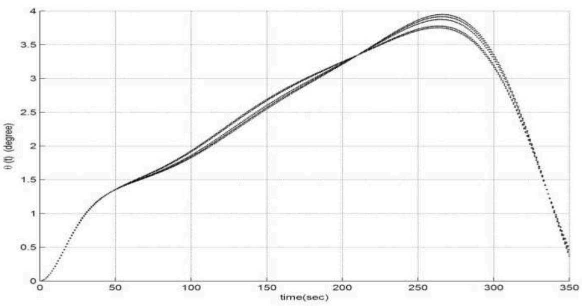

Fig. 9. Pitch Angle $\theta(t)$.

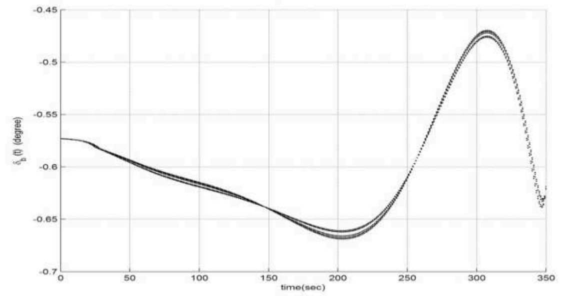

Fig.10. Deflection of bow plane $\boldsymbol{\delta_b(t)}$.

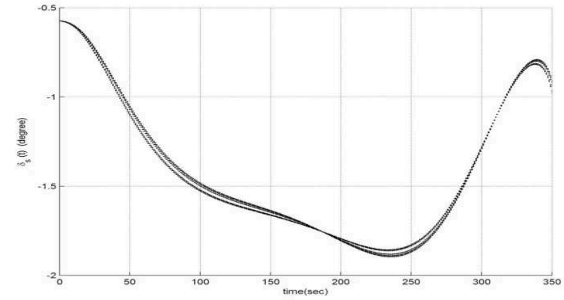

Fig. 11. Deflection of stern plane $\boldsymbol{\delta_s(t)}$.

As shown in Fig. 8 through Fig. 11, despite the real uncertainty in the mass of the submarine, the control of its rising maneuver has carefully been performed with applying the range of variable mass in the operation of the depth changes. Therefore, we can conclude it that the robust nonlinear optimal controller has been desired results.

Conclusion

In this paper, according to the highly complex nature of the submarine, its model was extracted with six degrees of freedom in nonlinear form. While in most previous presented articles in this field, the designs are based on linear models, less degrees of freedom or the simplification model. As a result, the system is closer to reality and it is easier for implementation. Then, nonlinear optimal controller was designed using gradient descent method with systematic step selection that the vehicle accomplishes the maneuvering of its rising. It caused that the time of solving of the problem is significantly decreased compared to previous articles and the results were obtained with very well convergence rate. Considering the uncertainty of the model parameters, the robust controller was designed beyond the previous papers. The maneuverability of movement in the depth channel was performed well using this controller. Also, stability and performance of the robust nonlinear optimal controller against uncertainties in the model parameters was desirable that the vehicle maneuver in the depth channel.

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