# Controller Design for the Pitch Control of an Autonomous Underwater Vehicle

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**Abstract-In recent years, the Autonomous Underwater Vehicle (AUV) has found its application in a large number of areas, especially in the ocean environment. But due to its highly non-linear nature with six degrees of freedom and the presence of hydrodynamic forces, the equations for AUV control become complex and difficult to design. Hence, in order to overcome this complexity and non-linearity, a reduced-order subsystem is derived for controlling the pitch. Linear Quadratic Regulator (LQR) and Fractional Order PID (FOPID) techniques have been applied for determining the controller for better performance of pitch control in the presence of disturbance.**

*Keywords-Autonomous Underwater Vehicle (AUV); IMC-PID; LQR; FOPID*

## I. INTRODUCTION

An AUV is an automatic submersible vehicle that can function in the absence of real time controller, without any human interference [1]. The presence of nonlinearity in the vehicle dynamics makes difficult to apply linear controller to the AUVs and the complexity in the dynamics of AUVs makes the design of its controller difficult. Due to the presence of high non-linearity, time-varying characteristics, unpredictable hydraulic coefficients, and the interference caused by sea currents and waves, the dynamics of the AUV become quite complex. The design of a controller for AUV is a challenging task as the complexity in design basically lies in finding the hydrodynamic parameters and the non-linearity in the dynamics of the vehicle [2]. In order to control the pitch of AUV many methods have been proposed. The LQR-based controller has been designed for the derived divine plane model of AUV and the performance is analyzed with Matlab/Simulink in [3, 4].

The current paper, gives a detailed study of the Particle Swarm Optimization (PSO) algorithm used to optimize the Fractional Order PID (FOPID) controller for obtaining a fast and robust response for the pitch control of an AUV [1, 5]. The parameters obtained using the PSO-based FOPID will be utilized for obtaining the response for pitch angle. The response of the PSO based FOPID controller is compared with the response of IMC-PID and LQR controllers. With the help of the response, Rise Time, Settling Time, Overshoot and Integral of Time Absolute Error (ITAE) can be computed. ITAE has been considered as the objective function [6, 7].

## II. MODELING OF THE AUV

The mathematical modelling of an AUV requires the study of its kinematics and dynamics. The geometrical aspect describes the kinematics, while the dynamics of the vehicle describe and analyze the forces that cause motion [8]. To identify the location and direction of the AUV, the differential equation of the vehicle's 6-DOF (degrees of freedom) motion must be solved [9]. The positional and translational motion along $x$, $y$ and $z$ axes is represented using flow, amplitude, and heave [9] respectively, while the orientation and rotational motion are described with the help of roll, pitch, and yaw [1, 11, 12]

### A. Vehicle Kinematics

A two-coordinate frame has been used to analyze a vehicle path with 6 DOFs [13]. Because it is attached to the vehicle, the moving reference frame is known as a body-fixed reference frame [13, 14]. An inertial frame is used to describe the trajectory of the body-fixed frame. With the body-fixed frame, we can characterize the vehicle's linear and angular velocities, whereas the inertial frame describes its position and orientation [1]. Six-DOF vehicle motion can be represented in a generic sense by the following vectors [14]:

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$$\eta = \begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix} \quad (1)$$

$$v = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \quad (2)$$

$$\tau = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \quad (3)$$

where $\eta_1 = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$ is the position vector, $\eta_2 = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix}$ the Euler angle vector, $v_1 = \begin{bmatrix} u \\ v \\ w \end{bmatrix}$ the uniform speed vector [3], $v_2 = \begin{bmatrix} p \\ q \\ r \end{bmatrix}$ the rotational speed vector, $\tau_1 = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$ represents the direction of the forces, and $\tau_2 = \begin{bmatrix} K \\ M \\ N \end{bmatrix}$ is the moments vector.

TABLE I.        MOTION OF THE AUV

| DOFs | Motion | Forces and moments | Velocity [10] | Position and Euler angles [10] |
|---|---|---|---|---|
| 1 | Surge | $X$ | $u$ | $x$ |
| 2 | Sway | $Y$ | $v$ | $y$ |
| 3 | Heave | $Z$ | $w$ | $z$ |
| 4 | Roll | $K$ | $P$ | $\phi$ |
| 5 | Pitch | $M$ | $q$ | $\theta$ |
| 6 | Yaw | $N$ | $r$ | $\psi$ |

The Euler angle transformation $\dot{\eta} = J(\eta_2)v$, where $J(\eta_2)$ is the Jacobian matrix, represents plotting among the two coordinate systems [14].

### B. Vehicle Dynamics

The vehicle dynamics consist of translational as well as rotational motion [3, 8]. The equation for the translatory movement of the vehicle is:

$$m(v_0 + \omega * v_0 + \dot{\omega} * r_g + \omega * (\omega * r_g)) = f_0 \quad (4)$$

and the rotational movement of the vehicle is:

$$I_0\dot{\omega} + \omega * (I_0\omega) + mr_g * (v_0 + \omega * v_0) = m_0 \quad (5)$$

By employing Newton's and Euler's equations and ignoring surge, sway, heave, and yaw, the equation of pitch control can be expressed as [8, 15]:

$$\begin{aligned} I_x\dot{p} + (I_z - I_y)qr - (\dot{r} + pq)I_{XZ} + (r^2 - q^2)I_{yz} \\ + (pr - \dot{q})I_{xy} \\ + m[y_g(\dot{w} - uq + vq) \\ - z_g(\dot{v} - wp + ur)] = K \end{aligned} \quad (6)$$

$$\begin{aligned} I_y\dot{q} + (I_x - I_z)rp - (\dot{p} + qr)I_{Xy} + (p^2 - r^2)I_{xz} \\ + (qp - \dot{r})I_{yz} \\ + m[z_g(\dot{u} - vr + wq) \\ - x_g(\dot{w} - uq + vp)] = M \end{aligned} \quad (7)$$

Assuming the velocity of the heave is very small and can be neglected, the state space equation of the system will be [16]:

$$\begin{bmatrix} I_y - M_q & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} \dot{q} \\ \dot{z} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} -M_q & 0 & M_\theta\theta \\ 0 & 0 & u_1 \\ -1 & 0 & 0 \end{bmatrix}\begin{bmatrix} q \\ z \\ \theta \end{bmatrix} = \begin{bmatrix} M_{fs} \\ 0 \\ 0 \end{bmatrix} \quad (8)$$

The transfer function for the pitch control can be obtained from the matrix representation as:

$$G_\theta(s) = \frac{\theta(s)}{f_s(s)} = \frac{\frac{M_{fs}}{I_y - M_q}}{s^2 - \frac{M_{fs}}{I_y - M_q}s - \frac{M_\theta}{I_y - M_q}} \quad (9)$$

The transfer function for the AUV can be obtained considering the following data: Fin lift $(M_{fs})$ = -1575.9kg.m$^2$/s, $I_y$= 469kg/m$^2$, added mass $M_q$ = -458 kg.m$^2$, hydrostatic $M_\theta$ = 13719.6kg.m$^2$/s$^2$, and takes the following form:

$$G_\theta(s) = \frac{-1.818}{0.0077s^2 + 0.507s + 1} \quad (11)$$

### III.    CONCTROLLER DESIGN

In this section, we will go over the designs of various controllers that will be used to control the pitch of the AUV. It is necessary for the controller to be observable in all the states in order to be used effectively.

### A. IMC-PID Controller

The Internal Model Controller (IMC) is composed of a constant controller $Q(s)$ and the plant model, where $G(s)$ is the model of the plant. It is equipped with an inbuilt filter controller $F(s)$. $Q(s)$ and $F(s)$ are corrected by increasing the robustness of the filter, which is achieved by selecting the filter parameter appropriately [2]. Figure 1 gives a representation of an IMC structure. The controller is given by:-
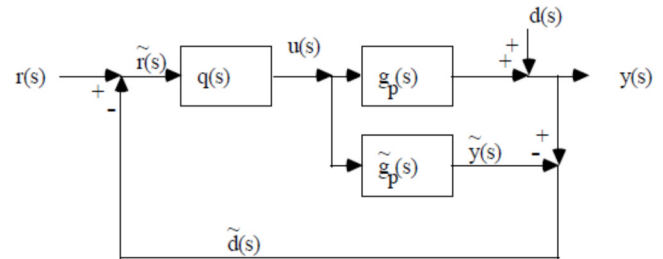
$$g_c(s) = \frac{q(s)}{1 - g_p(s)q(s)} \quad (12)$$



Fig. 1.    IMC structure.

### B. Linear Quadratic Regulator (LQR) Controller

The advantage of using LQR is that it provides practical feedback gain [3]. Conventional controllers have a drawback as they result in higher overshoot and due to the lack of proper tuning, often the controller is not optimal [17]. The state space model of the system is given by [3]:

$$\dot{x} = Ax + Bu \quad (13)$$

The LQR design method consists of designing the gain factor $K$, i.e. a state feedback. The objective function $J$ is taken in such a way that its minimization makes the system stable [3]:

$$J = \int_0^\infty (x^T Q x + u^T R u) dt \quad (14)$$

$Q$ and $R$ represent symmetrical diagonal matrices that decide the weight factors [3]:

$$Q, R \geq 0 \quad (15)$$

The main aim of the LQR controller is to give optimal feedback gain as described below [3]:

$$u = -Kx \quad (16)$$

The feedback gain ($K$) can be calculated using the Matrix Algebraic Riccati Equation (MARE) [3] as follows:

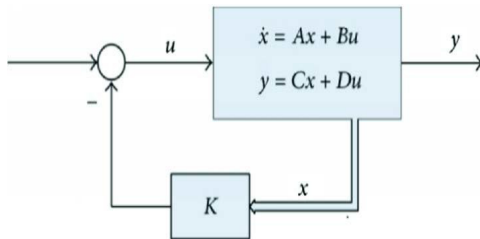$$u = -R^{-T} B^T P x \quad (17)$$

$$K = -R^{-T} B^T P \quad (18)$$

Fig. 2.     LQR structure.

## C. Fractional Order PID Controller [18]

Podlubny proposed the fractional order PID controller in 1997 [19], and since then, it has become widely used. It should be noted that the order of the integrator and differentiator in FOPID is different from the order of the integrator and differentiator in the typical PID controller. Both the integrator and the differentiator should be in the correct order [18, 20]. The transfer function of a PID controller of this type is:

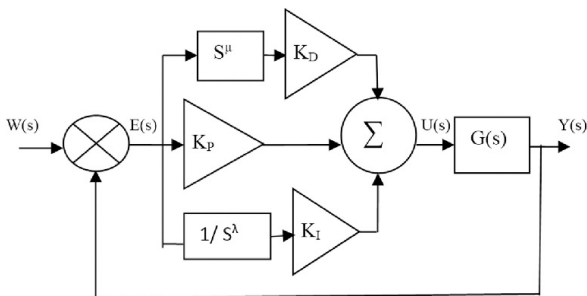$$G_{fo}(s) = K_p + \frac{K_i}{s^\lambda} + K_d S^\mu \quad (19)$$

Fig. 3.     FOPID structure.

Authors in [5] proposed the Particle Swarm Optimization (PSO) technique, in which a swarm is represented by $m$ particles. These particles are described by two variables, $x$ and $v$, representing the position and its corresponding velocity in the search space. The PSO algorithm is given in Figure 3. The algorithm starts with randomly initializing the particles and updating their position and velocity values until an optimized value is obtained [1]. The updated equation for position and velocity for the swarm in the search space is given by:

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (20)$$

$$v_i(t+1) = \omega v_i(t) + C_1 \emptyset_1 [b_i(t) - x_i(t)] + C_2 \emptyset_2 [g(t) - x_i(t)] \quad (21)$$

ITAE has been considered as the objective function and is given by:

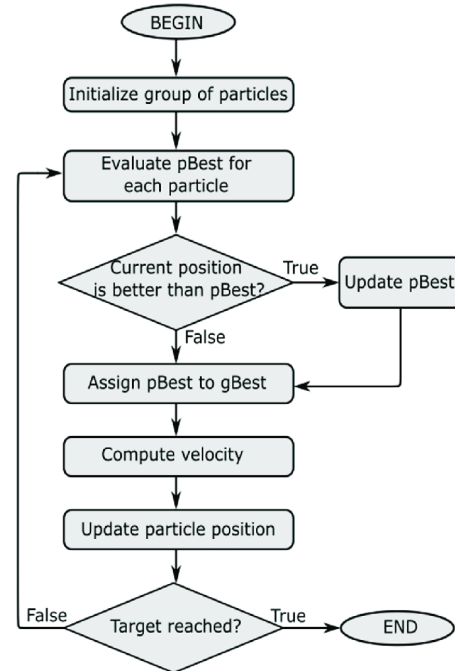$$ITAE = \int_0^\infty t|e(t)|dt \quad (22)$$

Fig. 4.     Flowchart of the PSO algorithm.

With the help of PSO, it is possible to optimize the parameters of the FOPID controller. The initial population is assumed to be 100 and the number of iterations is calculated to be 50.

## IV.     RESULTS AND DISCUSSION

### A. Simulation of Pitch Control For AUV

The step response for the pitch control of the AUV using IMC-PID, LQR-PID, and FOPID is shown in Figure 5. The performance comparison of the three controllers is shown in Table II.

TABLE II.     PARAMETER INDEX OF STEP FOR PITCH SUBSYSTEM

| Method | Over-shoot (%) | $T_r$(s) | $T_s$(s) | $T_p$(s) | ITAE |
|---|---|---|---|---|---|
| IMC-PID | 30.8 | 0.896 | 18.3 | 2.05 | 4.068 |
| LQR | 5.27 | 0.532 | 7.39 | 1.07 | 3.79 |
| FOPID | 3.55 | 0.0129 | 0.0558 | 0.031 | 2.867 |

### B. Simulation of Pitch Control For AUV in the Presence of Disturbance

The response of the pitch subsystem using IMC-PID, LQR and FOPID in the presence of sinusoidal disturbance is illustrated in Figure 6.
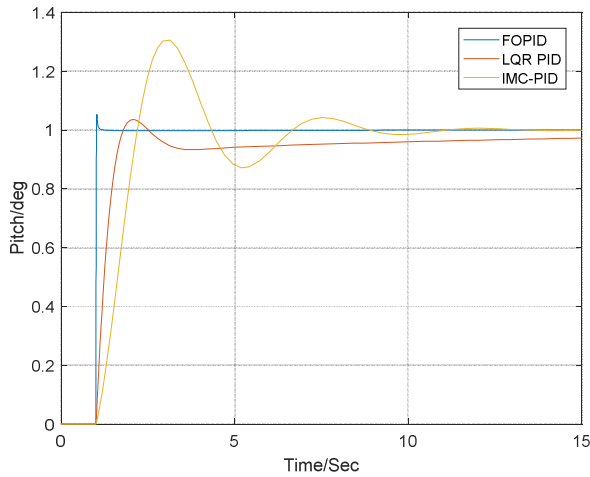
Fig. 5.    Step response of the pitch subsystem via FOPID, OPTIMAL PID, and IMC-PID.
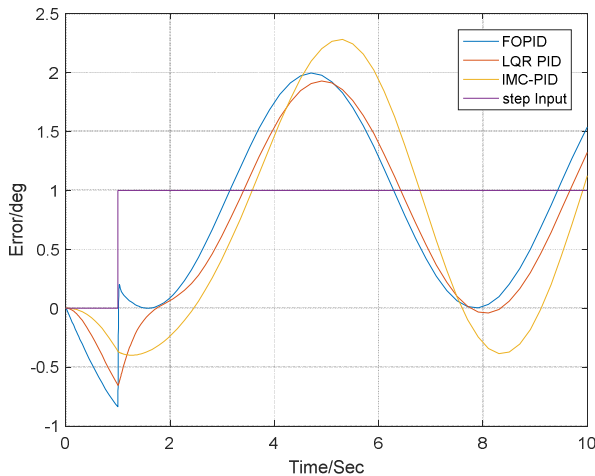


Fig. 6.    Response of the pitch subsystem via FOPID, OPTIMAL PID, and IMC-PID in the presence of disturbance.

TABLE III.     PARAMETER INDEX FOR THE RESPONSE OF THE PITCH SUBSYSTEM IN THE PRESENCE OF DISTURBANCE

| Method | Over-shoot (%) | $T_r$(s) | $T_s$(s) | $T_p$(s) | ITAE |
|---|---|---|---|---|---|
| IMC-PID | 32.33 | 2.236 | 36.66 | 4.579 | 11.642 |
| LQR | 5.96 | 1.601 | 10.96 | 1.015 | 10.978 |
| FOPID | 4.62 | 0.9720 | 0.0558 | 0.626 | 10.447 |

## V.    CONCLUSION

This study presents a PID control technique for AUV pitch subsystems that is of fractional order. When compared to optimum PID and IMC-PID, this technique has significantly shorter settling time, rising time, peak time, and overshoot. It demonstrates an increase in the quickness of response in the presence of a disruption. It is obvious from the simulations that the performance of the proposed FOPID is superior to that of the optimum controller and the IMC.

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