Robust $\mathcal{PT}^\lambda$ controller design for AUV motion control with guaranteed frequency and time domain behaviour

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Abstract

Autonomous underwater vehicles require a motion control system for performing underwater tasks such as exploring and developing marine resources. This study proposes a fractional-order proportional-integral ($\mathcal{PT}^\lambda$) controller for autonomous underwater vehicles motion control that simultaneously guarantees frequency and time domain behaviour. First, a stabilisation process is presented for the controlled system, and a three-dimensional stable surface is obtained. Subsequently, the controller parameters can be tuned. Then, to guarantee frequency and time domain control performance simultaneously, the frequency domain behaviour is studied through a modified flat phase property, and the time domain behaviour is improved through parameter optimisation. The set-point regulation and noise suppression performances of the autonomous underwater vehicles motion control system indicate that the proposed $\mathcal{PT}^\lambda$ controller provides more flexibility in improving the system’s robustness and transient performance.

1 | INTRODUCTION

An autonomous underwater vehicle (AUV) is a type of small, efficient, and intelligent underwater robot that integrates artificial intelligence, system integration, detection and recognition technologies, etc., [1, 2]. Compared with other underwater robots, AUVs afford unique advantages such as a small size, low noise, and low costs. AUVs have broad application prospects in underwater engineering [3] because they can complete scheduled underwater tasks through an autonomous decision-making and control system. This makes them suitable for military tasks such as mine detection, mine clearance, intelligence collection, and target indication and civilian tasks such as marine environmental measurement, observation, and data collection.

The motion control system is key to ensuring flexible AUV operation in complex marine environments [4]. The requirements of AUV motion control performance have increased sharply because of trends such as increasing miniaturisation, motorisation, and flexibility. However, the dynamic and hydrodynamic characteristics of AUVs are hard to model and may be quite different from their nominal values in practice. Further, the AUV control performance will be affected by factors such as aging, component damage, disturbances caused by wind, waves, and currents, sensor noise, and transmission channel...
delay. Finally, owing to the limitations of human resources, time, and costs, an AUV cannot be debugged and verified at each stage of its design and development. Therefore, the main concerns in AUV motion controller design are stability, robustness, and easy tunability and implementation.

Propportional-integral-derivative (PID) control has a simple structure and is easy to implement. It is the most mature control method applied in the industrial field [5] and is also one of the most commonly used control methods in AUV motion control. For example, Jalving and Storkersen applied a PID controller to the NDREA underwater vehicle and successfully conducted some sea tests [6]. Perrier and Canudas-De-Wit added a non-linear control loop to an actual linear PID controller that was independent of the system model [7]. Zanoli and Conte used a PID controller to conduct simulations and experiments related to the depth and fixed-point control of an underwater vehicle and achieved satisfactory control performance [8]. Khodayari and Balochian designed an adaptive fuzzy PID controller and applied it to the dual-channel tracking control of an underwater vehicle for direction and depth control [9]. Refsnes and Sorensen proposed a modified PID controller that considered the effect of ocean currents and applied it to the Minesniper MKII underwater vehicle [10]. Liu and Xu proposed an S-surface control method that combined fuzzy control and PID-type control to simplify the intelligent controller design process and achieved good robustness and transient performance [11].

Although PID controllers provide the above-mentioned advantages, their application to underwater vehicle motion control inevitably has some drawbacks. For example, a traditional PID-type controller is sensitive to parameter uncertainties, noise, and disturbance. Further, the differential action is especially sensitive to measurement noise, making it hard to estimate the velocity vector of an underwater vehicle. Moreover, a closed-loop system with a PID controller may become unstable when parameter uncertainties occur together with environmental changes. Therefore, studies have proposed some combinations of PID and intelligent control methods to improve the robustness of the system [4, 12]. Nonetheless, the controller parameter tuning process remains complex, and the controller is hard to implement; these factors may reduce the advantages of PID control.

Recently, owing to innovations in fractional calculus, fractional-order control has attracted much research attention in engineering fields [13–19]. As a representative example, Podlubny was the first to propose a fractional-order PID ($\text{PI}^\lambda \text{D}^\mu$) controller [20]. $\text{PI}^\lambda \text{D}^\mu$-type controllers benefit from additional integral and differential orders and can, therefore, offer more flexibility in improving the system's robustness and transient performance [21–24]. More importantly, $\text{PI}^\lambda \text{D}^\mu$-type controllers are an extension of PID controllers and are similarly easy to tune and implement, making them suitable for various practical applications. For example, $\text{PI}^\lambda \text{D}^\mu$ controllers based on frequency response shaping have been used for AUV depth and attitude control [25, 26]. However, studies on $\text{PI}^\lambda \text{D}^\mu$ controllers remain limited; in particular, some primary issues such as stability and robustness analysis have not yet been discussed.

Previous studies have proposed some robust $\text{PI}^\lambda \text{D}^\mu$-type controllers based on the flat phase property and magnitude/magnitude/phase margins [27, 28]. The robustness of such controllers has been verified in some practical applications [27, 29]. However, to find a feasible parameter pair, these studies adopted a trial-and-error approach for finding the crossover frequency; therefore, they emphasised only the frequency domain behaviour and ignored the transient performance in the time domain.

As an improvement over previous studies in this area, the present study provides a robust $\text{PI}^\lambda$ controller design for an AUV motion control system that can simultaneously fulfil the time and frequency domain requirements. First, the system stability is discussed, and the controller parameter intervals are obtained to fulfil the robust frequency domain requirements. Then, the crossover frequency is optimised to improve the transient control performance in the time domain. Therefore, all the primary concerns, namely, stability, robustness, and transient performance, of the AUV motion control system can be guaranteed. Moreover, the flat phase property is improved, thereby avoiding the problem of solving several complicated non-linear equations that may not have a solution [28].

An AUV motion control system with the proposed $\text{PI}^\lambda$ controller affords the following advantages:

- Obtain the preferable frequency and time domain transient control performance simultaneously.
- Maintain a stable surface when the internal or external environment changes.
- Be robust to load and parameter uncertainties and disturbances.
- Obtain at least one controller parameter pair under the required frequency and time domain specifications.

The rest of this paper is organised as follows. Section 2 introduces the AUV motion control system. Section 3 describes the stabilisation process and the selectable parameter sets. Section 4 presents the controller design process with improved frequency and time domain specifications. Section 5 presents simulation results that verify the control performance of the proposed method. Finally, Section 6 presents the conclusions of this study.

## 2 AUV MOTION CONTROL MODEL

Without loss of generality, the CISCREA AUV motion control model which has the most typical AUV configuration is studied in this paper [30].

The four-degree-of-freedom non-linear mathematical model including surge, sway, heave and yaw motion can be expressed as

$$\left(M_{RB} + M_A\right)\ddot{v} + D(|\dot{v}|)\dot{v} + g(\eta) = \tau,$$  \hspace{1cm} (1)

where $M_{RB}$ is the inertial matrix caused by mass and inertia of underwater vehicle; $M_A$ is the added mass matrix caused
by the hydrodynamic force from the inertial action of the surrounding liquid during the acceleration of the underwater vehicle; the damping matrix \( D([\dot{q}]) \) represents the hydrodynamic force which has a function relationship with the speed of the vehicle, and it is quite difficult to calculate or estimate accurately; the restoring force \( g(r) \) is related to the gravity and buoyancy; \( \tau \) is the propeller force, \( \eta = [x, y, z, \dot{\phi}] \) and \( \dot{r} = [u, v, w, \dot{r}] \) are position and velocity vectors. Most of the existing AUVs are multi-input-multi-output systems [31]. These degrees of freedom can be decoupled under certain circumstances in the practical manipulation process, so each of them can be treated as a single-input-single-output system. Because of the propeller configuration, some AUVs have self-stability in pitch and roll motion. Therefore, we only consider the yaw motion control in this paper. Fast, accurate and stable yaw action is the basis premise for an AUV to explore complex space, observe detected space and perform precise operation in marine environment.

Assuming the attitude of the controlled AUV is always perpendicular to gravity, the gravity and buoyancy are not considered, so the AUV non-linear yaw model can be decoupled from Equation (1) as [30]:

\[
(I_{YRB} + I_{YLA}) \ddot{\phi} + (D_{YLA} + D_{YN} |\dot{\phi}| + D_{YL}) \dot{\phi} = \tau, \tag{2}
\]

where \( \phi \) is the yaw angle, \( I_{YRB}, I_{YLA} \) are inertial tensors of the controlled AUV and the added mass from \( M_{RB}, M_{A} \), \( D_{YLA}, D_{YN} \) are linear and non-linear damping coefficients, and \( D_{YL} \) is the artificial linear damping coefficient, these are extracted from \( D \). According to Equation (2), the yaw model is non-linear, and the non-linearity mainly generates from the quadratic damping effect. However, complex non-linear controller is hard to tune and implement for AUV control, which may increase the design burden and implementation cost. It is better to simplify the controlled model as well as maintain a high degree of control performance. According to the numerical simulation and pool experiment tests in [30], when the highest surge speed is about 1 m/s, \( D_{YLA}, D_{YN} \) are negligible compared to \( D_{YL} \). Then, define \( \Delta = D_{YN} |x| + D_{YL} \), and the non-linear \( \Delta \) is about 23% of \( D_{YL} \) under the worst damp condition, so Equation (2) can be transformed into

\[
(I_{YRB} + I_{YLA}) \ddot{\phi} + (D_{YLA} + \Delta) \dot{\phi} = \tau, \tag{3}
\]

where \( \Delta \) is treated as the uncertainty of \( D_{YL} \).

Remark 1. It is difficult to analyse and study the control methods of the original systems (1) and (2) because they are both non-linear systems with complex dynamics. To simplify the studied systems (1) and (2), the equivalent system (3) is obtained by approximating the linear part and non-linear part \( \Delta \). Then, the corresponding approximate linear system (4) is proposed by transforming system (3) into frequency domain. By using the approximate system (4) in frequency domain, the corresponding robust FOPI controller can be achieved theoretically.

Then, the approximate linear AUV yaw model is obtained as a second-order linear system with uncertainties:

\[
P(s) = \frac{K_Y}{s(T_Y s + 1)}, \tag{4}
\]

where \( K_Y = 1/(D_{YL} + \Delta) \) and \( T_Y = (I_{YRB} + I_{YLA})/(D_{YL} + \Delta) \).

The propeller model of AUV can be expressed by a first-order time-delay transfer function as

\[
P_M(s) = \frac{K_M}{T_M s + 1} e^{-L_s}, \tag{5}
\]

where \( K_M, T_M, L \) are motor parameters.

The overall AUV yaw model is obtained as

\[
P(s) = \frac{K}{s(T_Y s + 1)(T_M s + 1)} e^{-L_s}, \tag{6}
\]

where \( K = K_Y K_M, T_1 = T_Y, T_2 = T_M \).

Summing up the above discussion, the main problems of AUV motion control become: the uncertainties of dynamic and hydrodynamic parameters as well as load difference which are integrated into system gain \( K \); the non-linear quadratic damping effect which is integrated in \( K, T_Y \); the internal and external noise of marine environment.

3 | STABILITY ANALYSIS

\( P^L \dot{x} \)-type controllers are the extension of PID-type controllers. Two extra tuning parameters, namely integral and differential orders, are introduced on base of the original PID controller composition. Benefitting from these extra parameters, systems with \( P^L \dot{x} \)-type controllers could achieve more superior transient performance, robustness and adjustment flexibility. However, the corresponding stability analysis and parameter tuning process may become more complicated [28].

The \( P^L \dot{x} \) controller \( C(s) \) proposed in this paper can be expressed as

\[
C(s) = k_p + \frac{k_i}{s^\lambda}, \tag{7}
\]

where \( k_p, k_i \) are proportional and integral parameters, and \( \lambda \) is the integral order.

For the overall AUV yaw model (6), its open-loop transfer function \( F(s) \) under \( P^L \dot{x} \) controller (7) is obtained as

\[
F(s) = P(s) C(s) = \frac{K e^{-L_s} (k_p \lambda + k_i)}{s^{\lambda+1}(T_Y s + 1)(T_M s + 1)}. \tag{8}
\]

Note that constant \( K \) is a system gain, which does not have connection with the stability of controlled system. Thus, \( K \) is always ignored in stability analysis. With omitting \( K \), the corresponding
close-loop transfer function \( G(s) \) is implied by
\[
G(s) = \frac{F(s)}{1 + F(s)} = e^{-Ls}(k_p \lambda^2 + k_i) + e^{-Ls}(k_p \lambda^2 + k_i) + \lambda^4 + 1)(T_1 s + 1)(T_2 s + 1).
\]

So the corresponding characteristic equation \( D(s) \) (the denominator of \( G(s) \)) of the studied AUV yaw control system is obtained as
\[
D(s) = e^{-Ls}(k_p \lambda^2 + k_i) + \lambda^4 + 1)(T_1 s + 1)(T_2 s + 1). \tag{9}
\]

Then, it is necessary to find out the parameter intervals which can guarantee the stability of the studied AUV yaw system. These intervals could serve as the upper and lower boundaries in the control performance optimisation process in next section. In this way, the controller parameters are optimised on the premise of maintaining system stability. Put the parameter intervals of \( k_p, k_i, \lambda \) together, a three-dimensional surface which is the stable space of the controlled system can be achieved.

The controlled system stability mainly depends on the root locations of Equation (9). The stability boundaries can be achieved in accordance with RRB (real root boundary, \( s = 0 \)), IRB (infinite root boundary, \( s = \infty \)) and CRB (complex root boundary, \( s = jw \)) curves. It has been discussed in [32] that IRB did not exist in a strictly proper control system. Therefore, RRB and CRB are discussed to find the stable surface in this section.

**RRB can be described as**
\[
D(s = 0) = k_j = 0. \tag{10}
\]

Therefore, \( k_j = 0 \) is one of the stability boundaries.

**CRB is obtained as**
\[
D(s = jw) = 0 = e^{-jw - \lambda w}(k_p \lambda^2 + k_i) + \lambda^4 + 1)(-T_1 T_2 w^2 + T_1 jw + T_2 jw + 1) + (C_1 + S_1 j)k_p \lambda^2 + (C_2 + S_2 j)k_i + w^2 (C_3 + S_3 j)(jw - T_1 T_2 w^3 j - T_1 w^2 - T_2 w^2), \tag{11}
\]
where \( \phi_w \) is the desirable phase margin, and
\[
C_1 = \cos(\lambda \pi / 2 - Lw - \phi_w),
S_1 = \sin(\lambda \pi / 2 - Lw - \phi_w),
C_2 = \cos(-Lw - \phi_w),
S_2 = \sin(-Lw - \phi_w),
C_3 = \cos(\lambda \pi / 2),
S_3 = \sin(\lambda \pi / 2),
\]
which means both the real part and imaginary part of Equation (11) are equal to 0. Hence, it is obtained that
\[
C_1 k_p \lambda^2 + C_2 k_i + A_1 = 0,
S_1 k_p \lambda^2 + S_2 k_i + A_2 = 0, \tag{12}
\]

where
\[
A_1 = w^2 (-T_1 C_3 w^2 - T_2 C_3 w^2 - S_3 w + S_1 T_1 T_2 w^3),
A_2 = w^2 (C_3 w - T_1 T_2 C_3 w^3 - S_3 T_1 w^2 - S_1 T_2 w^2).
\]

From Equation (12), \( k_p, k_i \) can be expressed as
\[
k_p(\lambda, w) = \frac{A_2 C_1 - S_3 A_1}{S_1 C_2 - C_1 S_2},
\tag{13}
\]

Hence, under a fixed \( w \), a three-dimensional stability surface of \( (k_p, k_i, \lambda) \) can be obtained by sweeping over \( \lambda \in (0, 2) \) with small enough increments. All the parameter pairs on this stable surface can ensure the stability of the studied AUV yaw control system.

### 4 | \( P^\delta \) CONTROLLER DESIGN WITH IMPROVED FREQUENCY AND TIME DOMAIN BEHAVIOURS

The parameter pairs on the stability surface in the last section only guarantee the stability of the studied AUV yaw control system. On this basis, the frequency and time domain behaviours are taken into consideration in this section.

#### Improved frequency domain behaviour

Gain and phase margins are the most widely discussed specifications for robust controller design. In accordance with their definitions, they can be depicted as [28]:

i. **Phase margin specification**
\[
\text{(Arg}[F(jw)]\big|_{\omega = \omega_m} = -\pi + \phi_w, \tag{14}
\]

where \( \omega_m \) is the crossover frequency.

ii. **Gain crossover frequency specification**
\[
\left| \frac{d \text{Arg}[F(jw)]}{dw} \right|_{\omega = \omega_m} = 1. \tag{15}
\]

iii. **Robustness specification** Flat phase property which makes the controlled system robust to gain variations is frequently used in \( P^\delta \) \( F^\mu \)-type controller tuning [27]. It is described as
\[
\left| \frac{d \text{Arg}[F(jw)]}{dw} \right|_{\omega = \omega_m} = 0. \tag{16}
\]

However, there are two problems in this original flat phase property. One is that it can only maintain the phase curve flat at one frequency point; moreover, there is a system of non-linear
equations to be solved in Equation (16), which may not have an analytical solution under fixed $\phi_m$ and $w_m$.

Therefore, in this study, we improved the robustness specification in Equation (16) as

$$\left| \frac{d(\text{Arg}[F(jw)])}{dw} \right|_{w \in [w_{\text{min}}, w_{\text{max}}]} \leq \delta, \quad (17)$$

where $0 < \delta \ll 1$ is a criterion which maintains the flatness of the phase curve, and $w_m \in [w_{\text{min}}, w_{\text{max}}]$ is the flat phase interval.

The controlled system open-loop transfer function which satisfies the first two specifications is achieved as

$$e^{-j\phi_m F(jw)} = -1. \quad (18)$$

Substituting Equations (6)–(8) into Equation (18) obtains

$$k_p(\lambda, \phi_m, w) = \frac{A_2 C'_2 - S'_2 A_1}{S'_2 C'_1 - C_2 S_1}, \quad (19)$$

$$k_i(\lambda, \phi_m, w) = \frac{A_2 C'_1 - S'_1 A_1}{C_1 S'_1 - C_2 S_2},$$

where

$$C'_1 = \cos(\lambda \pi/2 - Lw - \phi_m),$$

$$S'_1 = \sin(\lambda \pi/2 - Lw - \phi_m),$$

$$C'_2 = \cos(-Lw - \phi_m),$$

$$S'_2 = \sin(-Lw - \phi_m).$$

When $\lambda$ is fixed, a two-dimension space composed by the $k_p$ and $k_i$ curves from Equation (19) can be achieved as shown in Figures 2 and 3 (with $I_{YRB} = 0.3578$, $I_{YA} = 0.138$, $D_{YLA} = 1.2$, $K_M = 1$, $T_M = 0.05$ of Equation (6)). It is illustrated that different $\lambda$ and phase margin $\phi_m$ give rise to different stable spaces.

Then, sweep over $\lambda \in (0, 2)$ with small enough increments, the three-dimensional stable surfaces will be achieved as shown in Figure 4 with different $\phi_m$. It is clear that a bigger $\phi_m$ will lead to a smaller stable surface.

### 4.2 Improved time domain behaviour

In the previous studies, crossover frequency $w_m$ is always given manually. Here, we find $w_m$ and other controller parameters through optimisation to improve the time domain control performance. In the optimisation process, the Genetic Algorithm (GA) is used to find the global optimised solution. Inspired by the time response criteria analysis in [24], time domain specifications including steady state error $e$, overshoot $M_s$, rising time $t_r$, and control signal $u$ are integrated in the objective function

$$J = \int_0^{\infty} \left[ \omega_1 |e(t)| + \omega_2 M_s + \omega_3 t_r + \omega_4 u^2(t) \right] dt. \quad (20)$$

### 5 SIMULATION

In this section, the simulation results are shown to verify the control performance of the proposed $D^\lambda$ controller for the studied AUV motion control system. Besides, fair comparisons are made between PID control and the proposed control scheme. The system parameters are $I_{YRB} = 0.3578$, $I_{YA} = 0.138$, $D_{YLA} = 1.2$, $K_M = 1$, $T_M = 0.05$ from the CISCERA AUV [30]. In order to fully compensate the impact of
linearisation, ±30% parameter uncertainties are employed on the controlled system. According to the last two sections, the controller parameters are obtained as $k_p = 0.12$, $k_i = 0.09$, $\lambda = 0.57$ with $\phi = 15^\circ$, and $w_m = 0.8$ rad/s.

Figure 5 gives the bode diagram of the controlled system, which verifies the specification in frequency domain. The phase derivation achieved from the improved flat phase property in Equation (17) is shown in Figure 6. It can be seen that $\lambda = 0.57$ gives the smallest $\delta$. Moreover, the stable surface with the obtained parameter pair $(k_p, k_i, \lambda)$ is illustrated in Figure 7.

In order to verify the effectiveness and superiority of the designed $P^\lambda$ controller, the set-point regulation and noise suppression performance of the studied AUV yaw control system with the proposed controller is compared with that with traditional PID controller in the following subsections.

5.1 | Set-point regulation with load and parameter uncertainties

Robustness with respect to load and parameter uncertainties could compensate the dynamic and hydrodynamic uncertainties and linearisation effect of an AUV motion control system.
Figures 8 and 9 show the set-point regulation performances of $P^A$ and PID controller, respectively. In order to show the robustness of the controlled system, ±30% load and parameter uncertainties are employed on the system, which can fully compensate the linearisation effect and other uncertainties [30]. It is shown that the control performance of system with $P^A$ controller outperforms the other one with much less settling time, smaller overshoot and control signal with and without parameter uncertainties. In addition, the control performance under load and parameter uncertainties changes moderately with $P^A$ controller and sharply with PID controller. Therefore, the robustness to parameter uncertainties of the controlled system with $P^A$ controller is verified.

5.2 Noise suppression

The noise suppression capability which could compensate sensor noise and other unpredictable noise of the controlled system is tested in this subsection. The random noise signal with $[-0.3, 0.3]$ in amplitude which could represent the worst noise disturbance is added into the feedback loop of the controlled system with sampling time 0.01 s. The noise suppression performance with $P^A$ and PID controllers are demonstrated in Figures 10 and 11, respectively. It is clearly shown by the
FIGURE 10 Noise suppression performance with PID controller

comparison of these two figures that the steady state error and control signal of $PI^\lambda$ controller is much smaller than that of PID controller with and without load and parameter uncertainties, which will reduce the burden of the AUV propeller at the same time. These results show the superior noise suppression capability of the proposed $PI^\lambda$ controller.

6 CONCLUSION

This study proposed a design synthesis for a fractional-order proportional-integral ($PI^\lambda$) controller to achieve guaranteed frequency and time domain motion control performance for AUV system. Both frequency and time domain analysis specifications are taken into consideration in the parameter tuning process. The AUV motion control system with the designed controller can maintain a stable surface when the internal and external marine environment changes. It can also be robust to load and parameter uncertainties and disturbance. Therefore, all the primary concerns, including stability, robustness and transient performance, of the AUV motion control system can be improved. The simulation results of the set-point regulation and noise suppression tests showed superior robustness and noise suppression capability of the proposed $PI^\lambda$ controller. In future studies, we may perform experiments with the proposed controller for AUV motion control to further verify its practicability.

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DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are currently under embargo while the research findings are commercialised. Requests for data, six months after publication of this article, will be considered by the corresponding author.

CONFLICT OF INTEREST STATEMENT

The authors declared that they have no conflicts of interest to this work.

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