Optimized Design of Fractional-Order PID Controllers for Autonomous underwater vehicle Using Genetic Algorithm

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Abstract

Efficient control schemes of Autonomous underwater vehicle (AUV) are challenging due to uncertainties and highly nonlinearities. In this paper, improved fractional order PID controller is proposed for the control of AUV motion with six degrees of freedom (DOF). Genetic algorithm and Particle Swarm Optimization (PSO) are employed to find suboptimal coefficients of FOPID controller to improve performance of the AUV motion. These optimal adjusted coefficients of FOPID controllers minimize the step response characteristics such as maximum deviation and settling time. Simulation results are presented to verify the advantages of the FOPID with respect to the previous works specially proportional-integral-derivative controller (PID).

1. Introduction

The term Autonomous Underwater Vehicle (AUV) refers to a vehicle in which driven through the water by a propulsion system, controlled and piloted by an on-board computer [1]. The AUV has potential applications in various fields such as oceanographic studies, Geothermal, military purposes, environmental researches, identify hazards on the seabed and locating dangerous rocks or shoals in shallow waters and anti-submarine warfare ocean mining and oil industry [2,3] .However, AUVs have attracted many research interests in recent years as one type of underwater device Because of their complexity and nonlinearies thus stability and control of AUVs have always been challenging.

In the last two decades, people have investigated various control techniques to solve different challenges arising from the nonlinearities and time varying behavior of the vehicle's dynamics [1,4,5] .Due to nonlinear behavior of the underwater, the linear techniques of PID controller do not guarantee system's position stability [5]. In order to make the vehicle less sensitive to external disturbances some techniques have been proposed such as adding an acceleration feedback to the PID or using least square regulators to track time varying reference trajectories [4]. An experimental comparison between a proportional derivative (PD) controller and an adaptive nonlinear state feedback one have shown in [6]. In [7] also, Hsu et al. presented two methods in order to eliminate the steady-state depth error via modifying the depth command and adding a switching integral controller in the depth control loop. In [8] the development of tuning a FOPID controller using system gain margin and phase margin specifications has been discussed and reduction of rise time, settling time, and overshoot in FOPID then demonstrated. Nevertheless, it is only discussed for controlling Depth system of AUV and only one method of fractional order PID tuning is applied. Previous researches for adjusting the suitable coefficients of this controller are almost based on trial and error methods. Hong and et al. investigated depth Control of an AUV, based on sliding mode control (SMC) with integrator effect [9]. A state feedback control design based on the input-output linearization for dive-plane control has been proposed in [10]. In [11] suggested a fuzzy self-adapting PID controller for heading and depth subsystems of AUV. Several control techniques including different methods have been evaluated [1, 2, 4-11]. In this present work, the coefficients of FOPID will be found by utilizing Genetic Algorithms (GA) and PSO. In proposed algorithm, AUV model will be executed several times and parameters of depth and steering responses will be evaluated in the cost function then after some iteration, coefficients for FOPID controller will be tuned for a suboptimal system response. Then the design of FOPID is compared with PID based on GA.

The rest of the article is organized as follows. A mathematical model of AUV is expressed in section 2. Structures of the controller and GA method are proposed in section3.and the results of simulation are provided in section4. Finally, conclusion is expressed in section 5.

2. Mathematical model

In order to dissect dynamic model of the AUV, two coordinates are considered, earth-fixed coordinate and body-fixed coordinate. Thus, it is obvious that our considered AUV's motion has 6 degrees of freedom (DOF) in which three of them are connected with its translations and the others represent its rotations along x, y and z axes. More details of different quantities according to the SNAME are prepared in Table 1. The general motion of marine vehicle in 6 DOF can be described by following vectors [13]

$$\begin{aligned} &\eta = \left[\eta_1^T, \eta_2^T\right]^T, \eta_1 = [x, y, z]^T, \eta_2 = [\varphi, \theta, \psi]^T, \\ &v = \left[v_1^T, v_2^T\right]^T, v_1 = [u, v, w]^T, v_2 = [p, q, r]^T, \\ &\tau = [\tau_1^T, \tau_2^T]^T, \tau_1 = [X, Y, Z]^T, \tau_2 = [K, M, N]^T. \end{aligned} \quad (1)$$

The parameter η is the position and orientation vector in earth-fixed coordinates, and v is the velocity vector with coordinates in the body-fixed frame, and τ indicates the total forces and moments acting on the vehicle in the body fixed frame. By taking into account the inertial generalized forces, the hydrodynamic effects, the gravity, the buoyancy contributions and effects of the actuators, nonlinear equations of motion of 6 DOF underwater vehicle, proposed in [4].

$$\dot{\eta} = J(\eta)v. \tag{2}$$

$$M\dot{v} + C(v)v + D(v)v + g(\eta) = \tau . \tag{3}$$

where *J(□)* is the transformation matrix mapping from the body-fixed frame to the earth-fixed one. *M* is the inertial matrix, including hydrodynamic virtual inertia or added mass, *C(v)* is Coriolis-centripetal *D(v)* is the vehicle's damping matrix and *g(η)* is gravitational force and moment. $v=[u,v,w,p,q,r]^T$ and $\tau=[X,Y,Z,K,M,N]^T$ are the velocity and moment vectors, respectively.
The general equations of motion of 6 DOF AUV can be divided into three subsystems: speed control, steering or heading control, and depth control. In the following two subsection (i.e. (a) and (b)) we are going to concentrate on depth and steering system.

Table 1. Notations used to describe rigid-body dynamics in the body-fixed reference frame

Dof		External Forces and Moments	Linear and angular vel.	positions and Euler angles
1	Motion in the x-direction (surge)	X(N)	u ($m.s^{-1}$)	x (m)
2	Motion in the y-direction (sway)	Y(N)	v ($m.s^{-1}$)	y (m)
3	Motion in the z-direction (heave)	Z(N)	w ($m.s^{-1}$)	z (m)
4	Rotation about x-axis(roll)	K(N.m)	p ($rad.s^{-1}$)	φ(rad)
5	Rotation about y-axis(pitch)	M(N.m)	q ($rad.s^{-1}$)	θ(rad)
6	Rotation about z-axis(yaw)	N(N.m)	r ($rad.s^{-1}$)	ψ(rad)

2.1. Depth system

Make a change in deflection of stern planes, results changing the lift force on the fins. Then, the corresponding pitch moment will be changed and consequently, makes the pitch angle to change and in turn it affects the rising or diving of the vehicle and it is reasonable to manipulate the depth of the AUV[14]. Based on Eqs. (2) and (3), C. Yang and colleagues introduced four equations of motion for depth control of subsystem. In order to simplify this control problem, the equation for depth system should be linearized white respect to the equilibrium point

$$u = 1.5m/s \ , \theta = w = q = 0 \ . \tag{4}$$

U is the linear velocity of AUV. After some straight forward but laborious calculation and neglecting small variation of heave velocity (i.e. $w, \dot{w}$), the standard form of state-space for linearized subsystem of depth control as follows

$$\begin{bmatrix} \dot{q} \\ \dot{z} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} M_q/(I_{yy}-M_{\dot{q}}) & 0 & M_\theta/(I_{yy}-M_{\dot{q}}) \\ 0 & 0 & -U \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} q \\ z \\ \theta \end{bmatrix} + \begin{bmatrix} M_{\delta_S}/(I_{yy}-M_{\dot{q}}) \\ 0 \\ 0 \end{bmatrix} [\delta_s] \tag{5}$$

Where, v is heave velocity, q, θ and z are pitch rate, pitch angle and the depth respectively. Here, the Control variable is the deflection angle of stern planes δs which may be step or any other input.

2.2. Steering system

By moving the AUV in the horizontal plane, the change of rudder angle will be cause the yaw moment on the vehicle and resulted in changing the heading direction of the AUV. Using the same approach, the equation of steering control subsystem can be written as follows

$$\begin{bmatrix} m-Y_{\dot{v}} & -Y_{\dot{r}} & 0 \\ -N_{\dot{v}} & I_z-N_{\dot{r}} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{\psi} \end{bmatrix} - \begin{bmatrix} Y_v & Y_r-mu & 0 \\ N_v & N_r & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v \\ r \\ \psi \end{bmatrix} = \begin{bmatrix} Y_{\delta_r} \\ N_{\delta_r} \\ 0 \end{bmatrix} [\delta_r] . \tag{6}$$

Where v is sway velocity and r, ψ are yaw angle rate and yaw angle respectively. Here, the control variable is the deflection of rudder angle δr witch represents the control input [14].

3. Proposed Controller

Fractional order PID - The calculus fractional order is defined as

$$\alpha D_t^q = \begin{cases} \dfrac{d^a}{dt^a} & Re(a)>0 \\ 1 & Re(a)=0 \\ \int_a^t (d\tau)^{-a} & Re(a)<0 \end{cases} \tag{7}$$

Caputo definition of fractional order is defined as

$$\alpha D_t^q f(t) = \frac{1}{\Gamma(m-\alpha)} \int_a^t \frac{f^m(\tau)}{(t-\tau)^{a-m+1}} d\tau \tag{8}$$
$$, (m-1<a<m)$$

Grunwald-letnikov definition of fractional order is defined as

$$\alpha D_t^q f(t) = \lim_{h\to 0} \frac{1}{\Gamma(\alpha)h^\alpha} \sum_{k=0}^{\frac{t-\alpha}{h}} \frac{\Gamma(\alpha+k)}{\Gamma(k+1)} f(t-kh) \tag{9}$$

Riemann-Liouville definition of fractional order is defined as [15]

$$\alpha D_t^q = \frac{1}{\Gamma(m-\alpha)} \left(\frac{d}{dt}\right)^m \int_a^t \frac{f(\tau)}{(t-\tau)^{1-(m-\alpha)}} \tag{10}$$

Using FOPID causes some improvement in PID features .the equation of fractional order PID is described by

$$G(s) = K_P + \frac{K_I}{S^\lambda} + K_D S^\mu \tag{11}$$

There have two different between FOPID controller and PID controller:

1. Integral order In FOPID controller $\boldsymbol{K_I / S^\lambda}$.
2. Derivative order in FOPID controller $\boldsymbol{K_D S^\mu}$.

This difference can provide more flexibility in controller tuning, more control in dynamic behavior of the system and less sensitive to changes of the system parameters [16]. Design of a Fractional order PID includes a tune of five parameters, K_P,K_I,K_D,λ,μ, which λ, μ are Rational numbers and between 0 and 1. In PID controller λ=μ=1. FOPID and PID configuration showed in Fig. 1. $0 < \lambda, \mu < 1$

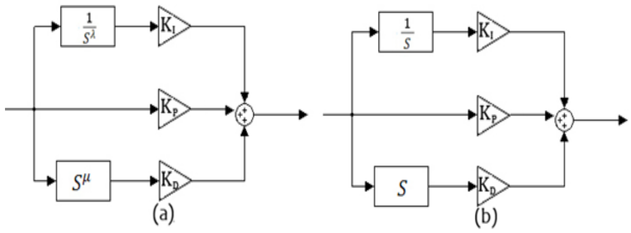

Fig. 1. Block diagram configuration of (a) FOPID (b) PID

GA is used to solve difficult search and optimization and can be used to solve difficult problems quickly and reliably[17]. Some of the advantages of Genetic Algorithm includes: work out problems with multifold solutions, easily transferred to existing models and the most important advantages of this algorithm that a number of convergence and stability results have already been taken for systems of this type [18]. The cost function is a function that needs to solve. Most search problems should be proposed as the search for the optimal value of a function. The function shows the correlation between the different parameters which seek to optimize [19]. In this paper, the cost function defined as

$$C.F = W_1 M_P + W_2 e_{ss} + W_3 t_s \tag{12}$$

Where, M_p is maximum overshoot, e_{ss} is steady state error, t_s is settling time of AUV model's response. W_1 , W_2 and W_3 are weights or weighting factors of M_p, e_{ss} and t_s , so the value of this factors depending on the importance of M_p, e_{ss} and t_s , in this paper , W_1= 0.3 , W_2 =W3 = 1. An illustrative flowchart of the Genetic algorithm is shown in Fig. 2. Some of parameters for GA are assumed as in Table 3.

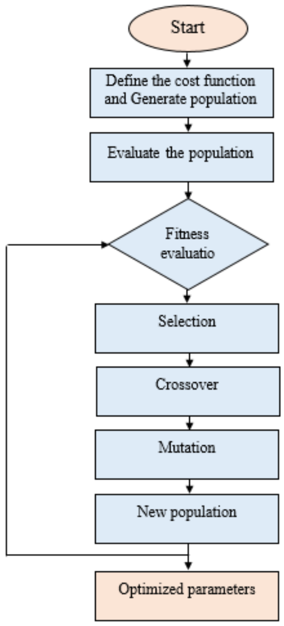

Fig. 2. GA flowchart

Table 2. AUV Specifications

Parameter	Quantity
$m(kg)$	50
$I_{xx}(kg.m^2)$	+1.77e-001
$I_{yy}(kg.m^2)$	+3.45e+000
$I_{zz}(kg.m^2)$	+3.45e+000
$M_q(kg.m^2/s)$	-6.87e+000
$M_{\dot{q}}(kg.m^2)$	-4.88e+000
$M_{\delta_s}(kg.m^2/s^2)$	-3.46e+001
$M_\theta(kg.m^2/s^2)$	-5.77e+000
$Y_{\dot{v}}(kg)$	−3.55e+001
$Y_{\dot{r}}(kg.m/rad)$	+1.93e+000
$N_{\dot{v}}(kg\,m)$	1.93
$N_{\dot{r}}(kg.m^2/rad)$	-4.88e+000
$Y_v(kg/s)$	-6.66e01
$Y_r(kg.m/s)$	2.2
$N_v(kg\,m/s)$	-4.47
$N_r(kg.m^2/s)$	-6.87e+000

4. Simulation results

In this paper, the calculation has been carried for fractional order Depth and steering subsystems based on Particle Swarm Optimization (PSO) and Genetic Algorithm. In order to auto-tuning of the fractional order PID controller coefficients, here GA algorithm was programmed in MATLAB. The AUV characteristics for system modeling are demonstrated in Table 2.

There are too many standard methods to masseur system's performance but generally unit step input is used to masseur the systems performance and stability. By adopting PSO and GA algorithms the FOPID confections can be easily tuned. The responses of depth system and steering system to the unit step are depicted in Fig. 2 and Fig. 3, respectively.

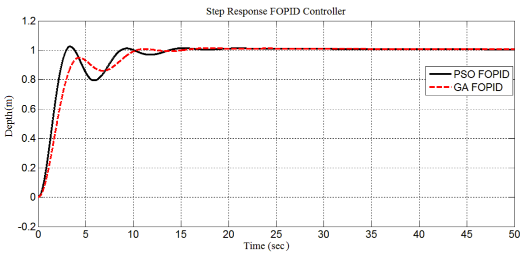

Fig. 2. Unit step response FOPID based on GA and PSO for depth system

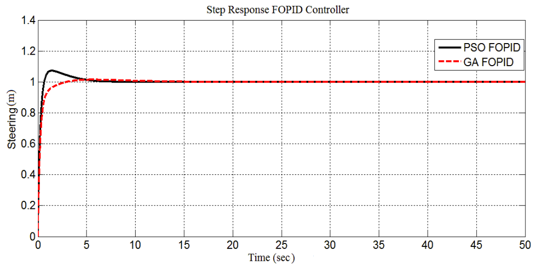

Fig. 3. Unit step response FOPID based on GA and PSO for steering system

System response to the unit step input depth system and steering system are showed in Fig. 4 and Fig. 5, respectively. It is seen that the system experiences satisfied overshoot, and quickly converges to the final value. It is helpful to study and compare the results between the IOPID controllers and FOPID controllers in which has been optimized with two different algorithms (see Table 4).

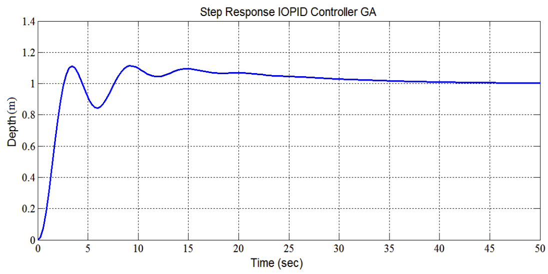

Fig. 4. Output response of the GA-PID controller for depth system

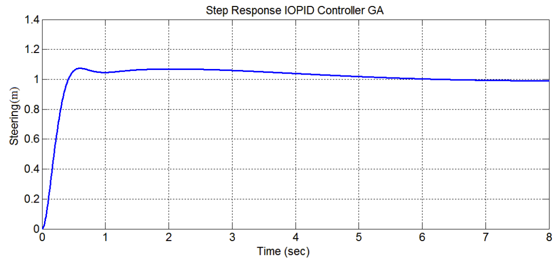

Fig. 5. Output response of the GA-PID controller for steering system

As shown in Table 4, PID controller output exceeding from its steady-state value is about 11% which means that our approach is not suitable because of 11% overshooting. Moreover, the results showed that FOPID based on GA has resulted in desired output in all channels; since, about 1.2% maximum overshoot for depth system, it has a 1.4% maximum overshoot in steering subsystem which is pleasant. Table 4 also demonstrates that in FOPID based on GA the overshoot and settling time decreases in two channels in comparison with the other two methods which mentioned (i.e. FOPID based on PSO and PID methods).

5. Conclusion

In this paper FOPID controller is proposed for depth and steering subsystems of an autonomies underwater vehicle.
First, the dynamic equations of AUV are represented. Then a performance criterion is considered and the controller parameters are tuned using GA and PSO. The simulation results show that the fractional order controller based on GA gives better performance than PID controller and FOPID controller based on PSO. For instance, the overshoot percentage and settling time are substantially decreased for pitch and steering channel output. However there are some other methods to tune the parameters of a fractional order PID controller which could be test on an actual system that will be used in future works.

Table 3. GA Parameters

Methods	Iteration number	Initial population
GA	100	50
PSO	100	50

Table 4. Performance of FOPID Controllers

	Settling Time	Max. deviation	k_p	k_I	k_d	λ	μ
Depth							
PID	33.32	0.1135	0.0501	0.0036	0.1088	1	1
FOPID GA	9.862	0.012	0.0351	0.0023	0.0588	0.386	0.98
FOPID PSO	12.57	0.025	0.025	0.0155	0.1057	0.1674	0.937
Steering							
PID	5.3865	0.0623	0.8473	0.2797	1.2064	1	1
FOPID GA	1.92	0.014	0.9364	-0.633	0.8765	0.057	0.96
FOPID PSO	4.021	0.072	0.9903	0.176	0.9426	0.7514	0.9896

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