PID Controller Design for Unmanned Aerial Vehicle Using Genetic Algorithm

Hengameh Noshahri, and Hamed Kharrati

Abstract— Control of unmanned aerial vehicles (UAVs) is challenging due to inherent nonlinearities and its coupled dynamics. In this paper, an improved proportional-integral-derivative (PID) controller is proposed for UAV motion control with 6 degrees of freedom (DOF). A genetic algorithm is employed to find suboptimal coefficients of PID controller to optimize performance of the closed-loop control system. Simulation results are presented to verify the effectiveness of the proposed control system and also to compare with previous works.

Keyword: UAV- PID Controller- Genetic Algorithms

I. Introduction

The term unmanned aerial vehicle (UAV) refers to a flying machine without an on-board human pilot [1]. They are being increasingly used in many domains especially for surveillance, environmental researches, security, search and rescue, and traffic monitoring. Researches have led to different designs for this type of aircrafts. A Quadrotor is one of the VTOL (vertical take-off and landing) designs which is proven to have promising flying concepts due to its unique ability for hovering, vertical, and low speed flight [2] [3]. Moreover, because of the recent instrumentation technologies, they can be miniaturized for extending their various applications. However, stability and control of Quadrotor UAVs have always been challenging.

The first step of determining a suitable control system is finding a mathematical explanation for dynamic modeling. In many studies a model with less than six degree of freedom (DOF) is considered which mainly includes only the attitude control or merely the altitude control. In addition, several model reductions have taken place by neglecting gyroscopic effects, drags, and other assumptions, causing inaccuracies in the model.

In [4], focus is on the rotational dynamics, considering the linear motion being a consequence of the rotations. Degrees of freedom are reduced to avoid control system complexity. Then, the gyroscopic effects resulting from Quadrotor's rigid body and the propellers rotation are neglected by limiting the study to hovering state. Finally, a linear model is implied for roll, pitch and yaw channels and a PID controller is designed for real system. However, our work with no such model reductions and also implying a nonlinear plant has shown better results in same initial and final conditions.

Similarly, by constraining the study to low-speed movement, drag coefficients are omitted from the equations of motion in [5]. After, leaving out the nonlinear terms of equations, a linear model is obtained and proposed control system is based on a model which obviously doesn't contain real conditions of the UAV. Finally, Ziegler Nichols method is used for determining the PID coefficients. Even after these simplifying assumptions, the output represents remarkable undesired instability.

The represented Kalman and PID controller in [6] eliminates the static error and ensures the system design simple. In addition, the Kalman filter can remove the noise that interferes with the true signals of system. Nevertheless, it is only discussed for controlling forward and vertical movement, which is inadequate for UAV control system.

Our aim is to use an accurate, six DOF model with least reduction in equations of motion. Several control techniques are evaluated in previous studies [2-10]. PID controller design is one of the most significant methods that we are going to concentrate on, in this article. Previous researches for tuning the appropriate coefficients of this controller are almost based on trial and error or analytical approaches. In this paper, Proportional, Integral and Derivative coefficients will be found by utilizing Genetic Algorithms (GA). In proposed algorithm, Quadrotor's model will be executed several times and parameters of attitude and altitude responses will be evaluated in the cost function; so that after some iteration, coefficients for PID controller will be tuned for a suboptimal system response.

II. Mathematical Modeling

As shown in Fig.1, Quadrotors have four fixed-pitch propellers in cross configuration and they don't have any tail rotor. If two diagonally opposite propellers rotate clockwise, the other two should rotate counterclockwise. The body will go up and down by increasing or decreasing the speed of the four propellers at the same time and it will move right, left, forward or backward by keeping the rotation of one pair constant and making angular speed deference between the other opposite propellers. In other words, the pitch movement (Theta direction in figure.1) is obtained by increasing (decreasing) the speed of the left motor while decreasing (increasing) the speed of the right motor. Increasing (decreasing) the speed of the rear motor while decreasing (increasing) the speed of the front motor will result in Roll movement (Phi direction shown in figure.1).

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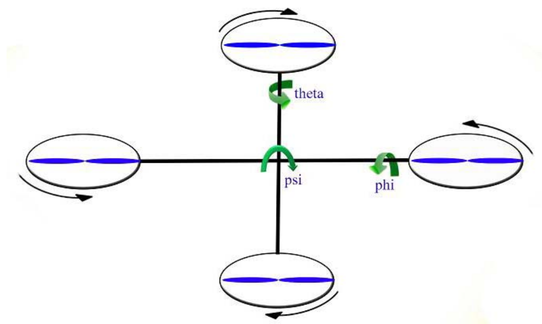

Figure 1. Quadrotor configuration

The yaw movement (Psi direction in figure.1) is obtained by increasing (decreasing) the speed of the front and rear motors together, meanwhile decreasing (increasing) the speed of the lateral motors together. All should be done while keeping the total thrust constant [5].

Although Quadrotor has four actuators, it remains an under-actuated and dynamically unstable system [2].

System identification and modeling after implementation of Newton-Euler formalism result in equations of motion. Thus, in terms of state-space form, we can define twelve state variables as in (1) and four inputs as in (2) which are mapped by (3) where Ω_i (i=1,2,3,4) is the angular rate of four propellers and b and d are thrust and drag factors, respectively. Finally, the entire system is described by (4).

$$X = [\varphi\ \dot{\varphi}\ \theta\ \dot{\theta}\ \psi\ \dot{\psi}\ z\ \dot{z}\ x\ \dot{x}\ y\ \dot{y}]^T \tag{1}$$

$$U = [\mathrm{U}_1\ \mathrm{U}_2\ \mathrm{U}_3\ \mathrm{U}_4]^T \tag{2}$$

$$\begin{aligned} \mathrm{U}_1 &= b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\ \mathrm{U}_2 &= b(-\Omega_2^2 + \Omega_4^2) \\ \mathrm{U}_3 &= b(\Omega_1^2 - \Omega_3^2) \\ \mathrm{U}_4 &= d(-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 + \Omega_4^2) \end{aligned} \tag{3}$$

$$\dot{X} = f(X, U) \tag{4}$$

Where:

$$\begin{aligned} \dot{x}_1 &= x_2 = \dot{\varphi} \\ \dot{x}_2 &= a_1\dot{\theta}\dot{\psi} + a_2\dot{\theta}\Omega_r + b_1\mathrm{U}_2 \\ \dot{x}_3 &= x_4 = \dot{\theta} \\ x_4 &= a_3\dot{\varphi}\dot{\theta} - a_4\dot{\varphi}\Omega_r + b_2\mathrm{U}_3 \\ \dot{x}_5 &= x_6 = \dot{\psi} \\ \dot{x}_6 &= a_5\dot{\varphi}\dot{\theta} + b_3\mathrm{U}_4 \\ \dot{x}_7 &= x_8 = \dot{z} \\ \dot{x}_8 &= g - \frac{\mathrm{U}_1}{m}\cos\varphi\cos\theta \\ \dot{x}_9 &= x_{10} = \dot{x} \\ \dot{x}_{10} &= \frac{u_x}{m}\mathrm{U}_1 \\ \dot{x}_{11} &= x_{12} = \dot{y} \\ \dot{x}_{12} &= \frac{u_y}{m}\mathrm{U}_1 \end{aligned}$$

In (4), Ω_r is the overall residual propeller angular speed which is indicated as:

$$\Omega_r = \Omega_1 - \Omega_2 + \Omega_3 - \Omega_4\,. \tag{5}$$

Where g is the gravity acceleration and m is the overall mass. The coefficients used in these equations are defined as bellow.

$$\begin{aligned} a_1 &= (I_{yy} - I_{zz})/I_{xx} \\ a_2 &= J_r/I_{xx} \\ a_3 &= (I_{zz} - I_{xx})/I_{yy} \\ a_4 &= J_r/I_{yy} \\ a_5 &= (I_{xx} - I_{yy})/I_{zz} \\ b_1 &= l/I_{xx} \\ b_2 &= l/I_{yy} \\ b_3 &= l/I_{zz} \\ u_x &= \cos\varphi\sin\theta\cos\psi + \sin\varphi\sin\psi \\ u_y &= \cos\varphi\sin\theta\sin\psi - \sin\varphi\cos\psi \end{aligned} \tag{6}$$

Where I_{xx}, I_{yy}, and I_{zz} are inertia moments; J_r is the rotor inertia and l is the horizontal distance from propeller's center to center of gravity.

According to [2], the model can be described in two sections. First six state variables are evaluated in angle section, because their evaluation doesn't depend on the rest of the variables. In second section, the translation section, the results of former section are used to define UAV's coordinate.

III. Proposed Controller

In this paper a PID controller is designed for a six degree of freedom model; therefore, the attitude and altitude of UAV are studied as outputs. In order to tune the controller, former described nonlinear plant model will be executed by a genetic algorithm. The schematic of controller system is depicted in Fig.2.

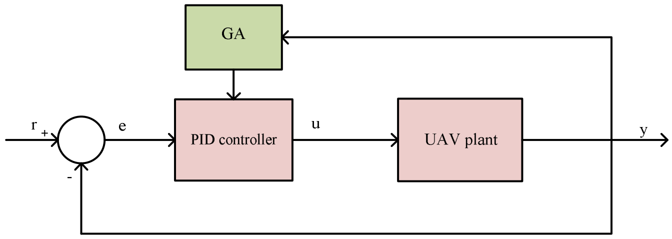

Figure 2. Controller system schematic

The genetic algorithm (GA) is an optimization and search technique based on the principles of genetics and natural selection. Some of the advantages of this algorithm includes: Manipulating both continuous and discrete variables, not requiring derivative information, dealing with large number of variables, simultaneously searching from a wide sampling of the cost surface. GA is a global optimization method; therefore, unlike other traditional methods, it can avoid being trapped in local solutions (minimums in cost function). In addition, it provides a list of optimum variables not just a single solution [11].

These characteristics make this algorithm a promising method for finding PID controller coefficients; because this task can be stated as a three dimensional optimization problem. In proposed method we use a binary genetic algorithm for having higher accuracy due to the sensitivity of PID controller to each of its coefficients. Therefore, according to the constrains and accuracy level which we have defined for the coefficients, number of the bites per chromosome are set and P, I, and D are introduced as genes of population's chromosomes. After defining parameters for GA; for example, number of chromosomes in the population, number of generations, selection and mutation rates, the first generation is randomly generated and algorithm starts a loop. In each iteration, after decoding the chromosomes and obtaining P, I, and D coefficients, these numbers are sent to the model to tune the controller. Then the system is run with predefined initial states and its response to step inputs is fed back to the algorithm. Now, settling time, steady state error and maximum overshoot are calculated and cost for a particular chromosome is evaluated based on a cost function defined as:

$$\text{cost} = (1-e^{-\beta})(M_p + e_{ss}) + e^{-\beta} t_s \,. \tag{7}$$

Where, t_s is settling time, e_{ss} is steady state error, and M_p is maximum overshoot of UAV model's response. We have assumed β to be 0.7 in order to give equal importance to every term. On next step, we sort costs for population members and a developed population is attained after mating, crossover and mutation. This loop is continued until a suboptimal set of coefficients is achieved. Algorithm flowchart is illustrated in figure 3.

IV. Simulation Results

For simulating the model, the GA algorithm was programmed in MATLAB and equations of motion were implemented through Simulink blocks. The UAV specifications for system modeling are assumed as in Table I.

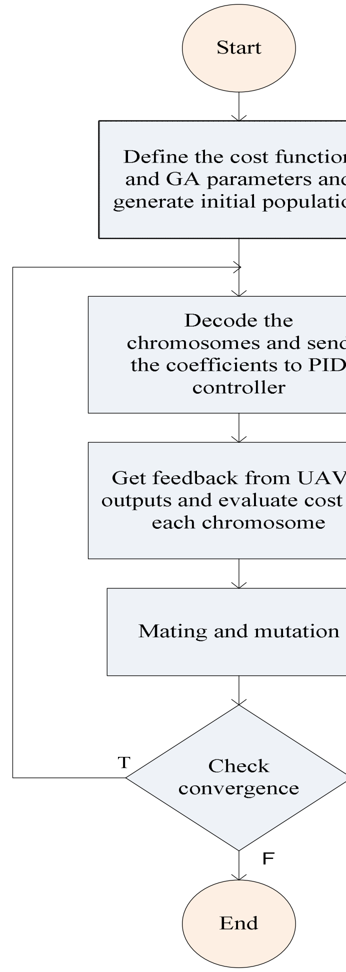

Figure 3. Algorithm procedure

TABLE I. UAV QUADROTOR SPECIFICATIONS

Variable	***Quantity***
m (*kg*)	0.65
g (m/s^2)	9.8
I_{xx} (kg.m^2)	7.5e-3
I_{yy} (kg.m^2)	7.5e-3
I_{zz} (kg.m^2)	1.3e-2
J_r (kg.m^2)	6e-5
l (m)	0.23
b (N.s^2)	3.13e-5
d (N.m.s^2)	7.5e-7

GA algorithm reduces the cost of the population's best chromosome during the proceeding iterations and defines PID coefficients for suboptimal outputs. Fig.4 represents system responses. The initial and desired values for each channel are determined according to Table II, alongside a comparison with results from [4] and [5].

As Fig.4 shows, the system experiences satisfying overshoot, or undershoot and quickly converges to the final value; where, the settling time is less than one second in most cases. The steady state error is negligible and it will be eliminated if the simulation continues for more seconds.

Although Table II compares the results between different studies, some characteristics are not discussed completely. For instance, the maximum overshoot percentage is zero for pitch channel output of [4], though the mentioned output suffers great chattering before approaching the final value, which causes serious problems for a real system. Moreover, the PID controller [4] has not resulted in desired output in all channels; since, beside the 2.5% maximum overshoot for roll angle, it has a 28.7% undershoot in yaw angle which is not desirable. The proposed controller in [5] also manifests instability, great chattering, long settling time, and also threshold in its outputs. Therefore, the tuned PID controller is not able to compensate the tracking error.

V. Conclusion

In this study a PID controller is proposed for attitude and altitude control of a 6-DOF UAV quad-rotor. First, the dynamic equations of UAV are represented. Then a performance criterion is considered and the controller parameters are fine-tuned using a GA. The performance of proposed controller is validated by simulation results and compared with published works.

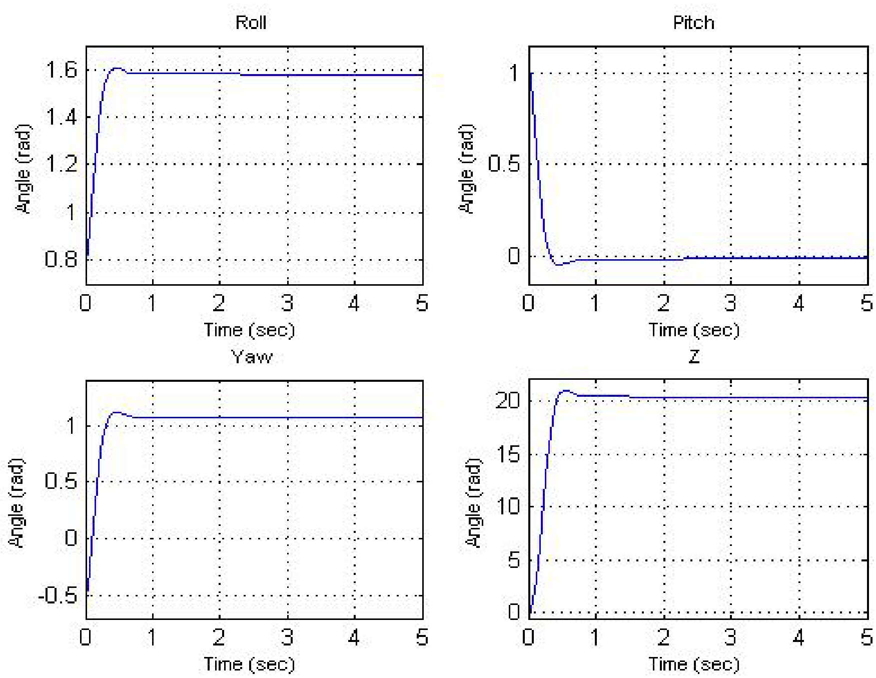

Figure 4. Simulation results

TABLE II. COMPARISON WITH PUBLISHED WORKS

	Proposed controller					**controller [4]**					**controller [5]**				
	Initial condition	***Desired value***	t_s *(s)*	M_p *(%)*	e_{ss}	***Initial condition***	***Desired value***	t_s *(s)*	M_p *(%)*	e_{ss}	***Initial condition***	***Desired value***	t_s *(s)*	M_p *(%)*	e_{ss}
Roll	$\pi/4$	$\pi/2$	0.665	4.45	0.004	$\pi/4$	0	3	2.5	0	0	0	17	125	0
Pitch	$\pi/3$	0	0.656	4.45	0.006	$\pi/4$	0	4	0	0.01	0	1	1	6	0
Yaw	$-\pi/6$	$\pi/3$	0.67	6.6	0.009	$\pi/4$	0	3.2	28.7	0	0	0	30	8	0
Z	0	20	1.81	4.69	0.16	Not studied	Not studied	Not studied	Not studied	Not studied	10	20	8	70	0

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