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Cascade PD controller gains selection for Quadrotor

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Abstract

A dynamic model of quadrotor has been used to derive relationship between objectives like settling time and overshoot with gains. A simple gains selection method has been proposed for Quadrotor cascade PD controller. The dynamic model verification has been carried out by comparing simulation results with experimental results available in literature.Various tests like point to point and trajectory tracking control are performed for validating proposed methodology. The performance is satisfactory as error is less than 3% of expected settling time. The present study eliminates trials for obtaining satisfactory performance of cascade PD controller.

Keywords: Quadrotor, Nonlinear System, PD Control, Simulation, Trajectory tracking

1. Introduction

Quadrotors are nonlinear, under-actuated, multiple input-multiple output (MIMO), open-loop unstable system which are being used for product delivery [1], inspection of plants or buildings [2 - 4], agriculture areas [5], traffic monitoring [6] etc. Quadrotor applications are increasing in real-life as it is an inexpensive and autonomous solution with varieties of other features like smaller size, vertical take-off and landing (VTOL), hovering, aggressive maneuvering capabilities [7]. There are many applications which demands quick response and may have encountered unfavorable environment to human being. Therefore, it has been necessary to design attitude, altitude and hovering control systems for Quadrotors.

Quadrotors are the aerial robot mainly consists of four basic elements: Four propellers with BLDC motors, Electronics Speed Control (ESC), position and orientation sensors and the controller. The four propellers are arranged in such a way that they have opposite directions of rotation and pitch for left-right and front-back propellers so that gyroscopic moment on the body is eliminated. The thrust is generated so that Quadrotor is lifted upward. To move in transverse directions, the moment along with thrust shall be generated in particular direction. It makes sense that as there are only four actuators, it is indeed difficult to control all DOFs independently. Thus, Quadrotors are under actuated system having 6 DOFs to be controlled with only 4 actuators. Forces and moments generated on the body are depicted in Figure 1. The governing equations of motion can be derived from either Euler-Lagrange’s method or Newton-Euler method [8] as follows:

$$m\ddot{x} = u(\sin\phi\sin\psi + \cos\phi\cos\psi\sin\theta) \quad (1)$$

$$m\ddot{y} = u(\cos\phi\sin\theta\sin\psi - \cos\psi\sin\phi) \quad (2)$$

$$m\ddot{z} = u\cos\theta\cos\phi - mg \quad (3)$$

$$\ddot{e} = \tau_e \quad (4)$$

Where, u = total lift produced by all propellers, m is the mass of the Quadrotor, $(x, y, z)^T$ is the position vector and $e = (\varphi, \theta, \psi)^T$ is the angular position(Euler angles) in inertia frame. $\tau_e = (\tau_\varphi, \tau_\theta, \tau_\psi)^T$is the torque vector for controlling angular motion of Quadrotor.

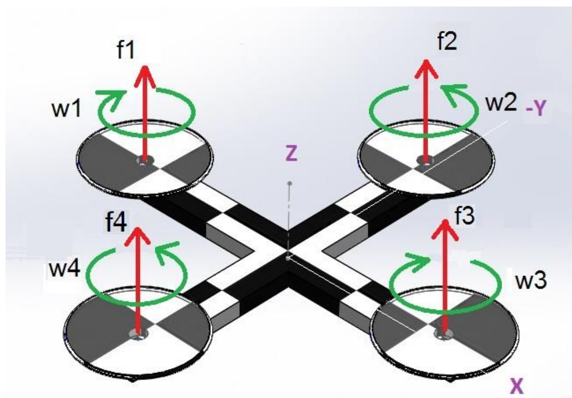

Figure 1Working principle of a Quadrotor.

Several attempts have been made by researchers for altitude, attitude and position control. Related literature has been summarized here. Luukkonen, Teppo [9] reported heuristics approach for position control of Quadrotor.ZeFang He and Long Zhao [10] suggested Ziegler-Nichols rules for tuning Quadrotor attitude PD control. Chen Wang [11] et. al. have proposed robust performance of PD/PID controller in case of mass change and battery drainage. Perez-Alcocer et. al. [12] has proposed Quadrotor PID control system when information on system parameters is imprecise. It is observed that though many researchers have used PD or PID control system for Quadrotor, yet there is lacking of systematic guidelines for selecting controller gains. In this paper, the systematic and simple expressions have been derived to obtain gains' value quickly. Thus, this research helps in minimizing trial and error time with assured performance.

2. Cascade Control Structure of Quadrotor

The Quadrotor control system is depicted as block diagram in figure 2. It has been observed that roll angle and pitch angle along with total thrust contribute Quadrotor motion along X and Y axis respectively. So, heuristic approach has been suggested by Luukkonen, Teppo [9] for trajectory control. Ignoring aerodynamic drag force on Quadrotor generated due to its slow motion, the desired attitude is estimated as

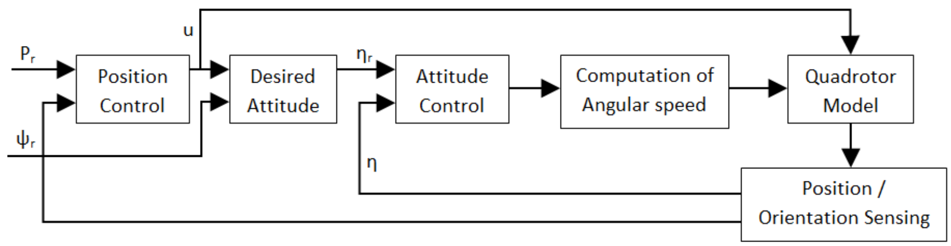

Figure 2 Block diagram of Quadrotor Control System.

$$\phi_r = \sin^{-1}\left(\frac{\ddot{x}S_{\psi_r} - \ddot{y}C_{\psi_r}}{\ddot{x}^2 + \ddot{y}^2 + \left(\ddot{z}+g\right)^2}\right); \theta_r = \tan^{-1}\left(\frac{\ddot{x}C_{\psi_r} + \ddot{y}S_{\psi_r}}{\ddot{z}+g}\right) \quad (5)$$

The position control and attitude control rules are defined as classical linear PID control The PID/PD control rules[9] are given as under:

$$u = \frac{m}{C_\phi C_\theta}\left(g + k_{zp}\left(z_r - z\right) + k_{zd}\left(\dot{z}_r - \dot{z}\right)\right)$$
$$\tau_e = I_{xx}\left(k_{\phi p}\left(e_r - e\right) + k_{ed}\left(\dot{e}_r - \dot{e}\right)\right) \quad (6)$$

3. Proposed Method for Gains Selection

From Figure 2, it is observed that the inner loop constitute attitude dynamics whereas the outer loop is constituted of position dynamics. In order to control quadrotor position, dynamics of roll and pitch Euler angles must be settled down before position dynamics gets settle. So, by assuming faster response to Euler angles' control than position control, we can omit effect of roll-pitch dynamical effects onto position control loops. Resultant position control loops from equation (1-4) is approximated in form of second order Laplace transform form as:

$$\frac{Z(s)}{U(s)} = \frac{1}{ms^2} \quad (7)$$

Additionally, gravitational force acts as constant fixed disturbance to Z-motion of the Quadrotor. The X-motion and Y-motion can be formulated only if attitude of the Quadrotor is controlled properly. So, considering attitude dynamics, control laws have been derived from (1) as follows:

$$\frac{\phi(s)}{\tau_\phi(s)} = \frac{1}{I_{xx}s^2}; \frac{\theta(s)}{\tau_\theta(s)} = \frac{1}{I_{yy}s^2}; \frac{\psi(s)}{\tau_\psi(s)} = \frac{1}{I_{zz}s^2} \quad (8)$$

Considering case of roll dynamics only, the closed loop control system is given by,

$$\frac{\phi(s)}{\phi_r(s)} = \frac{k_{p\phi} + k_{d\phi}s}{I_{xx}s^2 + k_{p\phi} + k_{d\phi}s} \quad (9)$$

From [14], information on the relative stability analysis for second order system is obtained.

Accordingly, the least settling time is obtained for second order system if damping ratio is 0.69 and for 5% tolerance, the settling time is given by,

$$t_s = \frac{4.5\xi}{\omega_n} \tag{10}$$

Putting damping ratio equals to 0.69 and from equations (8) and (9), following relationship between plant parameters and controller gain are obtained.

$$k_{p\phi} = \frac{9.64 \times I_{xx}}{t_{s\phi}^2}; k_{d\phi} = 4.28 \times \frac{I_{xx}}{t_{s\phi}} \tag{11}$$

Above gains are derived considering that step input and so second term in numerator term of equation (9) is ignored. Similarly, Controller gains for pitch and yaw motion are obtained as follows:

$$k_{pe} = \frac{9.64 \times I_{pp}}{t_{se}^2}; p = y, z; e = \theta, \psi$$
$$k_{de} = 4.28 \times \frac{I_{pp}}{t_{se}} \tag{12}$$

As stated previously, position control loop gains are selected by assuming that very fast attitude dynamics. Thus, dynamics of attitude control is ignored for position control. Additionally, position dynamics given by (1), is linearized by considering reference Euler angles as given by (2). These values are derived precisely by selecting high settling time in (8-10). Thus, closed control system for X-position is given by,

$$\frac{x(s)}{x_r(s)} = \frac{k_{px} + k_{dx}s}{ms^2 + k_{px} + k_{dx}s} \tag{13}$$

As it has been observed that equation (13) and equation (9) are identical, PD controller gains for x-position control are given by,

$$k_{pp} = \frac{9.64 \times m}{t_{sp}^2};\ p = x, y, z; k_{dp} = 4.28 \times \frac{m}{t_{sp}} \tag{14}$$

4. Results and Discussions

The classical PD controller is initially validated with experimental results presented by Perez-Alcocer et. al. [12]. Identical system and control parameters have been chosen for validating control system. The system parameters are as given in Table 1 while PD control gain parameters are given in Table II. The results are obtained using simulating Quadrotor control system using MATLAB software. Figure 3 shows trajectory control results for inputs,

$$x_d(t) = 0.4\cos\left(\frac{2\pi}{5}t\right);\ y_d(t) = 0.4\sin\left(\frac{2\pi}{5}t\right);\ \ z_d(t) = 0.6 \tag{15}$$

The results are identical as reported by Perez-Alcocer et. al. [12] which validates the dynamical model of Quadrotor and classical PD controller. After model validation, proposed methodology for gain selections using objective function has been evaluated. The proposed method of gain selection has been tested for point to point control as described below.

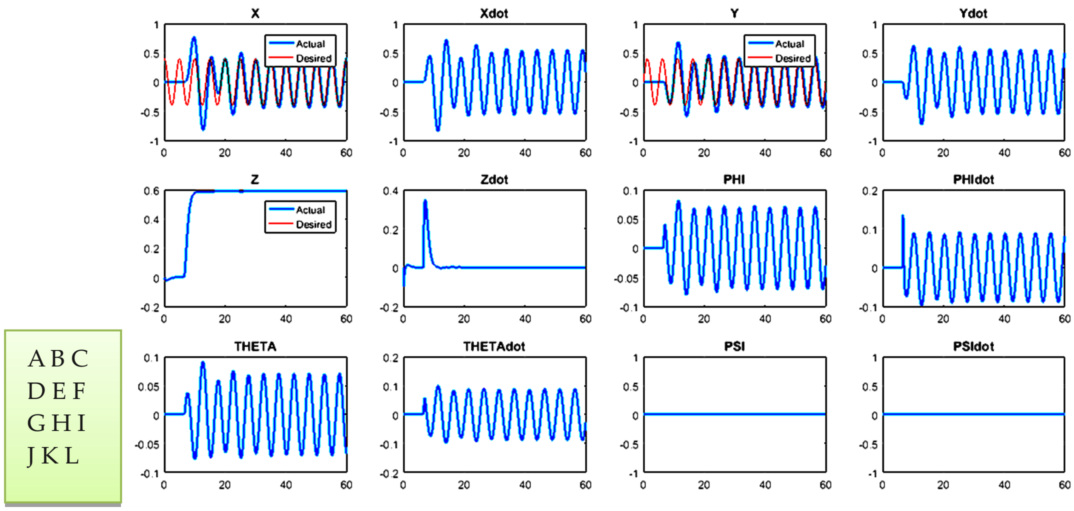

Figure 3 Quadrotor States Simulated Response Positions and Linear Velocities, Angular Positions and Angular Velocities

Table 1 System Parameters [12]

Description	**Value**	**Description**	**Value**
Gravitational constant, G	9.8 m/s^2	Thrust constant, K_τ	8.35e-8
Quadrotor mass, M	1.79 kg	Drag constant, K_D	0.41e-8
Moment of inertia about x-axis, I_{XX}	0.03 $kg.m^2$	Max force per rotor, u_{max}	8 N
Moment of inertia about y-axis, I_{YY}	0.03 $kg.m^2$	Distance between Quadrotor mass and the position of propeller axis, L	0.2 m
Moment of inertia about z-axis, I_{ZZ}	0.04 $kg.m^2$		

In point to point control, the Quadrotor was expected to fly from location $\{0, 0, 0\}^T$ to final location $\{1, 1, 1\}^T$. After reaching to location $\{1, 1, 1\}^T$, The Quadrotor should hover at same location. For testing proposed method, the parameters reported in Table 3 are chosen. As shown in Table 3, the settling time for position control loop is selected to be 10 time higher than settling time of attitude control loop. For position control loop settling times are set to 5sec while the same for orientation is set to 0.5 which means that all attitude dynamics settled down faster than dynamics of position control. So, it is important to notice that condition for ignoring attitude dynamics is fulfilled.

Though selected settling time is selected arbitrary, the minimum value is confined by maximum thrust and response of quadrotor dynamics. Selecting lower settling time thanpossible may cause actuator saturation and in turn oscillations. Thus, selecting lower settling time will result in unsatisfactory performance.

Table 2 System Parameters [12]

	X	Y	Z	Φ(Roll)	θ(Pitch)	Ψ(Yaw)
Proportional gain, K_P	0.27	0.27	2.41	1.29	1.44	2.00
Derivative gain, K_D	0.16	0.16	3.02	0.3	0.24	0.5

Table 3 Results for Proposed Method.

Parameter	X	Y	Z	Φ(Roll)	θ(Pitch)	Ψ(Yaw)
Settling time, t_s sec	5	5	5	0.5	0.5	0.5
Proportional gain, K_P	0.69	0.69	0.69	1.16	1.16	1.54
Derivative gain, K_D	1.53	1.53	1.53	0.26	0.26	0.34

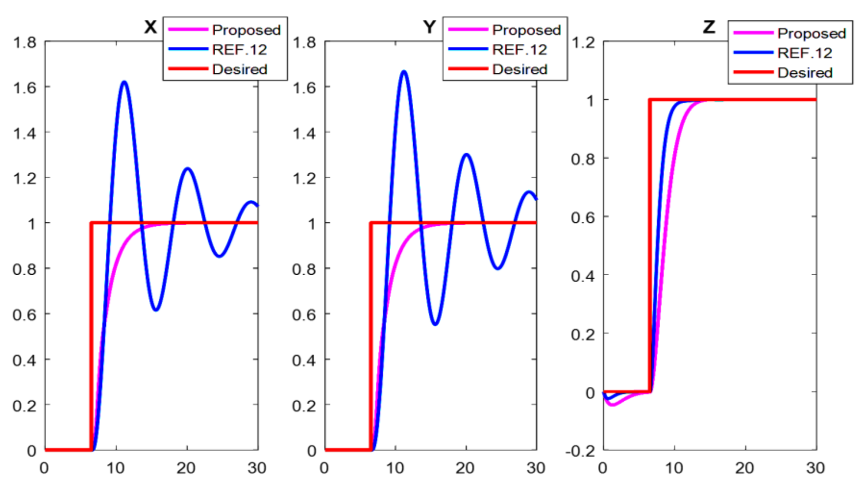

Figure 4 Step Response Comparison for Position of the Quadrotor

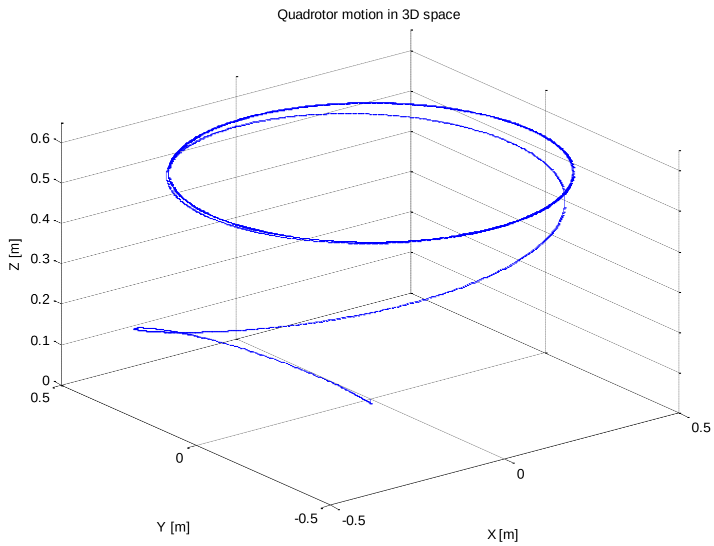

Figure 53D Motion for Trajectory Tracking in case of Proposed Method

Following figure 4, shows performance comparsion of gain proposed in [12] with gain proposed in this literature. As it can be seen that there is no overshoot and settling time for position dynamics is 5.84 sec. It is worthy to note that attitude performance is much better than proposed gains in [12]. The overshoot is about 62% and settling time is much larger. For X and Y positions of the Quadrotor. Though, performance to control altitude is satisfactory with gains in [12], the overall performance is much better for proposed method.

Results for other settling time minimum upto 2.5 sec have also been tested which shows average error of 2.98 % in position at selecting settling time. Thus, performance of proposed method is guaranteed.

The proposed method has been simulated and compared with results presented by Perez-Alcocer et. al. [12]. The trajectory is as defined in (15) has been used for testing. The results for proposed method are plotted in Fig. 3 and 5. From Fig.4, it has been seen that response for trajectory tracking is highly aggressive. It is noted that though input commands are for tracking 0.4m radius circle parallel to XY plane at the height of 0.6m, the radius being traced is 0.4596m and at the height of 0.5611m. The 3D plot in space has been depicted in fig. 5. Compared to previous method, the proposed method is oscillations free as observed in fig.3 and fig.5 respectively. The intermediate spiral motion in fig.14 is caused by same settling time for XY-motion and Z-motion which does not exist in method proposed by Perez-Alcocer et. al. [12]. This effect is desirable as given by trajectory equations (15).

5. Conclusions and Recommendations

Dynamic model of Quadrotor has been used, developed using Euler-Lagrange's method. The obtained model and PD control structure has been validated with experimental results available in literature.A simple method for gains selection has been proposed and tested for set of objective functions like overshoot and settling time. The proposed gains results in achieving all three positions approximately at same time. No overshoots have been observed. The average % deviation in position at settling time is 2.98%. Thus, results validate proposed method for different settling times.Though the method has good success, it is recommended that following conditions must be satisfied while operating Quadrotor with proposed method.

- The dynamics of attitude should be at least 10 times faster than dynamics of position control loop.
- It is essential that rapid continuous changes in desired input be avoided.

References

Md R Haque, M Muhammad, D Swarnaker. Autonomous Quadcopter for Product Home Delivery. In: International Conference on Electrical Engineering and Information & Communication Technology (ICEEICT),IEEE, 2014, p. 1-5.

Paolo Bellezza Quarter, Francesco Grimaccia, Sonia Leva. Light Unmanned Aerial Vehicles (UAVs) for Cooperative Inspection of PV Plants. IEEE JOURNAL OF PHOTOVOLTAICS, 2014, Vol. 4,pp. 1107-1113.

Nathan Michael, Shaojie Shen, Kartik Mohta, Yash Mulgaonkar, Vijay Kumar, KeijiNagatani, Yoshito Okada, SeigaKiribayashi, KazukiOtake, Kazuya Yoshida, Kazunori Ohno, Eijiro Takeuchi, Satoshi Tadokoro.Collaborative Mapping of an Earthquake-Damaged Building via Ground and Aerial Robots. Journal of Field Robotics, Wiley Periodicals Inc., 2012, Vol. 29, pp. 832-841.

Alexey Bulgakov, Alexey Evgenov and Cornell Weller. Automation of 3D building model generation using quadrotor. In: Creative Construction Conference 2015 (CCC2015), Procedia Engineering, Elsevier Ltd., 2015. Vol. 123, pp. 101-109.

JoãoValente, JaimeDel Cerro, AntonioBarrientos, DavidSanz. Aerial coverage optimization in precision agriculture management:A musical harmony inspired approach. Computers and Electronics in Agriculture, 2013, Vol. 99, pp. 153-159.

B. Coifman, M. McCord, R.G. Mishalani, M. Iswalt, Y. Ji. Roadway traffic monitoring from an unmanned aerial vehicle.2006, IEE Proc. Intell. Transp. Syst., Vol. 153, 2006, pp. 11-20.

S. NorouziGhazbi, Y. Aghli, M. Alimohammadi, A. A. Akbari, Quadrotors Unmanned Aerial Vehicles: A Review. et. al., et al. 1, March 2016, International Journal on Smart Sensing and Intelligent Systems, Vol. 9, No. 1, pp. 309-333.

Carrillo, Garcia L.R., Alejandro Enrique Dzul López, Rogelio Lozano, Claude Pégard. Modeling the Quad-Rotor Mini-Rotorcraft. Quad Rotorcraft Control: Vision-Based Hovering and Navigation. Springer, 2013, pp. 23-34, ISBN: 978-1447143987.

Luukkonen, Teppo. Modeling and control of Quadrotor. August 22, 2011.

He, ZeFang and Zhao, Long.A Simple Attitude Control of Quadrotor Helicopter Based on Ziegler-Nichols Rules for Tuning PD Parameters. The Scientific World Journal, Vol. 2014, pp. 1-13. http://dx.doi.org/10.1155/2014/280180.

Chen Wang, Meyer Nahon, Mike Trentini. Controller Development and Validation for a Small Quadrotor with Compensation for Model Variation. In: International Conference on Unmanned Aircraft Systems (ICUAS). Orlando, FL, USA, IEEE, 2014, pp. 902-909.

Perez-Alcocer, R., Javier, Moreno-Valenzuela and Roger, Miranda-Colorado. A robust approach for trajectory tracking control of quadrotor with experimental validation. ISA Transactions, Vol. 65, 2016, pp. 262-274

Kuo, Benjamin C. and Golnaraghi, Farid. Automatic control systems. 8th Ed., New Delhi: John Wiley & Sons, 2013. pp. 261-264. ISBN: 978-81-265-1371-0.

Min, Kyoung-Moo, Foong-Yi Chia, and Bong-Hwan Kim. "Design and Cfd Analysis of a Low-Altitude VtolUav."International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)9.2, Apr 2019, 555-562

Kumar, A. Sathesh, K. Mohan Babu, and M. Karthick. "Design And Analysis of Intelligent Quadrocopterto Avoid the Obstacles."International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) 8.3, Jun 2018, 841-848

Ahmed, Md Faiyaz, and YeoleShivraj Narayan. "Fabrication and Testing of Quadcopter Prototype for Surveillance."International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) Jun 2018, 99-105

Chowdhury, Aditya, and Vishnu G. Nair. "On the application of particle swarm optimization in minimum time launch vehicle trajectory optimization problem." *International Journal of Mechanical and Production Engineering Research and Development* 7.5 (2017): 359-366.

Danthala, S. W. E. T. H. A., et al. "Robotic Manipulator Control by using Machine Learning Algorithms: A Review." *Int J Mech Prod Eng Res Dev* 8.5 (2018): 305-310.