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DISTURBANCE UNCERTAINTY ESTIMATOR BASED ROBUST ATTITUDE CONTROL OF A QUADROTOR

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ABSTRACT

This paper presents a disturbance uncertainty estimator (DUE) based robust attitude control scheme for quadrotors. To show the effectiveness of the DUE mechanism, three simulation scenarios are handled. For the first simulation scenario, a classical proportional integral derivative (PID) attitude and altitude controller are designed, and applied to the Crazyflie 2.0 nano quadcopter platform under the nominal conditions. In the second simulation scenario, the trajectory tracking performance of the classical PID attitude controller is analyzed under the presence of the bounded unknown orientational disturbances. Finally, in the last simulation scenario, when the DUE mechanism is activated the behavior of the overall system performance is investigated under the conditions in the second simulation scenario. Simulation results show that while the attitude control structure satisfies very good trajectory tracking performance under the nominal conditions, it is poorly affected in the presence of the unknown external disturbances. However, when the DUE mechanism is activated, lumped external disturbances are predicted very well, and the overall control scheme is made more robust even under the external disturbances.

INTRODUCTION

Disturbance and uncertainty estimation and cancellation in the control systems are still an active field, as they have the adverse effect on the performance and stability of the physical systems. To deal with the disturbance and uncertainty, there are many techniques in the literature. [Chen, Yang, Guo and Li, 2016] handle disturbance uncertainty observer based control and related methods. Furthermore, [Kürkçü, Kasnakoğlu and Efe, 2018] present a novel disturbance uncertainty estimator structure and [Kürkçü and Kasnakoğlu, 2018] use this method to design a robust autopilot system.

Another popular area is the robust control of unmanned aerial vehicles (UAVs), especially quadrotors because of many advantages from civilian to military applications ([Bouabdallah and Siegwart, 2007]). The robust control of quadrotors can be provided by using DUE structures ([Dai, Lu, Ren and Zhong , 2015], [Sanz, Garcia, Zhong and Albertos, 2016], [Lu, Ren, Parameswaran and Zhong, 2018]). In this study, we present DUE based robust attitude control of a quadrotor. The overall system performance are handled via simulation test scenarios.

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The rest of paper is organized as follows. Method section explains the quadrotor dynamics and DUE structure. Results and Discussion section investigates the all simulation scenarios, results and performance analysis details. Finally, conclusion is presented.

METHOD

Dynamical Model of a Quadrotor

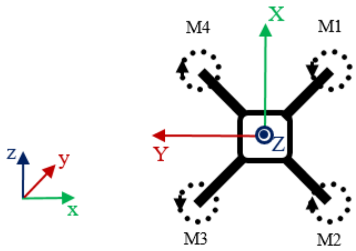

Figure 1: Cross configuration quadrotor model

In this section, the full mathematical model and control equations of a quadrotor are summarized. The cross-configuration quadrotor in Figure 1 is chosen to show the effectiveness of DUE structure presented in this study. The well-known quadrotor mathematical model obtained by Newton-Euler method under some assumptions([Bouabdallah and Siegwart, 2007]), and the other control input equations are as follows ($cos : c$ and $sin : s$):

$$\begin{bmatrix} m\ddot{x} \\ m\ddot{y} \\ m\ddot{z} \end{bmatrix} = \begin{bmatrix} (c_\psi s_\theta c_\phi + s_\psi s_\phi)U_1 + d_x \\ (s_\psi s_\theta c_\phi - c_\psi s_\phi)U_1 + d_y \\ (c_\theta c_\phi)U_1 - mg + d_z \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} I_x\dot{p} \\ I_y\dot{q} \\ I_z\dot{r} \end{bmatrix} = \begin{bmatrix} (U_2 + (I_y - I_z)qr - Jq\Omega_S) + d_\phi \\ (U_3 + (I_z - I_x)pr + Jp\Omega_S) + d_\theta \\ (U_4 + (I_x - I_y)pq) + d_\psi \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & s_\phi t_\theta & c_\phi t_\theta \\ 0 & c_\phi & -s_\phi \\ 0 & \frac{s_\phi}{c_\theta} & \frac{c_\phi}{c_\theta} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -\frac{l}{\sqrt{2}} & -\frac{l}{\sqrt{2}} & \frac{l}{\sqrt{2}} & \frac{l}{\sqrt{2}} \\ -\frac{l}{\sqrt{2}} & \frac{l}{\sqrt{2}} & \frac{l}{\sqrt{2}} & -\frac{l}{\sqrt{2}} \\ -\kappa & \kappa & -\kappa & \kappa \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} \tag{4}$$

$$\begin{gathered} f_i = K_F \Omega_i^2 \\ \tau_i = \kappa f_i \end{gathered} \tag{5}$$

Equations 1-2-3-4 show the translational, rotational dynamics of a quadrotor, the relationship between the Euler angle rates and the body angular rates, and the lift force and the torques acting on the quadrotor, respectively. Table 1 illustrates the variable names.

Quadrotor Physical Parameters: As a quadrotor platform, the Crazyflie 2.0 nano quadcopter is chosen. You can find the Crazyflie 2.0 nano quadcopter physical parameters from ([Förster, 2015]). Table 2

Table 1: Variable names

Symbol	Description
x, y, z	Relative position of the quadrotor in the inertial frame
ϕ, θ, ψ	Euler angles related to orientation of the quadrotor
p, q, r	Body anguler rates
m	Quadrotor mass
I	Quadrotor body inertia matrix
g	Acceleration of gravity
U_1	Total lift force
U_2, U_3, U_4	Torques acting on the quadrotor
J	Moment inertia of the propellers
Ω_i	i^{th} motor speed (rad/sec)
Ω_S	$\Omega_2 + \Omega_4 - \Omega_1 - \Omega_3$
d_j	Bounded and unknown external disturbance terms
f_i	Thrust generated by each rotor
τ_i	Torque generated by each rotor
K_F	Positive thrust factor
κ	Translation factor between the thrust and torque
l	Arm length of the quadrotor

shows the Crazyflie 2.0 physical parameters. Finally, the Crazyflie 2.0 nano quadcopter rotor dynamics are the first-order transfer function as follows:

$$\frac{\Omega(s)}{\Omega_d(s)} = \frac{1}{T_{rot}s + 1} \tag{6}$$

where T_{rot}: time constant of the rotor dynamics, Ω_d: desired rotor speed, Ω: actual rotor speed.

Table 2: The Crazyflie 2.0 physical parameters

Symbol	Value(Unit)	Symbol	Value(Unit)
m	$0.028(kg)$	l	$0.065(m)$
K_F	$1.61x10^{-8}(N.s^2)$	κ	0.006
I_x	$16.571710x10^{-6}(kg.m^2)$	I_y	$16.655602x10^{-6}(kg.m^2)$
I_z	$29.261652x10^{-6}(kg.m^2)$	g	$9.8(m/s^2)$
J	0	T_{rot}	0.05
Ω_{max}	$3050(rad/sec)$	Ω_{min}	$0(rad/sec)$
U_{1max}	$0.71(N)$	U_{1min}	$0.07(N)$
τ_{max}	$1x10^{-3}(Nm)$	τ_{min}	$-1x10^{-3}(Nm)$
ϕ, θ_{dmax}	$0.5(rad)$	ϕ, θ_{dmin}	$-0.5(rad)$

DUE Based Attitude Control Structure

Figure 2 shows the general attitude control structure including DUE mechanism. 'ATTITUDE & ALTITUDE CONTROLLER' block has below PID controller structure:

$$\mathbf{U} = \mathbf{K_p e} + \mathbf{K_i} \int_0^t \mathbf{e}(\tau)\mathbf{d}\tau + \mathbf{K_d \dot{e}} \tag{7}$$

where $\mathbf{e} = \hat{\mathbf{x}}_{desired} - \hat{\mathbf{x}}$.

$$\hat{\mathbf{x}} = \begin{bmatrix} z \ \phi \ \theta \ \psi \end{bmatrix}' \tag{8}$$

In this study, PID parameters are found with manual tuning (Table 3).

Table 3: PID parameters

	z	ϕ	θ	ψ
K_p	6	$7I_x$	$7I_y$	$7I_z$
K_i	0	0	0	0
K_d	4	$4.5I_x$	$4.5I_y$	$4.5I_z$

'FORCE & TORQUES TO SPEED' block has the square root of the following equation:

$$\begin{bmatrix} \Omega_1^2 \\ \Omega_2^2 \\ \Omega_3^2 \\ \Omega_4^2 \end{bmatrix} = \begin{bmatrix} \frac{1}{4K_F} & -\frac{\sqrt{2}}{4K_F l} & -\frac{\sqrt{2}}{4K_F l} & -\frac{1}{4\kappa K_F} \\ \frac{1}{4K_F} & -\frac{\sqrt{2}}{4K_F l} & \frac{\sqrt{2}}{4K_F l} & \frac{1}{4\kappa K_F} \\ \frac{1}{4K_F} & \frac{\sqrt{2}}{4K_F l} & \frac{\sqrt{2}}{4K_F l} & -\frac{1}{4\kappa K_F} \\ \frac{1}{4K_F} & \frac{\sqrt{2}}{4K_F l} & -\frac{\sqrt{2}}{4K_F l} & \frac{1}{4\kappa K_F} \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} \tag{9}$$

'ROTOR DYNAMICS' and 'SPEED TO FORCE & TORQUES' blocks include equation 6 and equations 4-5, respectively.

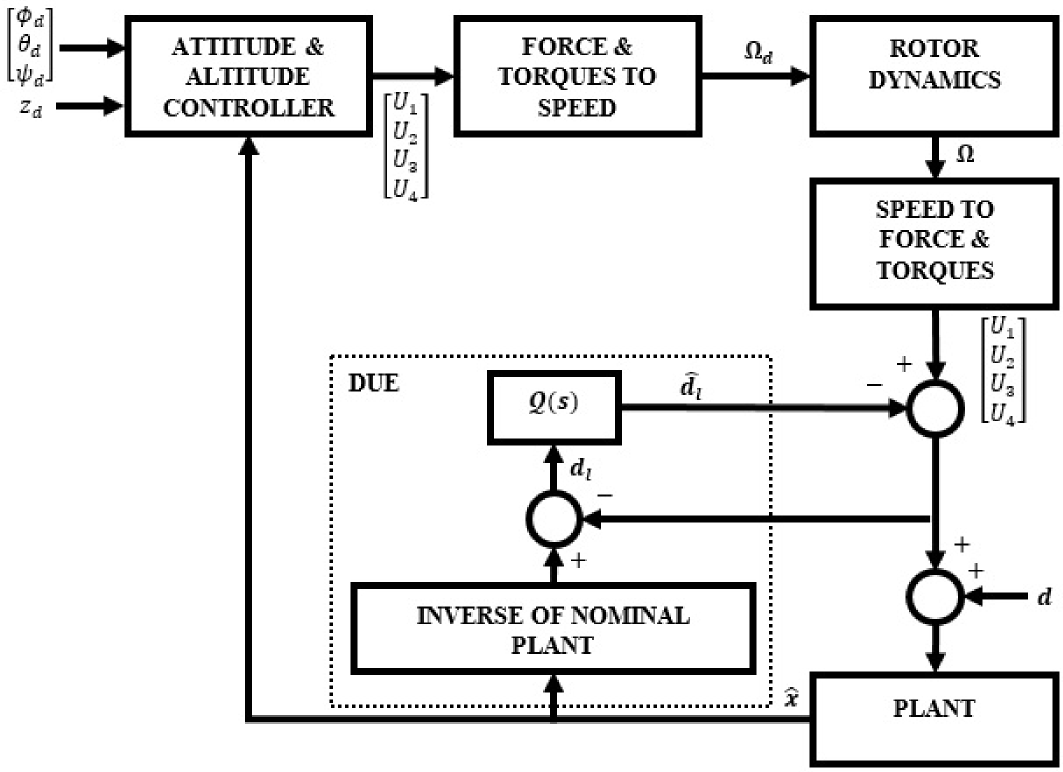

Figure 2: General control structure

As double integrator multiply with inverse inertial matrix of the quadrotor is obtained as the nominal model of the quadrotor for rotational dynamics. Therefore, 'INVERSE OF NOMINAL PLANT' block is as double derivative multiply with inertial matrix of the quadrotor.

$Q(s)$ Filter design: For DUE based control schemes, $Q(s)$ filter design is the most important step to predict accurately disturbances and uncertainties. It is usually selected as a low pass filter. In this study, a PD control structure is designed for the nominal plant of the quadrotor, and closed loop system is taken as $Q(s)$ filter.

Closed loop system is obtained as below:

$$Q(s) = \begin{bmatrix} \frac{301.7502s+12070}{s^2+301.7502s+12070} \\ \\ \frac{300.12s+12005}{s^2+300.12s+12005} \\ \\ \frac{170.8817s+6835}{s^2+170.8817s+6835} \end{bmatrix} \tag{10}$$

RESULTS AND DISCUSSION

In this section, under the light of the previous sections, three simulation scenarios are handled. The first one includes attitude trajectory tracking performance analysis under the nominal conditions that are unpresence of the disturbances and DUE mechanism. In the second simulation scenario, attitude control structure is analyzed under the presence of the unknown orientational disturbances, however DUE mechanism is not activated. The last simulation scenario includes the second scenerio besides DUE mechanism is activated. All simulation results are illustrated on the same graph. Table 4 shows the simulation details devoted to each scenario.

Table 4: Simulation details

Scenario	Time	Disturbance	DUE Mechanism
I	$0 < t < 10$	Passive	Passive
II	$10 \leq t < 40$	Active	Passive
III	$40 \leq t < 60$	Active	Active

For all scenarios, attitude reference signals and disturbances are selected as below:

$$\begin{bmatrix} z_d \\ \phi_d \\ \theta_d \\ \psi_d \end{bmatrix} = \begin{bmatrix} 1 \\ 0.1sin(2\pi t/10) \\ 0.1sin(2\pi t/10) \\ 0.1sin(2\pi t/10) \end{bmatrix} \tag{11}$$

where z_d is meter, and ϕ_d, θ_d, ψ_d are radian.

$$\mathbf{d} = \begin{bmatrix} d_z \\ d_\phi \\ d_\theta \\ d_\psi \end{bmatrix} = \begin{bmatrix} 0 \\ 1e-5\Gamma(t)+\Delta(t) \\ 1e-5\Gamma(t)+\Delta(t) \\ 1e-5\Gamma(t)+\Delta(t) \end{bmatrix} \tag{12}$$

where $\Gamma(t)$ is a chirp signal with $0.1Hz$ initial and $1Hz$ target frequency, $\Delta(t)$ is a white noise signal with $2e-16$ power magnitude and 0.001 sampling time.

Figures 3, 4, 5, 6 illustrate the all simulation results: attitude and altitude tracking results, control inputs, angular speeds of the motors and estimated disturbances, respectively. Simulation results show that while the attitude control structure satisfy very good trajectory tracking performance under the nominal conditions, it is poorly affected in the presence of the unknown external disturbances. However, when DUE mechanism is activated, lumped external disturbances are predicted very well ($\hat{d}_l$), and the overall control scheme is made more robust even in the precence of the external disturbances.

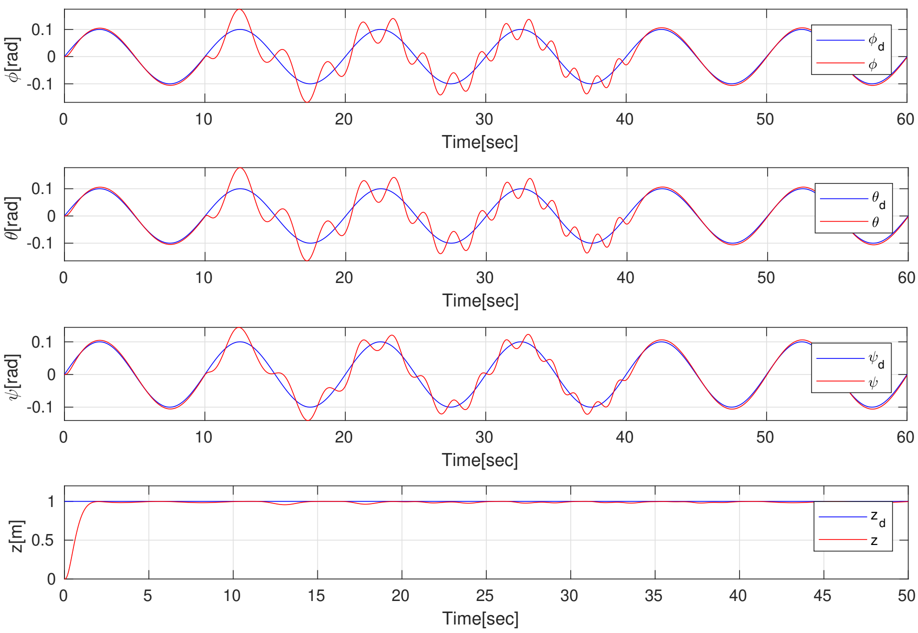

Figure 3: Attitude and altitude results

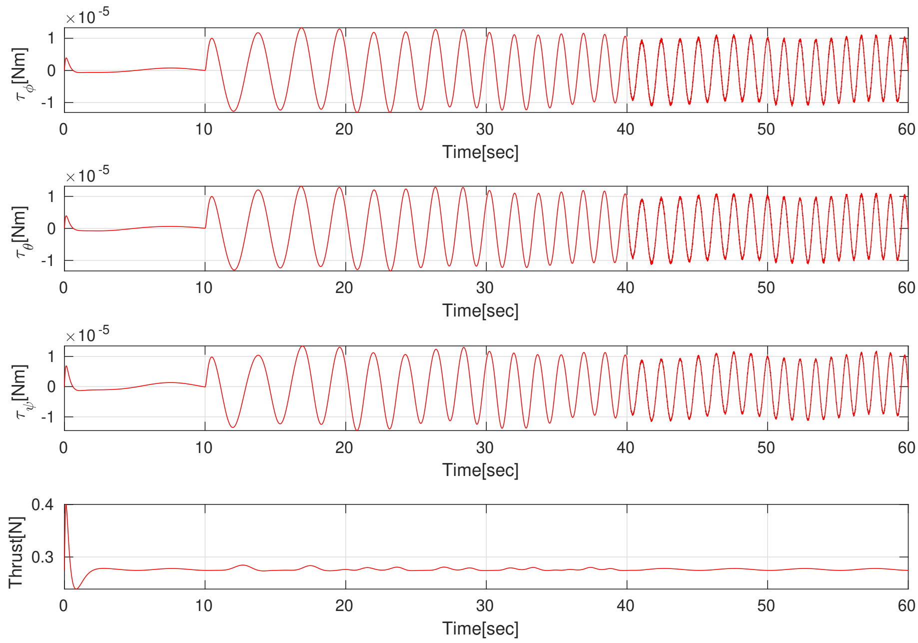

Figure 4: Control inputs

CONCLUSIONS

In this paper, a DUE based robust attitude control scheme was developed and applied to the Crazyflie 2.0 nano quadcopter platform. Three simulation scenarios were handled to show the effectiveness of the DUE mechanism. For the first one, a classical proportional integral derivative (PID) attitude and altitude controller were designed, and applied to the Crazyflie 2.0 nano quadcopter platform under

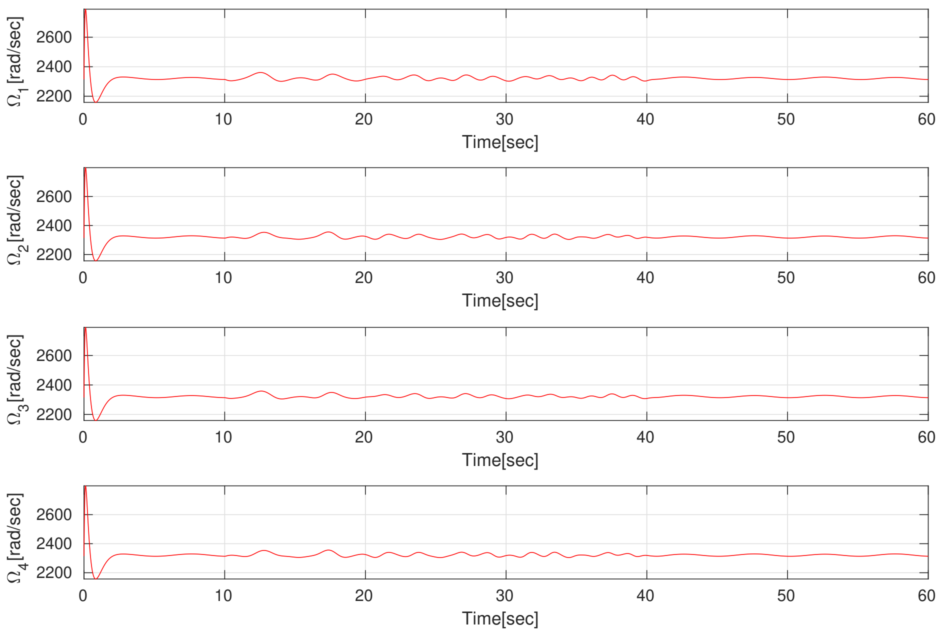

Figure 5: Angular speeds of the motors

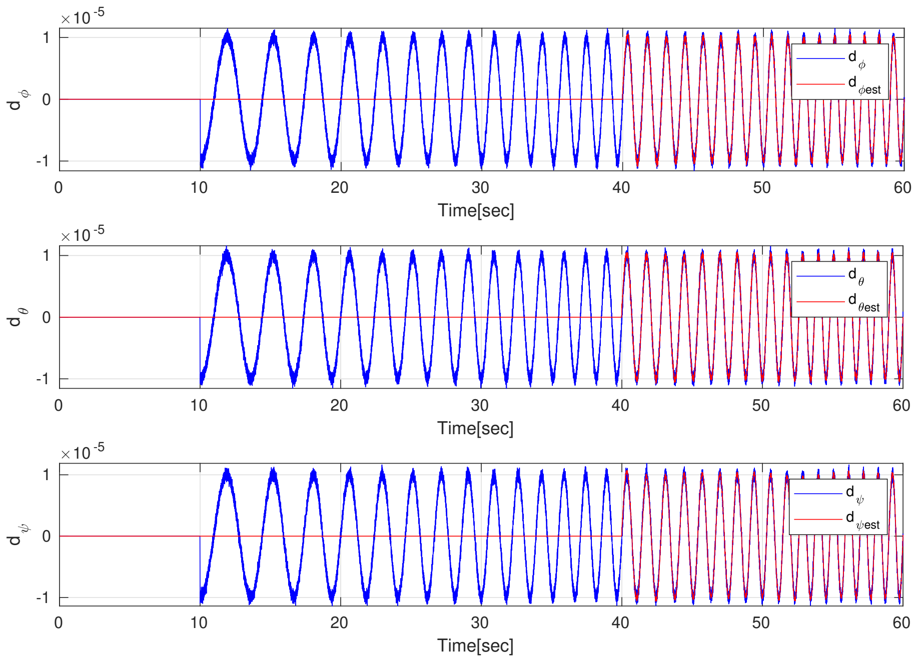

Figure 6: Disturbance estimation ($\hat{d}_l$)

the nominal conditions. In the second simulation scenario, the trajectory tracking performance of the classical PID attitude controller was analyzed in the presence of the bounded unknown external disturbances. Finally, when the DUE mechanism is activated the behavior of the overall system performance was investigated under the conditions in the second scenario. Simulation results show that while the attitude control structure satisfied very good trajectory tracking performance under the nominal conditions, it was poorly affected in the presence of the unknown external disturbances. However, when the DUE mechanism is activated, lumped external disturbances were predicted very well, and the overall control scheme was made more robust even under the external disturbances.

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