Control of Hexarotor Unmanned Aerial Vehicle for Outdoor Environment using Disturbance Observer

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Abstract

This paper presents control structure of a hexarotor unmanned aerial vehicle (UAV) that performs hovering and trajectory tracking with acceleration control in inertial coordinate. A cascade control structure has been implemented in the hexarotor UAV, enabling the control of attitude and position in each step. For robust position control of the hexarotor UAV, the outer loop controller with disturbance observer algorithm that generates disturbance compensated desired acceleration is designed. With this structure, exogenous disturbance affecting the hexarotor UAV could be estimated and compensated. Simulation result will be shown to evaluate the flight performance that compensates the atmospheric disturbance of the hexarotor UAV in outdoor flight situation.

Keywords: Hexarotor, Robust control, Disturbance observer, Acceleration Control

1. Introduction

Despite significant advances in technologies related with drone hardware platforms and sensors **[1] [2]**, outdoor flight is still difficult to obtain satisfactory flight performance because of the atmospheric interferences such as gust, or wind. Especially when drone has to move or hover with precise path or position, the atmospheric interference directly generates unwanted inertial coordinate acceleration that makes drone to off course. Many researchers found ways to solve this problem in rigid attitude control. Methods with modifying the integral time for improved disturbance rejection in PID control **[3]** or applying model predictive control in attitude control **[4]** are such examples. These methods are highly efficient when the atmospheric disturbance affects control torque generation, making it hard to control drone's attitude. But when atmospheric disturbance affects into drone's centre of mass that 'pushes' it from one way to another, rigid attitude control cannot be a solution. For solving this problem, the position controller should have capability to control the inertial coordinate acceleration. Once controller earns the capability of controlling the inertial coordinate acceleration, the controller should observe magnitude of the acceleration generated due to the atmospheric disturbance and compensate it.

In this paper, we aim to develop an inertial acceleration controller of the multirotor drone by adopting disturbance observer (DOB) algorithm, which provides a robustness of the controller to outer disturbance. First, the configuration, kinematics and the dynamics of the hexarotor drone will be introduced. After that, the introduction of the proposed DOB structure will be shown. In the end, simulation results will be shown with graphical analysis.

2. Hexarotor Modelling

a. Discription

The gole of this research is to make better positioning performance of the hexarotor drone with minimizing the effect of the atmospheric disturbance. To simplify the structure of the position controller (or outer loop controller), the inertial coordinate's x and y position is controlled independently of z position and yaw angle. Thus, total thrust of the hexarotor drone is controlled only by an independent height controller (or z position controller) and yaw value is controlled by an independent yaw controller.

b. Kinematics and Dynamics of the Hexarotor

The position and attitude kinematics of the hexarotor is given by

$$\begin{cases} \dot{X} = R(\Theta)V \\ \dot{\Theta} = W(\Theta)\Omega \end{cases} \tag{1}$$

where $X = [x, y, z]^T \in \mathbb{R}^3$ the inertial coordinate position of the drone and $V = [u, v, w]^T \in \mathbb{R}^3$ the linear velocity in body-fixed frame. $\Theta = [\phi, \theta, \psi]^T \in \mathbb{R}^3$ denote the attitude by the Euler angle and $\Omega = [p, q, r]^T \in \mathbb{R}^3$ is the angular velocity of the drone in body-fixed frame.

The dynamics of the hexarotor drone is as follows. First, the attitude dynamics of the hexarotor is given by

$$T = J\dot{\Omega} + \Omega \times (J\Omega) \tag{2}$$

where $T \in \mathbb{R}^3$ is the torque applied into the airframe, $J \in \mathbb{R}^{3\times3}$ the moment of inertia matrix. Second, the position dynamics of the hexarotor is given by

$$\ddot{X} = g\begin{bmatrix}0\\0\\1\end{bmatrix} - R(\Theta)\frac{(\sum_{i=1}^{6} F_i)}{m}\begin{bmatrix}0\\0\\1\end{bmatrix} \tag{3}$$

where g is the gravitational acceleration and m is the total mass of the drone.**[5]**

c. Modelling of the Hexarotor

When the hexarotor needs to maintain its altitude, the independently operating height controller controls total thrust to keep its altitude. From equation (3), considering $\ddot{z}$ as 0 in hovering state, the total thrust should be $\sum F = \frac{mg}{cos\phi\ cos\theta}$. This means that high value of the roll and pitch angles make $\sum F$ so big that the hexarotor cannot generate enough power to keep its altitude. For this reason, we must control drone's attitude with small boundary. This limit gives us legitimacy of small angle assumption, which means that we can think $cos\phi \approx 1$, $cos\theta \approx 1$, $sin\phi \approx \phi$ and $sin\theta \approx \theta$.

Reminding from the equation (2), attitude dynamics of the hexarotor is composed with the inertial moment term and the gyroscopic term. But the gyroscopic effect is so small in conventional-sized drone that we can simply neglect it. Applying the near angle assumption, the matrix W in equation (1) can be treated as $W \approx I \in \mathbb{R}^{3\times3}$, making the transfer function of the drone's dynamics as

$$T = J\,\dot{\Omega} = J(W^{-1})^2\left(W\ddot{\Theta} - \dot{W}\dot{\Theta}\right) = J\ddot{\Theta} \tag{4}$$

The rotation inertial moment J is near diagonal matrix, which non-diagonal component of the matrix is so small comparing to diagonal components. So, we can think the roll and pitch attitude is independent to each other. Using a PID controller for attitude control, the transfer function of inner loop dynamics is

$$\begin{gathered}\frac{\Theta(s)}{e(s)} = \frac{T_{pitch}(s)}{D(s)-\Theta(s)}\frac{\Theta(s)}{T_{pitch}(s)} = \frac{Ps + I + Ds^2}{s}\frac{1}{J_{pitch}s^2} = \frac{Ps + I + Ds^2}{J_{pitch}s^3}\\ \Lambda(s) = \frac{\Theta(s)}{D(s)} = \frac{Ds^2 + Ps + I}{Js^3 + Ds^2 + Ps + I}\end{gathered} \tag{5}$$

where $\Lambda(s)$ is the transfer function between the desired attitude and current attitude. As we can see, the system is 3^{rd} order with relative degree 1.

d. Acceleration Control of the Hexarotor

Considering the small angle assumption applied into the hexarotor drone, we can rewrite the inertial acceleration dealt in equation (3) as

$$\begin{aligned}\ddot{x} &= -\frac{u_1}{m}(\theta\ cos\psi + \phi\ sin\psi)\\ \ddot{y} &= -\frac{u_1}{m}(\theta\ sin\psi - \phi\ cos\psi)\\ \ddot{z} &= g - \frac{u_1}{m}\end{aligned} \tag{6}$$

where $u_1 = \sum F$. As mentioned previously, height control of the hexarotor drone is operated independently. So total thrust is given as $u_1 = ||[0\ 0\ \sum F]^T|| = m||a||$ in the position controller's perspective. Rewriting it, we can say x and y acceleration of equation (6) as

$$\frac{d^2}{dt^2}\begin{bmatrix} x \\ y \end{bmatrix} = G(||a||,\psi)\begin{bmatrix} \phi \\ \theta \end{bmatrix}$$

$$G(||a||,\psi) = -||a||\begin{bmatrix} sin\psi & cos\psi \\ -cos\psi & sin\psi \end{bmatrix} \tag{7}$$

From this equation, we can achieve [inertial acceleration] – [roll, pitch angle] relationship with given norm of current acceleration and current yaw. This means when the controller wants the drone to move with desired x, y acceleration, the signal could be converted into the desired roll and pitch angles. With the combination of the attitude controller that we have dealt in previous section, x and y acceleration in inertial coordinate is controllable with

$$\begin{bmatrix} \phi_{des} \\ \theta_{des} \end{bmatrix} = G(||a||,\psi)^{-1}\begin{bmatrix} \ddot{x}_{des} \\ \ddot{y}_{des} \end{bmatrix} \tag{8}$$

The block diagram of the inertial acceleration controller is shown in **Figure 1**.

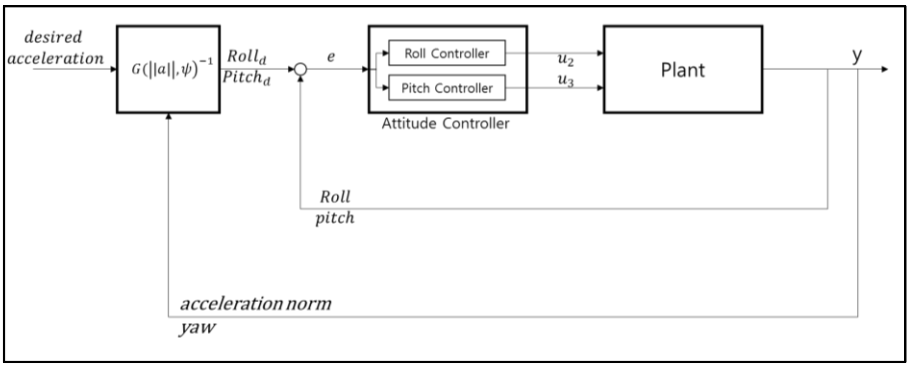

Fig. 1: Acceleration control structure of the hexarotor drone

3. Disturbance Observer

a. Plant Re-definition

The aim of this paper is to build the control structure that reduces the effect of disturbances generated by the atmospheric activity, which gives direct effect to the airframe's desired inertial acceleration following. To achieve the goal, we need to re-define the meaning of the 'Plant'. The concept of 'Plant' that we used in previous session was only the set of the airframe dynamics and the propeller dynamics. But in the sense of acceleration controller (or position controller, outer loop controller), the inner loop dynamics that is the set of [drone dynamics], [attitude controller] and [desired acceleration to desired attitude converter] are all can be seen as the 'Plant'. In **Figure 2**, the blue box shows an inner loop system that acceleration controller should control. So, during this chapter, the word 'Plant' indicates the overall inner-loop dynamics.

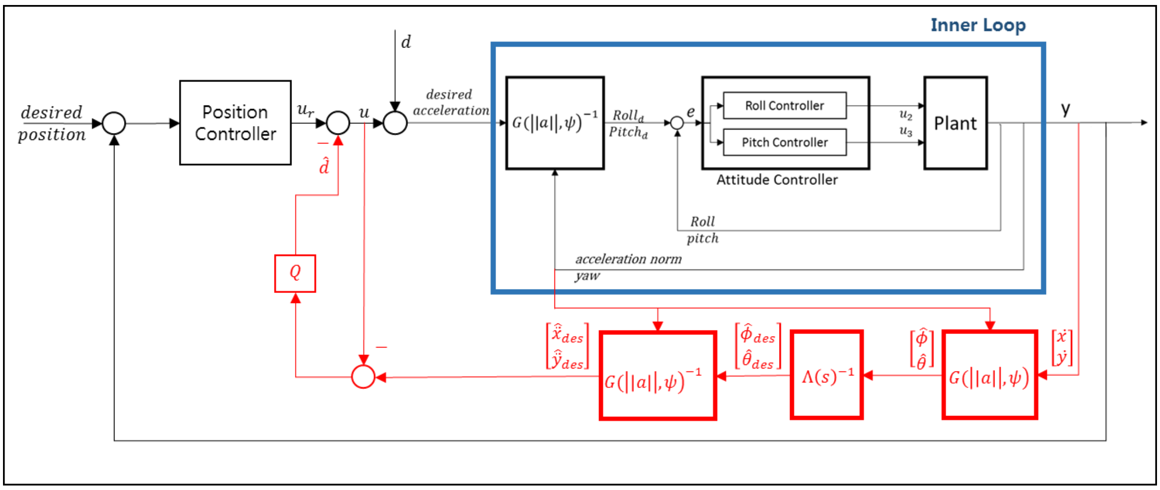

Fig. 2: Position control structure of the hexarotor with proposed DOB structure

b. Disturbance Observer based Acceleration Control

The disturbance affecting the hexarotor's inertial coordinate acceleration control goes into the body frame directly. But the effect of the disturbance can be converted into the equivalent disturbance which contaminates desired acceleration right after u in **Figure 2**.

In this section, the DOB based inertial acceleration controller will be introduced. As typical DOB structures has, the control signal consists of two parts; one the outer-loop control signal, the other a disturbance estimation signal. **[6]** First, for disturbance estimation in DOB structure, INS sensor attached in the airframe of the hexarotor measures the inertial acceleration $\ddot{X}$. Then, the estimated current roll and pitch angle $\widehat{\Theta}$ can be calculated as $\widehat{\Theta} = \mathrm{G}(||\mathrm{a}||, \psi)\ddot{X}$ with $\ddot{X} = [\ddot{x}\ \ddot{y}]^{\mathrm{T}} \in \mathbb{R}^2$. After that, estimated desired roll and pitch angle $\widehat{\Theta}_{des}$ can be calculated as $\widehat{\Theta}_{des} = \Lambda(s)^{-1}\widehat{\Theta}$ with $\widehat{\Theta} = [\hat{\phi}_{des}\ \hat{\theta}_{des}]^T \in \mathbb{R}^2$. Multiplying $\mathrm{G}(||\mathrm{a}||, \psi)^{-1}$ to $\widehat{\Theta}_{des} = [\hat{\phi}_{des}\ \hat{\theta}_{des}]^T \in \mathbb{R}^2$, the estimated inertial x and y acceleration $\hat{\ddot{X}} = [\hat{\ddot{x}}_{des}\ \hat{\ddot{y}}_{des}]^{\mathrm{T}}$ can be calculated as follows.

$$\hat{\ddot{X}} = \begin{bmatrix} \hat{\ddot{x}} \\ \hat{\ddot{y}} \end{bmatrix} = \mathrm{G}(||\mathrm{a}||, \psi)^{-1}\Lambda(s)^{-1}G(||a||, \psi)\begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} \tag{9}$$

The red structure in **Figure 2** shows the sequence of DOB that estimates outer disturbances. First, we can treat $\hat{\ddot{X}}$ as $\hat{u} + \hat{d}$ since $\hat{\ddot{X}}$ is estimated input to inner loop controller. Then, subtracting u from $\hat{\ddot{X}}$ is $(\hat{u} - u) + \hat{d} \approx \hat{d}$ that is lumped estimated disturbance. In next control step, subtracting $\hat{d}$ from u or $u_r - \hat{d}$, final input $u + d$ will become $(u_r - \hat{d}) + d \approx u_r$ in ideal situation.

The nominal airframe dynamics $\Lambda(s)$ is minimum phase, linear time-invariant system whose relative degree is $r \geq 1$. During the calculation of $\hat{d}$, the inverse of the nominal plant $\Lambda(s)$ is improper function that brings unstable response due to its self-contained pure differentiator trait. To supress it, we put additional filter called Q-filter with relative degree higher than r that makes overall transfer function proper. **[7]**

c. Simulation Result

With the simulation, the performance of the proposed controller is evaluated and compared with non-DOB applied situation. The inertia matrix in simulation is given by

$$\mathrm{J} = \begin{bmatrix} 0.0282 & 0 & 0 \\ 0 & 0.0282 & 0 \\ 0 & 0 & 0.149 \end{bmatrix}$$

The controller is separated into three groups, one the height controller which generates u_1, another yaw controller that controls yaw angle separately, and finally the x and y inertial coordinate acceleration controller. The simulation was done by Matlab Simulink. Simulation results are as follows.

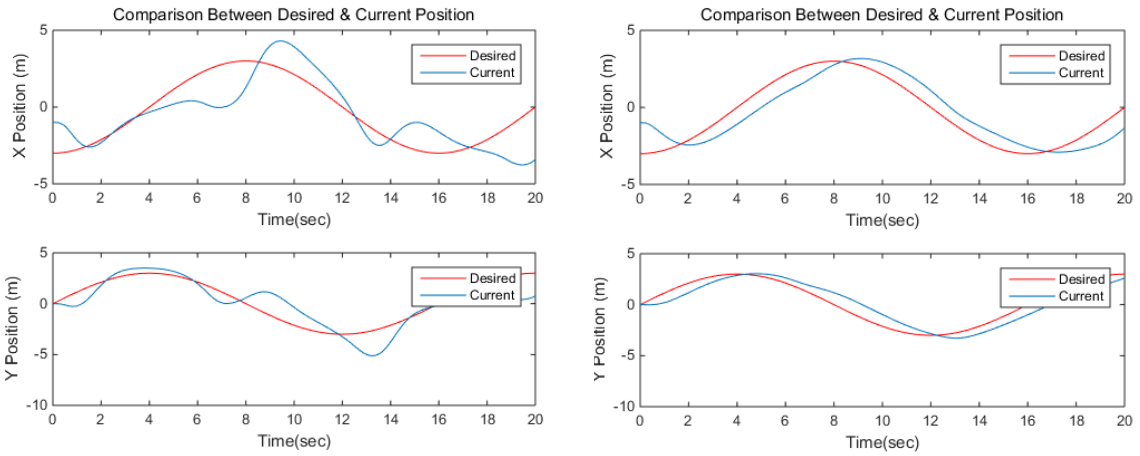

Fig. 3: Comparison Between DOB-OFF situation (left) and DOB-ON situation (right)

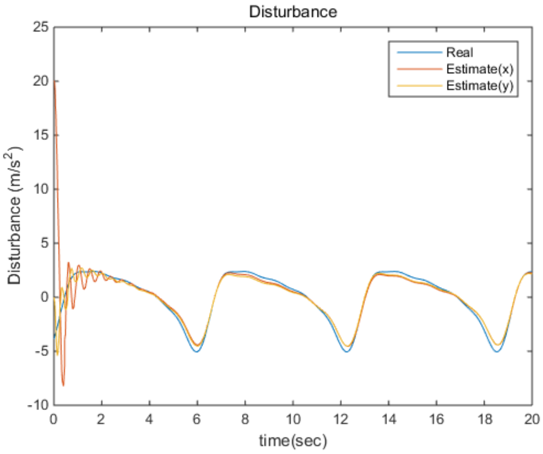

Fig. 4: Comparison between actual disturbance (blue) and estimated disturbance (red, yellow)

The disturbance model is combination of trigonometric function, ranging from -5 to 2.5. **Figure 3** shows the flight path log of x and y inertial axis of both DOB-off and DOB-on situation. Hexarotor drone in DOB-on situation seems to follow the desired path better than DOB-off situation. Seeing **Figure 4**, the estimation value of disturbance in first few second was oscillating but after 4 second, it well follows the real disturbance value. This means that disturbance is well estimated and the final desired acceleration cancels the outer disturbance with good performance.

4. Conclusion & Future Work

In this paper, robust control using position DOB structure for quadrotor's outer disturbance rejection has been implemented. This structure can deal with both inertial coordinate X and Y axis directional disturbance such as atmospheric disturbance that we can face during outdoor flight with harsh wind condition. Unlike some other control methods, position DOB structure predicts outer disturbance and cancels the effect, making system reliable.

Due to this method's trait, it could be used into another purpose such as slung load oscillation effect rejection or internal force rejection when multiple drones lift object with cooperative manipulation. Implementing the proposed structure to realistic situation will be the future work.

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