

## Experimental Studies of a Disturbance Observer for Attitude Control of a Quad-Rotor System

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**Abstract:** This paper presents a simple design of a disturbance observer (DOB) for a quad-rotor system. To achieve robust attitude control of a quad-rotor system against disturbance, DOB is employed. Based on the conventional DOB structure, a proposal of simple modification allows an efficiency of calculation for estimating the disturbance term. The proposed DOB does not require the delayed calculation so that efforts of designing Q filter can be minimized. The effectiveness of the proposed DOB is evaluated through experimental studies of attitude control of a quad-rotor system.

**Keywords:** Disturbance observer (DOB), calculation efficiency, quad-rotor system.

### 1. INTRODUCTION

Recently, interests in developing and controlling quad-rotor systems are enormously increased due to promising applications as an unmanned aerial vehicle (UAV) in various areas. Quad-rotor systems are a kind of under-actuated systems that have four rotors to generate six-axis motions in the air.

Four rotor configuration leads to structural advantages of stable hovering, omni-directional mobility, fast maneuverability, simple control, and more power generation for payload over single-rotor systems.

Although practical applications of quad-rotor systems are not concretely revealed at a current stage, a possible scenario of applications is feasibly presented and demonstrated in the literature [1-11].

Quad-rotor systems are one of unmanned aerial vehicles that perform autonomous navigation-based surveillance and monitoring-based security services. Navigation-based surveillance becomes a key role of UAVs. Traffic monitoring tasks by quad-rotor systems are beneficial to inform drivers in real-time fashion when traffic is congested due to highway accidents or rush-hour traffic. Another feasible application of quad-rotor systems is security service. Quad-rotor systems can monitor any suspicious activities in the dangerous area and prevent any possible attack.

In the technical framework, omni-directional mobility and flexible maneuverability of quad-rotor systems are two important characteristics suitable for urban applications. In the narrow space, quad-rotors can move any direction and speedy turning motion can be done. Less space requirement and less noise of quad-rotor systems are definitely advantages for urban applications as well.

In control aspects, unlike single-rotor systems, dynamics of quad-rotor systems is relatively simple that it can be approximated as a simple inertial system. This makes control easy and simple.

Various control algorithms have been applied to control quad-rotor systems [1-10]. Nonlinear sliding mode control [1], an inverse dynamics control method [2], and a neural network control method have been presented [3] along with other control methods [4-6].

Control of physical quad-rotor systems has been presented [7-11]. Aggressive maneuvering of quad-rotor systems has been tested [7]. Real time stabilization and tracking control of a quad-rotor have been tested [8]. A quad-rotor system equipped with both flying and driving capabilities has been presented and its performances have been demonstrated [9, 10].

In the previous research, an acceleration-based DOB structure has been presented [11]. The acceleration-based DOB has been derived from the conventional DOB proposed by Ohnishi [12].

Since dynamics of a quad-rotor system is approximated as an inertial system, accelerations are estimated by using gyro sensors. An acceleration-based DOB estimates disturbance based on the estimation of thrust forces from acceleration measurements and compared with control inputs.

In the acceleration-based DOB configuration, here a simple modified DOB is proposed. Modification made to the acceleration-based DOB structure improves calculation efficiency. Experimental studies on a physical quad-rotor system are performed to prove the effectiveness of the proposed DOB scheme.

### 2. QUAD-ROTOR MODEL

A quad-rotor system has four rotors to generate thrust forces inducing six-axis motions, three translation,  $q_1 = [x, y, z]^T$  and three rotation,  $q_2 = [\phi, \theta, \psi]^T$ . This forms the variable vector  $q = [q_1, q_2]^T$  as

$$q = [x, y, z, \phi, \theta, \psi]^T \quad (1)$$

where  $\phi, \theta, \psi$  are roll, pitch, and yaw angle, respectively.

The coordinate of a quad-rotor system is shown in Fig. 1. Each  $i$ th rotor generates a thrust force,  $f_i$  and a sum of each thrust force becomes  $f_{th}$ .

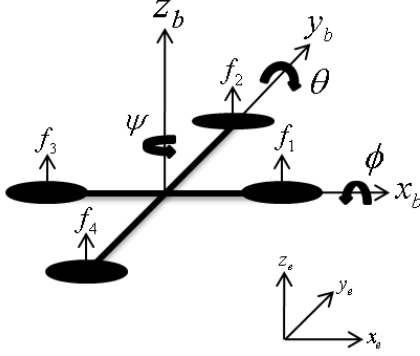


Fig. 1 Coordinate of a quad-rotor system

Simplified dynamics can be described under the assumption of ignoring air disturbance and other uncertain terms as in [10, 11]

$$\begin{aligned}
 m\ddot{x} &= f_{th}(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi) \\
 m\ddot{y} &= f_{th}(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi) \\
 m\ddot{z} &= f_{th}\cos\phi\cos\theta - mg \\
 I_x\ddot{\phi} &= (f_2 - f_4)l \\
 I_y\ddot{\theta} &= (f_3 - f_1)l \\
 I_z\ddot{\psi} &= C(f_1 - f_2 + f_3 - f_4)l
 \end{aligned} \quad (2)$$

where  $f_{th}$  is a total thrust,  $I_x, I_y, I_z$  are moments of inertia about  $x, y, z$  axis, respectively,  $l$  is the distance between a rotor and the center of gravity,  $C$  is a constant, and  $g$  is the gravitational acceleration.

### 3. CONTROL STRUCTURE

#### 3.1 Attitude Control

To achieve successful hovering posture, stable attitude should be attained by controlling three angles, roll, pitch, and yaw angle and elevation.

Since the attitude control is tested on the test-bed, only three angles are tested without elevation control. Simple PD control methods are used for the attitude control. Control inputs for each angle are given by

$$\begin{aligned}
 u_\phi &= k_{p\phi}(\phi_d - \phi) + k_{d\phi}(\dot{\phi}_d - \dot{\phi}) \\
 u_\theta &= k_{p\theta}(\theta_d - \theta) + k_{d\theta}(\dot{\theta}_d - \dot{\theta}) \\
 u_\psi &= k_{p\psi}\psi_{rc} + k_{d\psi}\dot{\psi}_{gyro}
 \end{aligned} \quad (3)$$

where  $k_{p\phi}, k_{d\phi}, k_{p\theta}, k_{d\theta}$  and  $k_{p\psi}, k_{d\psi}$  are controller

gains.

In experimental studies, roll and pitch angles are sensed by a gyro sensor so that control loop can be closed. However, yaw angle is controlled without a sensor so that  $\psi_{rc}$  is a commanded signal from wireless joystick and  $\dot{\psi}_{gyro}$  is measurement data from a gyro sensor, which forms open loop control. In practice, yaw angle can be detected by magnetic compass.

Control of each angle is performed by actuating each rotor. Therefore, the relationship between control input for each angle and each rotor should be specified as below

$$\begin{aligned}
 f_1 &= u_{th} + u_\phi + u_\psi \\
 f_2 &= u_{th} - u_\theta - u_\psi \\
 f_3 &= u_{th} - u_\phi + u_\psi \\
 f_4 &= u_{th} + u_\theta - u_\psi
 \end{aligned} \quad (4)$$

where  $u_{th}$  is the thrust control input that include the elevation control.

#### 3.2 Conventional Disturbance Observer

The role of a disturbance observer in the control system is to cancel out disturbance by estimating based on system models. Fig. 2 shows the disturbance observer structure proposed by Ohnishi [12]. If the estimated disturbance,  $\hat{D}$  is identified exactly same as  $D$ , then a control input signal to the system eventually becomes disturbance-free such that  $T = \tilde{T}$ .

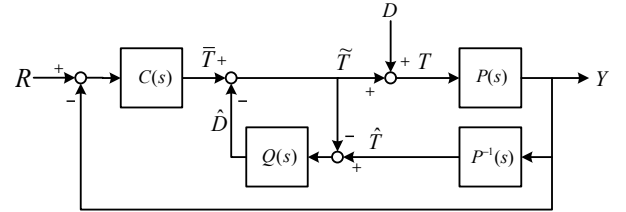


Fig. 2 DOB proposed by Ohnishi

In order to estimate the control input signal,  $\hat{T}$ , the inverse of the system model,  $P^{-1}$  should be available such that  $\hat{T} = P^{-1}Y$ . Then the disturbance is estimated by subtracting  $\tilde{T}$  in Fig. 2 from the estimated control input.

$$\hat{D} = \hat{T} - \tilde{T} \quad (5)$$

The control input is calculated by

$$T = D + \tilde{T} = D + \bar{T} - \hat{D} \quad (6)$$

When the disturbance,  $D$  and the estimate one,  $\hat{D}$  are identical, the control input,  $T$  becomes  $\bar{T}$ .

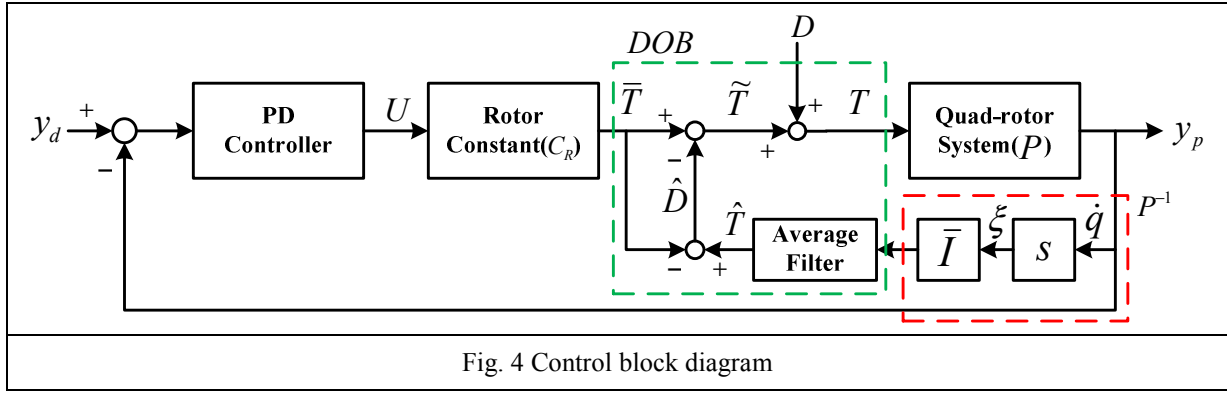


Fig. 4 Control block diagram

$$T = \bar{T} \quad (7)$$

The performance of DOB due to time-delay, noise in the control loop or inaccurate plant model can be degraded. So the Q filter is used to tune the estimation to improve the performance.

However, design of Q filter is quite difficult to satisfy the specification and becomes a more important factor in DOB design.

### 3.3 Disturbance Observer Design

To minimize a burden to design Q filter, the DOB structure in Fig. 2 can be modified. Instead of estimating disturbance with  $\hat{T}$  and  $\tilde{T}$ ,  $\hat{D}$  can be estimated with  $\hat{T}$  and  $\bar{T}$ . This configuration eliminates a time -delay in the DOB loop.

In the DOB structure given in Fig. 2, one sample delay is required to use  $\tilde{T}$  to estimate disturbance. Delay may be compensated by the design of Q filter.

Here DOB can be constructed by using  $\bar{T}$  instead of using  $\tilde{T}$ .

$$\hat{D} = \hat{T} - \bar{T} \quad (8)$$

The control input is calculated as same as (6) by

$$T = D + \bar{T} - \hat{D} \quad (9)$$

When the disturbance,  $D = \hat{D}$ , the control input,  $T$  becomes  $\bar{T}$ . Uncertainties such as modeling error or noise can be compensated by designing Q filter or simply by increasing a gain,  $K_{dob}$  as shown in Fig. 3.

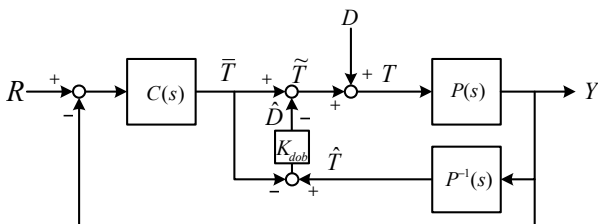


Fig. 3 Proposed DOB structure

For practical application to a quad-rotor control,

The proposed DOB structure is shown as Fig. 4 in detail.

Inverse model of a quad-rotor system,  $P^{-1}$  is obtained by experimental studies. Here moments of inertia about x,y,z axis are identified by a gyro sensor. Measuring acceleration and comparing with control input can estimate moments of inertia [11].

## 4. EXPERIMENTS

### 4.1 Experimental Setup

Attitude control of a quad-rotor system shown in Fig. 5 is tested.



Fig. 5 Quad-rotor system

Table 1 lists parameters of a quad-rotor system used for experimental studies.

Table 1 System Parameters

Parameters	Values
Distance between rotor and COG ( $l$ )	0.2 m
Moment of Inertia about x, y axis ( $I_x, I_y$ )	0.004 Kg· m
Rotor-Force Constant ( $C_R$ )	0.2
Mass	0.95Kg
Weight	0.04 g
Maximum thrust	2Kg
MCU	ATMEGA644 8bit processor
Sampling time	4 msec

Each parameter value is identified by experiments. Moment of inertia terms are identified through several experiments by comparing sensing data with applied torque values. Moment of Inertia about x, y axis ( $I_x, I_y$ ) is same as 0.004 Kg·m.

Fig. 6 shows the test-bed system. A quad-rotor is placed on a free joint at the top of the test-bed. A weight is attached to one axis to cause asymmetrical structure and to change the COG location, which is considered as a disturbance. Since the system has imbalance of the structure due to a weight, we can check the balancing control performance of DOB.

A quad-rotor system is required to maintain stable attitude under the situation shown in Fig. 6. Although COG is not located at the center of the system, the controller is required to maintain balance.



Fig. 6 Quad-rotor system test-bed

#### 4.2 Experimental Results

Two control methods are tested. One is a linear control method given in (3). Another experiment is when DOB is used along with a PD control method.

##### 1) PD control method

Fig. 7 shows the attitude control performance by a linear control method. The first plot of Fig. 7 shows that the roll angle keeps falling down to -5 degrees by a weight and comes back to zero degree in regular fashion, which the controller keeps trying to maintain balance. The second plot is sensor-based control input measured by a gyro,  $\hat{T}$ , and the third plot is about  $\bar{T}$ .

Comparing  $\hat{T}$  and  $\bar{T}$ , we see that the disturbance effect is included in the term  $\hat{T}$ . If the disturbance is not given to the system then similar patterns between  $\hat{T}$  and  $\bar{T}$  are expected. Note that positive control input patterns of  $\bar{T}$  are quite similar.

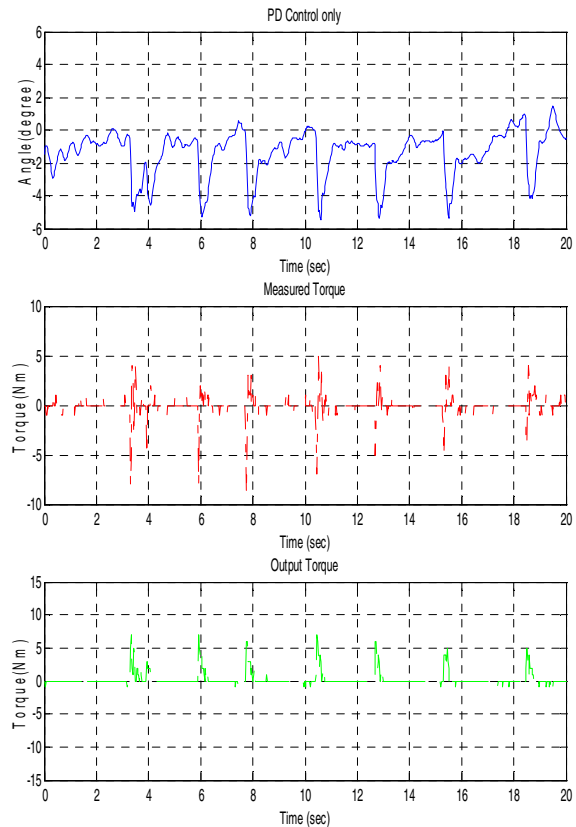


Fig. 7 PD Control

##### 2) PD control with DOB

The next experiment is to test attitude control of a quad-rotor system by the proposed DOB method. Fig. 8 shows the attitude control results. The first plot of Fig. 8 clearly demonstrates that the roll angle error is much smaller than that of the linear control method. The angle error is about 2 degrees. One of the reasons for the regular patterns of the roll error is the dynamic effect of the moving weight.

The similar pattern of two control inputs,  $\hat{T}$  and  $\bar{T}$ , shown in the second and the third plots indicates that DOB tries to compensate for the disturbance.

Although the angle error is minimized in half by DOB, the error is still present. The error can be further minimized by increasing the gain. However, exact identification of the model and reasonable sensing accuracy are required *a priori* to obtain better disturbance rejection. It is suggested to completely reduce the error. Further experimental studies are suggested in the future.

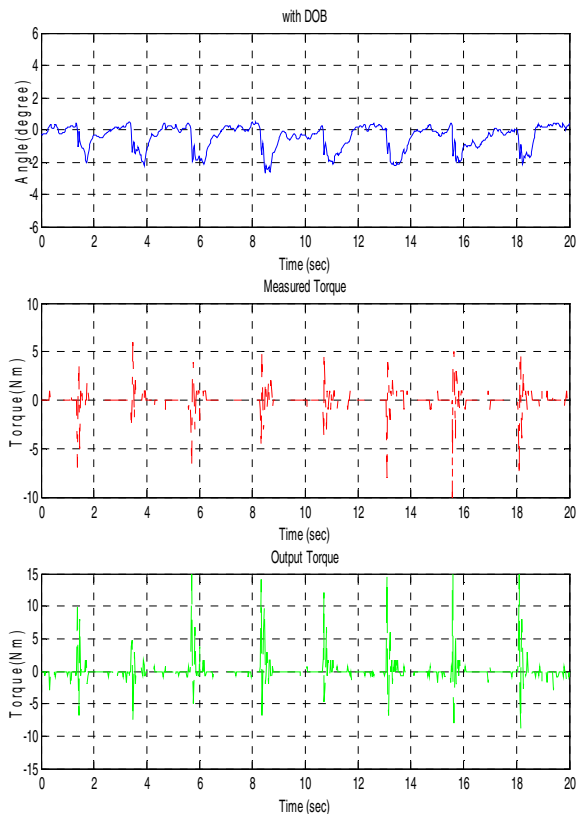


Fig. 8 PD Control with DOB

## 5. CONCLUSION

The modified DOB structure is presented and its performance is demonstrated by experimental studies. Experiment results confirm that the modified DOB can reject disturbance by introducing a constant gain to the system instead of designing Q filter. The attitude error has been minimized, but not completely. This is because of the nature of the DOB structure that carries problems of modeling errors, time-delay, sensor noise, and possibly ignorance of complete dynamics.

It would be worthwhile to design Q filter instead of gains to suppress sensor noise and to compare performances in the future.

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