Wind Disturbance Rejection for Unmanned Aerial Vehicle Based on Acceleration Feedback Method

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Abstract—Wind disturbance has always been a critical issue for safety flight of unmanned aerial vehicle (UAV) and increases the challenges for UAV system control. To this end, this paper presents an acceleration feedback (AF) method for UAV to enhance its ability of wind disturbance rejection. Compared with conventional AF control where only angular AF is used for precise attitude control, we further consider linear AF for precise position control. The proposed method was designed and implemented on a hex-rotor where a model free controller, cascaded PID, is used. In order to make it easy and fast to implement AF method on such model free system, a novel, effective and simple method for parameters identification of multi-rotor is proposed. The comparison results of trajectory tracking between PID and AF enhanced PID controller under continuous and gusty wind verify that the proposed method is not only robust but effective for both types of wind disturbances.

I. INTRODUCTION

UAV has drawn increasing attentions from robotics community over the last decades, and it has been used widely in military and civilian applications such as border patrol [1], search and rescue [2], surveillance and aerial photograph. However, the operation environments of UAV always exist various threats such as the vehicle downwash when operating close to walls and floors, turbulent airflow when flight between buildings [3] and strong wind during adverse weather. In fact, wind disturbance is the most general and primary type of disturbance to UAV since that the UAV is driven by the aerodynamic force of it rotor. Strong wind disturbance may, or may weaken stability and down grade performance of the system such as position accuracy reduction and attitude sway, which may not threaten safety flight of UAV but can cause failure of missions. Thus, robustness against wind disturbance is one of the critical issue, which must be considered in control system design to obtain high performance of UAV to broad its application.

So far, numerous remarkable works has been focusing on disturbance rejection control to improve the robustness of the UAV. Among all these works, methods for disturbance rejection can be mainly divided into two types. The first one is that controller is designed based on the dynamic model of the system and it can suppress the disturbance itself such as proportional integral derivative (PID) based controller, [4] and some nonlinear methods such as nested saturation control [5] and backstepping [6]. PID controller is the most classical and wildly used since its simple structure, clear parameters and easy implementation. But parameters tuning of PID needs lots of experiments and rich experiences to obtain high precision control performance. \( H_\infty \) control is well known robust against uncertainties and modeling errors and yet it is difficult to achieve a balance between robustness and conservation since the uncertainty is usually supposed unknown [7]. Nested saturation control and backstepping are examples of nonlinear control techniques and able to provide larger regions of attraction.

The second type of disturbance rejection method is based on known disturbance or the states those contain disturbance information, which can be called disturbance based control (DBC). The key is the accurate estimation of disturbance or obtaining the relationship between disturbances and system states. There are two distinct approaches for disturbance observer including time-domain disturbance observer (DOB) and frequency-domain DOB [8]. Extended state observer (ESO) is one of the time-domain DOB. It expands disturbances and uncertainties as system states, then a state observer is designed to estimate these states. ESO also plays a vital part in active disturbance rejection control (ADRC) method [9]. The original frequency-domain DOB is proposed by Ohishi et al. [10], and the key is to obtain disturbance estimation by filtering the differences between control input and the calculated input using the inverse mode of nominal plant. Recently, it has been starting deploying on multi-rotor for real time attitude tracking [11].

Whether external disturbances of force and torque or internal disturbance of parameter perturbation, the effects of them are always reflected by acceleration information (including linear and angular acceleration). Thus, acceleration based method has been researched and applied for disturbance rejection, and it is also the essence of DOB [10]. Acceleration feedback (AF) control method is first proposed and applied by Studenny and Belanger in [12]. In our previous work [13], [14], the applications of AF method on force control and direct-drive manipulator control demonstrates this method is not feasible but effective for robot control. Moreover, AF combined with \( H_\infty \) method has been applied on unmanned helicopter control, and the simulation results demonstrate the improvements of the method [4], [7].
In this paper, an AF enhanced controller is designed and implemented on UAV for high precision attitude and position control. There are some researches focusing on disturbance rejection of UAV [11], [15]–[18] etc. However, some of them are only simulations or only tested on fixed test bed, and others are tested under small disturbance. Compared with these works, our main contributions of this paper are twofold:

- It is the first time that applying AF method on UAV system for both attitude and position control against strong wind disturbance and achieving significant success. Linear and angular acceleration, the dependency of AF, can be measured or estimated by online sensors, which is necessary for outdoor applications.
- In order to easily and fast deploy AF method on a model free system, a novel, effective and simple method for parameters identification of UAV is proposed.

The remainder of this paper is organized as follows. The theoretical analysis of AF method is detailed in Section II. Section III introduces the dynamic model of the hex-rotor used as experimental platform. Then in Section IV, the controller with AF enhanced method is designed. Finally, in Section V, experimental results of rejecting two types of wind disturbances are shown, along with some concluding remarks in VI.

II. AF ENHANCED METHOD

In this section, the analysis of conventional AF method with high gain for disturbance rejection is conducted. However, there may exist two problems for high gain AF: 1) algebraic loop; 2) the implementation of high gain in practical system. To this end, a modified AF method with a pre-filter are introduced to overcome these shortcomings.

The generalized dynamic model of a mechatronic system with multiple degree of freedoms (DOFs), which includes UAV system, is established by Euler-Lagrange equation as

\[
M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) + F(q, \dot{q}) = \tau + \Delta \tag{1}
\]

where:
- \( q \in \mathbb{R}^n \) generalized position and angle;
- \( M(q) \in \mathbb{R}^{n \times n} \) inertial matrix;
- \( C(q, \dot{q})q \in \mathbb{R}^n \) Coriolis force;
- \( G(q) \in \mathbb{R}^n \) gravity;
- \( F(q, \dot{q}) \in \mathbb{R}^n \) friction or other resistances;
- \( \tau, \Delta \in \mathbb{R}^n \) driving force and external disturbances.

High gain AF is an enhanced control method suitable for single input single output system, and it has been verified in many mechatronic systems. Consider any DOF in (1)

\[
J_{ii} \ddot{q}_i = \tau_i + \tau_{ui} \tag{2}
\]

where \( J_{ii} \) is an inertial coefficient which could be moment of inertia (or mass), \( \tau_i \) is the control input, and

\[
\tau_{ui} = \Delta_i - \sum_{j=1}^{n} C_{ij}(q, \dot{q})\dot{q}_j - G_{ii}(q) - F_{ii}(q, \dot{q}) \tag{3}
\]

consists of various coupling torque (or force) and external disturbance torque (or force) and other disturbances. The key of high gain AF is turning (2) from torque (force) driving to acceleration (angular or linear acceleration) driving, so that the disturbance can be suppressed. By designing AF as an inner loop, we have

\[
\tau_i = k_a(v - \ddot{q}_i) \tag{4}
\]

where \( k_a \) is a positive constant and called gain of AF, and \( v \) is the reference generated by original controller. Combining (4) and (2), we can obtain

\[
\ddot{q}_i = \frac{k_a}{J_{ii} + k_a}v + \frac{1}{J_{ii} + k_a}\tau_{ui} \tag{5}
\]

if \( k_a \) is chosen big enough, that is \( k_a \gg 1, k_a \gg J_{ii} \), then

\[
\ddot{q}_i \approx v \tag{6}
\]

Thus, we obtain a new acceleration tracking controller which can track the reference acceleration input. What’s more, the equation shows disturbance \( \tau_{ui} \) is no longer affect the system of such an acceleration actuator. However, as we mention above, there exists two problems when take it into practical:

**Algebraic loop:** substitute (4) into (2), then

\[
J_{ii}\ddot{q}_i = k_a(v - \ddot{q}_i) + \tau_{ui} \tag{7}
\]

where there exits two acceleration parts. To present more clearly, Fig. 1 shows the illustration of (7), where the thick lines represents AF loop. Apparently, in this loop, there is no dynamic part, which causes an algebraic loop. However, algebraic loop is not allowed in practical system, because it will increase the instability and weaken the transient performance of the system. There are some researchers find a way to avoid this by adding a delay part or low pass filter [14], [19], but this will introduce nonlinearity.

**High gain implementation:** as we mention above, the key to suppress disturbance is increasing the gain of AF \( k_a \). However, in many cases, this is difficult or even forbidden in practical system due to the flexible limitation and unmodeled dynamics of the system. If the implementation of high gain is invalid, the cornerstone of high gain AF would collapse. Although some works improve this shortcoming [14], it increases the complexity of controller design and reduces the generality of AF method.

To overcome these two problems, we introduce a modified AF method with a pre-filter as following. Combine (2), (4) and (7), then

\[
\tau_i = \frac{k_a}{1 + k_a/J_{ii}}v - \frac{k_a}{J_{ii} + k_a}\tau_{ui} \tag{8}
\]
Thus, we can conclude that the essence of high gain AF is based on known disturbance information. It will appear that the input of current moment is determined by current measurement, which directly causes algebraic loop. Thus, the key to eliminate algebraic loop is avoiding the static process from acceleration measurement to control input. We utilize acceleration information to obtain disturbance rather than adding an acceleration close loop directly, then to avoid algebraic loop, a dynamic module, also called pre-filter, is added into controller which turns (8) into

$$\tau_i = \frac{k_a}{1 + k_a/\tau_{ii}} v - \frac{k_a}{J_{ii} + k_a/\tau_{ii}} B(s) \tau_{ui}$$ \hspace{1cm} (9)

Taking (9) into (2), then any DOF of the system can be described as

$$J_{ii} \dot{q}_i = \frac{1}{k_a} \frac{1}{1 + k_a/J_{ii}} v - \frac{B(s) - (J_{ii}/k_a + 1)A(s)}{(J_{ii}/k_a + 1)A(s)} \tau_{ui}$$ \hspace{1cm} (10)

Furthermore, the high gain of AF $k_a$ in the controller is only in the form of reciprocal in equation (10), and a bigger $k_a$ results in stronger a disturbance rejection ability. Thus, let $k_a \rightarrow \infty$, that is $k_a \gg \max(1,J_{ii})$, then (9) and (10) are approximated as

$$\tau_i = J_{ii} v - \frac{B(s)}{A(s)} \tau_{ui}$$ \hspace{1cm} (11)

$$\dot{J_{ii}} \dot{q}_i = J_{ii} v + \frac{A(s) - B(s)}{A(s)} \tau_{ui}$$ \hspace{1cm} (12)

The new controller is shown in Fig. 2. As can be seen, the gain of AF $k_a$ is no more than an temporary value which only exist in analysis and disappear in controller structure. Although $k_a$ is chosen to be infinity, it does not cause any problem in implementation. Thus, the key to suppress disturbance is not high gain $k_a$ anymore but the dynamic module determined by $A(s)$ and $B(s)$.

Actually, as can be seen in (12), disturbances $\tau_{ui}$ effects system after filtered by

$$Q(s) = \frac{A(s) - B(s)}{A(s)}$$ \hspace{1cm} (13)

Thus, we can decide a proper $Q(s)$ based on the main frequency of uncertainty $\tau_{ui}$. Normally, the uncertainty or disturbance of UAV is with low frequency. A high pass filter will be enough to suppress it, for example, if $Q(s)$ chosen as

$$\frac{B(s)}{A(s)} = \frac{a}{s + a}, Q(s) = \frac{s}{s + a}$$ \hspace{1cm} (14)

then

$$\dot{J_{ii}} \dot{q}_i = J_{ii} v + \frac{s}{s + a} \tau_{ui}$$ \hspace{1cm} (15)

Thus, the disturbance with low frequency in $\tau_{ui}$ would be filtered, and the cut frequency of this high pass filter is determined by $a$.

### III. DYNAMIC MODEL OF HEX-ROTOR

A hex-rotor is used as an UAV platform to verify our method. It is a kind of multi-rotor and has six identical rotors and propellers located at the vertices of a regular hexagon as shown in Fig. 3. Hex-rotor is modeled as a rigid body with multiple DOF, and of course, it is a special case of mechatronic system mentioned in Section II.

Two frames, an inertial reference frame $\{i_x, i_y, i_z\}$ and a body-fixed frame $\{b_x, b_y, b_z\}$, are involved. And the origin of the body-fixed frame is located at the center of the mass. The first and the second axis of body-fixed frame, $b_x$ and $b_y$, lie along the symmetry axes of the vehicle as shown in Fig. 3, and the third axis $b_z$ is normal to $b_x$ and $b_y$ and points downward. The configuration of this hex-rotor UAV is defined by location of the center of mass and the attitude with respect to the inertial frame. Thus, the configuration manifold is the special Euclidean group $se(3)$ and special orthogonal group $so(3) = \{ R \in \mathbb{R}^{3 \times 3} \mid R^T R = I, \det R = 1 \}$, and $R$ is the rotation matrix from body-fixed frame to inertial frame.

We suppose that the thrust of each propeller is normal to the hex-rotor plane, and the thrust of each propeller $f_i$ can be approximated by

$$f_i = n\Omega_i^2$$ \hspace{1cm} (16)

where $\Omega_i$ is the rotation speed of each rotor. Then, the total thrust of the propellers is $f = \sum_{i=1}^{6} f_i$ along the direction of $b_z$. Therefore, the total thrust can be given by $-fR e_3 \in \mathbb{R}^3$ in the inertial frame, where $e_3 = [0, 0, 1]^T$. We also assume the torque generated by each propeller is directly proportional to its thrust. Given that there are three propellers rotate clockwise and the others rotate counterclockwise as shown in Fig. 5, thus the torque generated by each propeller is $\tau_i = \pm c_{\tau f} f_i$, for a fixed constant $c_{\tau f}$. Under these assumptions, and the special structure of hex-rotor, the total thrust $f$ and the total moment $M$ generated by propellers can be written as

$$\begin{bmatrix} f \\ M_1 \\ M_2 \\ M_3 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ -d & d & d & -\frac{1}{2}d & d & -\frac{1}{2}d \\ 0 & 0 & \sqrt{3}d & -\sqrt{3}d & \sqrt{3}d & -\sqrt{3}d \\ -c_{\tau f} & c_{\tau f} & -c_{\tau f} & c_{\tau f} & c_{\tau f} & -c_{\tau f} \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \end{bmatrix}$$ \hspace{1cm} (17)
where \( \delta \) is the distance from propeller center to the origin of body-fixed frame. For a given \( f \) and \( M \), the thrust of each rotor \( F_i \) can be obtained by calculating the generalized inverse of (17). The dynamics of the UAV is described as

\[
\begin{align*}
\dot{m} = & \ m\ddot{e}_3 - f R e_3 + d_f \\
J\dot{\omega} = & \ M - \omega \times J \omega + d_r
\end{align*}
\]  
(18)

where \( m, g \) and \( d_f \) are the total mass, acceleration of gravity and disturbance force or uncertainty respectively, and \( J, \omega \) and \( d_r \) are the moment of inertia, angular velocity and disturbance torque respectively.

IV. AF ENHANCED CONTROLLER DESIGN

A. Tracking controller with AF Method

As mentioned in Section II, AF method, as an enhanced method, is independent with original controller of dynamic model. Thus, a cascaded PID controller based on geometry tracking theory [20] is adopted as original controller in this paper, other method such as \( H_{\infty} \) is also available. The controller can be divided into two parts: outer loop controller, consists of position and velocity tracking controller; inner loop, consists of attitude and angular velocity tracking controller. The illustration of AF enhanced controller structure is shown in Fig. 4.

The tracking error for position is defined as \( e_x = x_d - x \), then position tracking controller using PID is described as

\[
v_d = k_{Px} e_x + k_{Dx} \dot{e}_x + k_{Ix} \int e_x dt
\]  
(19)

where \( v_d \) is reference of velocity tracking controller and \( k_{Px}, k_{Dx} \) and \( k_{Ix} \) are positive constants. The same structure also works in velocity tracking controller which generates force reference \( F_d \). Consider linear motion in (18) without any disturbance under ideal situation, where \( \ddot{x} \) is equal to acceleration reference \( \ddot{x}_d \), then

\[
m\ddot{x}_d = F_d + mge_3
\]  
(20)

However, there exists a disturbance \( d_f \) in practical system along with a desired AF enhanced term \( v_f \)

\[
m\ddot{x} = F_d + mge_3 + v_f + d_f
\]  
(21)

As described in (12), \( v_f \) and \( d_f \) should satisfy

\[
\frac{v_f(s) + d_f(s)}{d_f(s)} = Q(s)
\]  
(22)

If \( A(s) \) and \( B(s) \) are chosen as (14), combine it with (20) and (21), the designed AF enhanced term is decided by

\[
v_f(t) = a \int (F_d + mge_3 - m\ddot{x})dt
\]  
(23)

Then \( \dot{F}_d \) and \( v_f \) are new reference and decomposed into two parts which are length \( f = \| \dot{F}_d + v_f \| \) and direction

\[
b_{zd} = - \frac{\dot{F}_d + v_f}{\| \dot{F}_d + v_f \|}
\]  
(24)

Combining \( b_{zd} \) and yaw reference \( \psi_{\omega} \) , the reference of rotation matrix \( R_d \), can be calculated. Similar with [20], the attitude tracking error \( e_R \) and angular velocity tracking error \( e_w \) are chosen to be

\[
e_R = \frac{1}{2} (R^T R_d - R_d^T R)^\forall
\]  
(25)

\[
e_w = R^T R_d \omega_d - \omega
\]  
(26)

where the vee map \( \forall: \mathfrak{so}(3) \rightarrow \mathbb{R}^3 \) is an operator in \( \mathfrak{so}(3) \) to get the rotation vector. Then, same as (19), two PID structure are adopted for attitude tracking and angular velocity tracking controller respectively. The output of angular velocity tracking controller is defined as \( M_d \). Similar with (23), the designed AF enhanced term for torque is

\[
\tau(t) = b \int (M_d - \omega \times J \omega + J\dot{\omega}) dt
\]  
(27)

where \( b \) is the cut frequency as described in (15) and \( \dot{\omega} \) is angular acceleration measured by sensors.

B. An Novel Method for Parameters Identification

From (23) and (27), we can conclude that AF is a model based method, and the implementation of AF needs to know the mass \( m \), the moment of inertia \( J \) and desired force \( F_d \) and torque \( M_d \) generated by controller. \( m = 1.5kg \), and \( J = diag(0.0145, 0.00141, 0.0266) \) is determined by bifilar pendulum method [21]. In fact, for most multi-rotor, we cannot control the force of the propellers directly since their motors are always controlled without rotation speed closed-loop. More specifically, the control input of motors is Pulse-Width Modulation (PWM) signal instead of rotation speed. In experiment, we found the same PWM signal may generate different rotating speed, mainly because the battery voltage continued decreasing during the whole flight. The control output \( F_d \) generated by velocity PID controller shown in Fig. 4 is not a real force reference in practical hex-rotor. It’s a normalized value and its norm is limited from
0 to 1 corresponding to the minimum and maximum total thrust. Thus, (23) cannot be used directly. Fortunately, the relationship between $F_d$ and gravity can be determined by introducing an intermediate variable, that is battery voltage. Based on this, a novel and simple method is proposed to solve these problems.

First, the hex-rotor needs to hover at a fixed point for a period to collect data of $F_d = [F_{dx}, F_{dy}, F_{dz}]$ and battery voltage $V$. Given UAV is in hovering status, $F_{dx}$ and $F_{dy}$ can be considered as zero, and $F_{dz}$ is equivalent to gravity. Assume the relation between $F_{dz}$ and $V$ satisfy

$$mg \Leftrightarrow F_{dz} = f(V)$$

then

$$m\ddot{x} \Leftrightarrow f(V)\frac{\ddot{x}}{g}$$

Thus, combining (23), we can obtain

$$v_{SF} = a \int [(f_d - f(V))(e_3 + \frac{\ddot{x}}{g})]dt$$

(30)

where $v_{SF}$ is the an scaled variable of $v_f$ in (23). The relation between $F_{dz}$ and $V$ under hovering condition is fitted by a linear function. The fitting result is illustrated in Fig. 5. The data we choose for fitting are from 150s to 330s where the hex-rotor is considered as hovering status, and the fitting function is

$$f(V) = -0.0587V + 1.2435$$

(31)

The hovering test results with AF method are shown in Fig. 6. In the left two axes, $f(V) = 0.61$ is chosen as a constant without considering the relation with battery voltage, while in the right two axes, (31) is applied on AF enhanced controller. As can be seen, the hovering accuracy increases greatly in vertical and horizontal directions.

V. EXPERIMENTAL RESULTS

A. Experimental setups

The main experimental setups for wind disturbance rejection are shown in Fig. 7. The frame of the hex-rotor is DJI F550 with an open source control stack namely Pixhawk. The motor of UAV is DJI2212 with maximum trust 4N (totally 24N). Wind disturbance is generated by an axial flow fan with 60cm diameters, and the maximum wind speed at outlet is up to 12m/s which is a level 6 wind and can provide strong enough disturbance. A 3-axis ultrasonic anemometer named WindMaster is used for wind velocity measuring. Moreover, an OptiTrack motion capture system is used to provide position information. Linear acceleration is measured by an onboard accelerometer and angular acceleration is estimated by a simple online KF filter based on the angular velocity measured by an onboard gyroscope.

Analyses of wind disturbances: We collected about 50 seconds of natural wind data under bad weather. As shown in Fig. 8, the maximum speed of wind is up to 8m/s, and the bottom figure shows the single-sided amplitude spectrum of the wind. The constant component, where its frequency is 0Hz, is nearly 6m/s. The amplitude of wind is lower than 0.4m/s at 0.3Hz, and the bigger frequency is with lower amplitude. Therefore, we can conclude that the frequency of natural wind is at low frequency level, which is important for AF enhanced controller design as discussed in Section II. Two types of strong winds, continuous and gusty wind, are collected and analyzed before the experiment as shown in Fig. 9, and the distance from the fan to desired hovering point are 1.8m and 2.2m respectively. Continuous wind is generated by keeping the fan working all the time, while for gusty wind, the fan is turned on and off at a period of 3s. As can be seen, continuous wind has small fluctuations around a constant component about 7.8m/s, and there is no large value at other frequencies. Gusty wind has smaller constant component about 6m/s since a farther distance, and the second high frequency component, obviously shown in the spectrum result, is 0.95m/s, where the frequency is 0.31Hz. From these analyses, we can conclude two types of winds generated by the fan is a well simulation of natural strong wind.

B. Disturbance Rejection against Continuous Wind

Disturbance rejection for continuous wind can be divided into two parts: position tracking test under windless condition...
and strong continuous wind condition, and each part contains a PID controller test and two AF enhanced controller test, namely linear AF enhanced (L-AF) controller (Linear AF and PID) and linear and angular AF enhanced (LA-AF) controller (Linear and angular AF and PID). Flight test results are shown in Fig. 10, and the moments of controller switching are label in the bottom. As can be seen, before 113.7s, the hex-rotor takes off and tracks a fixed position $(0, 0, 1.2)^T$ with PID controller. Then, from 113.7s to 134.5s, the controller is switched to LA-F controller, and from 134.5s to 154.4s, the LA-AF enhanced controller is used. Then, at 154.4s the controller is switched back to PID and the fan is turned on. From 244.4s to 324.7s, the LA-F controller is used, and at 324.7s, the controller is switch to LA-AF controller again. Finally, the hex-rotor starts landing at 400s.

The results show a good performance of AF enhanced method. First, under windless condition, AF enhanced controller performs as well as PID controller. Then, after the fan turned on, L-AF controller is more stable and a higher accuracy of position and attitude (yaw angle) has been achieved compared to PID. Moreover, when LA-AF controller is applied at 324.7s, the accuracy of yaw angle is further promoted. The root mean square errors (RMSEs) of position and yaw are listed in Table I. Compared with PID controller, the accuracy of LA-AF controller is 4.8 times higher in position and 5.2 times higher in yaw angle. In the experiment, we also find, L-AF controller is better than angular AF enhanced controller for high precision position control since linear acceleration is the first chanced value whenever position changed.

However, there are some points that need to be stated here. Firstly, there is a little hump of the data shown in Fig. 10 right after controller switched, which is caused by the interaction between (23) and integral part of PID. Secondly, the attitude (roll and pitch) changes more acutely when applied AF enhanced method, so that it can suppress disturbance faster and better. Thirdly, the error of position presents periodicity, because the wind is too strong that hex-rotor is blown out of the wind field. Finally, the improvement of position accuracy in Z-axis is lower than it in X-axis and Y-axis since vertical disturbance also effects the thrust of propellers.
C. Disturbance Rejection against Gusty Wind

The results of disturbance rejection for gusty wind are shown in Fig. 11. This time, the hex-rotor stay in the wind filed all the time rather blown out of wind field. When the hex-rotor hovers steady, the fan is turned on at 142.5s, and LA-AF controller is applied at 232s. The RMSEs of position under gusty wind for PID and LA-AF are 0.1704m and 0.0651m respectively and RMSEs of yaw are 0.1385rad and 0.0412rad respectively. Compared with PID controller, the accuracy of LA-AF controller is 2.6 times higher in position and 3.3 times higher in yaw angle.

VI. CONCLUSIONS

This paper presents an AF method to enhance the ability of UAV for rejecting wind disturbance. A modified method of traditional high gain AF with a pre-filter is adopted to eliminate the algebraic loop and make it easier to be implemented. To deploy AF method easily and fast on a model free controller such as PID, a novel and simple method for parameters identification is proposed, and the results of the experiment have verified its effectiveness. In addition, the analyses of different types of winds demonstrate the wind disturbance generated by fan is a well simulation of natural strong wind, which turns out that our research is authentic and practical. At last, the experimental results for disturbance rejection under continuous and gusty winds demonstrate the effectiveness and robustness of our acceleration feedback method. More importantly, given the linear and angular acceleration is measured by onboard sensors, it is promising to apply AF method on disturbance rejection applications in outdoor environment.