Effect of Disturbance Observer on Attitude Control of Quadrotor Drone in Turbulent Conditions

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***Abstract*—Quadrotor drones are highly dynamic open-loop systems subject to a number of external forces that can make them unstable and difficult to control. To address this, classical control theory has been utilized, with a Proportional Integral Derivative (PID) controller enabling the stabilization of the drone during take-off and landing. Recently, disturbance observer control has been incorporated to reduce the effect of ground effect on the drone, while on the XY plane only minor disturbances are experienced. To extend the capabilities of the DOB, a non-linear geometric tracking controller based on the state space model of the quadrotor will be implemented to control the drone during take-off, landing, and flight in turbulent conditions and sudden external forces. The unified system aims to handle any external forces and provide stability for the drone during all phases of flight.**

***Index Terms*—Disturbance Observer, Non-linear, Quadrotor, Control System.**

I. Introduction

Quadrotor drones are agile and versatile unmanned aerial vehicles (UAV) that are used for various applications in a wide range of domains such as search & rescue [1] [8], precision agriculture [2], cargo deliveries [3]. These applications have a variety of technical challenges that need to be overcome through robust, precise control of the drone at all times to perform given tasks effectively and accurately without human supervision. Despite the versatility that a drone offers, there are several disadvantages like the fact a quadrotor drone is inherently an open-loop unstable and under-actuated system, as it has four actuators to control six degrees of freedom. The controller also has to be capable to overcome this handicap through it's control scheme.

A. Aim

A classical Proportional-Integral-Derivative (PID) controller is commonly used in drones to control their motion. However, its performance is limited in the presence of external disturbances, as the controller does not take into account these external forces. This can cause the drone to deviate from the desired trajectory and oscillate. To address this, a disturbance observer can be used to attenuate the disturbances and reduce the oscillations. The observer's algorithm estimates the disturbance forces based on the measured trajectories and then compensates for the disturbances. The observer can then be used to modify the controller's output, thus allowing the drone to track the desired trajectory more accurately. This disturbance observer can be used to enable the drone to perform better in turbulent conditions and provide increased accuracy in its motion control.

B. Technical challenges

The disturbance observer has been implemented in a limited scope to account for disturbances in 2D, that is, in the X and Y axis [6] or to account for the ground effect in the vertical Z axis during take-off and landing [7]. The challenge lies in attempting to implement a DOB that can handle disturbances in all three coordinate axes during take-off, flight and landing.

C. What has been done

Generally, in a PID-controlled system, we have a predefined set point measurements from multiple sensors and a PID controller that works to reduce error through the Proportional, Integral & Derivative gains. A cascaded PID controlled consists of two loops, an inner and an outer loop, the inner loop is a faster rate loop that regulates the angular velocity and the outer slower stabilize loop uses the input set-point and measurements from the sensors. Ideally in a cascaded PID, the faster inner PID loop controller can mitigate the effects on the slower outer PID controller, resulting in a more fluid and dynamic performance [4].

There has been research done in these areas [6] where simulation and experimental flight tests have been conducted to demonstrate the performance of a DOB to reject disturbance and achieve fairly precise position control of a quad rotor [6], they have used a Q-filter to deal with drift and noise from onboard sensors [6]. This implementation is limited to correcting drift and noise in the x and y direction only, our implementation would aim to correct major disturbances from turbulent winds which could come from any direction. Furthermore, in [6], they use optical flow sensors to estimate the current position instead of relying on GPS which updates the location at a lower frequency (low refresh rate).

In [9], a Nonlinear DOB has been implemented for active disturbance rejection in the attitude control loop for quadrotors [9]. The weighted sum of the noise-to-output transfer function and the load disturbance sensitivity function, as well as the infinity-norm minimization, are combined to create an optimization framework for tuning the parameters in the NDOB structure. A step, sinusoidal, and square wave disturbance is introduced in the system to observe the system performance.

Furthermore, research carried out in [7] where a disturbance observer improves the rejection of the ground effect compared to the baseline cascaded PID controller [7].

D. Approach

Instead of the classical control methods, we will be using the geometric tracking controller as stated in [22] This type of controller uses feedback from the system's sensors to continuously adjust the control signals sent to the actuators in order to correct any deviations from the desired trajectory. The controller calculates the necessary correction by comparing the desired geometric path with the actual position of the system and computing the error between the two. This error is then used to generate the control signals that will drive the system back onto the desired path. The goal of a geometric tracking controller is to enable the system to follow the desired trajectory as closely as possible, with minimal error and maximum accuracy. Geometric tracking controllers are often used in the control of quadrotor drones. In this application, the controller is used to ensure that the drone follows a desired geometric path, such as a predefined flight path or a set of waypoints. The controller uses feedback from the drone's sensors, such as its GPS, gyroscopes, and accelerometers, to continuously compute the necessary control signals that will drive the drone along the desired path. The controller takes into account factors such as the drone's position, orientation, and velocity, as well as the forces acting on it, such as wind and drag, in order to generate the control signals. By using a geometric tracking controller, a quadrotor drone can accurately and reliably follow the desired path, even in challenging environments.

II. Problem Statement

Drones have become an integral part of our lives, from the delivery of goods to providing aerial surveillance. Real-world applications of drones such as payload pickup/drop and precision landing require precision control of the drone position and orientation both during calm and turbulent conditions. It is a challenge to control a quadrotor drone since it is an under-actuated non-linear dynamic system. To mitigate this, a cascaded PID controller and a robust Non-Linear Disturbance Observer are used to accounting for the disturbances and uncertainties.

The linear control method is the most widely used approach, owing to its straightforward design and implementation procedures. Wang SH designed a double-gain proportional–differential (PD) controller to stabilize the attitude dynamics of a quadrotor, and verified the effectiveness of the proposed controller via flight experiments in [12]. Su JY developed a proportional-integral-derivative (PID) attitude controller for a quadrotor in [13]. Ma ZH adopted the backstepping control approach to solving the problem of quadrotor attitude stabilization in [14]. Yilmaz designed an attitude controller for quadrotors by using nonlinear dynamic inversion in [15]. Wang J presented a double-loop controller using dynamic inversion for quadrotors in [16], and Liu proposed a state feedback controller for robotic quadrotors to restrain the effects of nonlinearities and uncertainties [17]. Patel employed the Sliding Mode Controller (SMC) to design the flight controller for a fully-actuated subsystem of a quadrotor [18].

III. Project Overview

In this work, we propose a disturbance observer-based controller for a quadrotor drone. The controller is designed using state space modelling and is capable of detecting and accounting for uncertainties during flight. This enables better control of the quadrotor and improved performance throughout the duration of the flight.

To evaluate the effectiveness of our controller, we perform simulations in a simulated environment. The inputs to our system include the desired position of the quadrotor and external disturbances in the form of step and impulse responses. The output of our system is expected to be a stable flight along all three axes, even under moderate and unexpected disturbances, such as wind gusts.

To design the controller, we first model the dynamics of the quadrotor using state space equations. The equations of motion for the quadrotor are derived using the principles of rigid body dynamics, and take into account the mass, inertia, and forces acting on the quadrotor.

Next, we design the disturbance observer using the state space equations. The disturbance observer estimates the external disturbances acting on the quadrotor and uses this information to adjust the control inputs to the quadrotor. This allows the quadrotor to maintain its desired trajectory despite the presence of external disturbances.

Finally, we combine the disturbance observer with a feedback controller to form the overall control system. The feedback controller uses the estimated disturbance and the desired position of the quadrotor to compute the control inputs, which are then applied to the quadrotor to maintain a stable flight.

Simulation results show that our controller is effective at mitigating the effects of external disturbances on the quadrotor. The quadrotor is able to maintain a stable flight along all three axes, even in the presence of moderate and unexpected disturbances. This demonstrates the effectiveness of our disturbance observer-based controller for improving the performance of a quadrotor drone.

Furthermore, we have also attenuated the effect of ground effect a specific type of disturbance encountered by drones, when they are close to the grounds and the thrust generated by the drone's propellers is reflected by the ground, disturbing the drone.

We have assumed there is no drag and neglected it's effects for the ground effect. As per [7] the ground effect with these assumptions is:

$$T_{IGE} = \frac{1}{1 - \frac{3R}{25z}} T_h$$

IV. Dynamic Model

To model a quadrotor we must first start with its mathematical model. Our quadrotor drone has four input vectors, i.e the total thrust in the Z axis, pitch, roll and yaw angles to control the quadrotor drone in three dimensions. Using these four inputs, we get the following six outputs:

x - Position of the quadrotor along x-axis.

y - Position of the quadrotor along y-axis.

z - Position of the quadrotor along z-axis

ϕ - Roll angle of the quadrotor.

θ - Pitch angle of the quadrotor.

ψ - Yaw angle of the quadrotor.

To aid in our understanding, we looked at research papers that are similar to our project. In [19] they consider a non-linear PID controller (NLPID) to stabilize the translation and rotation of a 6-Degree of Freedom (DOF) quadrotor system. They designed six NLPID controllers each for the quadrotor parameters such as roll(ϕ), pitch(θ), yaw(ψ), x, y and z positions. They also derived the mathematical model of the 6-DOF quadrotor system in such a way that the acceleration and velocity vectors are taken into consideration. This allows for a more accurate nonlinear model for the 6-DOF quadrotor drone. Although they have used a non-linear state space model, they have not used a disturbance, observer-based controller. We will attempt to build upon their work and integrate a disturbance observer into our quadrotor drone controller to handle disturbances along all three axes.

The dynamic model of a quadrotor can be obtained in simulation by defining the various variables that affect the drone during operation. This includes the mass, moment of inertia and acceleration due to gravity that acts on the drone and several other forces.

J - Moment of Inertia.

d - Distance from the center of mass of the drone to the propeller center of the drone.

m - mass of drone in kg.

g - acceleration due to gravity in the negative Z axis direction.

If the body's origin was fixed the quadrotor's center of mass is where the frame is positioned. The dynamic equation of motion is given as

$$\begin{aligned}
\dot{x} &= v \\
\dot{R} &= R\widehat{\Omega} \\
m\dot{v} &= -mge_3 + Rf_b + d_x \\
J\dot{\Omega} &= -\Omega \times J\Omega + M + d_\Omega
\end{aligned}$$

where,

k_x - Gain Constant.

x_{err} - Error in x axis.

k_v - Gain Constant.

v_{err} - Error in velocity.

m - Mass of the drone.

g - Acceleration due to gravity.

e_3 - Transformation matrix along the Z axis.

a_{des} - Desired Acceleration.

d_{barx} - External force acting upon the drone(disturbance) calculated by the DOB in the previous time step.

R - Rotation matrix in $SO(3)$.

Kx, Kv, Kw, Kr, Ks - positive constants.

Km - positive definite matrix.

dt - Time step interval.

$time$ - Total Time.

We can define symbols to represent the various forces. The force is calculated by the controller given by the following equation: $f_b = -dot((-k_x * x_{err} - k_v * v_{err} - m * g * e_3 + m * a_{des} - d_{barx}), R * e_3)$

V. Non-Linear Disturbance Observer

Wind Disturbances or any other disturbances are common during a drone's flight and have a negative impact on the system as a whole. Therefore, it is very important for controller design to account for this disturbance and minimize it as much as possible. Compared to traditional approaches like high gain control and integral control approaches, Disturbance observer-based control (DOBC) is an active and efficient method of handling disturbances both constant and time-variant. This means that a DOBC could achieve good disturbance-rejection performance without scarifying the nominal performance [21]. A DOBC is generally designed as

$$u = ke_y - \hat{d} + ay_r,$$

here d is an estimation of disturbance by a disturbance observer and k is the feedback control gain. Using the tracking error variable and System control law mentioned in [21] we get,

$$\dot{e}_y = -(a + k)e_y + e_d,$$

where $e_d = \hat{d} - d$ is the disturbance estimation error. We can design an appropriate disturbance observer like

$$\dot{e}_d = f\left(e_d\right),$$

which could regulate the disturbance estimation error e_d and would also be globally asymptotically stable which depicts that the disturbances can be suppressed asymptotically, as long as they can be accurately estimated by a disturbance observer.

A non-linear approach proposed in [21] for a quadrotor drone as shown below is demonstrated.

$$\begin{aligned}
\dot{z}_\Omega = -l(\Omega)\left[J^{-1}\left(\lambda(\Omega) + z_\Omega\right) - J^{-1}(\Omega \times J\Omega) + J^{-1}M\right] \\
\bar{d}_\Omega = z_\Omega + \lambda(\Omega) \\
\dot{z}_x = -l(v)\left[\frac{1}{m}\left(\lambda(v) + z_x\right) - ge_3 + \frac{Rf_b}{m}\right] \\
\bar{d}_x = z_x + \lambda(v)
\end{aligned}$$

here z_i represents the internal state of the observer, $\bar{d}_\Omega$ represents the dsiturbance estimate in attitude dynamics and $\bar{d}_x$ represent the disturbance estimate in translational dynamics

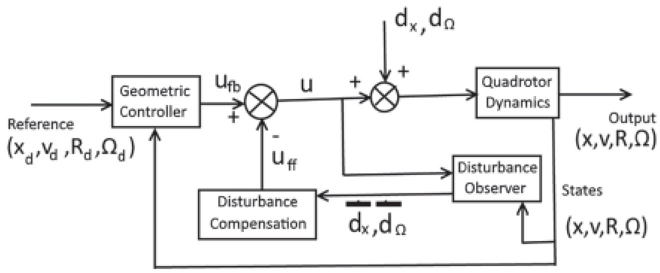

Fig. 1: Roboust Controller Design [20]

and $\lambda(i)$ is a nonlinear function. Thus, $l(\Omega)$ and $l(v)$ are designed as:

$$l(\Omega) = \frac{\partial\lambda(\Omega)}{\partial i} \; l(v) = \frac{\partial\lambda(v)}{\partial i}$$

We would specify certain parameters like K_m and K_s which are positive definite gain matrices

$$\lambda(\Omega) = K_m\Omega \text{ therefore } l(\Omega) = K_m I_{3\times3}$$

And also,

$$\lambda(v) = K_s v \text{ and therefore } l(v) = K_s I_{3\times3}$$

where, $I_{3\times3}$ is identity matrix.

A. Roboust Controller Design

Keep the above DOBC into consideration we can design a robust controller for a quad rotor drone where the control force and torque required to track any desired path $(x_d(t), v_d(t), R_d(t), \Omega_d(t))$ while accounting for any external constant or time-variant disturbances is given by:

$$f_b = (-K_x e_x - K_v e_v + m(\dot{v}_d - g e_3) - \bar{d}_x) \cdot R e_3$$
$$M = -R_d^T e_R - K_\Omega e_\Omega + J\dot{\Omega}_d + \Omega \times J\Omega - \bar{d}_\Omega$$

where $K_x, K_v, K_\Omega \in \mathbb{R}^{3\times3}$ are positive definite gain matrices. Here, f_b is the control law and M is the torque to the quadrotor. This approach assures f_b to always results in a positive thrust to the quadrotor as opposed to other methods where the total thrust might become negative at some point. For a standard VTOL vehicle, it is required that $f_b^T e_3 > 0$.

A schematic of the geometric controller with the nonlinear disturbance observer is presented in Figure 1. The control input, u, is the sum of the feedforward compensation $u_f f$ and the feedback control input $u_f b$ which are used for controlling the attitude and translational dynamics of the quadrotor. The nonlinear disturbance observer is used to estimate the external disturbances in the dynamics. The disturbance estimates are represented by $\bar{d}_x$ and $\bar{d}_\Omega$ respectively. The external disturbances in the attitude and translational dynamics are represented by d_ω and d_x.

Using the given variables and their assigned values, the simulation can be executed in MATLAB. The output of the simulation can be depicted graphically. The generated plots will provide a visual representation of the simulation results.

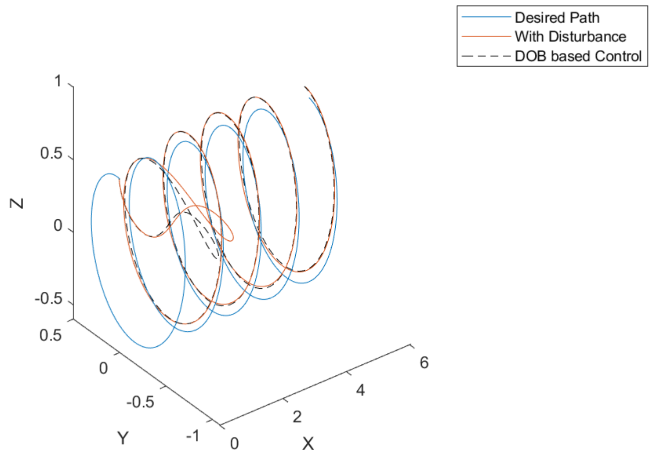

Fig. 2: Scenario I: Plot of the drone path in 3 dimensions under different conditions

VI. Simulations

. A reference trajectory used for these simulations is given as follows where $x_d(t) = \begin{bmatrix} 2t/5 & 2sin(\pi t)/5 & 3cos(\pi t)/5 \end{bmatrix}$ and $b_d(t) = \begin{bmatrix} cos(\pi t) & sin(\pi t) & 0 \end{bmatrix}$ and initial conditions are $\begin{bmatrix} x(0) & y(0) & z(0) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}$ and $R(0) = I_{3\times3}$.

Constants set were $J = diag([0.0820, 0.0845, 0.13377]) m = 4.34kg \; g = 9.81 \; K_x = 16m \; K_v = 5.6m \; K_R = 8.81 \; K_\omega = 2.54 \; Km = diag([0.02, 0.2, 0.05]) \; Ks = 0.02 \; time = 10s \; dt = 0.01s$ These constants were obtained by tuning them to reduce the RMS Error of the drone from the desired path. ground effect We have considered the following scenarios similar to [20] where bounded disturbance and constant disturbances are considered with also cases with time-variant disturbances.

A. Scenario I: Finite Slope and Bounded Disturbance

The external disturbances are given by $d_x(t) = 0.6 d_\Omega(t) = [1.3tan^{-1}(t/2) \; 2tan^{-1}(t/2) \; 2.6tan^{-1}(t/2)]$ which results in a finite slope and bounded disturbance. The results observed are shown in the Figures

Fig 2 describes the behaviour of the quadrotor drone along 3 dimensions under different conditions. It contains the plot of the drone's trajectory and path during:

1) The desired path
2) With Disturbance acting on the drone without the use of DOB.
3) With DOB being used to correct for the disturbances caused.

We also can see the plots for the position, velocity and acceleration of the drone along all three axes throughout the duration of operation of the drone in fig3 and the error in the position of the drone in fig4 and fig5 show angular error along the axes.

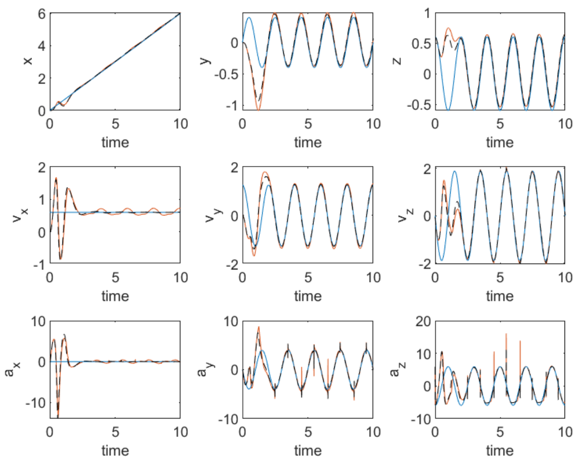

Fig. 3: Scenario I: Position, Velocity and Acceleration plots of the drone.

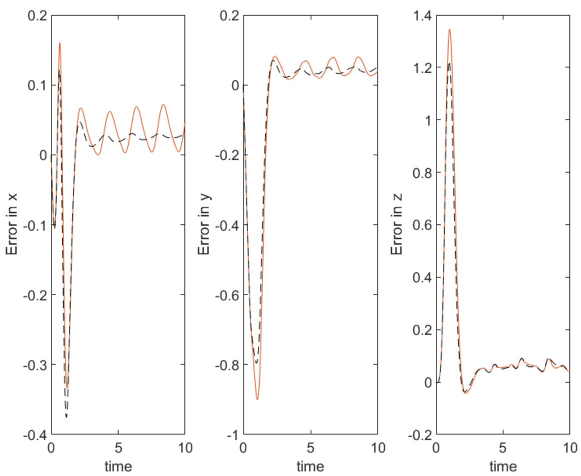

Fig. 4: Scenario I: Positional Error

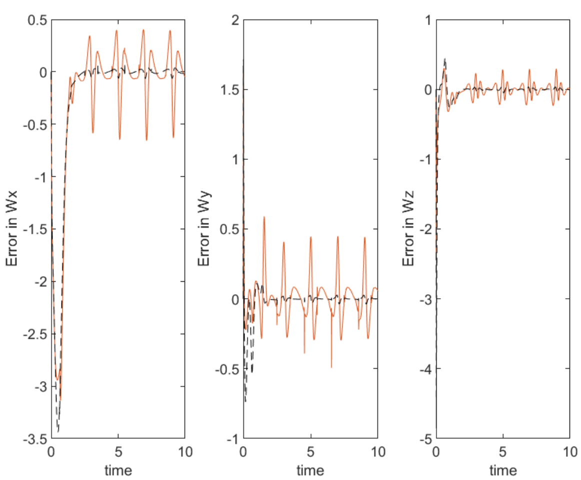

Fig. 5: Scenario I: Attitude Errors

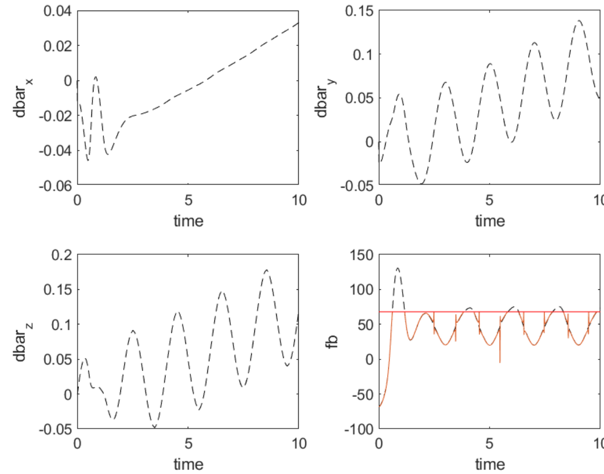

Fig. 6: Scenario I: Attenuated Disturbance and limited Total Thrust.

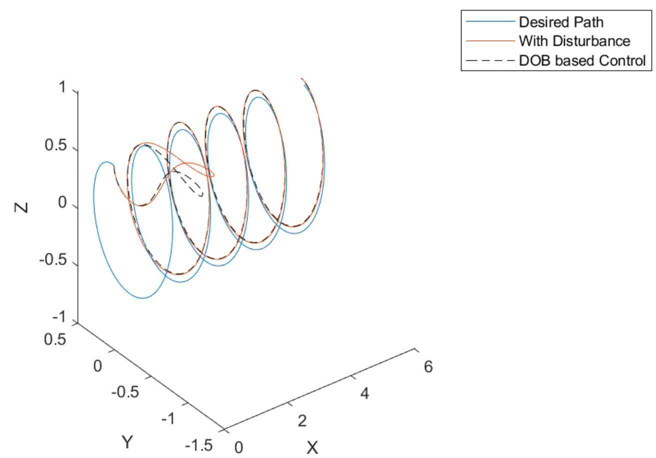

Fig. 7: Scenario II: Plot of the drone path in 3 dimensions under different conditions

B. *Scenario II: Constant Disturbance*

The external disturbances generated in the simulation the environment are assumed to be constants and are given by $d_x(t) = 0.6d_\Omega(t) = [1.3; 2.0; 2.6]$.

This type of scenario might occur when there is a change in dynamic parameters like mass, a moment of inertia or center of gravity. It is observed in [20], that better position tracking is obtained with the nonlinear disturbance observer. The estimate of the disturbances present in position and attitude dynamics converges to the actual disturbances within a few seconds as observed in [20]. We have similar plots as seen in Scenario 1 in Fig 7, Fig 13, and Fig 9 but the error does not increase with respect to time.

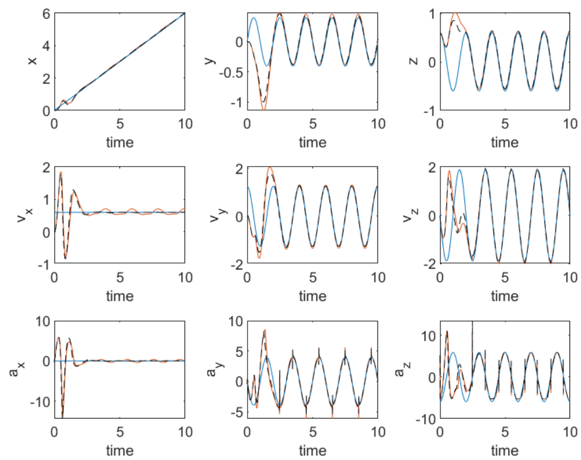

Fig. 8: Scenario II: Position, Velocity and Acceleration plots of the drone.

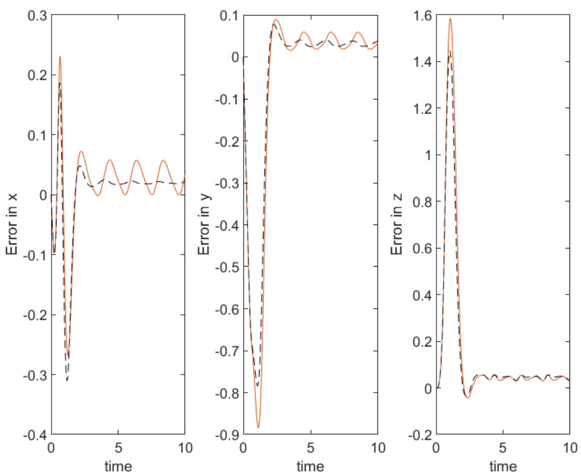

Fig. 9: Scenario II: Positional Error

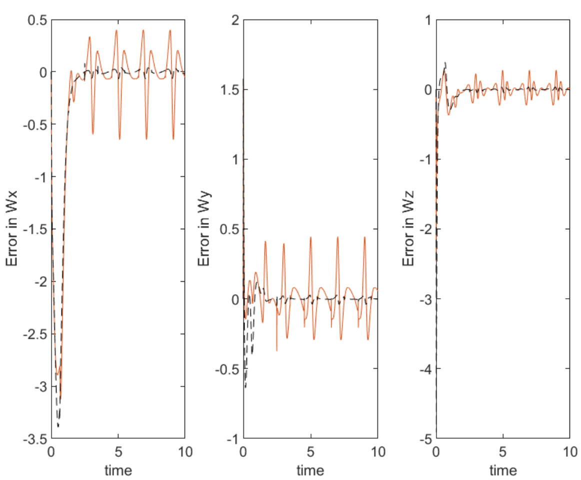

Fig. 10: Scenario II: Attitude Errors

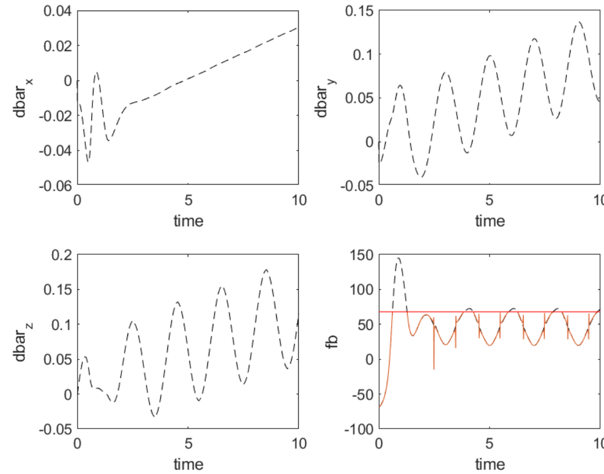

Fig. 11: Scenario II: Attenuated Disturbance and limited Total Thurst

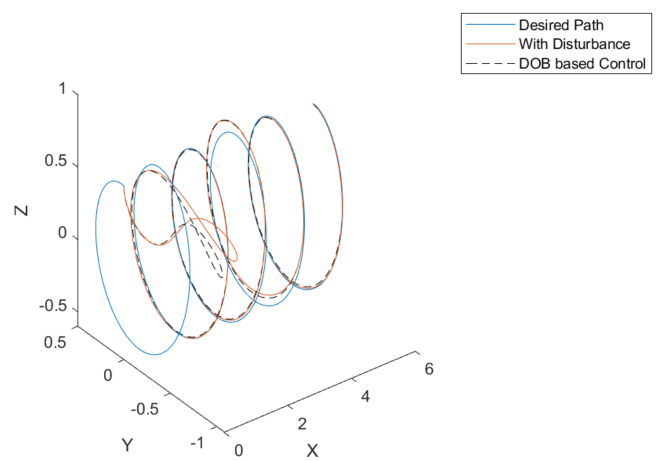

Fig. 12: Scenario II-A: Plot of the drone path in 3 dimensions under different conditions

C. *Scenario II-A: Constant Disturbance At Time Interval*

We illustrated a step disturbance using the same constant disturbance for $d_x(t)$ and $d_\Omega(t)$ from Scenario 2 but just for 1s from time interval t = 5 to t = 7 to observe that the DOBC stays proximal to the desired trajectory regardless of sudden disturbance during flight, this can be observed in Fig 12 and regardless of sudden large errors maintains trajectory in Fig 13.

VII. A Comparison with Sliding mode control Controller in Scenario II

Sliding mode control (SMC) is a robust, nonlinear control technique with desirable characteristics such as good accuracy, easy implementation, simplicity, fast response time and minimal tuning requirements. It is designed to maintain control of a system despite changes in the system's parameters or external

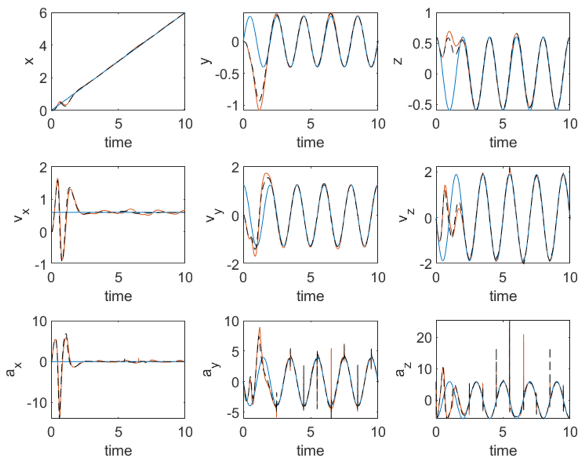

Fig. 13: Scenario II-A: Position, Velocity and Acceleration plots of the drone.

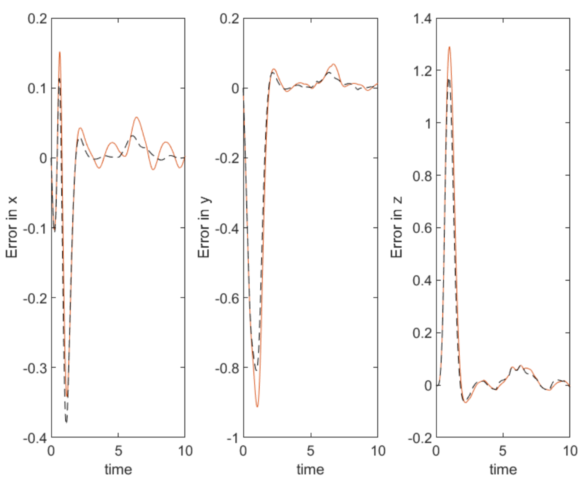

Fig. 14: Scenario II-A: Positional Errors

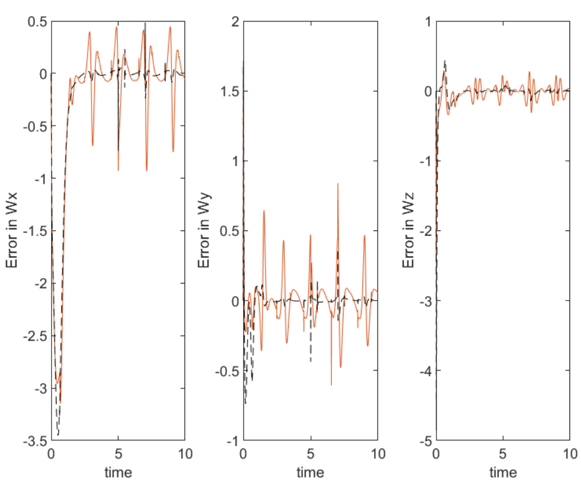

Fig. 15: Scenario II-A: Attitude Errors

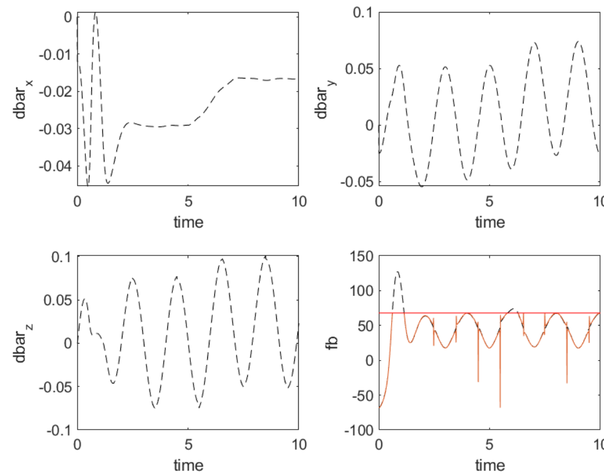

Fig. 16: Scenario II-A: Attenuated Disturbance and limited Total Thurst

disturbances. This is achieved by using a switching control law that moves the system's dynamics between different operating modes, in order to stabilize the system. Its operation involves driving the system state onto a surface in the state space called the sliding surface and then maintaining the states close to this surface. This is accomplished by designing the sliding surface to meet desired design specifications and by selecting a control law that will draw the system state to the sliding surface.

The dynamic behaviour of the system can be tailored by choosing an appropriate sliding function, and the closed-loop response of the system becomes insensitive to external disturbances and uncertainties. SMC is particularly suited for controlling nonlinear systems that experience disturbances and heavy uncertainties such as a quadrotor. In Fig 17, a 3-d plot positional plot in Scenario 2 with SMC Controller is shown, and we can observe the system stabilize in the x-axis from Fig18.

SMC has several advantages over other control techniques. It is computationally efficient, meaning that it can be implemented with minimal resources. It is also well-suited for controlling nonlinear systems, as it can handle nonlinearities and uncertainties. Additionally, SMC can be used to stabilize systems that experience external disturbances and heavy uncertainties, making it suitable for a wide range of applications.

VIII. Results and Analysis

The controller was tested on a quadrotor drone that was subjected to disturbances such as wind gusts, constant disturbance and ground effect, and vibrations as seen in the above experiment scenarios. The proposed DOB-based controller is capable of providing robustness to different kinds of disturbances since it was able to effectively detect and compensate for them and ensured that the quadrotor maintained its trajectory regardless. In Plots 4, 9 and 14 we observe that the DOB-based controllers have significantly lower positional errors staying closer to the 0 axis line and a similar observation can be inferred from

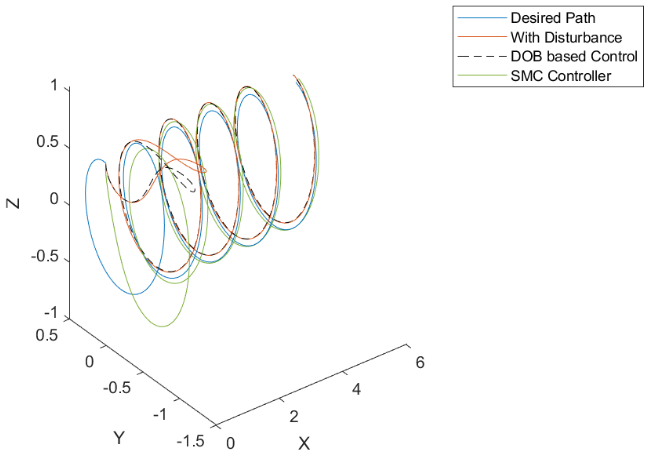

Fig. 17: Plot of the drone path in 3 dimensions under different conditions

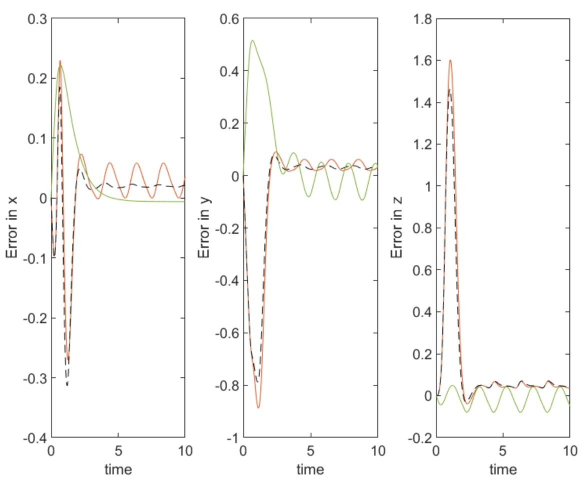

Fig. 18: Positional Errors

attitude error 5, 10, 15. It should be noted that In Fig 6, 11, 16 The red line is the max thrust limit of the Drone, The Orange line is the thrust generated by the drone, and the dotted line is the projected thrust as per the controller with no limitations.

Table I Shows the positional and attitude RMS errors for both the ideal conditions with disturbance and the DOB-based controller for the data recorded from time $t = 0$ to $t = 10$ at every time-step $dt = 0.01$. We see that the positional and rotational RMS errors are significantly less than Ideal conditions since an ideal controller would only account for error corrections in the current state, whereas a DOB is a feed-forward approach and attenuated any anticipated disturbance to maintain trajectory.

RMS Error	Ideal	DOB based Control
Scenario I	0.4362, [0.8187, 0.1746, 0.1825]	0.3913, [0.8087, 0.1452 0.2936]
Scenario II	0.4951, [0.8132, 0.1660, 0.1832]	0.4426, [0.8039, 0.1261 0.2946]
Scenario II-A	0.4190, [0.8274, 0.1867, 0.1845]	0.3762, [0.8116, 0.1499 0.2938]

TABLE I: Root Mean Squared Errors of Positional and Attitude [ϕ,θ,ψ] translations

IX. CONCLUSION

We successfully ran simulations of the quadrotor drone in turbulent conditions using step disturbances and plotted their graphs. The controller was able to effectively detect and mitigate external disturbances, such as turbulence and wind, during takeoff, landing, and flight.

The use of this type of controller has resulted in improved stability and precision in the quadrotor's movements, as well as increased robustness to external disturbances. This has been demonstrated through extensive testing and analysis, showing that the disturbance observer is able to accurately estimate and compensate for disturbances such as wind gusts and other external forces.

It uses an observer to estimate the external disturbances acting on the quadrotor, such as the ground effect and updates the control inputs in real-time to compensate for these disturbances. The disturbance observer is able to accurately estimate and compensate for ground effect, resulting in improved stability and precision in the quadrotor's movements.

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