Adaptive Control of Unmanned Quadrotor with Partial Actuator Failure using Model Reference Adaptive Control (MRAC) with Dynamic Inversion

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***Abstract*— Unmanned Aerial Vehicles (UAVs) often experience disturbances during operation, which will degrade its performance and may cause potential failure, affecting safety risks to civilians and other 3rd parties. In such event, UAVs with the common cascaded PID control might not be sufficient to compensate for this reduction in performance. This paper proposes to analyze algorithm for adaptive control, mainly focused on the model reference adaptive control (MRAC) such that despite any uncertainty the plant parameters remain close to the behavior of a desired reference model along with dynamic inversion as an adaptive controller for such scenarios which helps in decoupling of the flight states for the non-linear system. The results of the proposed method have been compared with the conventional PID based controller by implanting faults in motor outputs. In addition, the performance of the controls is evaluated in terms of trajectory following capability.**

Keywords—Model Reference Adaptive Control, Dynamic Inversion, Lyapunov Function.

I. Introduction

Since the beginning of 2010s, the world has seen a great increase in number of Unmanned Aerial Vehicles (UAVs), otherwise known colloquially as drones. The release of cheap commercial drones allows widespread adoption usage across various industries with various use cases. Some examples will include the use of camera drones in photography & cinematography in the creative sector, delivery drones for courier services, inspection drones for infrastructure inspection and much more.

As flying machines are slowly entering in our daily lives, they need to be sufficiently safe and reliable. During operation, UAs often experiences external disturbances from various factors such as wind, sensor errors, actuator failure etc. Among these factors, actuator failure is dangerous as it may lead to track deviation and loss of control (LOC) of UAVs. The cascaded PID control, which is adopted by a lot of UAVs for its simplicity, may not be capable in mitigating the effects of actuator defects or disturbances.

In this study, a model reference adaptive control (MRAC) with dynamic inversion is proposed as a solution to the problem of actuator faults in a quadrotor. The faults can be due to motor not performing to its desired capabilities. The trajectory following performance of the MRAC with dynamic inversion will then be evaluated against a cascaded PID control.

II. Problem Formulation For Conventional Controllers

Quadrotors are inherently unstable but are extremely agile systems. So, there is a need of a feedback controller for the system to be able to fly and stabilize. The standard and most widely used approach for the various control variables like roll (ϕ), pitch (θ), yaw (ψ) is cascaded PID controllers which are required to be tuned and the tunning process is time consuming and for every quadrotor. The popularity of PID controllers is due to its functional ease and simplicity [1]. However, conventional feedback controllers may not perform effectively because of the variation in process dynamics due to the non-linear actuators, environmental conditions, and variations in the character of the disturbances.

A. PID control

To control a system using PID control technique, the plant system needs to be linearized, then the controller shall be tuned according to the linearized system and subsequently implemented for the non-linear system. The tuning process is necessary to stabilize the system and then again finely tuned for the non-linear model. This requires a lot of effort and time-consuming simulations. Analytical pole placement methods are widely used when considering a low order system. An ordinary approach is, the adoption of a second-order model and then specify a desired natural frequency and damping ratio for the system [2].

During the linearization process, several assumptions are made, such as small perturbations and simple integral relations [3], which results in reduction in bandwidth and physical capabilities of the plant. Parameter uncertainty, external disturbances, time delays, and poor performance for an integrating process are also some limitations of PID controllers [4].

B. Model Referencing Adaptive Control

An adaptive control technique can be implemented to augment an existing controller to optimize the performance. An adaptive controller learns the system parameters in real time, and induce additional gains to the control law, so it will react to changes in dynamics of a quadrotor. Adaptive control has been utilized to deal with propellers failures [5], shifting loads [6], actuator uncertainty [7] etc.

MRAC (Model Referencing adaptive control) compute the plant such that the error between a desired trajectory described by stable reference dynamics (M) and true trajectory of the plant(P) tends to zero. A stable controller-parameter adjustment mechanism, which is determined using the Lyapunov Stability theory [8]. The direct MRAC [9] model in Fig. 1 illustrates the working mechanism of the control system. The adaptive mechanism takes the errors as input and cultivate the adaptive gains which are fed to the controller.

State Feedback Equations:

$$\lim_{t\to\infty} x_P(t) = x_M(t) \quad (1)$$

$$\lim_{t\to\infty} \|x_P(t) - x_M(t)\| = \lim_{t\to\infty} \|e_c(t)\| = 0 \quad (2)$$

The main objective is to keep the system stable during adaptive learning process.

MRAC has been used in fixed wing aircraft undergoing asymmetric fault [10]. In [11], 3 MRACs for a Quadrotor, namely MIT rule MRAC, Conventional MRAC and a modified MRAC is formulated and evaluate against a Linear Quadratic Regulator (LQR) baseline under propeller failure.

MRAC with dynamic inversion has been previously implemented in [12]. In this paper, we intend to implement MRAC with dynamic inversion to evaluate its trajectory tracking performance when experiencing partial actuation failure.

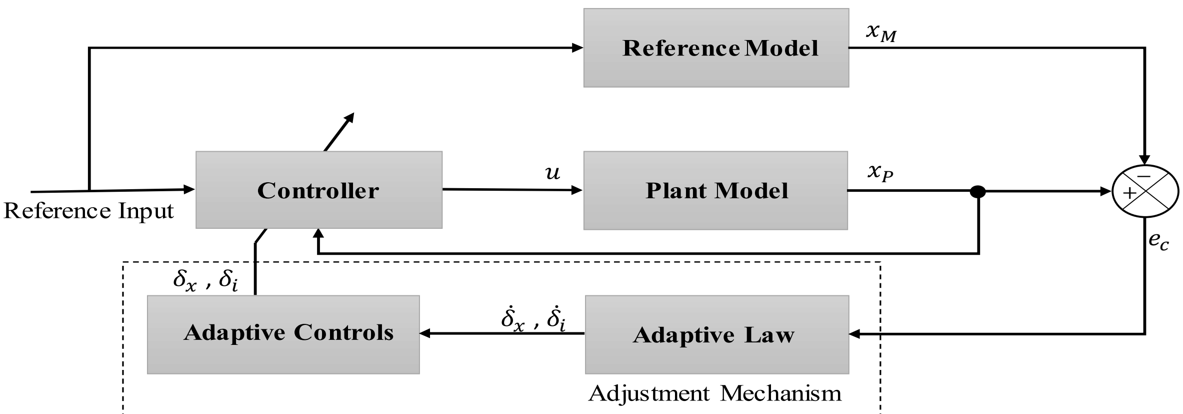

Fig. 1:Direct MRAC model

III. SYSTEM DYNAMICS

A quadropter consists of four rotors at a symmetric position to each other. It is a dynamic vehicle with four input forces F_1, F_2, F_3, F_4 and six Degrees of Freedom (6 DOF), Three degrees for rotational and three degrees for translational motion. The motion of a quadrotor is highly coupled and can be controlled by varying the RPM of the four rotors individually, thereby changing the Thrust, Roll, Pitch and Yaw motions.

A sketch of the quadrotor model is shown in Fig 2. There are following twelve states which are practically suitable for quadrotor in 6 DOF are [13]:

Position along x axis	-	x
Position along y axis	-	y
Position along z axis	-	z
Velocity along x axis	-	$\dot{x}$
Velocity along y axis	-	$\dot{y}$
Velocity along z axis	-	$\dot{z}$
Roll Angle	-	ϕ
Pitch Angle	-	θ
Yaw Angle	-	ψ
Roll Rate	-	$\dot{\phi}$
Pitch Rate	-	$\dot{\theta}$
Yaw Rate	-	$\dot{\psi}$

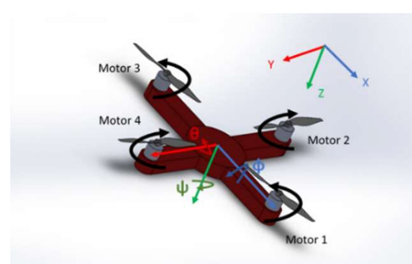

Fig. 2: Quadrotor model

The *x*-axis moment (M_x) or rolling moment (L) with lever arm 'r' at center of gravity is given by:

$$M_x = r_1F_1 + r_2F_2 + r_3F_3 + r_4F_4 \quad (3)$$

Due to the symmetricity of the quadrotor and same moment arm lengths, Arms 1 and 3 will have no impact on moment:

$$r_1 = r_3 = 0 \tag{4}$$
$$r_4 = -r_2 = l \tag{5}$$

Thus, the rolling moment can be written as:
$$L = -lF_2 + lF_4 \tag{6}$$

The *y*-axis moment (M_y) or pitching moment(M) with lever arm 'r' at center of gravity is given by:

$$M_y = r_1F_1 + r_2F_2 + r_3F_3 + r_4F_4 \tag{7}$$

Similarly, due to the symmetricity of the quadrotor and same arm lengths, Arms 2 and 4 will have no impact on moment:
$$r_2 = r_4 = 0 \tag{8}$$
$$r_1 = -r_3 = l \tag{9}$$

The pitching moment can then be written as:
$$M = lF_2 - lF_3 \tag{10}$$

The imbalance between the rotating propellers creates the yaw motion of the quadrotor [13]. This reactive torque is taken positive along the counterclockwise rotation and vice versa. The yawing moment (N) or the z-axis moment (M_z) at the center of gravity is given by:

$$M_z = N = c(-F_1 + F_2 - F_3 + F_4) \tag{11}$$

where 'c' is the force-to-moment scaling factor for a fixed motor-propeller set [14], which is an uncertainty and must be compensated.

These resulting moments can be denoted in matrix form as:

$$\begin{bmatrix} L \\ M \\ N \end{bmatrix}_{3\times1} = \begin{bmatrix} 0 & -l & 0 & l \\ l & 0 & -l & 0 \\ -c & c & -c & c \end{bmatrix}_{3\times4} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix}_{4\times1} \tag{12}$$

Using Coriolis Theorem, the body fixed moments L, M, N can be expressed in the form of angular accelerations as [15]:

$$\begin{bmatrix} L \\ M \\ N \end{bmatrix} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} + \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{13}$$

Given the above equations, the rotational kinematics for angular accelerations can be simplified as [16]:

$$\dot{p} = \frac{I_{yy} + I_{zz}}{I_{xx}} rq + \frac{L}{I_{xx}} \tag{14}$$
$$\dot{q} = \frac{I_{zz} + I_{xx}}{I_{yy}} pr + \frac{M}{I_{yy}} \tag{15}$$
$$\dot{r} = \frac{I_{xx} + I_{yy}}{I_{zz}} pq + \frac{N}{I_{zz}} \tag{16}$$

A pure kinematic dependency between body fixed angular rates p, q, r and the Euler angles ϕ, θ, ψ is given by [17] :

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\cos\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\theta \\ 0 & \frac{\sin\phi}{\cos\theta} & \frac{\cos\phi}{\cos\theta} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{17}$$

The above equation can also be stated in inverted form as:

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\phi & \sin\phi\cos\theta \\ 0 & -\sin\phi & \cos\theta\cos\phi \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \tag{18}$$

For small angles assumptions:
$$\sin\alpha \approx \alpha;\ \cos\alpha \approx 1;\ \tan\alpha \approx \alpha \tag{19}$$

Euler angle rates can be written as:
$$\dot{\phi} \approx p + r\theta + q\phi\theta \tag{20}$$
$$\dot{\theta} \approx q - r\theta \tag{21}$$
$$\dot{\psi} \approx r + q\phi \tag{22}$$

IV. Controller Model For Altitude Hold And Attitude Control

The state space representation of the plant model is:
$$\dot{x}_P = Ax + Bu \tag{23}$$

where A is the state matrix, x is the input vector, B is the input matrix, and u is the input vector.

A. Dynamic Inversion

The quadrotor parameters are highly non-linear and can be identified from the translational and rotational dynamics of the system. In a non-linear system, the concept of dynamic inversion decouples the control inputs without making any assumptions. This decoupling leads to better performance by exploiting full capabilities of the plant [18].
Consider the dynamic system with:

State vector: $$x_{n\times1} = [x_1 \dots\dots x_n]^T = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix}_{3\times1} \tag{24}$$

Input vector: $$u_{m\times1} = [u_1 \dots\dots u_m]^T = \begin{bmatrix} p \\ q \\ r \end{bmatrix}_{3\times1} \tag{25}$$

Output vector: $$y_{m\times1} = [y_1 \dots\dots y_m]^T \tag{26}$$

From the state matrix of the system, it is observed that inputs are influenced by first derivatives of states. For the dynamic inversion, we can then consider the states (x) are taken as outputs (y):

$$x_{n\times1} = [x_1 \dots\dots x_n]^T = [y_1 \dots\dots y_m]^T = y_{m\times1} \tag{27}$$

The first order reference model in frequency domain can be stated as:

$$y = \frac{y_{commanded} - y}{sT} \quad (28)$$

Hence, now the outputs are defined as:

$$y = x = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} \quad (29)$$

We define pseudo controls inputs (v), which are equal to time derivative of output (y) that are directly influenced by input (u) as given by

$$\dot{y} = v \quad (30)$$

In frequency domain: $Y = v/s$ (31)

The results are input/output dynamic, which means that there is a linear dynamic relationship between the new inputs as v and the outputs as y.

Hence, the Pseudo Controls are written as:

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = \begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \\ \dot{y}_3 \end{bmatrix} = \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \quad (32)$$

Equation (18), the inverted non-linear system can be implemented as linearized state feedback as:

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\phi & \sin\phi\cos\theta \\ 0 & -\sin\phi & \cos\theta\cos\phi \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \quad (33)$$

The resulting system consists of decoupled states and linear dynamics consisting of pseudo controls (v) and the outputs (y), which can be visualized in Fig. 3.

Dynamics from the desired input to the controlled output being linear and constant over the entire flight regime [19]. This assumption free method increases the total bandwidth of the model; hence the handling qualities of the quadrotor could be improved.

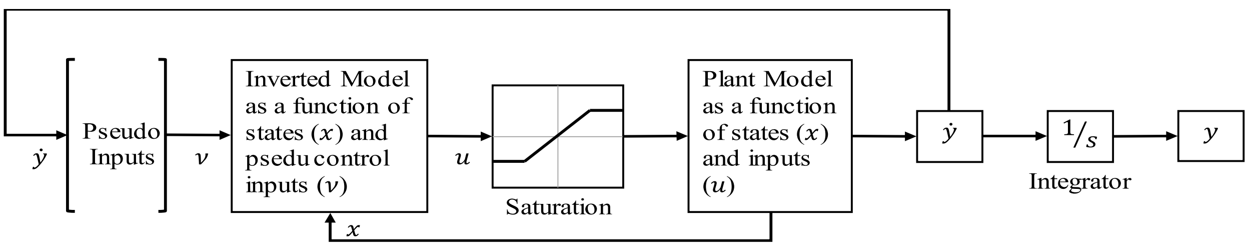

Fig. 3: Dynamic Inversion

B. MRAC

Model Reference Adaptive Control (MRAC) aims to force the dynamic response of the controlled system to approach that of a reference system asymptotically, despite parametric uncertainties in the plant [20].
The plant dynamic equation is given by:

$$\dot{x}_P = A_P x_P + k_P u \quad (34)$$

where A_P is known linear part but k_P is non-linear and is unknown. For this plant model, we now consider a reference model which is stable and linear model. So, the errors from the plant model can be subtracted from the chosen reference model.

The reference model can be generated and to be similar to the plant model. Hence, reference model [21] can be written as:

$$\dot{x}_M = A_M x_M + k_M i \quad (35)$$

Referring to Equation (2), the control objective is to minimize the error between plant (P) and the reference model (M).
i.e.

$$\lim_{t\to\infty} \|x_P(t) - x_M(t)\| = \lim_{t\to\infty} \|e_c(t)\| = 0 \quad (36)$$

C. Control Law

To define the control law for the adaptive gains. The control Law can be written as:

$$u = \delta_x x_P + \delta_i i \quad (37)$$

where δ_x and δ_i are the updated gains for the plant.

Inserting the control law to the plant dynamics gives the closed loop dynamics for the system.

$$\dot{x}_P = A_P x_P + k_P(\delta_x x_P + \delta_i i) \quad (38)$$
$$\dot{x}_P = \{A_P + k_P\delta_x\}x_P + \{k_P\delta_i\}i \quad (39)$$

On comparing the above equation with the reference model, we can define the matching conditions as:

$$A_M = A_P + k_P\delta_x^* \quad (40)$$
$$k_M = k_P\delta_i^* \quad (41)$$
$$\delta_x^* = \frac{(A_M - A_P)}{k_P} \quad (42)$$

$$\delta_i^* = \frac{(k_M)}{k_P} \tag{43}$$

D. Error Dynamics

From the control objective, we define error dynamics $\dot{e_c}$ as:

$$\dot{e_c} = \dot{x}_P - \dot{x}_M \tag{44}$$

$$\dot{e_c} = \{A_P + k_P\delta_x\}x_P + \{k_P\delta_i\}i - \{A_M x_M + k_M i\} \tag{45}$$

After some mathematical manipulations and intuitively using the matching conditions, we can rewrite the equations as:

$$\dot{e_c} = \{A_P + (k_P\delta_x^* - k_P\delta_x^*) + k_P\delta_x\}x_P + \{k_P\delta_i - k_M\}i - A_M x_M \tag{46}$$

Rearranging the terms and substituting known variables leads to the following equation:

$$\dot{e_c} = \{(A_P + k_P\delta_x^*) + k_P(\delta_x - \delta_x^*)\}\, x_P - A_M x_M + \{k_P\delta_i - k_P\delta_i^*\}i \tag{47}$$

Substituting A_M, e_c and considering the updated $\delta - \delta^*$ gains as $\tilde{\delta}_x$ and $\tilde{\delta}_i$, respectively:

$$\dot{e_c} = A_M e_c + k_P\tilde{\delta}_x x_P + k_P\tilde{\delta}_i i \tag{48}$$

which is used as states instead of original states, For the Linear Time Invariant System, the Lyapunov candidate function holds [20]:

$$A^T P + PA + Q = 0 \tag{49}$$

For an arbitrary positive definite matrix Q taken as identity matrix, we define Lyapunov Candidate function as [22]:

$$V = \frac{1}{2}\left[e_c^2 + \left(\frac{|k_P|}{\gamma_x}\right)\tilde{\delta}_x^2 + \left(\frac{|k_P|}{\gamma_i}\right)\tilde{\delta}_i^2\right] \tag{50}$$

Time derivative of Lyapunov function:

$$\dot{V} = A_M e_c^2 + \tilde{\delta}_x\left\{e_c k_P x_P + \left(\frac{|k_P|}{\gamma_x}\right)\dot{\tilde{\delta}}_x\right\} + \tilde{\delta}_i\left\{e_c k_P \tilde{\delta}_i i + \left(\frac{|k_P|}{\gamma_r}\right)\dot{\tilde{\delta}}_r\right\} \tag{51}$$

E. Adaptive Gains

By setting the terms in brackets to zero, we will obtain the parameter update laws:

$$\dot{\delta}_x = -\gamma_x \frac{k_P}{|k_P|} e_c x_P \tag{52}$$

$$\dot{\delta}_i = -\gamma_r \frac{k_P}{|k_P|} e_c i \tag{53}$$

The block diagram for the resultant MRAC is shown in Fig 4.

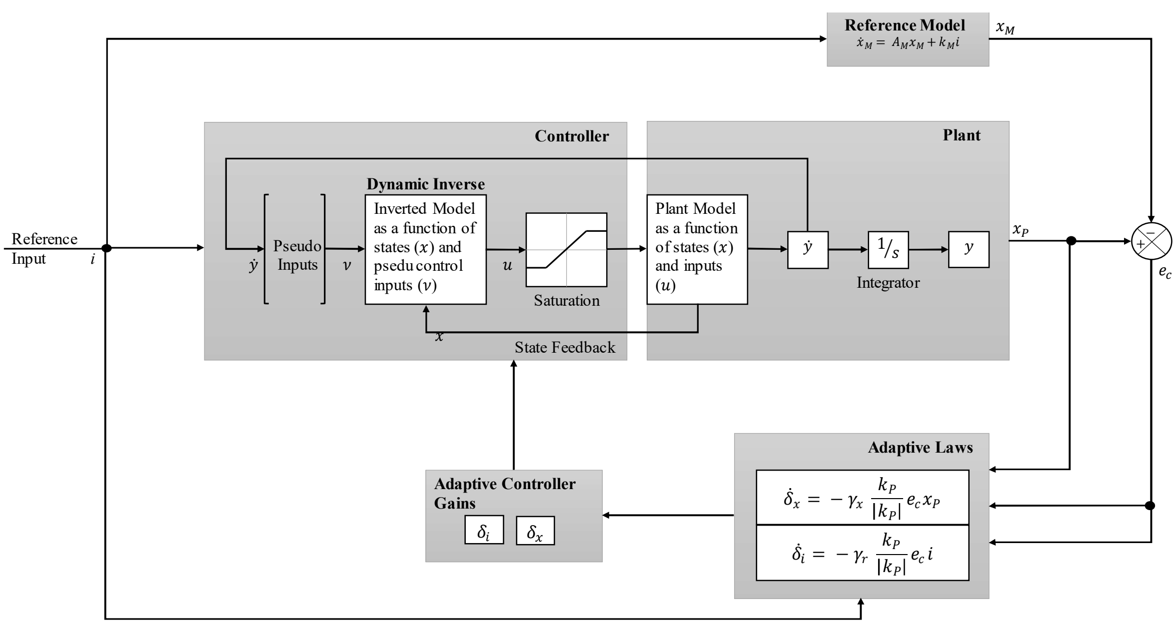

Fig. 4: Model Reference Adaptive Control

F. Hardware Model

The Parrot Mambo [23] was chosen for use in this paper for its ability to be coded using MATLAB/Simulink and it is relatively cheap in price for testing purpose and low maintenance, the small frame size with propeller guards which help to maximize the flight capabilities in a laboratory environment. The basic structure, axis of rotations and motor rotations are illustrated in Fig. 5.

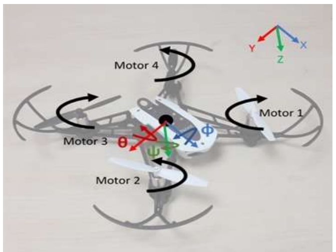

Fig. 5: Parrot Mambo

Table 1: Physical Properties of Parrot Mambo *[15]*

Variable	Value
I_{xx}	5.8286e-05 kg/m^2
I_{yy}	7.1691e-05 kg/m^2
I_{zz}	1.0000e-04
m	63 g
g	9.81 m/s^2

V. SIMULATION RESULTS

To verify the performance of the control, the simulation was performed to follow a trajectory. The quadrotor should take off to a height of 1.5 m and follow two squares. The position was given through waypoint follower [24] toolbox in Simulink. The quadrotor should maintain its altitude and then land to the same position from where it took off.

A. Ideal Case (*Full power motor*)

The following results were acquired without any disturbances in the system. The UAV Animation toolbox depicts the output trajectory as shown in Fig. 6, while the commanded and desired state inputs are shown in Fig. 7.

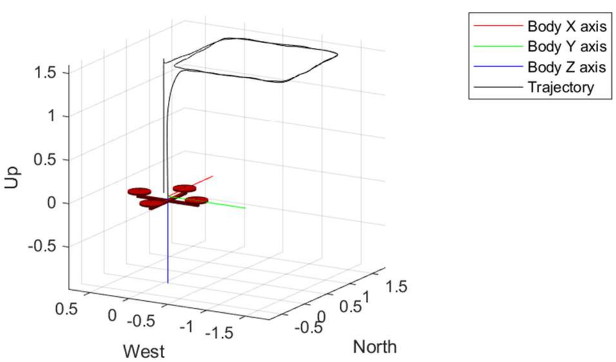

Fig. 6: Trajectory of quadrotor under ideal case

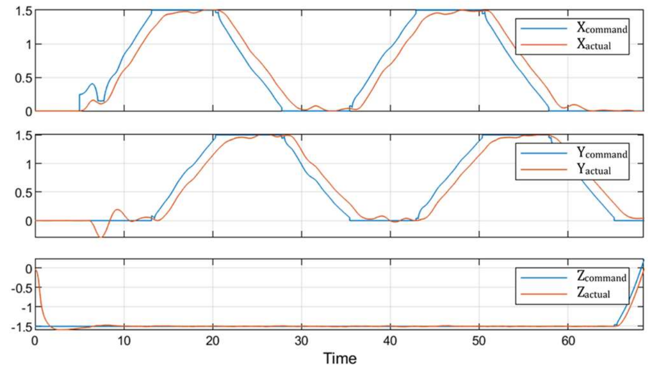

Fig. 7: Commanded state input and actual UAV state followed by quadrotor (Ideal Case). *Y*-axis is distance in meters

B. Single Bias (*Single motor fault*)

To capture the results of the controller under partial actuator failure, single actuator faults to the quadrotor flights [25], a gaussian bias of mean 80%, frequency of 10Hz and standard deviation of 5% is applied to Motor 4, the inputs are shown in Fig. 8.

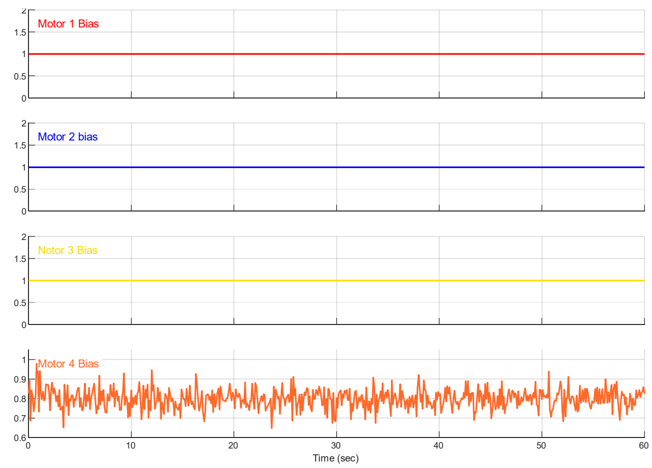

Fig. 8: Induced actuator bias for partial bias

This disturbance was introduced to the motor after the quadrotor takes off that is after 6 seconds, and the following results depicts the output trajectory with this input bias, as shown in Fig. 9.

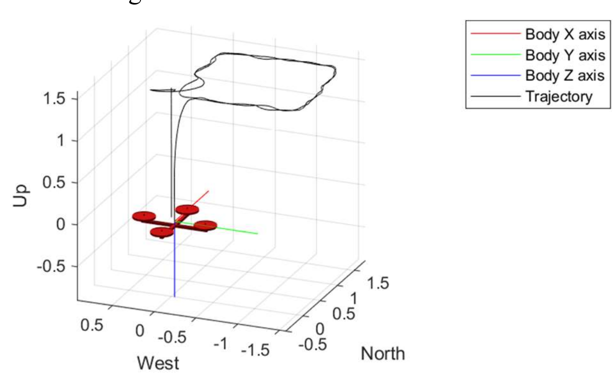

Fig. 9: Trajectory of UA for partial bias case

From the depicted results, the controller gains are adjusting according to the reference trajectory and fights against the disturbances. The deviation in the trajectory after taking off is due to the input bias, which is the controller compensating in real time.

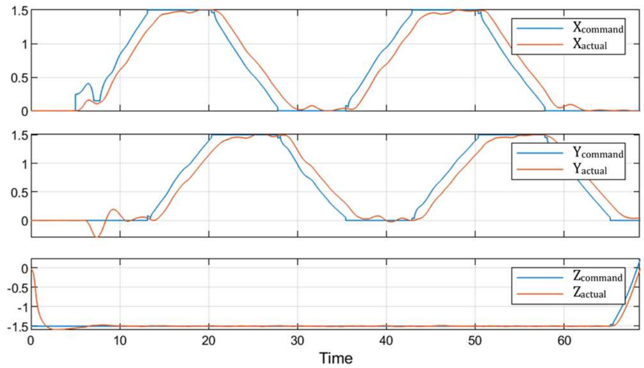

Fig. 10: Commanded state input and actual UAV state followed by quadrotor (Partial bias to single motor)

Figure 10 depicts the deviation of the system from the desired path and how the system manages to hold the altitude after the disturbance was introduced. The motor torque outputs are depicted in Fig. 11.

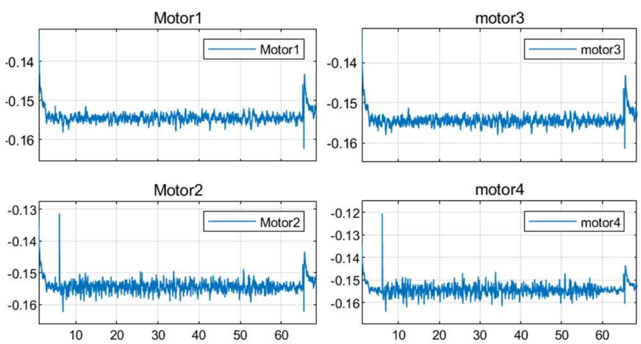

Fig. 11: Actuator Output under partial bias

The motor outputs experienced a spike at the 6th second. However, the controller provides the outputs to compensate this disturbance. Motor 2 reacts to follow the commands of Motor 4 to balance the moments and make sure the system does not lose its altitude.

VI. Comparison with PID

A. Simulation Test with multiple bias input

Another test was performed with motors at different performances as shown in Fig. 12. All motors have standard deviations of 5% of bias but with different means values: Motor 1 at 60%, Motor 2 is at 100%, Motor 3 at 90% and Motor 4 at 80%, respectively. To compare the performance of the controller, the similar bias values are given to a tuned PID model of the quadrotor.

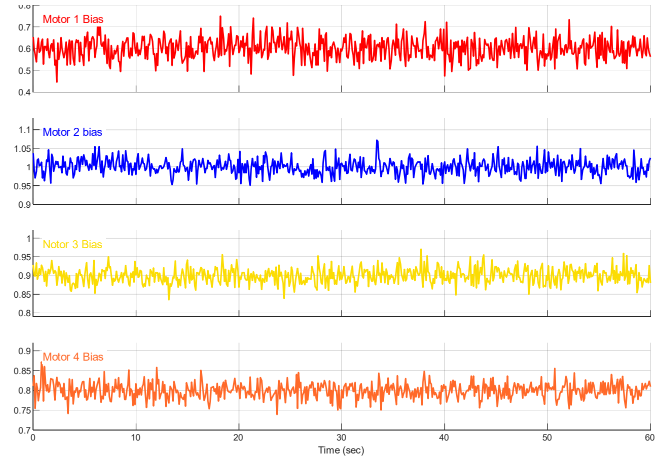

Fig. 12: Induced actuator bias for complete bias input with MRAC and dynamic inversion

The resulting simulation results depicts the redundancy and integrity of the model up to what extinct the system is capable to adapt the changes and react accordingly as shown in Fig. 13, Fig. 14, and Fig. 15.

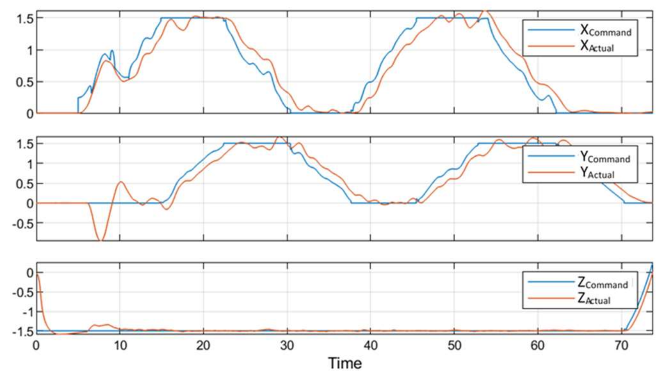

Fig. 13: Commanded state input and actual quadrotor state under multiple bias input with MRAC and dynamic inversion

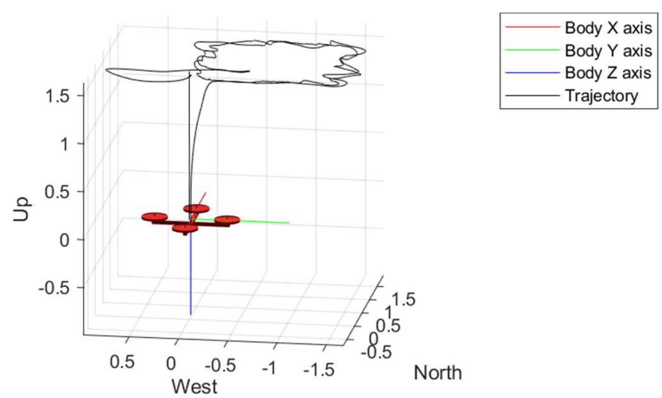

Fig. 14: Trajectory of UA with MRAC Control and dynamic inversion under complete bias input

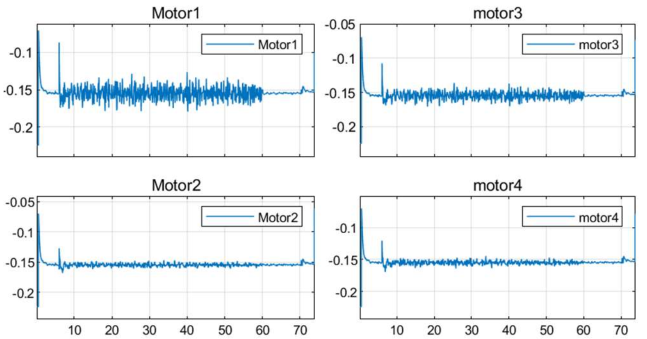

Fig. 15: Actuator Output under complete bias input with MRAC and dynamic inversion

For comparison, the same bias is injected to PID model and the results are shown in Fig. 16.

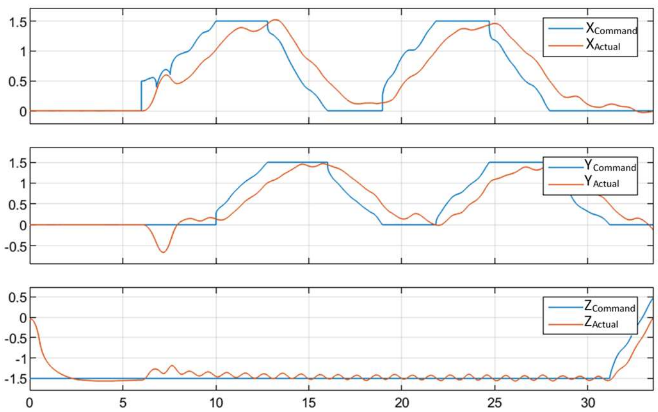

Fig. 16: Induced actuator bias for multiple input bias with PID

The result depicts high oscillations and poor handling in simulations, as shown in Fig. 17.

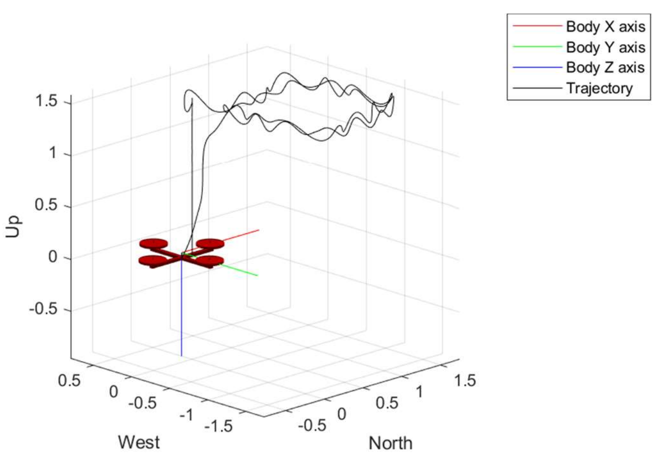

Fig. 17: Trajectory of Quadrotor with PID under multiple input bias

B. Experiment Test

The same bias input as in previous case was also performed in an experiment with a parrot mambo attached with four motion capture markers on front side and two on the rare side in a laboratory with motion capture cameras to determine the path of the quadrotor, as shown in Fig. 18, Fig. 19, and Fig. 20.

Fig. 18: Motion capture markers on Parrot Mambo

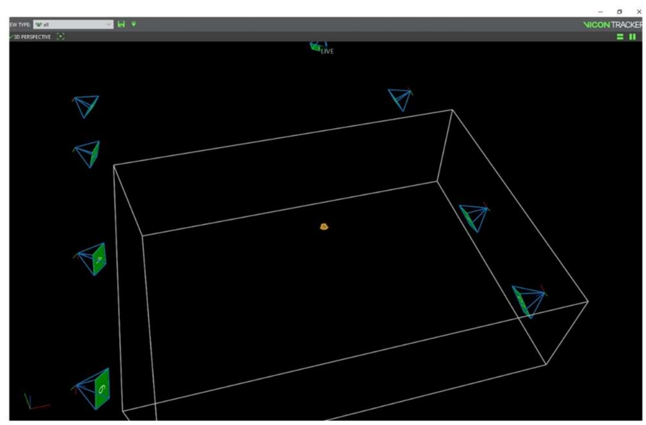

Fig. 19: Object Located via Motion Capture Cameras

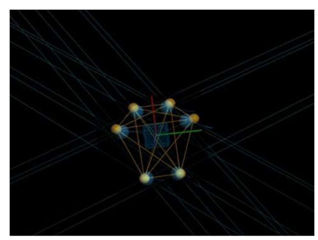

Fig. 20: Identified Parrot Mambo (Axis Allocation)

The extracted csv file was used to plot the data in MATLAB, Solid lines displays the results from the MRAC model and dotted line depicts the PID model result, as shown in Fig. 22.

Fig. 21: Path Following Parrot Mambo

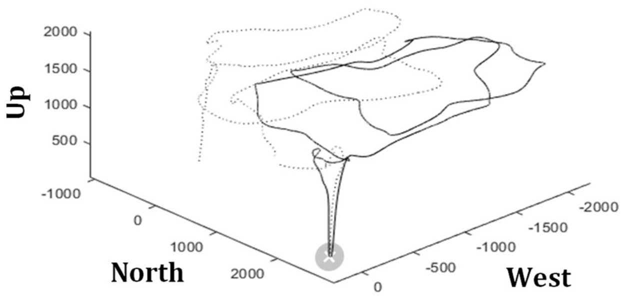

Fig. 22: Experimental results for MRAC with dynamic inversion and PID

One can draw from the results of Fig. 22 that, due to the sensors delays the model is performance is deteriorated but maintaining the integrity, it is still capable enough to land at the desired position. After comparing with PID model, the drift from trajectory in continuous and the system did not land on the desired landing position.

These finding proves that MRAC is able to outperform PID control when experiencing actuator failure. They are also useful in determining the track deviation of UAS experiencing actuator failure and could be used by the Air Traffic Controller or UAS Traffic Management (UTM) systems to perform safety risk management [26].

VII. Future Work

Damping modification is necessary to the MRAC model to make it further agile. The model is capable enough to adapt the changes but keeps on adding and updating the parameters even if there are no errors. So, a damping need to be implemented to consider, if the system is already at zero error, the controller must not implant additional gains. This can be performed by various methods. For example, the methods of sigma modification [27] and e-modification [28].

A. sigma modification

In [27] modify the parameter update law to counter act the parameter drift into the regions of instability. The main advantage of this scheme is that it retains the features of algorithm without any leakage.

B. e-modification

E-modification [28] is an enhanced scheme used in adaptive law, in which the product of the system output error and the signal behind the adjustable controller parameter is created as a signal. This signal is then passed through a first order lag filter. As the output error becomes zero, the lag filter becomes a simple integrator.

Further experimentation could also be carried out by assigning the UAS to perform other tasks, such as landing on a ship under wind disturbances, which was previously performed using visual servo-ing control in [29].

VIII. Conclusion

Actuator failures and faults are a key concern in ensuring safe and reliable UAV operation. A conventional cascaded PID may not be able to mitigate the issue when experiencing an actuator failure. This will lead to degradation of UAV flight performance and potential crash, as evident from the fluctuations in actual trajectory as compared to desired trajectory, causing safety risk and harm to 3rd parties.

To mitigate this disturbance, a Model Reference Adaptive Control (MRAC) is used as the adaptive controller. The adaptive controller can deal with the fluctuation in actuator performance while following closely to the desired trajectory as compared to the conventional cascaded PID. This allows UAV operations to be carried out safely and reliably even when actuator faults are present.

These findings shows that MRAC is a more suitable than PID in dealing with actuator failure. It is also useful informing behaviors of UAS undergoing actuator failure, and hence providing valuable insights for UTM safety risk management.

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