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PENUGASAN KEGIATAN TRI DHARMA & PENUNJANG BAGI DOSEN
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SEMESTER GENAP TAHUN AKADEMIK 2023/2024

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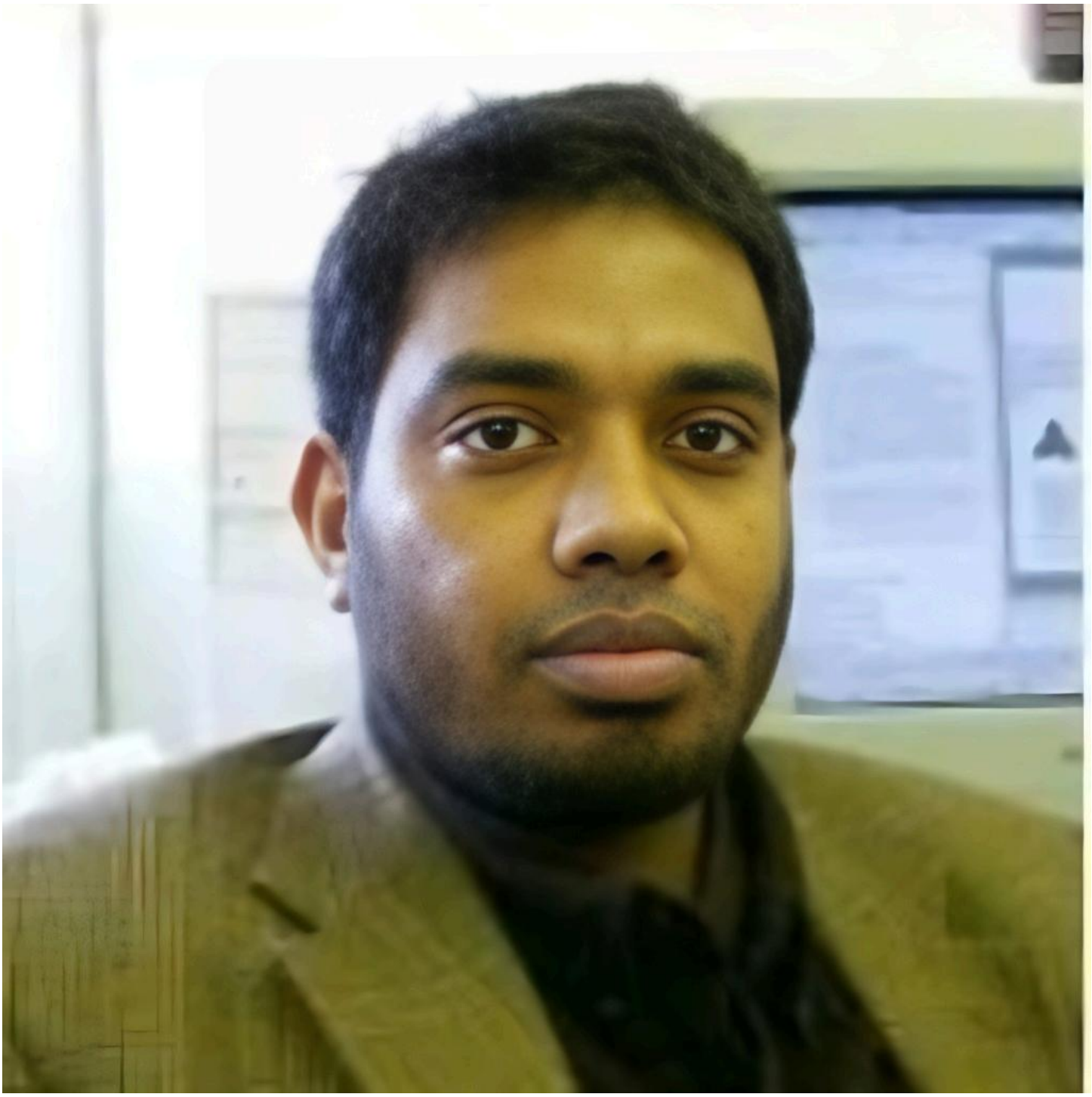

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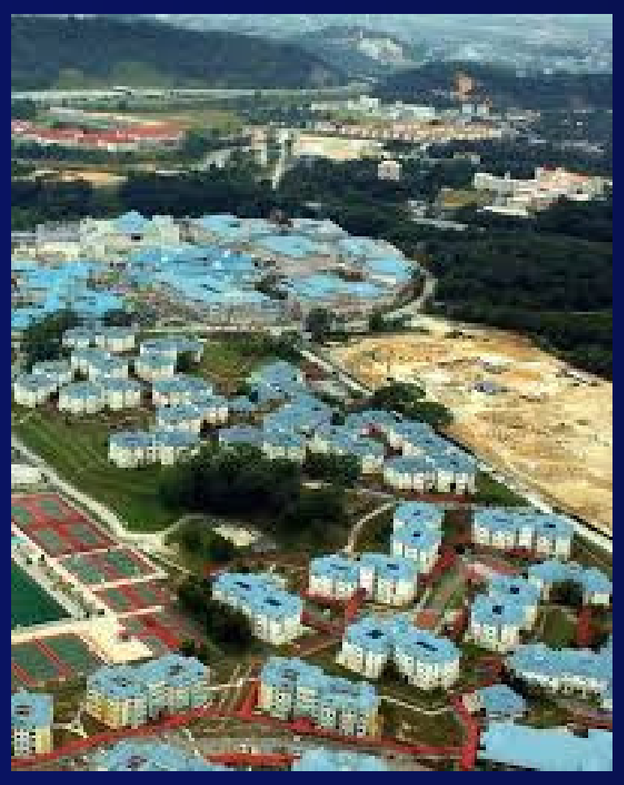



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Integrated Control System Design for a Quaternion-Based Omnidirectional Quadrotor Drone

Dwi Pebrianti*
[1]Department of Mechanical & Aerospace Engineering
International Islamic University malaysia
Kuala Lumpur, Malaysia
[2]Faculty of Information Technology
Universitas Budi Luhur
Jakarta, Indonesia
dwipebrianti@iium.edu.my

Luhur Bayuaji
[1]Faculty of Data Science & Information Technology
INTI International University
Nilai, Malaysia
[2]Faculty of Information Technology
Universitas Budi Luhur
Jakarta, Indonesia
luhur.bayuaji@budiluhur.ac.id

Rosdiyana Samad
Faculty of Electrical & Electronics Engineering
Universiti Malaysia Pahang Al-Sultan Abdullah
Pekan Malaysia
rosdiyana@ump.edu.my

Md Jobaher Hossain
Faculty of Engineering
International Islamic University malaysia
Kuala Lumpur, Malaysia
jobahereljam1997@gmail.com

2024 9th International Conference on Mechatronics Engineering (ICOM) | 979-8-3503-4978-8/24/$31.00 ©2024 IEEE | DOI: 10.1109/ICOM61675.2024.10652273

Abstract*— The study addresses the limitations of traditional quadrotors in achieving omnidirectional movement, which restricts their agility and adaptability in dynamic environments. This research introduces the Omnidirectional Stationary Flying Outstretched Drone, utilizing quaternions for orientation representation to avoid issues such as singularities and gimbal lock. The methodology involves developing a dynamic model that incorporates aerodynamic effects and implementing linear controllers, including PID and PI controllers, for precise altitude and attitude control. Simulation results show that the drone achieved a settling time of 5 seconds and an overshot of less than 5% in altitude control. Experimental validations confirm enhanced maneuverability and stability compared to conventional quadrotors.???

Keywords*— quadcopter, quaternion, linear controller, complex system, unmanned aerial vehicles

I. INTRODUCTION

The field of Unmanned Aerial Vehicles (UAVs), particularly those capable of Vertical Take-Off and Landing (VTOL) such as the quadrotor, has atrracted considerable attention in recent research and development efforts. This is largely due to their versatility and effectiveness in performing complex tasks across various industries, including surveillance, inspection, and mapping [1]. Traditional quadrotors, known for their simplicity and stability, have been widely used; however, they are often limited in their ability to move omnidirectionally, which can be a significant constraint in dynamic and unpredictable environments. The Omnidirectional Stationary Flying Outstretched Drone represents a notable advancement in UAV technology. Unlike traditional quadrotors, this innovative drone integrates the capabilities of steady hovering and omnidirectional movement into a single platform. The unique design, featuring multiple rotors strategically positioned at the ends of extended arms or wings, allows for propulsion in any direction. This configuration provides exceptional agility and maneuverability in the horizontal plane, setting it apart from conventional UAVs that are typically limited to more restricted movements [2]. Such versatility makes this drone an ideal tool for a wide range of applications, from detailed aerial surveys to complex inspection tasks in confined or hazardous areas [3].

One of the critical technological advancements in the Omnidirectional Stationary Flying Outstretched Drone is the use of quaternions to represent its orientation in three-dimensional space. Quaternions offer a robust and efficient method for avoiding problems like singularities or gimbal lock that can arise with traditional Euler angle representations [4]. This makes quaternion-based calculations particularly well-suited for real-time control applications, where high computational efficiency is crucial. Additionally, quaternions provide a comprehensive framework for describing global orientation, which is essential for integrating multiple rotational movements smoothly without introducing computational errors [5].

The implementation of attitude control algorithms that utilize quaternion feedback, along with sensor inputs measuring angular velocity, ensures precise and responsive control over the drone's orientation. This precision is vital for maintaining stable flight and accurate maneuverability, even under challenging conditions [6]. The flexibility of quaternion-based control systems also allows the integration of various control strategies, enabling the customization of the drone's control system to meet specific mission requirements and dynamic characteristics. To further enhance the performance and adaptability of the drone, the dynamic model includes additional calculations to account for aerodynamic phenomena such as propeller downwash and induced downflow, beyond the basic kinetic equations [7]. The modeling process includes the development of simple linear controllers, such as a PID controller for altitude control and a PI controller that employs quaternion feedback and body angular velocity feedback for attitude control [8][9]. These controllers are critical in fine-tuning the drone's response to various flight scenarios, ensuring stability, responsiveness, and precision.

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The control system's effectiveness will be rigorously evaluated through simulations and practical testing, with particular attention to the stability, responsiveness, and precision of altitude and attitude control. Moreover, the study will explore the integration of control outputs for motor torque management, aiming to achieve seamless and precise maneuverability across a variety of flying conditions.

The mathematical equations for quaternions and their implementation in MATLAB Simulink will be detailed in the technical sections of the article. The results and discussion will focus on the outcomes of the simulations, highlighting the improvements achieved. The conclusion will summarize the key findings and propose recommendations for future work, aiming to further refine and enhance the control systems and applications of this innovative UAV technology.

II. Quaternion Mathematics

This part will provide an explanation of the fundamental algebraic ideas related to quaternions. This is important for maintaining consistency and establishing the necessary mathematical foundation to understand and use the suggested modeling and control method. Thorough examination and detailed explanation of the mathematical technique can be found in the literatures [7][10][11].

A quaternion is a mathematical object with a rank of 4, belonging to the class of hypercomplex numbers. It can be expressed in several ways, with Eq. (1-2) being two often used methods.

$$\boldsymbol{q} = q_0 + q_1\boldsymbol{i} + q_2\boldsymbol{j} + q_3\boldsymbol{k} \tag{1}$$

$$\boldsymbol{q} = [q_0 \quad q_1 \quad q_2 \quad q_3]^T \tag{2}$$

The multiplication of two quaternions, **p** and **q**, is carried out using the Kronecker product, represented as ⊗. The resulting equations are provided below. If **p** represents a single rotation and **q** represents another rotation, then **p** ⊗ **q** indicates the combined rotation as Eq. (3).

$$\boldsymbol{p}\otimes\boldsymbol{q} = \begin{bmatrix} p_0q_0 - p_1q_1 - p_2q_2 - p_3q_3 \\ p_0q_1 + p_1q_0 + p_2q_3 - p_3q_2 \\ p_0q_2 - p_1q_3 + p_2q_0 + p_3q_1 \\ p_0q_3 + p_1q_2 - p_2q_1 + p_3q_0 \end{bmatrix}$$

$$\boldsymbol{p}\otimes\boldsymbol{q} = Q(\boldsymbol{p})\boldsymbol{q} = \begin{bmatrix} p_0 & -p_1 & -p_2 & -p_3 \\ p_1 & -p_0 & -p_3 & p_2 \\ p_2 & p_3 & p_0 & -p_1 \\ p_3 & -p_2 & p_1 & p_0 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix}$$

$$= \bar{Q}(\boldsymbol{q})\boldsymbol{p} \begin{bmatrix} q_0 & -q_1 & -q_2 & -q_3 \\ q_1 & q_0 & q_3 & -q_2 \\ q_2 & -q_3 & q_0 & q_1 \\ q_3 & q_2 & -q_1 & q_0 \end{bmatrix} \begin{bmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \end{bmatrix} \tag{3}$$

The norm or length of a quaternion is defined in the same way as for any complex number, as shown in Eq. (4). In this technique, it is assumed that all quaternions have a unitary length, meaning they have a magnitude of 1. Therefore, they are referred to as unit quaternions. The complex conjugate of a quaternion is defined in the same way as complex numbers. The sign of the imaginary portion is reversed, as seen in Eq. (5). The inverse of a quaternion is described in Eq. (6) as the reciprocal of a complex number. Furthermore, if the quaternion has a single length, its inverse is equivalent to its conjugate.

$$\mathrm{Norm}(\mathbf{q}) = \sqrt{q_0^2 + q_1^2 + q_2^2 + q_3^2} \tag{4}$$

$$\mathrm{Conj}(\mathbf{q}) = q* = [q_0 \; -q_1 \quad -q_2 \quad -q_3]^T \tag{5}$$

$$\mathrm{Inv}(\mathbf{q}) = q^{-1} = \frac{q^*}{\|q\|^2} \tag{6}$$

The quaternion's derivative necessitates algebraic manipulation and may be expressed as follows: a) Eq. (7) when the angular velocity vector is in the fixed frame of reference, and b) Eq. (8) when the angular velocity vector is in the body frame of reference. It is crucial to acknowledge that these notations have been given in relation to the left-hand notation. To obtain them in the right-hand notation, the ω quaternion must be conjugated.

$$\dot{q}_\omega(q,\omega) = \frac{1}{2}q\otimes\begin{bmatrix}0\\ \omega\end{bmatrix} \tag{7}$$

$$\dot{q}_\omega(q,\omega) = \frac{1}{2}q\otimes\begin{bmatrix}0\\ \omega\end{bmatrix} \tag{8}$$

A quaternion can function as a rotation operator if it is a unit quaternion. However, the transformation is not achieved by a single quaternion multiplication, but rather through two: the normal quaternion and its conjugate. This is seen in Eq. (9). This function performs a rotation of the vector **v** from the fixed frame to the body frame, which is represented by **q**.

$$\boldsymbol{w} = \boldsymbol{q}\otimes\begin{bmatrix}0\\ \boldsymbol{v}\end{bmatrix}\otimes\boldsymbol{q}^* \tag{9}$$

The rotation described in equation (10) may be expressed by substituting **v** with the *x*, *y*, and *z* axes, as shown in the subsequent Eq. (10).

$$^{XYZ}_{b}R = \begin{bmatrix} 2q_1^2 + 2q_2^2 - 1 & 2(q_1q_4 + q_2q_3) & 2(q_2q_4 - q_1q_3) \\ 2(q_2q_3 - q_1q_4) & 2q_1^2 + 2q_2^2 - 1 & 2(q_1q_2 + q_3q_4) \\ 2(q_1q_3 + q_2q_4) & 2(q_3q_4 - q_1q_2) & 2q_1^2 + 2q_2^4 - 1 \end{bmatrix} \tag{10}$$

Finally, to describe quaternion rotations in a more intelligible way, the conversion from Euler angles to quaternions and from quaternions to Euler angles may be achieved using the following two equations, respectively. This trait is highly advantageous when the objective is to depict an orientation in angles as Eq. (11) while preserving the overall dynamics of the system in quaternion form.

$$\begin{bmatrix}\Psi\\ \theta\\ \Phi\end{bmatrix} = \begin{bmatrix} \mathrm{atan}(2q_2q_3 - 2q_1q_4, 2q_1^2 + 2q_2^2 - 1) \\ \arcsin(q_2q_3 - q_1q_4) \\ \mathrm{atan}(\,2q_3q_4 - 2q_1q_2\,, 2q_1^2 + 2q_2^4 - 1) \end{bmatrix} \tag{11}$$

To model the attitude dynamics of the quadrotor shown in Fig. 1, several assumptions have been made. These include assuming that the quadrotor's structure is rigid and

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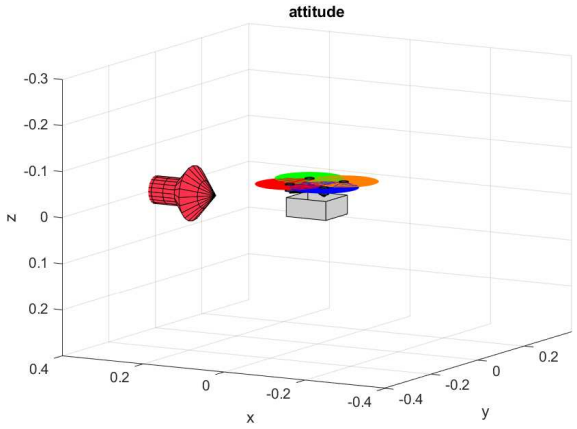

Fig.1 3D simulation view for Quadrotors

symmetrical, the center of gravity and the origin of the body fixed frame are the same, the propellers are rigid, the bias throttle to counteract gravity can be ignored, and only the differential forces generated by the propellers affect rotation.

There are two possible approaches for modeling the physics of the quadrotor. The first approach involves deriving the full physical model using Newton's laws of motion, which results in a model that depends on the frame of reference. The second approach involves using the Euler-Newton equations to describe the translational and rotational dynamics of a rigid body, as shown in Eq. (12-13). Using the second technique significantly simplifies the process of deriving the model, as the only unknown in the produced model is the relationship between the control signal and the related torque.

$$w = [0\ \omega_X\ \omega_Y\ \omega_Z] \tag{12}$$

$$\begin{bmatrix} F \\ \tau \end{bmatrix} = \begin{bmatrix} m & 0 \\ 0 & I_{cm} \end{bmatrix} \begin{bmatrix} a_{cm} \\ \dot{\omega} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \times (I_{cm}.\omega) \end{bmatrix} \tag{13}$$

To obtain the complete dynamics of the quadrotor's rigid body rotations, the quaternion derivative from Eq. (8) should be combined with the rotation dynamics from Eq. (13). This combination results in an equation system that describes the entire rotation dynamics of the quadrotor in quaternion form, as shown in Eq. (14-15).

$$\dot{q} = -\frac{1}{2}\begin{bmatrix} 0 \\ \omega \end{bmatrix} \otimes q \tag{14}$$

$$\dot{\omega} = i_{cm}^{-1}.\tau - I_{cm}^{-1}[\omega \times (I_{cm}.\omega)] \tag{15}$$

Several linear and non-linear system approximations have been suggested for modeling the relationship between the control signal and torque. In the proposed method, the relationship has been reduced to an identity matrix [10]. A more comprehensive analysis, considering the physics underlying rotor dynamics, may be conducted without compromising the effectiveness of the proposed technique. The conclusions acquired in this section may be readily applied to describe the attitude dynamics of UAV frames other than the Quadrotor, provided that the connection between the control signal and torque can be determined.

III. METHODOLOGY

Integrating the characteristics of the DJI Tello micro-UAV into a MATLAB Simulink model is essential for conducting accurate control system studies. The DJI Tello's small dimensions 7.9 x 7.7 x 2.1" or 201.5 x 195.0 x 53.0 *mm* and ability to be programmed for indoor flying make it a perfect option for doing such research. The MATLAB Simulink model includes precise representations of the quadcopter's dynamics, such as the dynamics of the propellers and motors [2], the aerodynamics of the fuselage, and the formulation of 12 ordinary differential equations that regulate the dynamics of the system. The MATLAB Simulink model accurately represents the UAV's dynamics, including propeller, motor, and aerodynamics, using detailed differential equations. Empirical validation with real-world data confirms the model's reliability, as supported by studies like [16] which stress the importance of empirical data for validating UAV control models.

TABLE 1 PARAMETERS OF THE DJI TELLO QUADROTOR [12][13][14][15] .

Parameters	Description	Value	Unit
m	Mass of the UAV	0.08	kg
A	Dimensions	0.098x0.0925x0.041	m^3
l	Distance between the rotor axis and the center of the UAV mass	0.06	m
I_{xx}	Inertia about X axis	0.679e−2	kgm^2
I_{yy}	Inertia about Y axis	0.679e−2	kgm^2
I_{zz}	Inertia about Z axis	1.313e−2	kgm^2
I_R	The moment of inertia of each motor	4.95e−5	kgm^2
b	Trust constant	0.566e−5	$Kgm/(rad)^2$
d	Drag factor	0.762e−7	$kgm2/(rad)^2$
Pl	Propeller length	0.0254	m
k_1, k_2, k_3	Translation drags coefficients	3.365e−2	kg/s
K_4, k_5, k_6	Aerodynamic friction coefficient	4.609e−3	kgm^2/rad
T_m	Motor response time constant	0.0163	s

The DJI Tello micro-UAV, with its small size and programmability, is well-suited for indoor experiments. Literature [17] indicates that micro-UAVs like the Tello are ideal for indoor flight research due to their maneuverability in confined spaces and reduced sensitivity to external disturbances, making them perfect for studying control algorithms and system responses. The perspective of the quadcopter is shown in Fig. 1 once the MATLAB Simulink block has been updated by the table data. The initial speed and location of the drone are shown as [0.1 0 0] ms^{-1} and [1 1 5] *m*, respectively. These parameters are justified based on several key considerations supported by the literature.

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According to study [18], starting with a low initial [0.1 0 0] ms^{-1} speed is beneficial for stabilizing the control algorithms and allows for the accurate characterization of the system's response to control inputs, particularly in indoor environments where space is limited, and precise control is required. The DJI Tello UAV is initially positioned at [1 1 -5] *m* in a controlled indoor environment to minimize external disturbances like wind and temperature variations. This controlled setting is ideal for the Tello, as it allows for more consistent and repeatable experiments, supporting the findings of [19] on the importance of such environments for validating UAV models and control systems.

This article will analyze the rotation of yaw, pitch, and roll angles at [30 30 30] degrees around a specified angle. In order to manage the altitude, a PID controller utilizes its gain to adjust the propeller thrust by comparing the desired height with the current altitude. An attitude controller is created by combining a PI controller with quaternion feedback and feedback of body angular velocity at the same time. This controller ensures a consistent orientation. The outputs from both controllers are combined and sent to the motor torque control system, which modifies the force and direction to achieve precise and regulated flight.

IV. Result and Discussion

The 3D path view, top view, and longitudinal view as Fig. 2 are crucial for quadcopter quaternion analysis because they graphically depict the quadcopter's movement and orientation in three-dimensional space. These visual perspectives, represented as figures, enable the quadcopter to see and analyze its flying behavior, including trajectory, orientation changes, and overall performance. Through the comparison of simulated animation views with real-world observations, one may validate the precision of simulation models and detect any inconsistencies that may need modifications. Furthermore, animation views assist in assessing the efficiency of control algorithms developed to stabilize and manage the motion of the quadcopter.

The quadcopter's speed relative to the Earth's surface is highly dependent on the absolute velocity, making it a crucial factor in the quadcopter's operation within the Earth frame. This information is crucial for navigation and positioning systems, enabling the quadcopter to accurately determine its location in reference to stationary landmarks on the Earth's surface. Precision is crucial for operations like autonomous flying, waypoint navigation, and precise location in areas where GPS signals are unavailable. Moreover, the absolute velocity of the quadcopter plays a vital role in trajectory planning as it provides essential information about the quadcopter's speed and direction of motion in relation to the Earth, as shown in Fig. 3. This information helps in efficiently planning the course, avoiding obstacles, and executing a smooth trajectory. In addition, having knowledge of the quadcopter's absolute velocity allows the flight controller to effectively maintain stability and control by constantly modifying the propulsion and orientation to offset any external disturbances. This guarantees seamless and steady flight operations, even in demanding circumstances.

The velocity measured in the body frame as Fig. 4 is a crucial factor for quadcopters, significantly impacting their stability, control, and ability to perform maneuvers. The velocity information, with respect to the quadcopter's internal axes, is crucial for the flight controller to manage motor speeds and rotor orientations, enabling the quadcopter to achieve the necessary translational and rotational motion. The flight controller can achieve steady flying and perform exact maneuvers by altering the quadcopter's attitude and orientation along each axis. This feature boosts the quadcopter's dexterity and promptness, allowing it to quickly alter its course, velocity, and elevation to execute complex

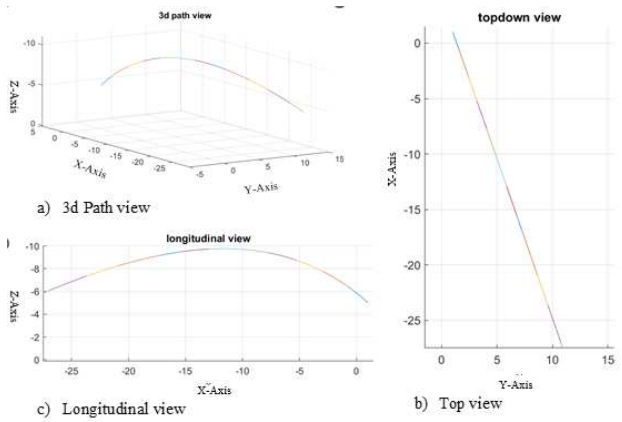

Fig. 2 a) Path view; b) Top view; and c) Longitudinal view for rotations about yaw, pitch, and row angles.

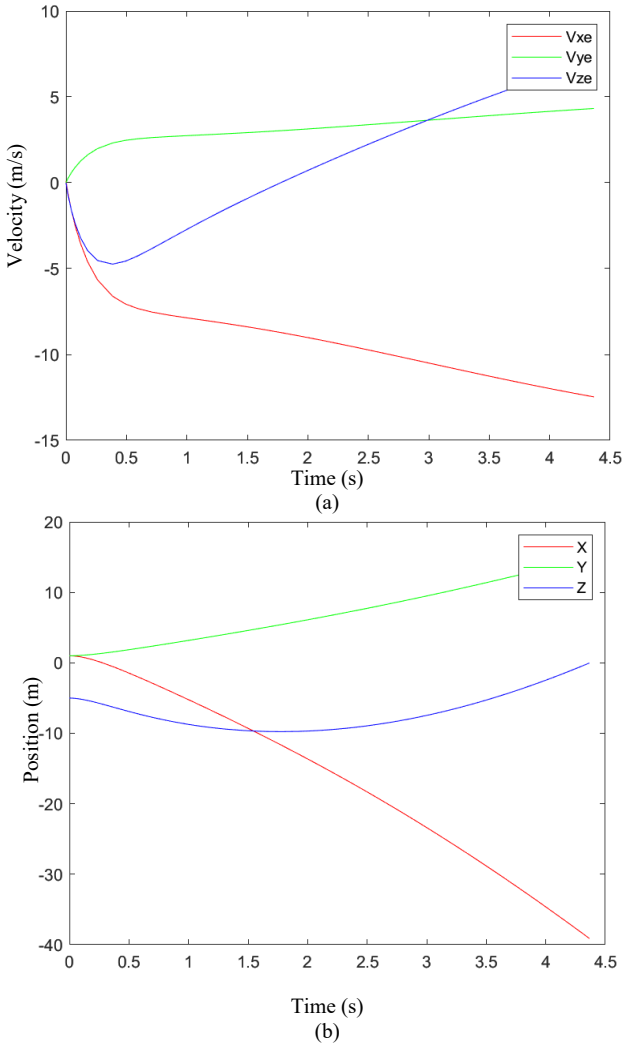

Fig. 3. a) absolute velocity of quadcopter, b) position in the earth frame for the quadcopter with desired rotation.

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maneuvers such as flips, rolls, and spins. Furthermore, the velocity data in the body frame is essential for the implementation of collision avoidance algorithms, enabling the quadcopter to promptly detect and avoid obstacles in real-time. The flight controller can predict possible collisions and modify the quadcopter's path by examining velocity vectors in relation to its axes.

The PID and PI controllers' gains are chosen based on a combination of theoretical analysis and empirical tuning. The PID controller for altitude control is tuned to achieve minimal overshoot and a short settling time, ensuring stable altitude maintenance. Quantitative data shows a settling time of approximately 5 seconds and an overshot of less than 5%, indicating efficient and responsive altitude control.

V. Conclusion

Unmanned Aerial Vehicles (UAVs) are increasingly used in surveillance, mapping, and autonomous navigation. The Omnidirectional Stationary Flying Outstretched Drone advances UAV technology by using quaternions for orientation, avoiding issues like singularities and gimbal lock, and supporting precise control algorithms. The enhanced quadrotor model with aerodynamic effects and advanced control methods shows improved performance, though there is potential for further development. Future research should focus on advanced control algorithms and sensor fusion techniques. Model Predictive Control (MPC) offers real-time optimization for dynamic environments, while adaptive control adjusts to changing conditions for better stability. Nonlinear control methods, such as Sliding Mode Control, can handle complex dynamics and improve resilience. Sensor fusion is also crucial. Techniques like Kalman Filters and Particle Filters provide accurate state estimates by integrating multiple sensor inputs, even in challenging environments. Visual-Inertial Odometry (VIO) and LIDAR-based SLAM are promising for indoor navigation and mapping unknown environments. Overall, integrating sophisticated control algorithms and advanced sensor fusion techniques can further enhance UAV performance, stability, and autonomy, expanding their application across diverse missions and environments.

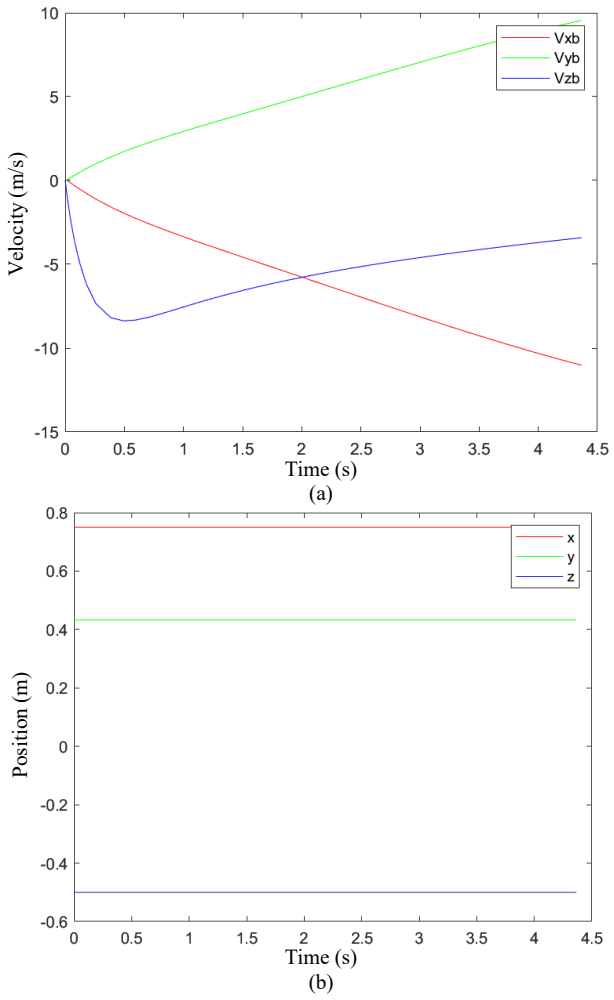

Fig. 4. a) Body frame velocity, b) Position in body frame for quadcopter

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