Modeling of a dual-axis tilt-rotor mechanism for a high-performance quadrotor

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Abstract

Purpose – This study aims to investigate the flight stability, control robustness and trajectory tracking performance of a quadrotor unmanned aerial vehicle (UAV) equipped with a dual-axis tilt-rotor mechanism, and compares its performance against conventional quadrotor designs.

Design/methodology/approach – A Newton–Euler approach is used to derive the full dynamic model of the tilt-rotor UAV (TRUAV). The prototype was manufactured using three-dimensional printing and computer numerical control (CNC) machining. A custom three-axis force and torque measurement device was designed and built for experimental characterization. The performance outcome was evaluated through MATLAB/Simulink simulations of 25 m square trajectory tracking and validated against experimental results.

Findings – The TRUAV demonstrated improved flight stability and control robustness compared to conventional quadrotors. In 25 m square trajectory tracking, the TRUAV completed the course in 10.6 s versus 17.15 s for the conventional quadrotor, representing approximately a 39.2% reduction in trajectory completion time. Rotor tilting produced approximately 5.6 times greater thrust and 3.22 times greater torque. Simulation and experimental results showed a close agreement, validating the proposed dynamic model.

Originality/value – This study presents a novel dual-axis tilt-rotor mechanism enabling independent pitch and roll tilting of each rotor, with the rotation center fixed at the propeller center for enhanced flight stability. To the best of the authors' knowledge, unlike prior work, this study provides explicit quantitative experimental benchmarking of a dual-axis TRUAV against a conventional quadrotor in terms of speed, trajectory tracking, thrust force and torque performance.

Keywords UAV, Quadrotor, Flight control, Conceptual design

Paper type Research paper

Introduction

In recent years, multi-rotor unmanned aerial vehicles (UAVs) have attracted extensive research attention due to their versatility and broad applicability across scientific and industrial domains. Among these endeavors, tilt-rotor platforms have gained particular interest because of their enhanced degrees of freedom, improved thrust vectoring capability, superior maneuverability and potential energy efficiency. Tilt-rotor mechanisms have been integrated into a wide variety of UAV configurations, including hybrid vertical take-off and landing (VTOL) aircraft combining fixed-wing and multirotor capabilities, tilting-rotor quadrotors and dual-fan UAV platforms (Notarstefano and Hauser, 2010; Bauersfeld and Ducard, 2020; Senkul and Altug, 2014; Amiri *et al.*, 2011). In some applications, the rotor tilts as part of the wing structure (Oner *et al.*, 2008), whereas in others, the rotors operate independently of the wing structure (Di Francesco *et al.*, 2015). Another notable configuration is the tail-sitter concept (Hochstenbach *et al.*, 2015), in which the aircraft transitions from a vertical orientation to horizontal forward flight. For the tilt-rotor platforms incorporating fixed wings, aerodynamic lift generated by the wings significantly improves power efficiency and flight endurance.

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However, the true capability of the tilting mechanism emerges through synchronized operation during flight. By appropriately positioning the rotors in the desired direction of motion, UAVs can achieve greater degrees of freedom, improved maneuverability and enhanced speed capabilities (Amiri *et al.*, 2011; Chipade *et al.*, 2018). Several studies have demonstrated superior performance in horizontal translation, large attitude changes and aggressive maneuvering compared to conventional quadrotors (Badr *et al.*, 2016; Oosedo *et al.*, 2016; Kumar *et al.*, 2017b).

Despite these advantages, the integration of tilting mechanisms introduces substantial technical challenges. Rotor tilting can compromise flight stability (Barkai *et al.*, 1998; Kumar *et al.*, 2017a). To address this challenge, various approaches have been proposed, including the use of active balance tails to enhance hover stability and flight smoothness in tilting-rotor UAVs (Xu *et al.*, 2024). Additionally, tilting mechanisms require more complex and computationally intensive dynamic models and advanced control strategies (Ryll *et al.*, 2012), and introduce mechanical alignment and assembly uncertainties (Invernizzi *et al.*, 2021). These challenges have hindered the practical implementation and performance optimization of tilt-rotor unmanned aerial vehicle (TRUAV) systems.

Most prior TRUAV studies have focused on single-axis rotor tilting mechanisms aimed primarily at expanding the vehicle's degrees of freedom. Although several studies have explored

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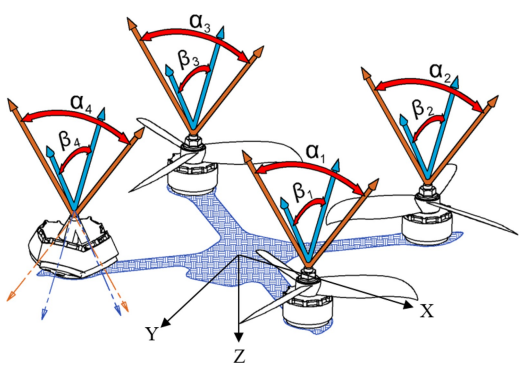
dual-axis tilt configurations (Elkhatib, 2017; Gasco, 2012; Bin Junaid *et al.*, 2018; Moutinho *et al.*, 2015), these efforts have predominantly concentrated on enhancing stability or increasing maneuverability, while comprehensive experimental evaluation of speed, acceleration and real-world flight performance remains limited. In particular, quantitative performance comparisons between dual-axis TRUAV and conventional quadrotors are still insufficiently addressed in the literature, leaving a critical gap in understanding the true operational benefits of such systems.

In contrast to the existing literature, this study investigates the flight performance of a quadrotor equipped with a dual-axis tilt-rotor mechanism, with a specific focus on speed and acceleration capabilities. Unlike prior dual-axis tilt-rotor designs, the proposed rotor configuration enables independent pitch and roll tilting, thereby enhancing dynamic responsiveness and improving translational acceleration along these axes. Furthermore, the propeller-centered rotation design preserves the inter-rotor geometry during tilting, ensuring consistent flight control parameters. This enhances flight stability without introducing additional mechanical complexity. In addition, a simplified and computationally efficient dynamic model of the proposed UAV is derived with the Newton–Euler approach, facilitating both real-time control implementation and analytical tractability. The flight performance of the proposed TRUAV is experimentally evaluated and explicitly benchmarked against a conventional quadrotor platform, providing quantitative evidence of performance improvements and offering new insights into the operational advantages of dual-axis TRUAV architectures.

Tilt-rotor system modeling and dynamic models

Figure 1 shows the basic model of the TRUAV investigated in this study. Servo motors mounted under each rotor enable all rotors to be independently tilted to different α angles. Roll and yaw manoeuvres are achieved through this α configuration. This tilting motion is facilitated by the drive gear placed on the servo motor and the counter gear, with limits restricted to $\pm 20^{\circ}$, and the center of rotation set at the propeller center (Point A). This propeller-centered rotation design ensures more stable flight by maintaining the inter-rotor distance. It also ensures that flight control parameters that depend on the quadrotor geometry remain consistent. Roll movement is achieved by tilting all rotors to the same α angle, whereas for yaw movement, opposite α angles are applied to the front and rear rotors. The rotors are also independently actuated about the β axis. The β tilting range is limited to $\pm 30^{\circ}$ and aims to enhance the quadrotor's performance during pitch motion.

Figure 1 Basic model of the TRUAV



Dynamic modeling of rigid bodies with six degrees of freedom commonly uses Newton's second law. To use this law, the forces and moments acting on the body must be analyzed. This necessitates determining the orientation of the model using Euler angles and analyzing the electromechanical components of the quadrotor. Thus, the force components F_x, F_y and F_z and moment components M_x, M_y and M_z are obtained to create the dynamic model of the UAV.

In three-dimensional (3D) space, the complete orientation of a body cannot be represented by a single angle. Therefore, it is necessary to relate the angular position and angular velocity of the body with respect to a reference coordinate system. Euler angles are used for this purpose. 3D rotation of a vehicle can be represented by a rotation matrix with Euler angles (ϕ, θ and ψ). The quadrotor's angles of rotation are referred to as pitch, roll and yaw with respect to rotations about the x, y and z axes, respectively. The Euler angle transformation matrix that relates the body frame to the world frame is given as follows:

$$R_n^b = \begin{bmatrix} c\psi c\theta & c\psi s\theta s\phi - s\psi c\phi & c\psi s\theta c\phi + s\psi s\phi \\ s\psi c\theta & s\psi s\theta s\phi + c\psi c\phi & s\psi s\theta c\phi - c\psi s\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \quad (1)$$

where $c = \cos$, $s = \sin$, $b =$ body frame and $n =$ world frame.

In a conventional quadrotor, the rotor thrust force vectors on the body frame are always in the Z-direction, and force components in the reference coordinate system are obtained by multiplying the rotation matrix with the rotor force vector. However, unlike a conventional quadrotor, in a TRUAV, because the rotors are tilted, there will be force components in the x, y and z directions on the body frame. The force components shown in Figure 2 for the TRUAV are different for each rotor.

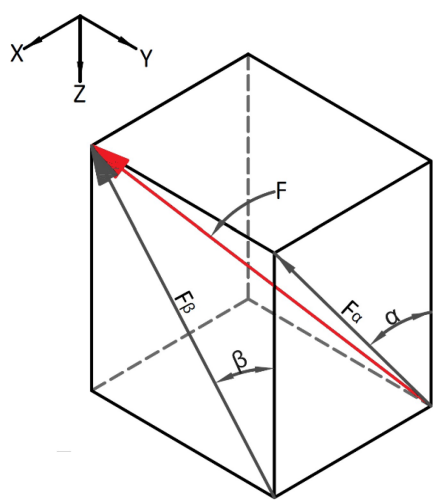
where:

F = thrust force vector due to rotor rotation;

F_β = projected force vector due to β angle of F force; and

F_α = projected force vector due to α angle of F force.

Figure 2 Force components for angled rotors



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The force components are obtained using the position and configurations of the thrust force vector in a unit Cartesian coordinate system, following the equations:

$$F_{\beta_i} = \frac{F_i}{\sqrt{c^2\beta_i t^2\alpha_i + 1}} \tag{2}$$

$$Fx_{\underrightarrow{i}_i} = F_{\beta_i} c\beta_i t\alpha_i \tag{3}$$

$$Fy_{\underrightarrow{j}_i} = F_{\beta_i} s\beta_i \tag{4}$$

$$Fz_{\underrightarrow{k}_i} = F_{\beta_i} c\beta_i \tag{5}$$

where i = rotor number and t = tan.

The component equations for the resultant vector obtained from the rotors are organized in matrix format and presented in equation (6):

$$F_{r_i} = \begin{bmatrix} F_{\beta_i} c\beta_i t\alpha_i \\ -F_{\beta_i} s\beta_i \\ F_{\beta_i} c\beta_i \end{bmatrix} \tag{6}$$

The resultant force acting on the TRUAV is obtained by summing the effects of gravity and the thrust forces from the rotors. The gravitational force acts along the negative z-axis in the reference coordinate system and equals mass multiplied by the gravitational acceleration. The components of the thrust force from the rotors in the reference coordinate system are obtained by multiplying them with the rotor force component matrix using Euler angles. By adding these two forces, the net force for one rotor is as given in equation (8):

$$\sum \overrightarrow{F}^n = \begin{bmatrix} 0 \\ 0 \\ mg/4 \end{bmatrix} + \begin{bmatrix} c\psi c\theta & c\psi s\theta s\phi - s\psi c\phi & c\psi s\theta c\phi + s\psi s\phi \\ s\psi c\theta & s\psi s\theta s\phi + c\psi c\phi & s\psi s\theta c\phi - c\psi s\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \times \begin{bmatrix} F_{\beta_i} c\beta_i t\alpha_i \\ -F_{\beta_i} s\beta_i \\ F_{\beta_i} c\beta_i \end{bmatrix} \tag{7}$$

$$= \begin{bmatrix} F_{\beta_i} c\beta_i t\alpha_i c\psi c\theta - F_{\beta_i} s\beta_i (c\psi s\theta s\phi - s\psi c\phi) + F_{\beta_i} c\beta_i (c\psi s\theta c\phi + s\psi s\phi) \\ F_{\beta_i} c\beta_i t\alpha_i s\psi c\theta - F_{\beta_i} s\beta_i (s\psi s\theta s\phi + c\psi c\phi) + F_{\beta_i} c\beta_i (s\psi s\theta c\phi - c\psi s\phi) \\ mg/4 - F_{\beta_i} c\beta_i t\alpha_i s\theta - F_{\beta_i} s\beta_i c\theta s\phi + F_{\beta_i} c\beta_i c\theta c\phi \end{bmatrix} \tag{8}$$

Since equation (8) is applied to all four rotors, the gravitational force mg is divided by four, and after the summation of equations, the net gravitational force is obtained. The linear acceleration equation continues with the application of Newton's second law as follows:

$$\begin{bmatrix} \ddot{X} \\ \ddot{Y} \\ \ddot{Z} \end{bmatrix} = \frac{1}{m} \sum \overrightarrow{F}^n \tag{9}$$

For a conventional quadrotor, the yaw moment is solely dependent on rotor speeds and occurs along the z-axis. In a TRUAV, the yaw moment depends on both rotor speeds and α angles, and torque can occur in the x, y and z directions. The torque originating from the rotation of the rotors for a single rotor is provided in equation (10). The torque components were obtained from the cross product of the rotor thrust force unit vector and the moment arm:

$$\overrightarrow{M}_{rot_i} = \left[k\Omega_i^2\right] \times \begin{bmatrix} \left(\frac{F_{\beta_i} c\beta_i t\alpha_i}{F_i}\right) \\ \left(\frac{F_{\beta_i} s\beta_i}{F_i}\right) \\ \left(\frac{F_{\beta_i} c\beta_i}{F_i}\right) \end{bmatrix} \tag{10}$$

When considering the direction of rotation of the rotors, the total rotor-induced torque is given in equation (11):

$$\sum \overrightarrow{M}_{rot} = \begin{bmatrix} k\left(\Omega_1^2 \frac{F_{\beta_1} c\beta_1 t\alpha_1}{F_1} - \Omega_2^2 \frac{F_{\beta_2} c\beta_2 t\alpha_2}{F_2} + \Omega_3^2 \frac{F_{\beta_3} c\beta_3 t\alpha_3}{F_3} - \Omega_4^2 \frac{F_{\beta_4} c\beta_4 t\alpha_4}{F_4}\right) \\ k\left(\Omega_1^2 \frac{F_{\beta_1} s\beta_1}{F_1} - \Omega_2^2 \frac{F_{\beta_2} s\beta_2}{F_2} + \Omega_3^2 \frac{F_{\beta_3} s\beta_3}{F_3} - \Omega_4^2 \frac{F_{\beta_4} s\beta_4}{F_4}\right) \\ k\left(\Omega_1^2 \frac{F_{\beta_1} c\beta_1}{F_1} - \Omega_2^2 \frac{F_{\beta_2} c\beta_2}{F_2} + \Omega_3^2 \frac{F_{\beta_3} c\beta_3}{F_3} - \Omega_4^2 \frac{F_{\beta_4} c\beta_4}{F_4}\right) \end{bmatrix} \tag{11}$$

As a result of rotor tilting, additional force components arise in the x, y and z directions, which will produce moments. The resulting torque, obtained by multiplying these force components with appropriate lever arms, is as follows:

$$\sum \overrightarrow{M}_{mkol} = \begin{bmatrix} bl_y(Fz_i) \\ bl_x(Fz_i) \\ bl_x(Fx_i) \end{bmatrix} \tag{12}$$

$$\sum \overrightarrow{M}_{mkol} = \begin{bmatrix} bl_y\left(\Omega_1^2 F_{\beta_1} c\beta_1 - \Omega_2^2 F_{\beta_2} c\beta_2 - \Omega_3^2 . F_{\beta_3} c\beta_3 + \Omega_4^2 F_{\beta_4} c\beta_4\right) \\ bl_x\left(-\Omega_1^2 F_{\beta_1} c\beta_1 - \Omega_2^2 F_{\beta_2} c\beta_2 + \Omega_3^2 . F_{\beta_3} c\beta_3 + \Omega_4^2 F_{\beta_4} c\beta_4\right) \\ bl_x\left(\Omega_1^2 F_{\beta_1} c\beta_1 t\alpha_1 - \Omega_2^2 F_{\beta_2} c\beta_2 t\alpha_2 + \Omega_3^2 F_{\beta_3} c\beta_3 t\alpha_3 - \Omega_4^2 F_{\beta_4} c\beta_4 t\alpha_4\right) \end{bmatrix} \tag{13}$$

The angular motion of the TRUAV is obtained by the sum of these two moments:

$$\sum \overrightarrow{M} = \sum \overrightarrow{M}_{rot} + \sum \overrightarrow{M}_{mkol} \tag{14}$$

According to the rigid body rotational law:

$$\overrightarrow{M}^b = I\dot{\overrightarrow{\omega}} + \overrightarrow{\omega} \times (I\overrightarrow{\omega}) \tag{15}$$

$$\begin{bmatrix} \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix} + \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \times \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \tag{16}$$

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By rearranging equation (16), the angular accelerations are obtained as follows:

$$\ddot{\phi} = \frac{\tau_\phi}{I_{xx}} + \dot{\theta}\dot{\psi}\left(\frac{I_{yy-}\ I_{zz}}{I_{xx}}\right) \tag{17}$$

$$\ddot{\theta} = \frac{\tau_\theta}{I_{yy}} + \dot{\phi}\dot{\psi}\left(\frac{I_{zz-}\ I_{xx}}{I_{yy}}\right) \tag{18}$$

$$\ddot{\psi} = \frac{\tau_\psi}{I_{zz}} + \dot{\phi}\dot{\theta}\left(\frac{I_{xx-}\ I_{yy}}{I_{zz}}\right) \tag{19}$$

Materials and methods

Controller system

The control of the TRUAV differs from the control of the conventional quadrotor. In this paper, the control algorithm is designed such that all servo motors can operate independently and each servo motor angle is controlled by the Adafruit HUZZAH32 development board. The motor tilt angles are governed by the pitch, roll and yaw pulse-width modulation (PWM) signal levels received from the flight controller. Proportional-integral-derivative (PID) control is chosen for the control and simulation of both the TRUAV and the conventional quadrotor. Automated PID gain selection using MATLAB/Simulink's (R2018b) Control System Toolbox was initially attempted. However, nonlinear and coupled dynamics of both platforms, particularly in the TRUAV, where control effectiveness changes continuously with rotor tilt angle, made this approach unsuitable. Consequently, the gains were tuned iteratively for each controlled axis. Initial values were selected based on the desired response speed of each axis and then refined step by step until the platform produced consistent and similar dynamic responses to pitch, roll and yaw manoeuvres, including comparable settling times and acceptable overshoot across all axes. The lateral position (X, Y) gains were iteratively adjusted until both the conventional quadrotor and the TRUAV exhibited equal lateral deviations, ensuring a fair and consistent performance comparison between the two platforms. The altitude (Z) gains were iteratively adjusted until the initial altitude deviation at takeoff was minimized to an acceptable level for both platforms. The TRUAV and conventional quadrotor use separate gain sets reflecting their distinct dynamic characteristics; the final gain values are summarized in Table 1.

Rotor/propeller thrust forces

The thrust force and moment equations for the rotor/propeller pair have been experimentally determined and are presented below:

$$\boldsymbol{F_i} = 2.526\ 10^{-1} - 5.529909\ 10^{-5}\Omega + 1.778857\ 10^{-8}\Omega^2 \tag{20}$$

Table 1 PID gain values for the conventional quadrotor and TRUAV

		Yaw		Altitude (Z)		Lateral (X,Y)	
Gain	Pitch/roll	Conv.	TRUAV	Conv.	TRUAV	Conv.	TRUAV
Kp	15	25	25	85	70	7	7
Ki	5	0	1	40	40	0	0
Kd	1	9.2	11.5	40	40	9.2	6.85

Note(s): *Conv. = conventional quadrotor

$$\boldsymbol{T_r} = -1.123\ 10^{-3} + 4.531858\ 10^{-7}\Omega + 1.22925\ 10^{-10}\Omega^2 + 1.3866723\ 10^{-15}\Omega^3 \tag{21}$$

Details related to these equations are provided in Bayraktar and Güldaş (2020), where information about the equipment used to obtain the experimental data is also given.

Dynamical characteristics of the tilt-rotor unmanned aerial vehicle

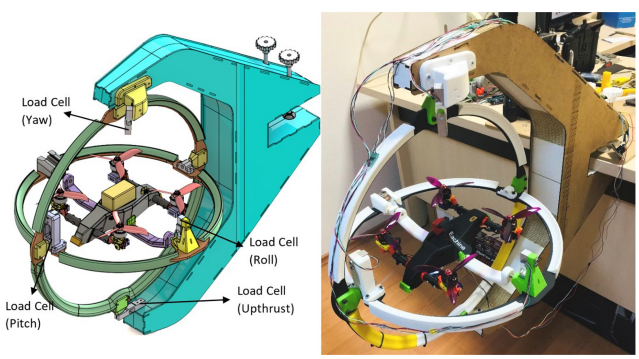
To determine the dynamic characteristics of the TRUAV, MATLAB/Simulink simulations and experimental measurements were conducted. In these studies, tilt angle limits of ±30° (β) for the pitch movement and ±20° (α) for the roll and yaw movements were implemented in the flight controller. Simulations and experiments were conducted within these angle limits. It should be noted that the total angular displacement of the rotors on the horizontal is the sum of the body attitude angle and the rotor tilt angle. Consequently, when the body pitch angle reaches 30° and the β tilt is simultaneously at its maximum of 30°, the rotors reach a combined horizontal displacement of 60°. Similarly, when the body roll angle is 30° and the α tilt is at its maximum of 20°, the total angular displacement reaches 50°.

The components comprising the body and the mechanism of the TRUAV were manufactured using the 3D printing method. To achieve tighter dimensional tolerances, finish milling was performed on a CNC vertical machining center. The inertia values and other parameters of the fabricated TRUAV are provided in Table 2. For the experimental performance test, a device incorporating three-axis force sensors and a z-axis torque sensor was designed and manufactured (Figure 3). The forces and torques generated during pitch, roll and yaw motions were measured using the UAV dynamic

Table 2 Physical and inertial parameters of the quadrotor

Description	Symbol	Value
Rotor-center of mass distance (*x*-axis)	l_x	0.085 m
Rotor-center of mass distance (*y*-axis)	l_y	0.0807 m
Quadrotor mass	M	0.574 kg
Moment of inertia about *x*-axis	I_{xx}	0.002312 kg m^2
Moment of inertia about *y*-axis	I_{yy}	0.001814 kg m^2
Moment of inertia about *z*-axis	I_{zz}	0.003787 kg m^2

Figure 3 Designed and manufactured TRUAV and UAV dynamic characterization device



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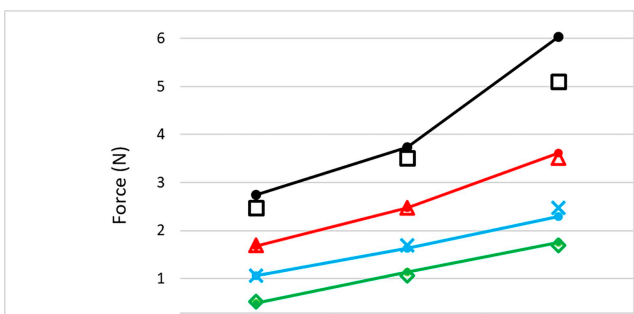
characterization device. Experiments were conducted with two types of quadrotors, one with rotor tilting and one without (conventional quadrotor). In the force measurement tests, the quadrotor's thrust force in the vertical (Z) direction was set to 2.942 N (300 g). The quadrotor's pitch angle was examined at 10°, 20° and 30°, with β rotor angle set at 10°, 20° and 30°. In the torque measurement tests, the α rotor angle was set to 10° and 20°, and the resulting torques were measured at each setting.

Experimental results

To analyze the force distribution of the TRUAV, geometric calculations were performed based on the rotor tilt angles. Figures 4 and 5 present both the analytically derived and experimentally measured force components and torque of the TRUAV with a total thrust of 2.942 N (300 g) along the z-axis. In the figures, the positions where β is 0° represent the conventional quadrotor model. In both figures, an increase in the tilt angle of the rotors results in increased thrust force and torque.

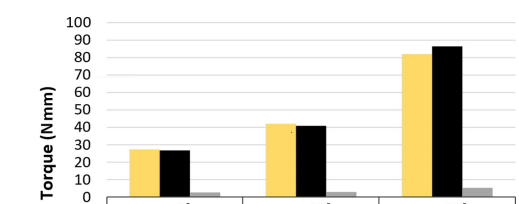
When the pitch angle was set at 10° and the β rotor tilt angle was at its maximum (30°), the TRUAV produced approximately 5.6 times greater thrust force than the conventional quadrotor. In contrast, at a body pitch angle of 30°, the same maximum β configuration yielded approximately 3.5 times greater thrust force compared to the conventional quadrotor. As shown in Figure 5, at zero tilt angle, the TRUAV produced a maximum torque of 26.76 N·mm. However, when the α rotor angle was 20°, this vehicle produced approximately 3.22 times greater torque, reaching 86.42 N·mm. These significant increases in terms of torque and thrust force highlight the advantages of the TRUAV. Additionally, the figures confirmed a close agreement between the calculated and measured values.

Figure 4 Thrust force values with respect to pitch angle (ϕ) at additional β rotor tilt angles



		φ= 10°	φ= 20°	φ= 30°
β= 0°	Calculated	0.519	1.071	1.699
	Measured	0.489	1.141	1.751
β=10°	Calculated	1.071	1.699	2.469
	Measured	1.062	1.638	2.296
β=20°	Calculated	1.699	2.469	3.506
	Measured	1.684	2.476	3.618
β=30°	Calculated	2.469	3.506	5.096
	Measured	2.748	3.740	6.038

Figure 5 Torque values at varying α rotor tilt angles

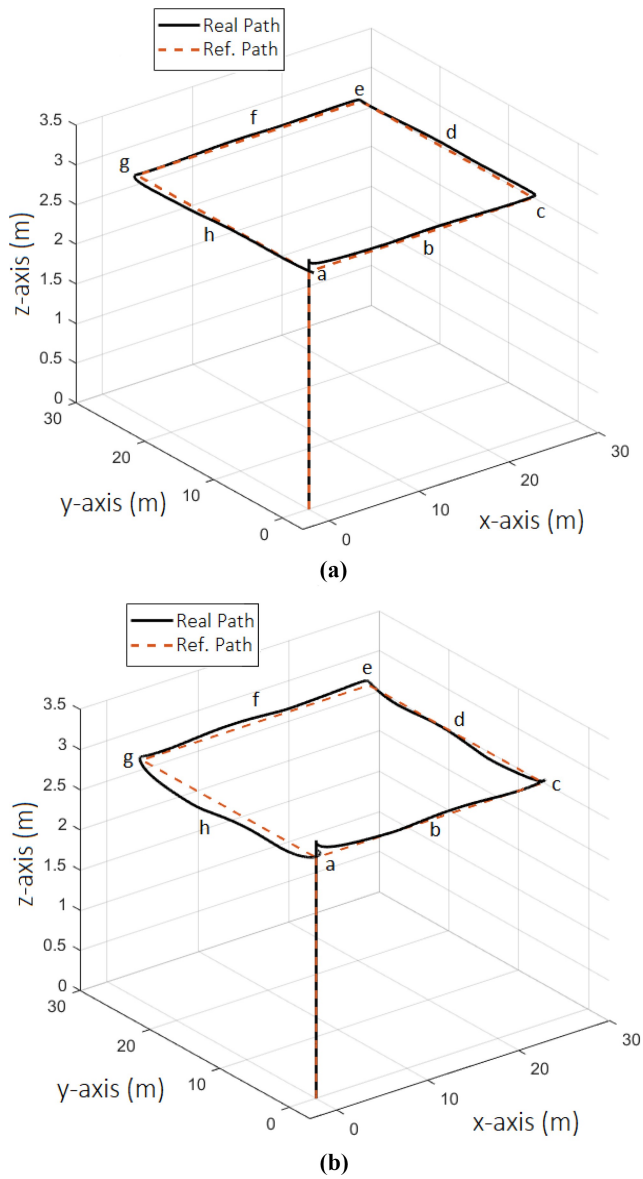


	α=0°	α=10°	α=20°
Calculated	27,43	41,86	82,06
Measured	26,76	40,67	86,41
Error%	2,5	2,92	5,3

Simulation results

To evaluate the performance differences between the tilted-quadrotor and the conventional quadrotor, a 25 m square trajectory tracking simulation was conducted. The trajectory completion time is an important performance metric of the quadrotor. Figure 6(a) shows the trajectory of the conventional

Figure 6 UAV square trajectory tracking simulations



Note(s): (a) Conventional quadrotor trajectory and (b) tilted-quadrotor trajectory

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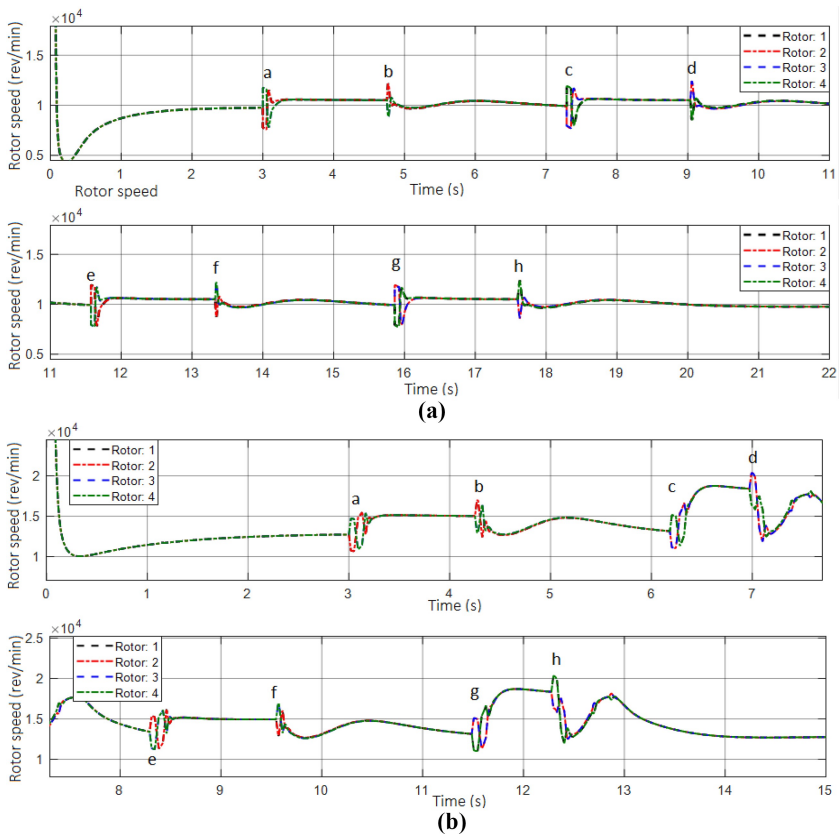
quadrotor (red dashed), while Figure 6(b) shows that of the TRUAV. When examining the figures, it is evident that the fixed-rotor quadrotor traces a trajectory closer to the reference path, while the tilted-quadrotor exhibits a larger deviation, especially in the z-axis direction. This occurs because of the instantaneous reduction in the z-axis thrust component caused by the change in rotor angles. Additionally, as the quadrotor reaches point "b" after ascending to point "a," the pitch angle becomes negative to initiate air braking. This behavior repeats in other segments of the trajectory. When the tilted-quadrotor transitions from a positive pitch angle to a negative pitch angle, there is a 120° change in rotor angles relative to the reference coordinate system. In contrast, for the fixed-rotor quadrotor, this change is only 60°. Consequently, this significant angle change causes the tilted-quadrotor to deviate more from the intended trajectory compared to the fixed-rotor quadrotor.

The graphs showing the rotor speeds of quadrotors during trajectory tracking are presented in Figure 7. The tilted-quadrotor demonstrates increased variability in rotor speeds after each change of direction to maintain its altitude and follow the trajectory. This rotor speed variability explains the increased trajectory deviation. Furthermore, due to the greater magnitude of these variations in the tilted quadrotor, the PID gains governing flight stability require more precise tuning.

This observation is supported by the existing literature. Govdeli *et al.* (2019) demonstrated that TRUAV configurations have one less control input compared to pusher configurations, making altitude control significantly more challenging. Consequently, the TRUAV must continuously adjust its rotor speeds to compensate for the reduced direct control authority. Park *et al.* (2026) also reported that tiltrotor platforms inherently come with increased control complexity, as the aerodynamic characteristics and control authority vary significantly in highly nonlinear and uncertain ways during flight mode transitions. Therefore, the increased rotor speed variability observed in the tilted-quadrotor is not a control artifact but a direct consequence of TRUAV dynamics, which inevitably leads to greater trajectory deviations and requires finer PID tuning. Furthermore, this continuous variation in control effectiveness also renders linearized gain-based control approaches inherently limited during aggressive tilting manoeuvres, as noted by Mancinelli *et al.* (2025), who showed that the control allocation problem for overactuated TRUAV systems cannot be adequately addressed using conventional algorithms relying on linearized control effectiveness simplification.

In the 25 m square trajectory tracking, the initial 3 s correspond to the takeoff phase in the simulation. This phase exhibits the same performance characteristics for both types of quadrotors. Excluding the takeoff phase, the tilted-quadrotor completed the 100 m total trajectory in 10.6 s, compared to 17.15 s for the conventional quadrotor. The tilted quadrotor completed the trajectory approximately 39.2% faster than the fixed-rotor quadrotor.

Figure 7 Rotor speeds during square trajectory tracking of quadrotors



Note(s): (a) Conventional quadrotor rotor speeds and (b) tilted-quadrotor rotor speeds

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In the square trajectory tracking, the conventional quadrotor reached a maximum speed of 10.05 m/s in both the x and y-axis directions (in Figure 8). In contrast, the tilted-quadrotor achieved a maximum speed of 14.5 m/s in the x-axis direction and 23.55 m/s in the y-axis direction. The higher y-axis speed is attributed to the 10° larger β angle in that axis.

In the tilted quadrotor, tilt motion is achieved through servo motors. The applied tilt motion is directed toward the target point, but as the quadrotor approaches the target, the tilt shifts in the opposite direction. This tilt reversal enables effective air braking. At approximately 6 s (in Figure 9), upon reaching the first target position, the servo motors tilt the rotors to 30° to initiate pitch motion. At approximately 7 s, as it approaches the second target position, the pitch angles are reversed to take advantage of the air braking capability. With its high air braking capability and dynamic motion capabilities provided by the servo motors, the tilted-quadrotor UAV completes the trajectory more quickly than the conventional quadrotor.

Conclusion

In this work, a dual-axis tilt-rotor quadrotor UAV was designed and manufactured, and its dynamic mathematical model was derived using the Newton–Euler formulation. Separate MATLAB/Simulink models were developed for both the TRUAV and conventional quadrotor platforms. Trajectory tracking and speed simulations were then conducted, and dedicated three-axis force and torque measurement setups were designed and built to validate the simulation results through experimental measurements.

The performance of the TRUAV and conventional quadrotor models in 25 m square trajectory tracking was evaluated to quantify their performance differences. According to the data obtained from this trajectory tracking:

- The increased variability in rotor speeds of the tilted-quadrotor indicates the need for more precise PID gain tuning to reduce trajectory deviations.

Figure 9 Servo motor angle responses of the TRUAV

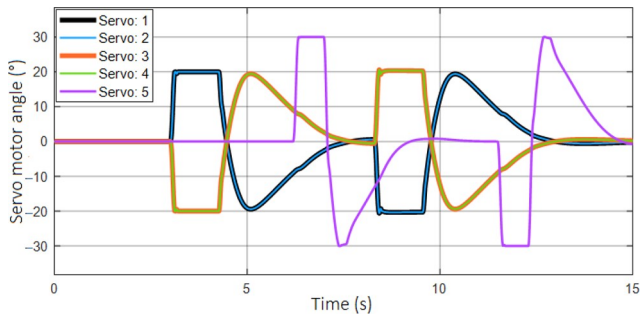
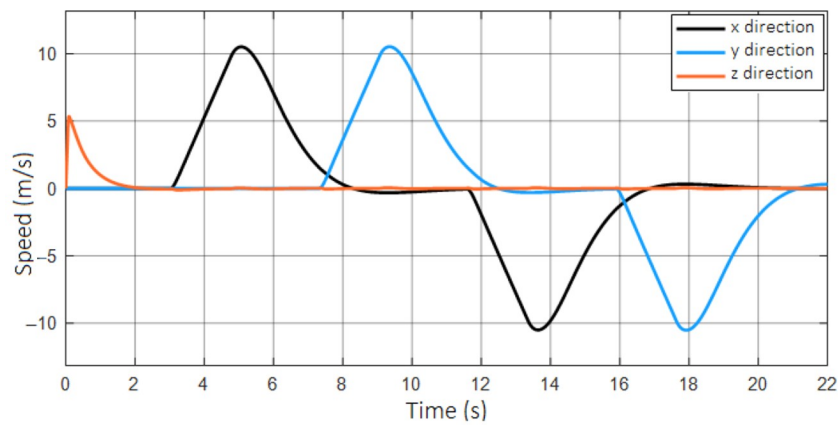
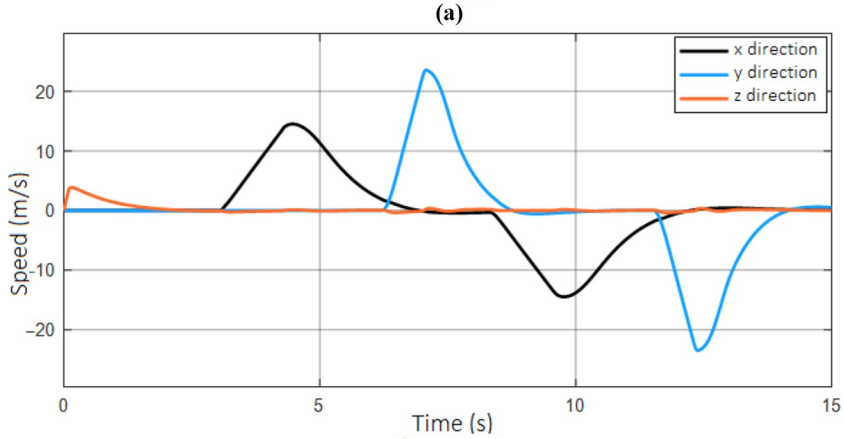


Figure 8 Speed of the conventional quadrotor and the tilted-quadrotor during square trajectory tracking



(a)



(b)

Note(s): (a) Conventional quadrotor's speed and (b) tilted-quadrotor's speed

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- Among the quadrotors covering a total distance of 100 m, the tilted-quadrotor completed the trajectory in the shortest time of 10.6 s. The conventional quadrotor, on the other hand, completed the trajectory in 17.15 s. The tilted-quadrotor completed the trajectory approximately 39.2% faster than the conventional quadrotor.
- The dynamic tilt and air braking capabilities of the tilted-quadrotor enable it to change direction in a shorter time.
- The experimental results further confirm the superior performance of the tilted-quadrotor. Significant increases in thrust force were recorded: approximately 5.6 times greater thrust at a 30° pitch angle, and 3.22 times greater torque at a 20° rotor tilt angle.

Future work could investigate the aerodynamic effects of yaw and roll motions on the drag characteristics of the tilted-quadrotor to further optimize its flight efficiency. In addition, alternative control strategies such as model predictive control or adaptive controllers could be explored to assess their suitability as replacements for the PID controller, particularly given the high angular variations that demand precise gain tuning in the current implementation. Furthermore, autonomous flight experiments could be conducted to experimentally compare the trajectory tracking performance of the fixed-rotor and tilt-rotor UAVs under real-world conditions.

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Further reading

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