Received: September 27, 2024 | Revised: November 11, 2024 | Accepted: November 15, 2024

JOURNAL OF APPLIED RESEARCH ON SCIENCE AND TECHNOLOGY
JARST
INSTITUTE OF RESEARCH AND DEVELOPMENT
RAJAMANGALA UNIVERSITY OF TECHNOLOGY THANYABURI
ISSN ONLINE: 2773-9473
https://ph01.tci-thaijo.org/index.php/
rmutt-journal

Investigation of propeller configuration effects on the flight stability of unmanned aerial vehicles

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ABSTRACT

This study investigates the flight stability of unmanned aerial vehicles (UAVs) by comparing two-, three-, and six-blade propellers. The experiment uses a self-made drone with a 3D-printed polylactic acid (PLA) frame and an Arduino-based flight control system to create an efficient UAV prototype. The flight tests are conducted in a controlled environment, eliminating flight confounders such as wind and temperature, and the three types of propellers are of similar size. Stability was assessed by measuring deviations in the drone's X and Y axes while hovering within ±30 degrees, and standard deviation (SD) was calculated to quantify variability. The tests revealed that propeller count significantly impacts stability and overall performance. The three-blade propeller provided the best stability, with the smallest SD in the X-axis at 10.85 and Y-axis at 11.85, and showed the least deviation over ±30 degrees during take-off and flight. While the 2-blade propeller has the least stability in flight, with a value of 15.08 in the X-axis and 16.3 in the Y-axis, showing a deviation exceeding ±30 degrees several times throughout the test, the 6-blade propeller demonstrates intermediate performance, with a value of 12.71 in the X-axis and 15.57 in the Y-axis, which is more stable than the 2-blade propeller but still less stable than the 3-blade propeller. The results of this study provide UAV design data by studying the factors in selecting propellers with different numbers of blades for drones, presenting information on the importance of propeller selection for drone flight performance and stability. The results of this study can be applied to various drone applications, such as aerial photography, agriculture, or industry. Finally, in the future, other factors are expected to affect the differences in the number of blades regarding energy efficiency and flight duration.

Keywords: Drone stability, Arduino control system, Unmanned aerial vehicles (UAV)

INTRODUCTION

The most dramatic evolution of some improvements due to recent advances in information technology and artificial intelligence already shapes many aspects of autonomous systems, especially UAVs. The systems cover every detail, from specifically non-piloted aircraft to piloted flying robots that can fly without a person on board [1]. Fixed-wing, hybrid vertical take-off, and landing (VTOL) hybrids comprise the three core UAV types, representing rotorcraft and tiltrotor models. Rotorcraft series: subcategorizing into single-rotor (helicopter style) and multi-rotor variants [2]. Drones bring many advantages over traditional vehicles in the same context, and one of the areas where we can see this transformation taking place is logistics. These benefits are as follows: high-speed operation at a constant speed; it handles no road infrastructure requirement; public navigation to a direct path with traffic wouldn't be an issue [3]. Industry leaders have anecdotally documented drone use across various applications, such as Shell for oil platform flare stack inspection, Zipline for medical supplies delivery in Africa, and IKEA for real-time warehouse inventory management [4]. Figure 1 highlights the core engineering fields responsible for the design of UAVs tailored to different missions. In the design of UAVs, primary emphasis has been placed on mechanical systems, which have been analyzed, and visualization tools have been used way ahead of the process. The chosen had to offer both in how light it was (most of the work that was done for these materials was aimed at ensuring they could hold up to the weight they needed to support while also allowing for the craft to fly as long as possible given necessarily limited battery life). This is particularly clear in the case of commercial UAV models and flying saucers, where the weight should be optimized to have enough efficiency on take-off and long-range autonomy [5]. Although UAV use is becoming more common, cost remains a major barrier to broad research adoption because of high primary acquisition, maintenance, and training costs. Low-cost prototyping appears to be a valid strategy in this context to grant local actors more

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DOI: 10.60101/jarst.2024.258251

agency, may they be biodiversity conservation managers [6].

The evolution of UAV materials has allowed manufacturing savings and has been the core approach to reducing UAV costs. Modern-day UAVs depend largely upon high-strength, low-weight carbon fiber composites to replace the earlier aerospace aluminum of manned aircraft [7]. In this context, additive manufacturing and 3D printing technology have become game changers in empowering the evolution of UAVs. It is a layer-wise process in which materials are deposited following digital models, providing flexibility and economic viability for small-batch production of parts with intricate geometries [8]. The fast development of 3D printing has dramatically changed prototyping, offering rapid and accurate facets in UAV production [9]. Polylactic acid (PLA), which is derived from starch like corn and sugar cane, has become one of the most common 3D printing materials. Its medium cost, biodegradability, and versatility make it a proper material for many fields of application (such as food packaging or medical devices) [10]. PLA provides a viable solution for using chassis fabrication in UAV construction. Though not as strong (good stiffness to weight) for lightweight applications, the lightweight nature of PLA is a large contributor to the weight savings achievable, consequently increasing fuel efficiency and payload capability for UAVs [11].

Control systems operated by microcontrollers underpin modern UAV operations. As a breakthrough technology in UAV technology, these purpose-built embedded systems are revolutionizing how specific device functions can be more efficiently handled and have correspondingly begun to find use within new drone designs and in wide-ranging environments like our homes and research laboratories. While general-purpose processors are too flexible, microcontrollers are designed for specific tasks that allow handling details across a range of devices and make them popular in modern technology [12]. Arduino is a general-purpose, open-source microcontroller platform that is widely used in the industrial sector. It is used in embedded systems and the Internet of Things (IoT). The advantages of this ecosystem, a combination of hardware, software, and developer communities for IoT, include cheaper, cost-effective system design, flexibility across platforms, and ease in interfacing with a wide range of input/output devices [13-14]. Arduino has achieved widespread appeal because of its easy-to-setup and easy-programming environment, leveraging C++-derived language as well as the Integrated Development Environment (IDE) to develop and execute code. Developers at any level of competency are afforded ease-of-use courtesy of this simple syntax and IDE. Its open-source architecture, versatility, and cost-effectiveness have since made it the platform of choice for many different applications within academia or at an industrial level [15].

The incorporation of private Arduino autopilot components in the flying versions of UAVs can control some activities and maneuvering actions throughout flight [16]. Rotary Wing UAVs, like quadcopters, have been the main driving factor for application development requiring vertical take-off, landing, and hovering. With best-in-class stability and control, they are a perfect choice for breaking the ice across various industries, and their compact body and lightweight ensure fluid deployment. The current research inclines toward performance enhancement via vibration and noise reduction, rotor efficiency optimization, as well as advanced stability systems [17]. Those drones employ four multi-bladed propellers that transform mechanical energy into aerodynamic thrust. Propeller designs vary from fixed-pitch to variable-pitch, and blade geometry, rotational speed, and airspeed are critical for the overall performance of a propeller [18]. Flow fields are considerably affected by distributed propellers in distributed propulsion systems, which lead to a non-linear aerodynamic performance. Off-axis freestream/axial directions incoming to the propeller cause oblique inflows, creating off-primary thrust and moment forces. The combined multi-directional effects can detriment flight stability, and therefore, it is necessary to have information pertaining to the propeller dynamics as soon as possible in the design process [19].

Zheng et al. (2020) studied flight stability and developed a fully tilt-controlled drone platform that can move in different directions and angles. During testing, the platform can tilt up to 30 degrees while hovering, and the drone remains stable at this angle. An important technical reason for maintaining the tilt angle of no more than 30 degrees is that exceeding this point can cause the thrust adjustment mechanism to lose its efficiency, resulting in instability and possibly preventing rotation. Therefore, it is necessary to maintain a tilt angle of no more than 30 degrees to maintain stability while hovering and precisely control the direction of movement [20].

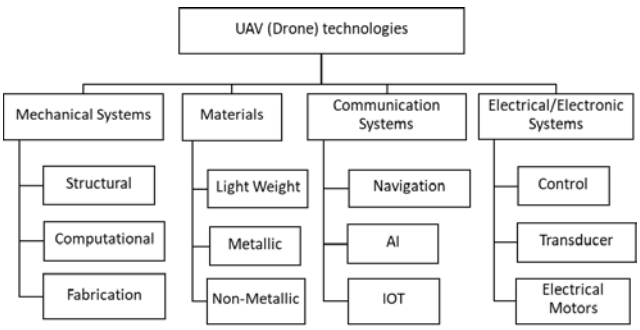

Figure 1 Key Technological Components of UAV (Drone) Systems.

This study presents the design and construction of a UAV using a PLA-printed frame controlled by an Arduino board. This UAV is made of PLA via a 3D printing process, which is low-cost and easy to customize. The

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DOI: 10.60101/jarst.2024.258251

main objective of the study is to analyze flight stability by comparing three types of propellers, 2-blade, 3-blade, and 6-blade propellers, to obtain information on the effects of different numbers of propellers on flight stability and controllability. Such studies are very important in designing UAVs that require stability for specific applications, such as aerial photography, precision agriculture, and infrastructure inspection. Therefore, this research provides information to understand the factors of the number of propellers on flight and can be used as a guideline for developing efficient UAV systems for practical applications in industry and further research. The experimental results can also be applied to develop propellers that can change the number of blades during flight, allowing the UAV to have higher flexibility and efficiency in various situations.

MATERIALS AND METHODS

A. Drone construction and materials

This study analyzes the flight stability of a drone by examining the effects of different propeller blade numbers. The drone is a 4-arm model, made from PLA material using 3D printing. Its structural frame supports the equipment and secures the arms. The drone's dimensions are 5.9 cm in width, 19.8 cm in length, and 12.8 cm in height. Each arm measures 2.3 cm in width, 14.3 cm in length, and 1.6 cm in height. The total weight of the drone, excluding the propellers, is 1.2 kilograms after all equipment is installed, as shown in Figure 2.

From Figure 3. The tested drone is equipped with an Arduino-based flight control system, a receiver for remote control operations, and a gyroscope sensor to monitor tilt angles during flight. The key components of the drone are as follows:

1. Components:
   - o Lower base body: 1 part.
   - o Upper base body: 1 part.
   - o Drone arms: 4 parts.
   - o 2-blade propellers: 4 parts.
   - o 3-blade propellers: 4 parts.
   - o 6-blade propellers: 4 parts.
2. Control System:
   - o Microcontroller ESP32: 1 part.
   - o Arduino UNO R3: 1 part.
   - o Remote control Flysky FS I6X: 1 part.
3. Electrical Components:
   - o Gyroscope sensor MPU6050: 2 parts.
   - o Receiver FS IA6B: 1 part.
   - o Battery lipo 3 cell 11.1 V: 1 part.
   - o Brushless motors A2212/6T 2200KV: 4 parts.
   - o Electronic Speed Controller (ESC) 30A 5V/2A: 4 parts.

The necessary software for the operation includes Arduino IDE for programming the drone's flight control and data collection via ESP32, which the ability to access Wi-Fi and Bluetooth. It uses the advantage of accessing Wi-Fi of the ESP32 to send data to the Blynk IoT platform to collect data during flight, which is used to design the drone's components and structure for 3D printing and Blynk IoT, an IoT platform for creating a dashboard to monitor real-time data and control devices over the internet.

Figure 2 UAV (Drone) from PLA material.

Figure 3 Materials and equipment for UAV installation.

B. Circuit diagram

Figure 4 presents the circuit diagram of the drone, comprising various components, each with distinct functions and operational roles. The specific details of each component are as follows:

Receiver FS IA6B: receives control signals from the remote control and transmits them to the Arduino board through Channels 1-4, connecting to the digital ports of the Arduino.

1. Arduino UNO R3: acts as an input, receiving signals from the receiver through Channels 1-4 to the digital ports of the Arduino and then controlling the operation of the brushless motors on all four arms via the speed controller.

2. Electronic Speed Controller (ESC): Adjusts the frequency of the electrical signals to control the speed and rotation of the brushless motors, providing a means for making propellers spin at a higher or slower rate. To maintain the speed of brushless motors,

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DOI: 10.60101/jarst.2024.258251

take control signals from Arduino in brushless motors. Furthermore, it also regulates power delivery for optimal motor performance via the ESC.

3. Duplicate both the gyro sensor MPU6050 (SDA and SCL port to Arduino). It measures rotation or tilt in multiple axes of the drone. The gyroscope then sends this information to the Arduino so that the drone can be balanced to steer through the air consistently.

4. Tercell 11.1 VDC: rated at 11.1 VDC, is the power provider to other parts on the PCB. Components that run with higher requirements (up to 12 VDC) like the ESC and the Arduino are powered right through it, while others, such as the gyroscope or ESP32, are powered. Full System Wiring Diagram This diagram also shows where every component is wired to.

5. The data collection methodology used is illustrated in the circuit diagram in Figure 5, where we collect the data from a gyroscope sensor measuring the axis. The measured values are sent to the ESP32 by the sensor, which collects the flight data in this way. This data is then sent to the Blynk IoT app for real-time recording and viewing, allowing us to analyze flight stability. The details are as follows:

5.1 The Gyroscope MPU6050 module connects to the ESP32 via the ports of SDA (GPIO21) and SCL (GPIO22). The sensor detects rotational and tilt movements across all axes, transmitting angular values or rotation rates to the ESP32 microcontroller.

5.2 ESP32 is a microcontroller and integrated Wi-Fi/Bluetooth solution that has been designed for long-distance data transmission applications. This time around, the ESP32 gets axis measurements from the Gyroscope MPU6050 sensor and sends that data to display in the Blynk IoT dashboard.

5.3 What is the Blynk IoT platform? In this case, it's used to show the axis data collected from the drone in real-time during flight. The results will then be analyzed to determine the flight stability of a drone in future studies.

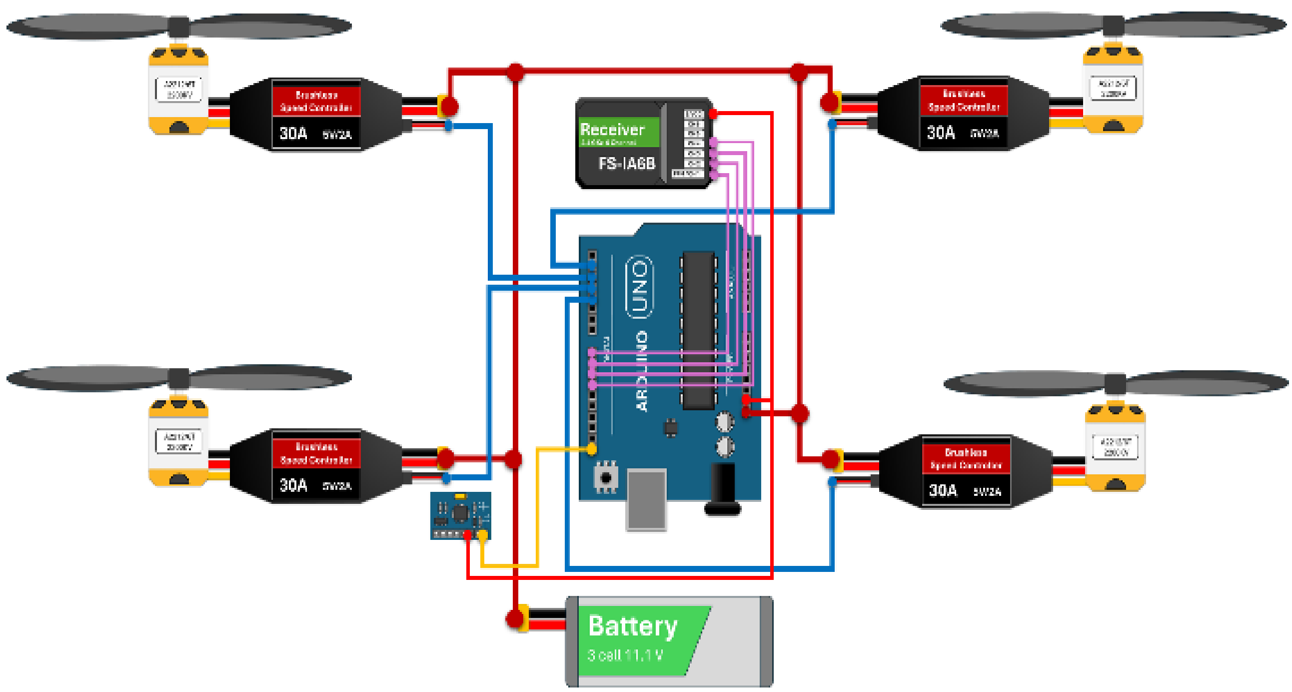

Figure 4 Circuit Diagram of UAV.

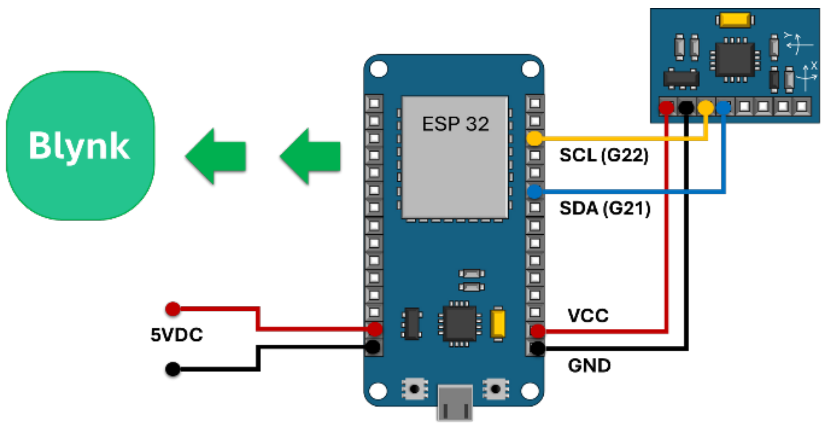

Figure 5 Circuit diagram of ESP32 for data collection.

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C. Experimental methodology

All tests will be performed in a controlled environment to ensure the most accurate measurements possible and keep testing as bias-free as possible. That includes tightly controlled temperature and humidity (free from outside breeze influence). The measures provide a commonality and consistency of conditions between all flight tests in the experiment.

Figure 6 Drone mounting base for flight testing.

The flight test set-up is shown in Fig. 6, and the levels are installed within a controlled, closed environment where environmental parameters are strictly controlled. The testing rig holds the drone at a constant altitude level, ensuring stable flight. To ensure the stability of the base, a leveled water scale was used to level up the surface and make it completely flat. This integral subsequent detail removes potential discrepancies, providing a constant and standardized surface from which every test article can launch.

Figure 7 Drone propeller configurations: (a) 2-blade, (b) 3-blade, and (c) 6-blade.

This study compares props with two blade weights of 3 grams, three blade weights of 5 grams, and six blade weights of 6 grams to assess the drone's stability (Figure 7). Each propeller has a diameter of roughly 4 inches, and since they are all lightweight, we may disregard their weight. These three propeller types were chosen because they are simple to purchase and assemble drone equipment. A single drone, shown in Figure 8, Including devices circuits and brushless motors was used for all the tests, and it had a weight of around 1.2 kilograms, a length of 37.4 cm, a width of 29.6 cm, and a height of 12.8 cm.

Figure 8 The drone is mounted onto the test stand.

In this work, the drone is attached in a free-joint mount at its center point, which restricts it to only being able to fly 20 cm high but with the ability to be tilted. The motors are started at maximum speed, and the time until they reach maximum is recorded for 2 minutes 30 seconds. Telemetry for tilt data is collected from Y and X axes to determine flight stability. During the testing, every type of propeller is exposed to equal conditions, in which it is certain that only one thing changes for the same situation during each flight stability test-the number of propeller blades.

RESULTS AND DISCUSSION

A. Effect of blade numbers on flight stability

This study utilized published data and test results from three different propellers to investigate the influence of the number of blades on flight stability. During each test, the drone flew at peak power for 2 minutes 30 seconds but eliminated the first and last 15 seconds for instability incurred in take-off and landing (landing was brutal). Analysis of a 2-min stable flight period In the assessment, deviations from the zero reference were measured within a threshold tilt range of ±30 degrees to consider for stability calculations. Tilts over this range indicated that either control was lost or stability had been diminished and were quantified in the X- and Y-directions, as illustrated in Figure 8.

Figure 8 X and Y axes of Drone.

In measuring data fluctuations, drone flight is affected by factors that alter its tilt from a stable

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axis. When testing different propellers, a high standard deviation (SD) indicates significant flight angle changes and instability, while a low SD suggests consistent and stable flight. The findings are detailed below.

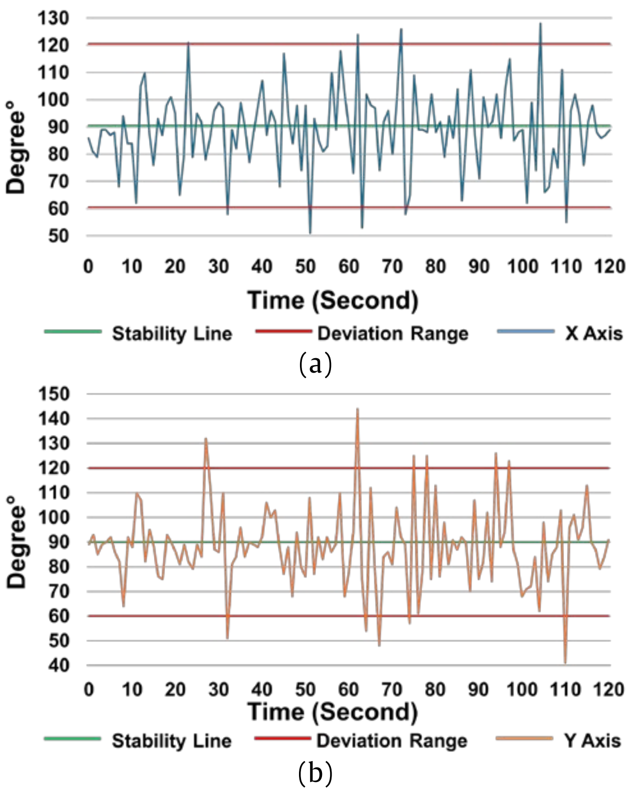

Figure 9 Drone stability tests results propeller 2-blade: (a) X Axis, (b) Y Axis.

Figure 9 provides a detailed analysis of the drone's flight stability equipped with two propellers. The graphs illustrate the drone's angular deviation from its stable hovering position, with the stability line (green line) as a reference. The results reveal that when using propellers 2-blade, the drone exhibited angular deviations exceeding the allowable limit of ±30 degrees (red line) along the X-axis on 9 occasions. Furthermore, in the Y-axis, deviations beyond ±30 degrees occurred 11 times. The calculation for evaluating flight performance shows that the SD for the 2-blade drone on the X-axis is 15.08, and on the Y-axis, it is 16.3.

Figure 10 presents the flight stability results for the drone fitted with 3-blade propellers. The data reveals that the drone surpassed the allowed angular deviation of ±30 degrees (red line) along the X-axis on 4 occasions. Similarly, 5 instances of deviation beyond 30 degrees were observed along the Y-axis. The calculation for evaluating flight performance shows that the SD for the 3-blade drone on the X-axis is 10.85, and on the Y-axis, it is 11.85.

Flight stability results for drones with 6-blade propellers are shown in Figure 11. The data thus shows that the drone exceeded the permitted roll angle ($-30 \leq \theta \leq 30$) (red line) along the X-axis in 7 cases. Also, a complete deviation was made over ±30 degrees nine times for the Y-axis. The calculation of the flight performance values shows that for the X-axis, a 6-blade drone has an SD of 12.71 and for the Y-axis it is 15.57.

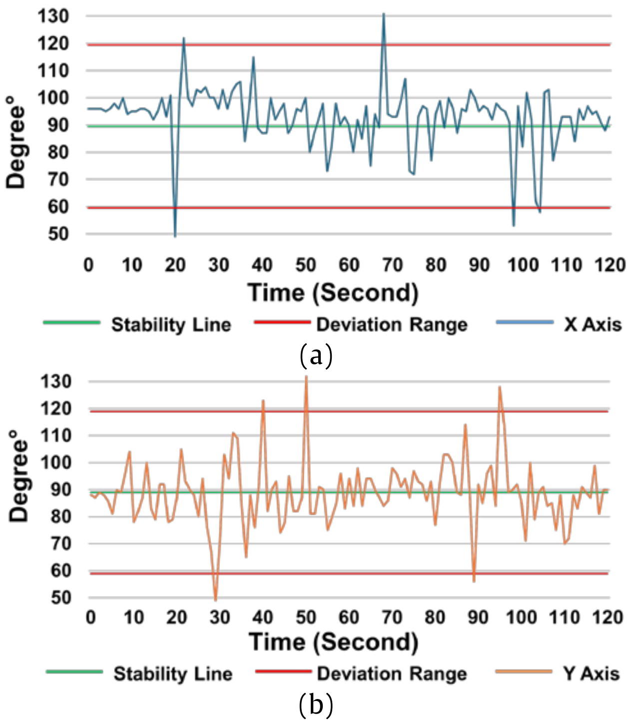

Figure 10 Drone stability tests results propeller 3-blade: (a) X Axis, (b) Y Axis.

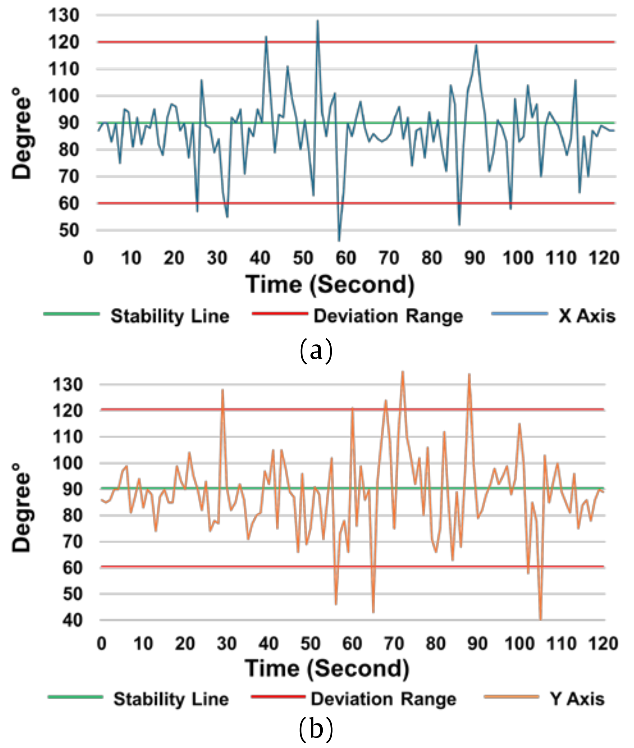

Figure 11 Drone stability tests results propeller 6-blade: (a) X Axis, (b) Y Axis.

B. Comparison of stability for three types of propellers

This study compared 2-blade, 3-blade, and 6-blade drone propellers in their flight stability.

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Stability was measured according to angular deviations (X and Y axes) and standard deviations (SD) of flight variances. The results show markedly different flight stabilities among propeller types, as shown in the following sections.

2-Blade Propellers: Drones with 2-bladed propellers registered the most significant angular deviations during testing. More precisely, 9 times X > ±30 deg and also Y > ±30 deg 11 times. Figure 9 shows many points that deviated from the stability line (green line) while remaining within ±30 degrees. The constant shifts of the axis indicate a lot of movement slop when you're flying these 2-blade propeller planes. The calculated SD values for the X and Y axes were 15.08 and 16.3, indicating many disturbance signals causing the flight performance to drop below that of other propellers by as much as 58% (in one scenario).

3-Blade Propellers: Drones with a 3-blade propeller showed the lowest angular deviations. Only 4 deviated significantly more than ±30 degrees along the X-axis and 5 along the Y. The graph in Figure 10 also has less departure from the stability line (green line), which means the balance is significantly better. This resulted in X-axis and Y-axis SD values that were more than a third of those for 2 blades: 10.85 and 11.85, respectively, meaning a generally much stabler flight with less deviation between any two flights.

6-Blade Propellers: The 6-bladed propeller drones exhibited fewer angular deviations versus the 2-blade ones but more than how the 3-blade ones acted. The X-axis saw 7 anomalies of at least ±30 degrees, and the Y-axis saw 9. As seen in Figure 11(a), the green line indicates the stability line, and during deviations away from this point, although normalized to ± 30 degrees was achieved a few times, the flight tended to stabilize towards that. Although it can be seen from Figure 11(b) that deviations from the stability line along Y are more common, they are still over ±30 degrees. For the X and Y axes, one could respectively only expect a standard deviation (SD) as low as 12.71 and 15.57 in comparison with 3 blades, which would mean this stability is superior to using a 2-blade propeller but not ideal yet.

The results showed that 3-blade propellers had the greatest stability, deviated less, and had lower SD values than other types. The flight deviations and oscillations were not severe; thus, they allowed effective and stable control during the recovery phase. In comparison, 2-blade propellers exhibited the most significant instability (the highest SD values) and wandered into ranges beyond ±30 degrees. 6-blade propellers showed more minor variations than 2-blade propellers, although still more significant than 3-blade propellers.

CONCLUSIONS

This study represent how propeller configurations affect UAVs during flight. The research shows that the number of propellers plays a crucial role in drone flight performance, with more propellers having a greater impact. The 3-blade propeller has lower standard deviation (SD) values, indicating greater stability and improved accuracy in drone flights. The 2-blade propeller show high instability and significant SD values (the variable most responsible for the instability in general); such as variability linked to unstable flight conditions. Although the 6-blade propeller has lower take-off deflection than the 2-blade propeller, its flight stability is still less than the 3-blade propeller. The results show the 3-blade propeller had the best stability, followed by the 6-blade propeller, which produced a better result than 2-blade propeller configurations. The results are useful in designing a high-stability UAV for applications like aerial photography or infrastructure inspection, improving control and accuracy. However, this study has several limitations, such as the weight constraints of the prototype drone and the specific motor and battery configurations, which may influence results. Future research should investigate the impact of propeller layouts on energy efficiency and performance under varying payloads and motor speeds, thereby broadening the applicability of this research to diverse industrial and agricultural UAV designs.

ACKNOWLEDGEMENT

I would like to thank Mr. Gittiwat Thananta for his guidance on electrical systems and drone design, Mr. Kusonsang Duangpakdee for his expertise in experimental design.

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DOI: 10.60101/jarst.2024.258251