

## Development of autonomous quadcopter unmanned aerial vehicle using APM 2.8 flight controller

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### ABSTRACT

This paper presents the development of a quadcopter unmanned aerial vehicle (UAV) using the APM 2.8 flight controller as the core of its navigation and control system. The project aims to design, assemble, and evaluate a stable and cost-effective quadcopter platform suitable for basic autonomous flight tasks such as waypoint navigation and altitude hold. The system incorporates essential components, including brushless DC motors, ESCs, a GPS module, a telemetry radio, and a power distribution system, integrated with the APM 2.8 running on the ArduPilot firmware. Waypoints are planned via Mission Planner software, with a flight control system embedded in the firmware. Real-world flight tests were conducted to evaluate the UAV's performance in executing autonomously predefined survey grid and zigzag waypoints trajectories over open terrain. The root mean square error (RMSE) was calculated to assess the performance of waypoint tracking accuracy. The results show that the quadcopter UAV achieved an RMSE of 1.78 meters during zigzag waypoint tracking and 1.56 meters during survey grid, demonstrating reliable flight control performance offered by the APM 2.8 for basic autonomous mission tasks. This work highlights the feasibility of using APM 2.8 for cost-effective UAV development in research, education, and prototyping purposes.

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## 1. INTRODUCTION

Unmanned aerial vehicles (UAVs), particularly quadcopters, have drawn a lot of attention lately because of their numerous and adaptable uses in a variety of sectors [1] such as disaster management [2], [3], land surveying [4], [5], traffic monitoring [6], [7], rescue [8], [9], surveillance [10], [11], exploration [12], [13], reconnaissance [14], [15], agriculture [16], [17], and many more. As a type of multi-rotor UAV equipped with four rotors, quadcopters offer a simpler stabilization mechanism compared to tricopters and are more cost-effective than hexacopters or octocopters, making them a popular choice for this research and practical implementations.

In the agricultural sector, the use of quadcopters is rapidly increasing for tasks that do not require heavy payloads. These include plantation monitoring [18]–[20], real-time crop analysis [21]–[23], and livestock tracking [24]–[26]. Such applications support the growing trend toward smart and precision farming, which emphasizes efficiency, productivity, and minimal resource usage. However, many commercially

available quadcopters in regions like Malaysia still rely heavily on manual operation through remote control, requiring skilled personnel and limiting scalability.

This study aims to address this gap by developing a quadcopter using the ArduPilot Mega (APM) flight controller, which supports autonomous flight capabilities. The ArduPilot open-source autopilot technology has been evaluated for performance using Mission Planner software. This technology works with a variety of vehicle designs, such as multicopter UAVs, fixed wing, and rotary wing UAVs. It also has built-in waypoint management and the capability to display different flight statistics while the trip is underway. Mission Planner can be used as a GCS for a UAV since it includes all of the characteristics listed above and is compatible with ArduPilot. The project focuses on designing and building a functional quadcopter capable of autonomous navigation based on predefined trajectories. Through this development, the system is intended to serve as a foundation for future applications in autonomous missions and educational research in UAV technologies.

## 2. QUADCOPTER UAV

Hardware and software are integrated to power a quadcopter. Figure 1 contains major components of quadcopter UAV.



Figure 1. Quadcopter components

### 2.1. APM 2.8 flight controller

The APM 2.8 Flight Controller is an open-source autopilot system developed as part of the ArduPilot project, designed to control and stabilize unmanned aerial vehicles (UAVs). It features an onboard Inertial Measurement Unit (IMU) with gyroscope and accelerometer sensors, a barometric pressure sensor for altitude control, and interfaces for external modules like GPS, telemetry, and radio receivers. APM 2.8 supports autonomous flight missions through waypoint navigation, which can be programmed and monitored using Mission Planner software. Although it's considered a legacy system compared to newer Pixhawk versions, APM 2.8 remains a reliable and cost-effective choice for research, education, and hobbyist UAV projects due to its simplicity, wide community support, and compatibility with various UAV configurations.

### 2.2. Electronic speed controller (ESC)

An electronic speed controller (ESC) is a crucial component in a quadcopter's propulsion system that regulates the speed, direction, and braking of a Brushless DC (BLDC) motor based on signals received from the flight controller. In UAVs, each motor is paired with an ESC, which converts low-power pulse width modulation (PWM) signals into high-power three-phase AC current needed to drive the motors efficiently. ESCs respond in real-time to flight commands, adjusting motor speed to maintain stability, execute maneuvers, and control altitude and direction. They also often include built-in safety features like motor cut-off, overcurrent protection, and sometimes telemetry feedback, making them essential for smooth and reliable flight performance.

### 2.3. Brushless DC (BLDC) motor

A Brushless DC (BLDC) motor is a highly efficient and durable electric motor commonly used in quadcopters and other UAVs due to its lightweight design, low maintenance, and precise control capabilities. Unlike brushed motors, BLDC motors do not have physical brushes or a commutator; instead, they use electronic commutation via an electronic speed controller (ESC) to switch current through the motor windings. This results in less friction, higher efficiency, and longer lifespan. In quadcopters, BLDC motors are responsible for generating the thrust required for lifting and maneuvering by rapidly spinning the propellers. Their ability to change speed quickly and accurately makes them ideal for maintaining flight stability and executing responsive control commands during both manual and autonomous operations.

### 2.4. Propeller

A propeller is a rotating aerodynamic device attached to the motor of a quadcopter, responsible for generating the lift and thrust necessary for flight. It operates based on aerofoil principles, where the rotation of the propeller blades through the air creates a pressure difference—lower pressure above the blade and higher pressure below—resulting in upward thrust. In quadcopters, there are typically four propellers arranged in a cross configuration, with alternating clockwise (CW) and counterclockwise (CCW) rotation to balance torque and maintain stability. The size, pitch, and material of the propeller affect the drone's efficiency, stability, and maneuverability. Properly balanced and matched propellers are essential for smooth flight performance, especially during rapid movements or autonomous missions.

### 2.5. Battery

A battery in a quadcopter serves as the primary power source, supplying electrical energy to all onboard components, including the flight controller, motors, ESCs, sensors, and communication modules. The most commonly used type is the Lithium Polymer (LiPo) battery due to its high energy density, lightweight structure, and ability to deliver high current output necessary for powering Brushless DC motors. Battery specifications—such as voltage (typically 11.1V or 3S for smaller drones) and capacity (measured in mAh)—directly affect flight time, power delivery, and overall performance. A power module is usually used between the battery and flight controller to manage power distribution and provide telemetry data like voltage and current. Proper battery selection, management, and safety practices are critical for ensuring efficient flight operation and preventing hazards such as over-discharge or overheating.

### 2.6. RC transmitter and receiver

A radio control (RC) transmitter and Receiver system is essential for manual control of a quadcopter, allowing the user to send commands wirelessly from the ground to the aircraft. The transmitter, held by the operator, sends control signals—such as throttle, pitch, roll, and yaw—over a specific radio frequency, typically 2.4 GHz. These signals are received by the RC receiver mounted on the drone, which decodes them and passes them to the flight controller (like APM 2.8) via PWM, PPM or serial bus protocols. This system enables real-time piloting and is often used for takeoff, landing, or as a backup control method during autonomous missions. Many transmitters also support additional switches and channels for controlling flight modes or triggering onboard functions like camera gimbals, making the RC system a versatile and critical component in UAV operations.

### 2.7. GPS module

A GPS module in a quadcopter is a navigation device that provides real-time geolocation and time data to the flight controller, enabling autonomous flight and waypoint navigation. It receives signals from multiple satellites to calculate the drone's precise latitude, longitude, and altitude, which are essential for maintaining stable position hold, executing GPS-based missions, and returning to home (RTH) in case of signal loss or low battery. Advanced modules, like the Ublox NEO M8N, also include a compass (magnetometer) that helps the flight controller determine the drone's orientation. The GPS module communicates with the flight controller through UART or I2C connections and must be properly calibrated and positioned away from magnetic interference for optimal performance.

### 2.8. Telemetry

Telemetry module refers to the wireless communication link between the drone and the ground control station (GCS), enabling the real-time transmission of flight data such as GPS position, altitude, speed, battery status, and sensor readings. Typically operating on frequencies like 433 MHz or 915 MHz, telemetry modules allow users to monitor and control autonomous missions through software like Mission Planner. This two-way communication lets the operator not only receive live data but also send commands—such as changing flight modes or updating waypoints—during flight.

## 2.9. Micro air vehicle link (MAVLink)

Micro air vehicle link (MAVLink) is a lightweight, open-source communication protocol designed for unmanned vehicles such as drones and ground robots. It enables efficient and reliable exchange of messages between the vehicle's autopilot and ground control stations, sensors, or companion computers. MAVLink supports real-time telemetry, command and control instructions, mission planning, and status reporting, making it a standard protocol in many UAV systems. Its compact message format optimizes bandwidth usage, allowing stable communication over wireless links with limited data rates, which is essential for safe and responsive autonomous flight operations.

## 2.10. Ground control station

A ground control station (GCS) is a software interface or hardware setup used to monitor, control, and communicate with UAVs during flight. It allows operators to plan missions, send commands, receive real-time telemetry data such as position, speed, and sensor information, and adjust flight parameters like waypoints and flight modes. The GCS serves as the primary link between the operator and the drone, providing visualization tools such as maps and flight status indicators to enhance situational awareness and ensure safe, efficient autonomous or manual control of the UAV throughout its mission.

## 2.11. Mission Planner software

Mission Planner is a popular, open-source ground control station software designed specifically for configuring, monitoring, and controlling UAVs running the ArduPilot autopilot system. It provides a user-friendly graphical interface for planning autonomous missions by setting waypoints, configuring flight parameters, and uploading mission scripts to the drone. Mission Planner also offers real-time telemetry monitoring, flight data logging, and advanced tools for calibrating sensors. Widely used by hobbyists and researchers, it simplifies the process of managing complex flight operations, ensuring precise navigation and stable autonomous flight.

## 3. HARDWARE INTEGRATION

The component assembly of a quadcopter using the APM 2.8 flight controller as illustrate in Figure 2. At the center of the frame is APM 2.8, which acts as the main control unit, connected to a GPS module for navigation and a telemetry receiver for communication with the ground station. A LiPo battery supplies power to the system through a power module, which also provides voltage and current monitoring. An ON/OFF switch is included for safe power management during setup and operation. The radio receiver allows manual control input from a remote transmitter when required.

Each arm of the quadcopter is equipped with a Brushless DC (BLDC) motor controlled by an ESC. These motors are responsible for generating lift and stability during flight, with propellers mounted on top. The ESCs receive signals from the APM to adjust motor speed based on flight conditions. This configuration supports both manual and autonomous operations, making the platform suitable for research and applications such as aerial mapping and precision agriculture.

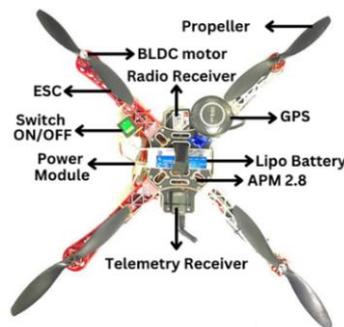


Figure 2. Assembly of a quadcopter component

## 4. RESULTS AND DISCUSSION

In this study, the waypoint navigation performance of an ArduPilot controlled quadcopter was evaluated using two distinct flight patterns: zigzag and survey grid trajectories, each designed with a specific

number of waypoints to define the desired paths. As seen in Figure 3 and Table 1, we create two flight paths (zigzag as in Figure 3(a) and survey grid as in Figure 3(b)) at the university field in order to test the quadcopters in this initial study. For the zigzag path, 7 waypoints were generated to form a simple open-loop with sharp corners, testing the quadcopter's ability to follow linear segments and make accurate 45-degree turns. In the survey grid path, 25 evenly spaced waypoints were used to create a smooth, continuous trajectory, allowing the quadcopter to maintain a consistent turning rate and evaluate its ability to follow sharp corner.

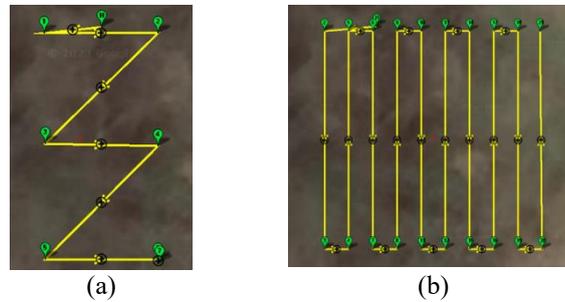


Figure 3. Flight trajectories of (a) zigzag and (b) survey grid

Table 1. Detail of flight path

Scenario	Area of the planned trajectory	Number of waypoints	Flight height
Zigzag	10m x 20m	7	5 m
Survey grid	20m x 20m	25	5 m

The root mean squared error (RMSE), as indicated in (1), is used to compare the actual GPS trajectory of each flight experiment data with the intended trajectory (waypoint path). When the targeted trajectory (waypoints) is represented by  $y_i$ , the number of waypoints is  $n$ , and the longitude or latitude data of the actual flight trajectory is represented by  $\hat{y}_i$ .

$$RMSE = \sqrt{\sum_{i=1}^n \frac{(\hat{y}_i - y_i)^2}{n}} \quad (1)$$

#### 4.1. Zigzag waypoint

The flight performance of the quadcopter UAV in waypoint navigation was assessed by comparing the desired trajectory (yellow) to the actual trajectory (purple) as shown in Figure 4. Despite minor deviations, the UAV successfully followed the intended zigzag path with high accuracy. The trajectory visualization highlights in the beginning that the quadcopter experienced slight overshoots during follow path but was generally able to recover and align with the planned route. The accompanying RMSE data quantifies this performance (Table 2), showing very small deviations in longitude and latitude with values of  $9.78E-06$  degrees and  $1.27E-05$  degrees, respectively, conversion to a meter value is 1.78 meters. The error of altitude is also minimal at 0.281 meters, indicating stable altitude control throughout the flight. These results confirm that the ArduPilot system provides reliable and accurate waypoint tracking under real flight conditions, with minimal tracking error that remains well within acceptable operational tolerances for typical UAV navigation applications.

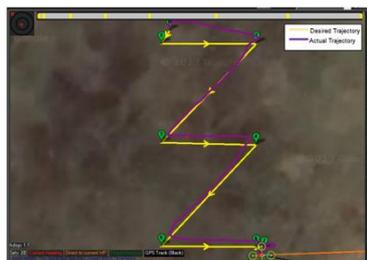


Figure 4. Trajectory of Zigzag

Table 2. Result of Zigzag RMSE values based on real flight analysis

Axis	RMSE of real flight (degree)	RMSE of real flight (meter)
Longitude	9.78E-06	1.78
Latitude	1.27E-05	
Altitude	-	2.81E-01

#### 4.2. Survey grid waypoint

The image displays a survey grid trajectory flown by a quadcopter during an autonomous waypoint mission. The yellow path represents the desired trajectory, while the purple path indicates the actual trajectory flown by the UAV as shown in Figure 5. The quadcopter follows a survey grid pattern over the surveyed area, highlights the quadcopter experienced slight overshoots during turn corner but was generally able to recover and align with the planned route. RMSE results show a high level of accuracy in tracking waypoints as shown in Table 3. The RMSE in longitude and latitude are 5.80E-06 and 1.28E-05 degrees respectively, which conversion to meter value approximately 1.56 meters. The altitude RMSE is 0.226 meters, indicating precise vertical control. These results demonstrate that the navigation and control system is effective in closely following the planned path with minimal deviation.



Figure 5. Trajectory of survey grid

Table 3. Result of survey grid RMSE values based on real flight analysis

Axis	RMSE of real flight (degree)	RMSE of real flight (meter)
Longitude	5.80E-06	1.56
Latitude	1.28E-05	
Altitude	-	2.26E-01

## 5. CONCLUSION

This project successfully demonstrates the development of an autonomous quadcopter using the APM 2.8 flight controller integrated with the Mission Planner software. The quadcopter was able to execute waypoint navigation missions with notable accuracy. Two predefined flight patterns zigzag and survey grid were used to evaluate system performance under various trajectory complexities. The results, validated through RMSE analysis, confirm that the quadcopter can reliably follow GPS-based waypoints, even in dynamically challenging paths. These findings highlight the effectiveness of the ArduPilot system in enabling autonomous UAV operations and suggest its strong potential for further applications in areas such as mission planning and educational research on UAV technologies.

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Mohd Ariffanan Mohd Basri	✓	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
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C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

## CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

## DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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