9 (1): 225-240 (2025)

Journal of Aviation

https://dergipark.org.tr/en/pub/jav

e-ISSN 2587-1676

Multirotor Unmanned Aerial Vehicle Systems: An In-Depth Analysis of Hardware, Software, And Communication Systems

Yahya Çelebi[1*], Hüseyin Aydın[2]

[1*]Şırnak University, Motor Vehicles and Transportation Technologies, Şırnak, Türkiye, 73000. (yahya.celebi@outlook.com)
[2]Batman University, Department of Mechanical Engineering, Batman, Türkiye, 72060. (huseyyinaydin@gmail.com)

Article Info

Received: 15 October 2024
Revised: 12 January 2025
Accepted: 14 January 2025
Published Online: 25 February 2025

Keywords:
UAV
Multirotor
Quadcopter
Unmanned Aerial Vehicle

Corresponding Author: *Yahya Çelebi*

REVIEW ARTICLE

https://doi.org/10.30518/jav.1567696

Abstract

This paper presents a comprehensive overview of multirotor unmanned aerial vehicle (UAV) systems, focusing on the mechanical integration of quadcopters. The rapid advancement and widespread adoption of UAVs have established them as a significant research and development field. This review examines the key components and technologies in UAV design and operation, including frame types, flight control boards, motors, electronic speed controllers, batteries, propellers, communication systems, and software. It analyzes various frame materials and configurations, detailing their advantages and limitations. The paper examines the essential role of flight control boards and inertial measurement units in maintaining stability and enabling autonomous flight. It explores motors, propellers, and power systems selection criteria and characteristics in detail. The review evaluates UAV communication technologies, including radio frequency, WIFI, Bluetooth, and infrared, comparing their capabilities and limitations. It also covers autopilot software and ground control stations for mission planning and execution. This comprehensive analysis serves as a valuable resource for researchers, engineers, and enthusiasts working with design, development, and application of multirotor UAV systems.

1. Introduction

With the development of societies, the importance of manpower and the increase in the value given to human beings have led to the reduction of the manpower directly used in technology. In this way, it has been ensured that people are isolated directly from risky tasks and the system is separated from human control. New technologies in this field are being developed every day. In this context, systems that do not have 'human' on board are called unmanned vehicles. Unmanned vehicles are expected to meet the following requirements: remote control capability and autonomous decision-making functionality.

Unmanned vehicles are divided into different types according to their areas of use. Some of these are Unmanned Aerial Vehicles (UAV), Unmanned Surface Vehicles, and Unmanned Underwater Vehicles (Wibisono et al., 2023). There are three main categories of unmanned aerial vehicles, which include low-altitude platforms known as LAPs, high-altitude platforms known as HAPs, and satellites. This work concentrates on UAV-enabled mobile edge computing, therefore UAVs are examined from multiple perspectives (Yazid et al., 2021). **Error! Reference source not found.** presents a classification of LAP-type UAVs based on their design characteristics, physical dimensions, operational range, and rotor configuration (Yazid et al., 2021).

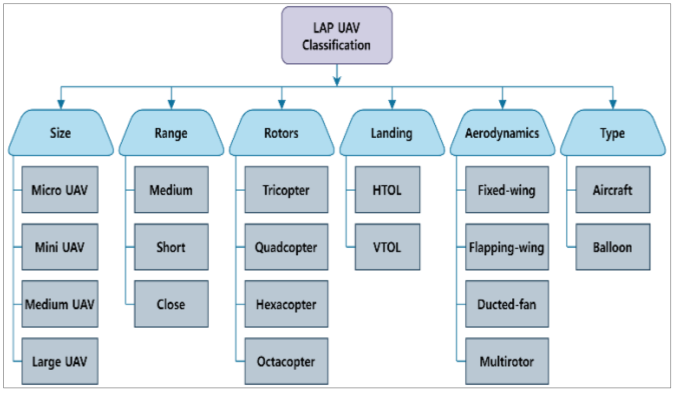

Figure 1. Classification of LAP UAVs.

Multicopters are aerial devices with more than two motors, controlled through yaw, roll, pitch, and lift solely by adjusting speed (rpm). Electro-mechanical sensors and computational devices provide stabilization. They are classified by their propeller count, including tricopter, quadcopter, hexacopter and octocopter (G. Özdoğan and K. Leblebicioğlu, 2022; Özen and Oktay, 2022). Quadcopter designs have emerged as the most common multicopter (Quan, 2017). The term drone, meaning male bee is another widely used name (Metz and Tarpy, 2022; Ural Bayrak et al., 2022). A UAV describes an unmanned vehicle operated remotely or autonomously without any onboard pilot or crew (Mohsan et al., 2022; Özen and

Oktay, 2024). UAVs have gained popularity due to decreasing costs of electronic components including microcontrollers, sensors, and lithium-based batteries. Open-source systems offer universities and enthusiasts low-cost software and hardware modifications options for UAVs (S. Rezwan and W. Choi, 2022). The UAV industry maintains significant growth, with market projections showing expansion from US $30.6 billion in 2022 to US $55.8 billion by 2030, at a Compound Annual Growth Rate (CAGR) of 7.8% (Y. Bai et al., 2023).

The United States hods the most share of investment in UAVs. The number of UAVs pilots trained surpassed the number of jet pilots trained per year in the United States since 2015. It is predicted that there will be 30,000 UAVs in the skies by 2030 (McKelvey et al., 2019). As of May 2022, the Federal Aviation Administration (FAA) in the United States reported significant UAV adoption, with 855,860 registered drones and 277,845 issued remote pilot licenses. These figures demonstrate the substantial integration of UAV technology into both recreational and commercial sectors across the country (Studiawan et al., 2023).

UAVs can be divided into 3 main groups: rotary wing, fixed wing and hybrid (Çelebi and Cengiz, 2024; Velusamy et al., 2022). Fixed-wing UAVs maintain lift through stationary and immobile. Their ability capability depends on the continuous forward motion of the fuselage, powered by either an internal combustion engine or an electric motor. These typically single-engine vehicles offer lower production costs compared to other UAV types. While fixed-wing UAVs require large areas for landing and take-off, they excel in long-range flight capabilities (Kuzu, 2018).

Rotary-wing UAVs uses propellers rotating counter to gravity to maintain lift. In rotary-wing UAVs, the fuselage remains stationary while the wings rotate, eliminating the need for forward motion. As a result, the movements of rotary-wing UAVs in the air are more controlled, allowing them to hover and perform takeoff and landing in small spaces. Due to the increased number of motors, motor controllers and batteries depending on the number of rotor blades, the production costs are higher compared to fixed-wing UAVs. Rotary-wing UAVs have shorter flight ranges. Hybrid UAVs are designed to harness the advantages of both rotary-wing and fixed-wing UAVs (Çabuk and Yıldırım, 2021, 2021; Genç et al., 2008; Kuzu, 2018).

For an object heavier than air, like an airplane, to fly, lift force is required (Gülçat, 2010). The main source of this lift is the airflow over the surfaces of the plane due to the thrust generated by the aircraft's engine and the speed the plane gains (Genç et al., 2008). To turn a multicopter in the desired direction, a positive torque must be applied. This is achieved by adjusting the torque of each motor. The torque effect is observed by changing the motor rotation speed. During hover, the applied torque is zero. To turn left or right, each motor must adjust their speeds accordingly. Reducing motor speed decreases thrust. Speed changes alter the thrust force applied by the motor. During quick rotation, the device may lose altitude. To maintain altitude while rotating, some motors must increase speed to compensate for the reduced thrust from slower motors (Kılıç, 2014).

Modern UAVs find applications across multiple sectors, primarily in military activities (intelligence gathering, border control, enemy detection, ammunition transport), and civilian fields such as energy (fault detection and gas measurements), agricultural applications (data collection), map-making, documentation of archaeological sites, forestry applications, and disaster management. Ongoing research and development continues to expand UAV applications in areas such as first aid (search and rescue) and traffic monitoring (road conditions) (Yürek, 2018). The wide range of UAV applications is presented in Table 1 (Çetin, 2019; Yürek, 2018).

Table 1. UAV application areas.

Field	Sub-application Areas
Agriculture and forestry	Crops and plants, trees, forests, soils, vegetation cover and plant growth
Atmospheric	Observation, and weather analysis and pollution
Military	Intelligence, border control and ammunition transport
Cultural	Protection of historical sites and archaeological studies
Environmental monitoring	Volcanic studies, soil, water environments, drainage, and rural roads and geological infrastructure
Logistics	Cargo
Disaster monitoring	Hurricane, typhoon, tornado, earthquake, fire, nuclear leak, waste detection, flood, avalanche and landslide epidemics
Photogrammetry	Digital elevation model and 3d mapping, mosaics, orthophotos, and rectification, measurements and cadastral applications
Urban	Supervision, monitoring, road information, urban planning, building façade analysis and City land use
Wildlife	Fauna and flora

Research interest in UAVs technology continues to grow worldwide, driven by successful projects successful projects. Like traditional helicopters, quadcopters can hover in the air. Quadcopters combine the advantages of vertical flight vehicles, hovering capability and horizontal flight vehicles. They also provide advantages with improved stability and simpler design compared to conventional aircraft. A quadcopter has four rotors: two rotate clockwise, and the other two rotate counterclockwise, enabling flight. This configuration allows for smaller propellers, which store insignificant amounts of kinetic energy, thus reducing potential damage during operation (Carvalho, 2013; Çetinsoy et al., 2008). The versatile design options of four-rotor UAVs enable researchers to achieve diverse technical specifications.

Although increasing a multicopter's flight range through using a higher capacity battery is possible, the extra weight from the larger battery limits the flight time. Multicopter propellers force air to flow downward to generate thrust (Başaran, 2017). The reaction of the wings to the air is quite important. The propeller affects the thrust force, flight speed, maneuverability, and flight stability of the multicopter (Hell et al., 2018).

While several academic surveys exist in the literature on multirotor UAVs (B B V L and Singh, 2016; Chen et al., 2023; Fu et al., 2019; Magnussen et al., 2014), they primarily focus on optimization parameters like control systems and trajectory generation, with only limited coverage of hardware components (Borah et al., 2016; Seidu et al., 2024). Notably, these studies lack comprehensive analysis of software and communication systems. This paper addresses this gap by providing a thorough overview of multirotor UAV systems, with particular emphasis on the mechanical integration of quadcopters. The study begins with a detailed analysis of hardware components, including frame types, flight control board specifications, motor characteristics, electronic speed controller parameters, and propeller and their selection criteria. Following this, the paper examines software systems, covering autopilot software platforms, ground control station implementations used for mission planning and execution tools. The final section explores communication technologies, discussing radio frequency systems, WIFI capabilities, Bluetooth integration, and infrared communication, along with a comparative analysis of their advantages and limitations. This comprehensive examination of components and systems serves as an essential reference for researchers, engineers, and UAV enthusiasts engaged in the design, development, and application of multirotor UAV systems.

2. UAV Hardware

UAVs come in various shapes and sizes. Despite their different configurations, the fundamental components remain the same. These include the controller, motor, battery and charger, propeller, motor driver, frame, flight controller, and power distribution. Advanced models may incorporate video cameras, Global Positioning System (GPS), compass, barometer, sonar sensors, autonomous flight capabilities, and telemetry. Most UAVs also integrate a gyro and accelerometer with their sensors (Kılıç, 2014; Kutlu, 2019; Öngül, 2017). Figure 1 shows a connection diagram of a rotary-wing UAV (Pala, 2018).

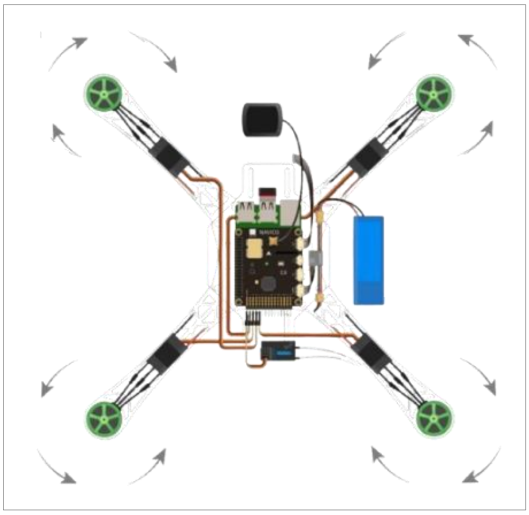

Figure 1. A connection diagram of a rotary-wing UAV.

2.1. Frame

The multicopter frame, also known as the body, is the skeleton of the UAV. The fundamental forces acting on the frame are gravity and air pressure.

2.1.1. Frame materials

Common materials for UAV frames include aluminum, wood, plastic, fiber glass, and carbon fiber (Elmeseiry et al., 2021). When considering the frame, it is essential to choose a material that is both lightweight and durable. The strengths and weaknesses of these materials are as follows:

a) **Wood:** A wooden frame is often used in such projects due to its low cost and light weight. However, wooden frames are significantly affected by weather conditions and are prone to breaking and warping. Additionally, mounting other components on a wooden frame can be challenging. Screws and other fasteners mounted on a wooden surface are likely to deform the holes if removed and reinstalled multiple times or if the wood warps (Altın, 2013).

b) **Carbon fiber:** Carbon fiber is an excellent material for UAV frames as it handles stress and deformation better than wood and is lighter than aluminum. However, it is not commonly chosen due to its difficulty in procurement and challenges with repair and maintenance (Altın, 2013).

c) **Aluminum:** While aluminum is widely used in modern UAV applications, its weight limitations lead manufacturers to seek alternative materials (Hairi et al., 2023).

2.2. Frame types

UAVs use three fundamental frame configurations for quadcopter:+-type, H-type and X-type (Peksa and Mamchur, 2024). Figure 2 shows the different quadrotor frame types: a) cross-shaped frame, b) H-shaped frame and c) plus-shaped frame.

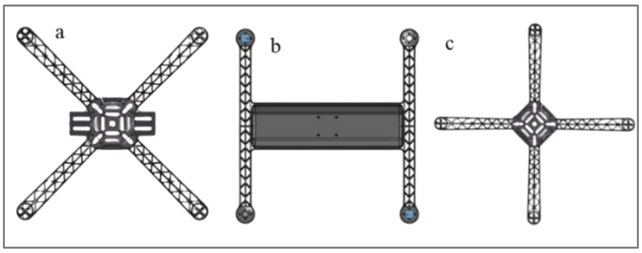

Figure 2. Quadrotor frame types: a) cross-shaped frame, b) H-shaped frame and c) plus-shaped frame.

a) **Cross-shaped frame:** X-type frame provides a more stable and easily manageable system during the construction. This feature drove early quadcopter design. The design requires less effort in controller system development because moments are equal on all axes, and the center of gravity is centralized. During pitch or roll movements, X-type quadcopters apply equal moments since the distances of the motors from the center axis are the same. The frame also enables a clearer field of view when capturing images (Kılıç, 2014).

b) **H-shaped frame:** This newer frame type offers durability and more space for additional payloads, benefiting users. However, H-type quadcopters face challenges with forces acting on the center of gravity can cause issues. To maintain consistent pitch and roll angles at the same angular velocity, equal moment values must be created. Consequently, during turns, motors farther from the rotation axis require more thrust, complicating the controller design (Batmaz, 2013).

c) **Plus-shaped frame**: The plus (+) frame configuration delivers enhanced maneuverability and control characteristics. However, this design concentrates impact force on a single arm during crashes (Al-Haddad et al., 2024). Some researchers further classify this frame type into X variations (D. A. Gandhi and M. Ghosal, 2018).

The primary difference between X-shaped and H-shaped designs is the varying forces applied to the motors during orientation changes. In static and steady positions, the forces applied to all motors in both X-shaped and H-shaped quadcopters are approximately the same.

2.3. Flight control board

This unit functions as the brain of the system, performing critical functions such as maintaining balance, reading control data, and battery monitoring. It is the most critical part of the system (Peksa and Mamchur, 2024). The flight controller in a UAV is typically an integrated circuit consisting of a microprocessor, sensors, and input/output pins. Flight control boards require parameter adjustments in the flight control software because they are not programmed to operate specific UAV types or configurations (Pala, 2018). The board calculates required motor speeds to meet user-desired movements and sends signals to the motors. It determines various criteria such as motor accelerations and target speeds and ensures quadcopter stability through angle and acceleration sensors. The system includes predefined scenarios for emergencies. For instance, some boards can return to the initial takeoff height and position when battery levels drop below critical levels. Some flight boards feature autonomous navigation on pre-programmed routes without user input. These boards include autonomous flight capabilities (Öngül, 2017). Figure 3 shows an illustration of a flight control board.

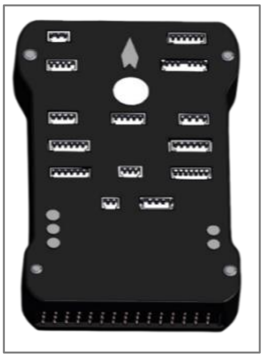

Figure 3. An illustration of a flight control board.

The first task of the flight control board is to receive data from the inertial measurement unit (IMU). The data produced by the IMU reaches the flight control board through various communication channels (Neumann and Bartholmai, 2015). These include protocols such as SPI, UART and I2C, or analog data transmission. The flight control board must receive this data for processing from the IMU (Podhradsky, 2012).

Common flight controller functions include (Kılıç, 2014):

a) **Gyrostabilization:** Helps keep the device stable and under the pilot’s control.
b) **Self-leveling**: Keeps the device stable in the air when the controller is released.
c) **Carefree**: Allows the device to be controlled according to its original orientation, even if its direction changes.
d) **Altitude hold:** Allows the device to maintain a specific distance from the ground without adjusting the throttle.
e) **Position hold:** Allows the device to hover at a specific location in the air.
f) **Return home:** Automatically makes the device land back at the takeoff point.
g) **Waypoint navigation:** Allows the device to follow predetermined points.

Controlling a quadcopter requires more complexity compared to airplanes. The flight controller manages the quadcopter using various sensors and telemetry systems. A flight control board may include accelerometers, gyroscopes, barometers, temperature sensors, current sensors, compasses, GPS circuits, voltage sensors, data recording elements, and OSD (On-Screen Display). These components can be external but maintain communication with the board. Flight controllers ensure stable flight and adjust motor speeds for various maneuvers (Elmas, 2019; Pala, 2018).

The basic sensor modules in the flight card are gyroscope, accelerometer, barometer and compass. Additional hardware like GPS modules, anemometers, and infrared sensors can enhance functionality and enable more precise flight.

2.3.1. Inertial measurement unit

The IMU is an electronic system embedded within the flight control board that measures the roll, pitch, and yaw angles of the aircraft (Tomaszewski et al., 2017). An IMU has degrees of freedom based on its data inputs and measurement axes. It primarily consists of an accelerometer and a gyroscope. Most IMUs combine a three-axis accelerometer and a three-axis gyroscope, creating a 6 Degrees of Freedom (6-DOF) IMU (Henderson et al., 2021). IMUs offer advantages over separate gyroscopes and accelerometers in managing measurement accuracy factors like drift and bias. Some IMUs incorporate a three-axis magnetometer, achieving 9 DoF. Adding a pressure sensor creates 10 DoF IMU modules (Filippeschi et al., 2017; Pala, 2018).

2.3.1.1. Accelerometer (Gyro)

UAV accelerometer measure static (gravitational) and dynamic (sudden acceleration or deceleration) accelerations along three axes. The sensor measurements uses gravitational acceleration g (9.8 m/s^2) or m/s^2 units (A. Zul Azfar and D. Hazry, 2011). Double integrating the output provides the position data, but drift may occur due to precision losses. The measurement range uses values of ±1g, ±2g, ±3g, ±4g, etc. Three-axis accelerometers detect gravity to determine downward direction which is crucial for rotary-wing UAV stability. The accelerometer typically resides on the flight control board (Altın, 2013; Çakıcı, 2019; Pala, 2018).

2.3.1.2. Gyroscope

A gyroscope measures angular velocity, representing movement around an axis. The measurement unit is expressed in degrees per second (°/s). It is used for direction estimation and adjustment. Like the accelerometer, a gyroscope cannot directly measure absolute angles and is subject to drift (Shaeffer, 2013).

2.3.1.3. Compass (Magnetometer)

An electronic magnetic compass measures the Earth's magnetic field along the x, y, and z axes to determine the UAV’s orientation relative to magnetic north. The drift angle of the gyroscope is corrected using information from the compass (Asif et al., 2024).

2.3.1.4. Pressure gauge (Barometer/Altimeter)

The altimeter sensor functions as a digital barometer that measures altitude using pressure levels. Sea level serves as the reference point. As altitude increases from sea level, atmospheric pressure decreases. The pressure sensor monitors this change to determine UAV altitude. Altimeter sensors output altitude data in mmHg, or directly in meters or feet. Most flight control boards combine pressure sensor and GPS altitude data to achieve more accurate altitude measurements (Çetinkaya, 2017; Pala, 2018).

2.3.2. External sensors

This section explains sensors that are not featured on the control board. These sensors allow for the acquisition of desired data with high accuracy.

2.3.2.1. GPS

GPS remains the most precise and fastest method for location determination. The method uses location data from GPS satellites to determine point coordinates either statically or kinematically (Colombo and Evans, 1998). It now includes data from Glonass and Galileo satellites. This method provides coordinates in the international terrestrial reference frame (ITRF-96) coordinate system and has advanced to provide faster, more accurate coordinate determination through the CORS-TR method (Altınışık, 2019). **Figure 4** shows GPS positioning schematic.

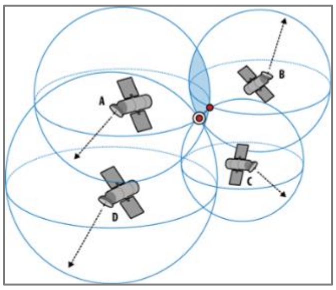

Figure 4. GPS positioning schematic.

Figure 5. A common GPS for UAVs.

There are 32 GPS satellites located 20200 km above Earth. These satellites regularly send time-stamped messages along with their position data to the Earth. GPS receivers use these messages to calculate their current position (Bretterbauer and Weber, 2003). GPS uses triangulation methods with satellites. While 27 satellites provide information, two-dimensional positioning required at least 3 satellites, and three-dimensional positioning needs at least 4 satellites. The intersection of these data points determines the current location which GPS sends to the device (Scott et al., 2016; URL, 2022d). Figure 5 illustrates a common GPS for UAVs.

2.3.2.2. Infrared sensor

Infrared sensors consist of two LEDs. One LED emits infrared light, while the other acts as a phototransistor, capturing the incoming light. The wavelength of the infrared beam can be adjusted. When the beam hits an object and reflects back onto the phototransistor, a signal is generated based on the intensity of the returning light (Kılıç, 2014). **Figure 6** shows the working principle of the infrared sensor.

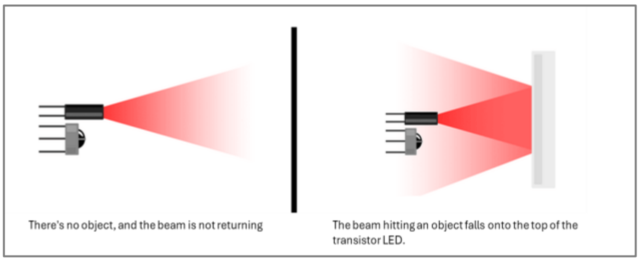

Figure 6. Working principle of the infrared sensor.

2.3.2.3. Anemometer

Anemometers are sensors that convert wind speed into electrical signals. There are three types of anemometers: cup, ultrasonic, and propeller.

a) **Cup anemometer:** Wind speed calculations use the time for the cup rotor to complete one rotation.
b) **Ultrasonic anemometer:** This design measures the time for sound waves to travel between transducers. The time difference determines wind speed.
c) **Propeller anemometer:** It operates similar to cup anemometers. When parallel to wind direction, it measures horizontal wind speed, and when perpendicular, it measures vertical wind speed.

Cup anemometers remain the most used type for wind speed measurements.

2.3.2.4. Voltage and current meter

The motor and control board are powered by a battery. To monitor this supplied energy, voltage and current meters are used.

2.4. Power distribution board

The power distribution board delivers energy to UAV components (T. Kidd et al., 2020). Motor operation requires power control units due to high currents (10 to 150 amperes) (Kaymak, 2019). Power modules vary based on system requirement. These modules regulate battery voltage, ensuring proper energy transfer to the control board for flight system operation (D. Erdos et al., 2013). An illustration of a common power distribution board for UAVs is presented in Figure 7.

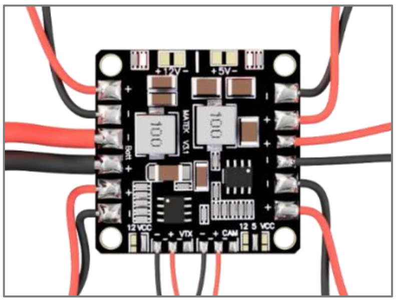

Figure 7. An illustration of a common power distribution board for UAVs

2.5. Motor

Motors provide thrust in quadrotors. While early quadrotors used gasoline, electric motors now dominate due to affordability and environmental benefits (Bin Junaid et al., 2018; Elmeseiry et al., 2021). UAV brushless DC motors use four-digit labels like AABB. AA represents stator width (diameter), and BB represents stator height (Balamurugan et al., 2020). In brushless motors, these measurements refer to copper winding dimensions inside the stator, unlike brushed motors, which use overall motor size. Larger width or height increases permanent magnet and electromagnetic coil sizes. Increased stator height emphasizes magnet size over coil size, while increased width prioritizes coil size. Extended stator size creates more surface area, intersecting more magnetic fields and improving cooling. These motors achieve higher power levels and speeds. Width increases add iron and copper, enhancing torque and efficiency (Elmas, 2019).

Motor bodies display codes like 12N14P**,** where N (poles) and P (magnets) indicate component counts. The number before N shows stator winding count, while the number before P shows permanent magnet count. Different motor sizes use varying pole and magnet numbers. Brushless DC motors, being three-phase, require pole numbers in multiples of 3 (9, 12, 15, 18) (Romano, 2018). Motors convert DC voltage to AC through three wires. Swapping output wires reverses rotation direction (Kaymak, 2019). UAV motor selection considers K_V rating, torque, weight, current draw, and connection mechanism.

2.5.1. Connection mechanism

Motor and propeller matching **is** crucial for design. UAV motors operate either inward or outward rotating. Inward rotating motors turn their internal rotor, while outward rotating motors turn their outer surface. Outward rotating motors offer easier propeller installation and system integration. Propellers attach to motors via plastic bands, connecting fittings, or shaft clamps. Secure attachment prevents flight vibrations (Batmaz, 2013).

a) **Brushed motor (inward rotating motor):** These convert electrical energy to mechanical energy by rotating windings inside fixed outer magnets. The rotor turns while stator windings remain stationary. Brushed refers to the armature-power cable connection. These motors show efficiency losses and shorter lifespans from brush and commutator wear (A. Junid et al., 2017). **Figure 8** shows an illustration of a brushless motor.

Figure 8. An illustration of a brushless motor.

b) **Brushless motor (outward rotating motor):** An ESC drives brushless motors (Eugene et al., 2019). The system creates a three-phase electromagnetic field between armature and power cables to generate rotation. Without brushes, these motors have less friction and quicker operation, achieving higher efficiency (typically over 80%). This efficiency increases cost for both motors and ESCs (A. Junid et al., 2017). **Figure 9** shows an illustration and components of a brushed motor.

Figure 9. An illustration and components of a brushed motor

Brushless motors provide longer operational life, higher efficiency, and eliminate additional gearboxes needed by brushed motors for high-speed torque. Their reduced friction enables up to 99% efficiency, extending flight time by approximately 50% compared to brushed motors (Öngül, 2017).

2.5.2. K_V rating

K_V defines the motor velocity constant in brushless DC motors, showing revolutions per minute (rpm) at 1 volt with no load. Simply put, K_V means revolutions per volt. Adding a propeller reduces RPM due to air resistance. Motors with higher K_V ratings attempt to spin the propeller faster and may draw more current. Higher K_V motors spin propellers faster but may draw more current. This requires larger propellers with lower K_V motors and smaller propellers with higher K_V motors. KV rating correlates with stator copper wire winding count. Magnetic strength of permanent magnets also affects KV rating; stronger magnets increase KV. Using high KV motors with oversized propellers forces operation as if with smaller propellers, demanding more torque, increasing current draw and risking overheating. Heavier UAVs typically use medium to low KV motors, while lighter UAVs use high KV motors (Elmas, 2019). For example, a 330 KV motor at 10 volts spins at 3300 RPM. With a 3S LiPo battery (12.6 V fully charged), the same motor reaches 4158 RPM without propeller (330 x 12.6).

2.5.3. Motor torque

Low K_V motors produce lower speeds but higher torque, while high K_V motors generate higher speeds and lower torque. High-torque motors respond more quickly due to their ability to change speeds rapidly, providing faster and more immediate reactions. In contrast, lower-torque motors exhibit slower, smoother responses (Elmas, 2019).

2.5.4. Weight

Another critical factor in motor selection is weight. The lightest motor is usually preferred in design. However, among motors with the same features, the lighter one often comes at a higher cost.

2.5.5. Current

Another important design parameter is the current drawn by the motor. Larger motors typically draw higher currents. Motors that draw high currents may operate less efficiently at lower speeds. In such cases, a smaller motor might enable the

UAV to take off more easily, while a larger motor might require more current to operate effectively (Batmaz, 2013).

2.6. ESC

ESCs control motor speeds (Green and McDonald, 2015). They primarily serve brushless motors, though brushed motors can operate without them using a flight control board power transistor (Özen, 2019). ESCs rank among the most crucial components and frequently appear in accident statistics. This necessitates high-quality, recommended products. Professional systems require high-amperage, quality ESCs (Kılıç, 2014). ESCs have specific characteristics and parameters that are essential for their selection. Generally, the following parameters are important when choosing an ESC (Öngül, 2017). ESCs can be used for both brushed and brushless motors. For brushless motors, ESCs are connected with three wires, while brushed motors are connected with two wires (URL, 2022a). An illustration of an ESC is given in Figure 10.

Figure 10. An illustration of ESC.

2.6.1. Voltage

The maximum voltage supported by ESCs indicates the maximum battery voltage they can handle. Exceeding this voltage may damage the ESC (Öngül, 2017).

2.6.2. Maximum burst current

An ESC handles maximum short-term current in bursts (about 10 seconds) but must not exceed its maximum rating. However, the maximum current should not be exceeded. Connecting motors that draw more current than this value could damage the ESC. The term burst varies and should be specified in parentheses. This value is not fixed due to various factors (Elmas, 2019; Öngül, 2017). ESCs are typically chosen based on the motor's expected peak current. An ESC with a rating about 1.2-1.5 times the motor’s maximum burst current is usually sufficient (Batmaz, 2013). For instance, a 2206 motor with a 5030 propeller draws 10 A at full thrust with a 4S LiPo battery, so a 12 An ESC would be adequate. However, if a 6045 propeller is used with the same motor, the maximum current draw might reach 20 A, in which case a 20 An ESC would be safer (Elmas, 2019).

2.6.3. Maximum continuous current

This is the maximum continuous current that ESC can support. ESCs can handle this current for extended periods. However, exceeding this value continuously may damage the controller. For UAVs and slow-flying aircraft, it is important to consider the maximum continuous current when selecting an ESC (Öngül, 2017).

2.6.4. Maximum rpm

This is the maximum rpm that an ESC can support. The rpm value specified might not directly correspond to the motor's rpm, as it is usually given along with the pole count. The maximum rpm is inversely proportional to the number of poles. For example, a controller rated for 240.000 rpm - 2 poles can operate a 4-pole motor at a maximum of 120.000 rpm (Öngül, 2017).

2.6.5. Pulse width modulation

Pulse width modulation (PWM) represents pulse width in square waves (Batmaz, 2013). It indicates the frequency range of the input signal that an ESC processes. Signals beyond this range remain unprocessed. This value is related to the signal from your radio device or flight controller (Öngül, 2017). ESCs connect to the control board and are managed via a PWM or digital signal (Özen, 2019). ESCs operate using PWM, with an update rate typically set at 50 Hz, which is sufficient for normal quadcopter operations. However, for applications requiring more agility and higher movement capabilities, ESCs with higher update rates should be used. Special or commercially available ESCs can operate at frequencies up to 450 Hz, or even 1 kHz with I2C protocol communication (Batmaz, 2013).

2.7. Battery and charger

The main limitation of a quadcopter is its flight time. Typically, a quadcopter's flight time is around 20 minutes. However, this time significantly decreases when carrying heavy payloads. With only the main components present, flight time can approach one hour (Carvalho, 2013). An illustration of a typical battery for UAVs is shown in Figure 11.

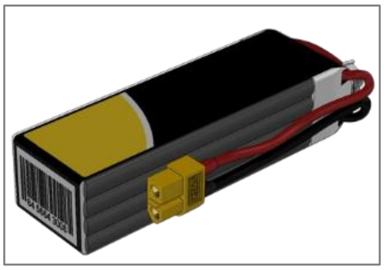

Figure 11. An illustration of a typical battery for UAVs.

Lithium Polymer (LiPo) batteries are recommended for multicopter systems (Kılıç, 2014). These batteries are commonly used in robots and are rechargeable (Çetinsoy et al., 2008). An illustration of a charger for battery of UAVs is presented in Figure 12. Here are some important considerations for battery use (Uz, 2019).

a) **Avoid constant charging:** Batteries should not be left on constant charge.
b) **Avoid extreme temperatures:** Batteries should not be exposed to excessive heat or cold.
c) **Battery type:** Use the type of battery suitable for the application.
d) **Charger:** Ensure that the charger is compatible with the battery used.
e) **Avoid short circuits:** Prevent short circuits in the battery.
f) **Do not fully discharge:** Batteries should never be left in a completely discharged state.

Figure 12. An illustration of a charger for battery of UAVs.

2.7.1. Battery technologies

Today, numerous battery technologies power UAVs (Altın, 2013; Uz, 2019). Each of these batteries has its own advantages in different areas. However, this section will discuss their pros and cons relevant to the study. The discussed batteries are as follows:

a) **Alkaline batteries:** These provide the most basic battery power. Using alkaline batteries means the quadcopter depends on non-rechargeable power. They work best where recharging proves impossible, such as in rural areas, forests, deserts, and other locations without power sources. These batteries are inexpensive and widely available. The main drawback concerns their low voltage and limited charge capacity. Most alkaline batteries are 1.5V with 700mAh capacity (Altın, 2013). For example, powering a motor needing 10.5V and 8A requires 7 batteries. Long-term alkaline batteries use proves impractical due to constant replacements, creating high costs and substantial waste.

b) **Nickel-Metal Hydride (Ni-MH) batteries:** These batteries dominate cordless phones. They represent the first rechargeable battery type, known for durability and reliability. They cost more than alkaline batteries and hold charge for shorter periods. Design challenges emerge because Ni-MH batteries max out at 9.5-10V. With DC motors, back electromotive force creates a 2-2.5V voltage drop, affecting ESC and motor power. Using two series-connected batteries adds weight. Ni-MH batteries stop working below certain capacity levels and need longer charging times versus other rechargeable types. They suit low-power systems where charging speed matters less, making them suboptimal for UAV projects (Altın, 2013; Uz, 2019).

c) **Nickel-Cadmium (Ni-Cad) batteries:** These feature low internal resistance, enabling high current output. They harm the environment. UAVs need high-energy-density power sources, but Ni-Cad batteries deliver low energy, requiring more units and increasing weight. They cost less and charge faster than Ni-MH batteries. Common in older laptops, they provide 1.2V nominal voltage. A 10.5V motor needs nine series-connected Ni-Cad batteries, each requiring individual charging. They share Ni-MH drawbacks for UAVs, offering only lower cost and faster charging benefits (Altın, 2013).

d) **Nickel-Zinc (Ni-Zn) batteries:** These power electric bicycles and vehicles but now serve smaller devices like cordless phones. They match Ni-MH and Ni-Cad sizes. Their 2.5-hour charging time makes them potential Ni-Cad alternatives (Altın, 2013).

e) **Lithium-Ion (Li-ion) batteries**: Li-ion batteries are among the most used battery types, along with LiPo batteries. They have high energy density but can be hazardous if not used properly. Li-ion batteries used in portable electronics are usually based on lithium cobalt oxide. Factors such as temperature, discharge current, charging current, and state of charge affect their lifespan. Li-ion batteries have low instantaneous high-current capabilities and can pose safety issues due to their high energy storage (Altın, 2013; Uz, 2019).

f) **Lithium-Polymer (LiPo) batteries:** Lithium-Polymer (LiPo) batteries represent the most advanced rechargeable battery currently available. They provide higher energy density per cell compared to predecessors though with slightly heavier. While conventional batteries deliver 1.2V to 1.5V per cell, LiPo batteries provide 3.6V to 4.7V per cell. LiPo batteries consist of series-connected individual cells, each with a nominal voltage of 3.7V. This enables higher-voltage power sources using fewer cells, reducing overall weight. The primary limitations of LiPo batteries involve cost and safety considerations. They exceed other types in price and permanent damage from rapid discharge. Each LiPo cell contains internal resistance (IR), limiting current draw according to Ohm's Law ($V = I \times R$ and $P = I^2 \times R$). Higher resistance increases power loss and heat generation, risking to overheating and damage during high-current operation (Altın, 2013; Elmas, 2019).

2.7.2. Cell count

The battery voltage is named according to the number of cells (S) in the battery (Elmas, 2019; Kaymak, 2019; Öngül, 2017). For example, a 14.8V battery is referred to as a 4-cell or 4S battery. The relationship between the number of cells and voltage is shown in Table 2.

Table 2. Relationship between number of cells and voltage

1S = 1 cell = 3.7V	2S = 2 cell = 7.4V	3S = 3 cell = 11.1V
4S = 4 cell = 14.8V	5S = 5 cell = 18.5V	6S = 6 cell = 22.2V

Voltage determines motor rpm. Higher cell count batteries increase UAV speed when motors and Electronic Speed Controller (ESC) support higher voltage (Elmas, 2019). After charging, each cell can provide up to 4.2V, but efforts should be made to avoid dropping below 3.4V during use, as this shortens the battery's lifespan. If the cell voltage falls below 3V, the cell is likely to quickly become unusable (Batmaz, 2013).

A LiPo battery combines one or more cells, each providing 3.7V nominal voltage. Series and parallel connections modify battery voltage and current capacity (Pala, 2018). **Figure 13** shows the schematic of batteries with a configuration of 4 series and 2 parallel (4S2P) connections (Pala, 2018).

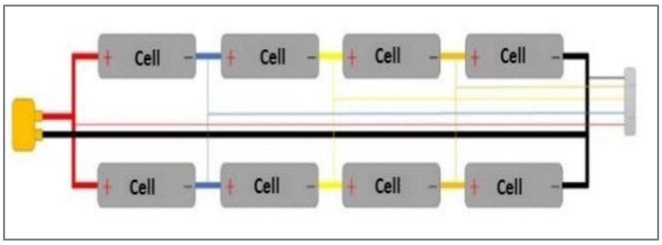

Figure 13. Schematic of a 4S2P battery with parallel and series connections

2.7.3. Capacity

Battery capacity uses mAh (milliampere-hours) measurements**.** mAh shows one-hour current draw before depletion (Elmas, 2019). For example, a 1300 mAh LiPo battery will be fully depleted in one hour if a constant current of 1.3A is drawn. If the current drawn is 2.6A, the time will be halved (1.3 / 2.6 = 0.5).

2.7.4. Discharge rate

The discharge rate (C rating) represents continuous discharge in LiPo batteries. Manufacturers print this rating on battery fronts. The C rating determines safe maximum constant current draw (Elmas, 2019):Maximum Current = Capacity x Discharge C Rating For example, a 3S 1000mAh 20C discharge rate LiPo battery can safely provide a maximum current of 1000mAh x 20C = 20A.

2.7.5. Charge rate

The charge rate is the inverse of the discharge rate, indicating the maximum constant current that can be safely applied during battery charging. The standard rate is typically 1C. The formula for calculating the charge rate is: Maximum Charging Current = Capacity x Charge C Rating. For example, a 3S 1000mAh LiPo battery with a 1C charge rate can safely accept a maximum charging current of 1000mAh x 1C = 1A

Goli et al. (Goli et al., 2023) conducted a comprehensive analysis of various motor-propeller-battery configurations, examining three motor types, five propeller designs, and two battery capacities. Their testing revealed that the 6000 mAh battery (B2) demonstrated superior performance characteristics compared to the 3300 mAh battery (B1), achieving higher motor speeds with lower current consumption to generate equivalent thrust. The study identified optimal component combinations, with the 12-inch diameter propeller (P4) achieving efficiency ratings of 12.9% with B1 and 11.4% with B2. The 700 KV motor (M1) proved most efficient, reaching 64.29% efficiency when paired with B1 and 62.01% with B2. Notably, the B2 configuration significantly enhanced payload capacity, supporting 5.82 N compared to B1's 2.02 N. Flight endurance tests, both with and without payload, consistently showed better performance with the B2 battery configuration.

2.8. External hardware

2.8.1. Arduino microcontroller

Arduino is an open-source microcontroller board produced by an Italian company, featuring a programmable microprocessor. Its simplicity, ease of programming, and Input/Output pins make it suitable for small to medium-sized projects (Bulut, 2019). An Arduino microcontroller can be programmed to read various data from UAV. For example, it can monitor the rpm data during flight through sensors or save collected data to an external SD card via an SD card module. Figure 14 depicts an illustration of Arduino microcontroller.

Specialized UAV hardware configurations can be effectively deployed for precision agriculture applications, particularly in weed detection and management. A notable example is demonstrated in Nagothu et al. (Kumar Nagothu et al., 2023)'s research, where they integrated a microcontroller and camera system for automated weed identification in agricultural fields. Their implementation leveraged machine learning algorithms to precisely locate weed infestations that could potentially impact crop yields. The system demonstrated impressive performance, achieving 91% accuracy in testing conditions and 94% accuracy with training data, highlighting the effectiveness of UAV-based solutions in agricultural monitoring and management.

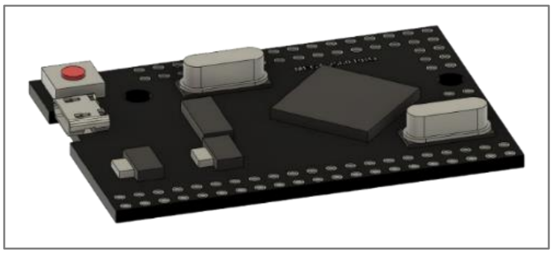

Figure 14. An illustration of Arduino microcontroller.

2.8.2. Secure digital card module and external memory card

A secure digital (SD) memory card is a data storage device. It was first introduced by SanDisk in 2001, based on the development of multimedia card technology. The SD card module can store operation results in text file format. This module records real-time data from other components (Bulut, 2019). An illustration of SD card module is given in Figure 15.

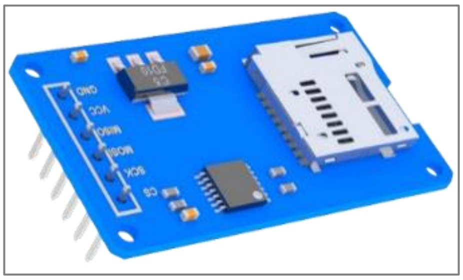

Figure 15. An illustration of an SD card module.

2.9. Motion control

There are two methods for controlling UAVs. It can be controlled directly with a remote control or through various software like ground control stations via devices such as computers, tablets, or smartphones. The choice between these methods depends on user requirements. The fundamental difference between the two systems is autonomous operation capability. In autonomous operation, the system operates independently without pilot intervention. The UAV executes pre-planned routes by itself (Raimundo, 2016; URL, 2022b).

2.9.1. Remote control and transmitter/receiver

The pilot commands the UAV using a control system that has existed for approximately 60 years. RC systems manage UAVs and transmit data including direction, motor speed, and servo controls. RC communication requires a transmitter and receiver. UAVs use four basic channels: roll, pitch, yaw, and throttle. Additional channels enable functions like arming/disarming the motors, changing flight modes, controlling camera equipment (gimbal), and releasing payloads (Pala, 2018). While remote control technology has evolved from single channel to multi-channel, and from AM, FM, and PPM to 2.4 GHz, the basic principles remain unchanged (Kılıç, 2014). Figure 16 shows an illustration of a remote-control device. Commands are transmitted from the radio transmitter on the controller to the receiver (Pala, 2018).

Figure 16. An illustration of a remote-control device.

Communication between the controller and the receiver uses various protocols. The receiver forwards signals to the controller, which then manages the UAV based on the RC signals. Telemetry-equipped controllers can be used. For example, critical information like the UAV's battery status can be transmitted to the controller in real time (Pala, 2018). An illustration of a remote-control transmitter is presented in Figure 17.

Figure 17. An illustration of a remote-control transmitter.

2.10. Propeller

A propeller is a critical component in aerial vehicles, converting rotational motion into propulsive force (Çelebi et al., 2024; H. N. P. Wisudawan et al., 2024). Effective propeller design requires a balance of durability, lightweight construction, rigidity, and consistent performance across various operating conditions. Propellers come in two rotational configurations: clockwise (CW) and counterclockwise (CCW). Their specifications are typically expressed in a diameter x pitch format, where pitch represents the theoretical distance the propeller would travel in a single complete rotation (M. B. Swedan et al., 2023).

Gajula and Tara (Gajula and Tara, 2023) conducted a study on optimizing motor-propeller combinations for a 500mm quadcopter frame. They evaluated three propeller variants (carbon fiber 8045, nylon 9045, and nylon 1045) paired with two motor options (2213 935KV and Generic 2212-1000 KV). Through systematic testing and precise calibration, they achieved remarkable improvements in performance. The optimized configuration, utilizing a Nylon 1045 propeller with a Generic 2213-935 KV motor, demonstrated a 43% increase in flight time compared to their initial efficient setup. This optimization extended the flight duration from 16 minutes to 23 minutes, highlighting the critical importance of component selection and proper system calibration in UAV performance.

3. Software

The software used on UAVs and ground stations varies. This software can be categorized into two groups: the software used on the flight control board of the UAV and the software used on the ground station.

3.1. Flight control board software

Flight control board software typically focuses on specific hardware, technology, or purposes. Some of the software used in flight control boards include Ardupilot, Baseflight, MultiWii, Cleanflight, Betaflight, iNav, OpenAero, and KISS (Pala, 2018).

3.1.1. Ardupilot

Ardupilot is the leading flight control board software for rotary-wing aircraft. The software controls multiple vehicle types, including fixed-wing and rotary-wing aircraft, hybrid vehicles, ground vehicles, and boats. Ardupilot software comprises three sections: Ardupilot for fixed-wing aircraft, Arducopter for rotary-wing vehicles, and Ardurover for ground-based vehicles (Peksa and Mamchur, 2024).

3.1.2. Baseflight

Baseflight was one of the first widely used 32-bit flight control board software, based on the 8-bit MultiWii flight controller software. However, Baseflight is no longer being updated today (Pala, 2018).

3.1.3. Multi Wii Copter

Multi Wii Copter is an autonomous system specifically developed for rotary-wing UAVs. It is open source, with all developments carried out by users, allowing observation of the program's evolution over time. The open-source nature of the system provides high software flexibility. However, Multi Wii Copter lacks consistency in advanced functionalities (Kumar et al., 2015).

3.1.4. Cleanflight

Cleanflight emerged an improved and user-friendly version of Baseflight aiming for wide use and reliability. Over time, Cleanflight evolved into Betaflight and iNav, which incorporated many new features, and was later merged as Cleanflight 2.0. However, there has been a significant slowdown in its development and updates (Pütsep and Rassõlkin, 2021).

3.1.5. Betaflight

Betaflight supports many flight control boards. It serves rotary-wing vehicles and fixed-wing FPV (First Person View) aircraft. The software benefits racers, acro/freestyle pilots, and beginners, remaining open source. The developers of Betaflight focus on reading sensor data at 32 kHz and sending this data to the motor to operate the flight controller and vehicle at the highest speed and performance (Pütsep and Rassõlkin, 2021).

3.1.6. iNav

iNav emphasizes navigation and autonomous vehicle features, including waypoint missions, return-to-home (RTH), and even autonomous landing. This open-source software incorporates features from Cleanflight with regular updates. It supports multi-rotor rotary-wing and fixed-wing vehicles (Pütsep and Rassõlkin, 2021).

3.1.7. Pixhawk

Pixhawk represents an open-source autopilot system for affordable autonomous aircraft. Pixhawk uses the same telemetry protocol (MAVLink) as Ardupilot, making it compatible with ground station software like QGroundControl. Both software systems are similar in terms of autonomous flight capabilities. The main difference lies in their commercial licensing: modifications to Pixhawk do not need to be disclosed as open-source, whereas developments made with Ardupilot for commercial use must be shared as open-source code (Peksa and Mamchur, 2024).

3.1.8. Keep It Super Simple

Keep It Super Simple (KISS) comes from Flyduino, which has been making rotary-wing vehicle components since 2011. It is closed-source and developed more slowly compared to open-source software. KISS is one of the most suitable flight control board software options for racing and acrobatic flight (Pala, 2018).

3.2. Ground control station systems

A ground control station serves as the central command interface software that enables operators to manage various aspects of UAV operations. It provides comprehensive functionality for mission planning and execution, real-time telemetry data monitoring, and direct flight control command issuance. Through this interface, operators can effectively oversee and manage autonomous UAV operations while maintaining continuous monitoring of flight parameters and system status (Aliane, 2024). UAVs operate using various remote control methods such as computers, tablets, autonomous software, or smartphones, and can operate under complete artificial intelligence (AI) control (Özen, 2019). The autopilot, or auto pilot, refers to a series of control mechanisms designed to keep an aircraft continuously stable in a horizontal position at predetermined coordinates and to issue commands to return to its previous position in case of changes. Ground station software manages tasks such as mission loading, mission execution, obtaining vehicle location information, and reviewing flight records (Pala, 2018). The term autopilot is derived from automatic pilot. Today, it means that all operations typically performed by a pilot are handled by an automated device. Autopilots function in air, land, sea, and space vehicles (Batmaz, 2013).

An autopilot system is a feature of the control board. When selecting a control board, it is important to consider whether the board includes autopilot software or if it can be added through later software updates. During route missions, maintaining stability can be challenging due to various internal (software or hardware) and external (weather conditions) factors. This difficulty is exacerbated with manual control. Automated flight and processor-managed control enhance the stability and performance characteristics of the quadcopter.

3.2.1. QGroundControl

QGroundControl enables autonomous flight control and mission planning for UAVs. As open-source software, it allows users to contribute to or customize its features for specific UAVs. QGroundControl supports all vehicle types (rotary-wing, fixed-wing, VTOL, etc.) compatible with ArduPilot and Pixhawk Pro. It functions across all platforms and mobile devices (T. Dardoize et al., 2019).

3.2.2. Mission Planner

Mission Planner is a fully featured ground station application. Through Mission Planner, flight data monitoring, mission planning, and flight simulation are possible. Multiple target points at various altitudes can be defined. Flight log files can be downloaded and reviewed (Peksa and Mamchur, 2024).

Suparta et al. (Suparta et al., 2023) developed an automated delivery system using a quadcopter equipped with MissionPlanner autopilot software. Their hardware configuration consisted of an APM 2.8 flight controller, Ublox NEO M8N GPS module with compass, Racerstar 920kV 2-4S Brushless Motors, Flysky FS-iA6B receiver paired with FS-i6 transmitter, DJI F450 frame with landing skids, and a 3300 mAh 35C LiPo battery. The payload system incorporated a BME280 sensor array controlled by an Arduino Uno R3 SMD. Navigation was implemented through waypoint programming using Mission Planner's Google Maps interface, with the BME280 barometer providing altitude verification at each waypoint. Testing demonstrated a 5% average positional error at waypoints, validating the viability of system for precise cargo delivery applications.

3.2.3. APM Planner 2.0

APM Planner 2.0 combines the user-friendly interface of Mission Planner with the multi-platform capabilities of QGroundControl software (Pala, 2018).

3.2.4. EZ-GUI

EZ-GUI is ground station software compatible with iNav, Cleanflight, Betaflight, and MultiWii-based flight controllers. It transmits flight control board data to the ground station. The software can perform mission loading. Its Android compatibility enables mobile devices to function as ground stations in the field (Pala, 2018).

4. Communication System

The first step in establishing a communication system is deciding the conditions for UAV communications. Depending on the design, UAVs can send data to the user during or after flight**s**. Similarly, a UAV may complete the flight without intervention after pre-flight task upload**s**, or the user can send commands to the UAV during flight (Batmaz, 2013).

Telemetry, by definition, refers to the remote monitoring or control of a system or facility, either wired or wireless. In UAV systems, telemetry transmits data such as battery status, altitude, speed, and position. In complex UAV systems where long-distance image and data transmission is required, high-gain and powerful receiver systems and directional antennas are needed. The size of these systems may increase due to the need for encrypted data transmission (Kılıç, 2014). The most significant advantage of an unmanned aerial vehicle is its remote controllability. During remote control, signals are sent to the receiver according to the user's requests via a transmitter, and these signals are interpreted through a microprocessor to control the UAV. Telemetry technologies include radio frequency remote control, Bluetooth control, computer control via wireless connection (WIFI), and infrared control systems. Before using these technologies, factors such as cost, application difficulty, and communication with microprocessors should be considered (Altın, 2013; Hoang and Poon, 2013) A general comparison of telemetry technologies for remote control is provided in Table 3 (Altın, 2013).

Table 3. Comparison of telemetry technologies.

Type	Radio Frequency	Wi-Fi	Bluetooth	Infrared
Operating Voltage	9-12V DC	9-12V DC	9-12V DC	6-9V DC
Communication Range	MHz	GHz	GHz	kHz
Average Price	Low	High	High	Low
Usage Difficulty	Medium	Medium	Medium	Low

4.1. Radio frequency

Radio frequency (RF) control uses radio waves at specific frequencies sent to a radio frequency receiver. The receiver uses a decoder to ensure that transmitted frequency signals are not interfered with or stopped by other frequencies emitted by hundreds of devices in the location. RF motion control technology has both advantages and disadvantages. Among the advantages: Unlike other motion control technologies, RF technology does not require the receiver to have a direct line of sight to the transmitter; hence, obstacles like walls do not negatively affect the signals sent to the receiver. RF technologies offer long ranges of communication, allowing for control from considerable distances. Since radio frequencies are not affected by light or weather conditions, they are ideal for outdoor environments. However, RF technology also has its disadvantages. Other devices operating on the same frequencies can interfere with the RF signals. Another drawback is security; transmitted signals can be detected by other receivers. The higher cost of RF technology can be a disadvantage for budget-constrained projects. Additionally, the slower speed of communication between the receiver and transmitter compared to other technologies can be a drawback. Despite these disadvantages and the higher cost, RF technology remains indispensable for projects requiring remote control (Altın, 2013).

Telemetry is an essential communication device for autonomous vehicles. This communication is achieved with one module on the vehicle and another on the ground. The ground pilot draws the necessary flight path for autonomous flight, and the ground telemetry module communicates with the vehicle telemetry module, sending this information to the control board (Özen, 2019). Radio-based telemetry, as shown in Figure 18, is used for data transfer between the unmanned aerial vehicle and the ground station, allowing for remote monitoring of the vehicle (Pala, 2018).

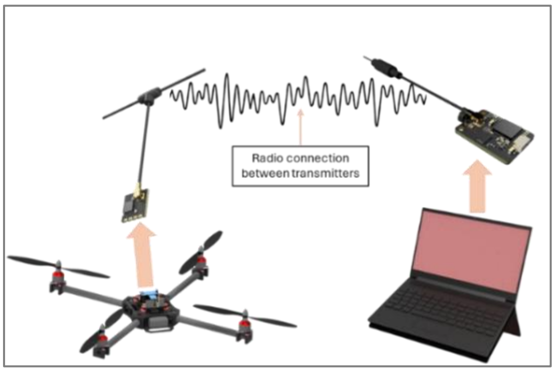

Figure 18. Telemetry system.

Varun et al. (M. Varun et al., 2023) conducted research on telemetry implementation in quadcopter systems, demonstrating how telemetry capabilities enable real-time remote monitoring and system control. Their findings highlighted the significant value of telemetry data in analyzing UAV performance metrics and operational behavior, providing operators with crucial insights for effective drone management and mission execution.

4.2. WIFI

This technology, commonly known as WIFI, derives its name from the initials of Wireless Fidelity (URL, 2022c). It enables communication at higher frequencies. WIFI allows different computers or devices to communicate wirelessly over a shared network. WIFI uses radio waves, operating at 2.4GHz, 3.6GHz, or 5GHz. WIFI adapters convert digital code into radio signals for communication and then interpret incoming radio signals back into digital codes. The advantages of WIFI communication include the lack of need for cables, as communication is done wirelessly. WIFI supports connections with multiple devices and allows for multi-point control. Additionally, Wi-Fi includes security measures such as firewalls to block external interference or unauthorized access, providing a secure control process. However, WIFI also has disadvantages. As the distance from the transmitter increases, the speed and accuracy of the connection can be significantly affected. WIFI technology is also quite expensive. Devices operating with WIFI consume more power compared to those using other communication technologies, leading to larger power consumption and battery size, and shorter active operation time (Altın, 2013).

4.3. Bluetooth

Bluetooth technology, like WIFI and radio frequency technologies, uses radio waves for communication between the transmitter and receiver. Due to its widespread use, Bluetooth provides an alternative method for controlling UAVs. The advantages of Bluetooth include flexibility in controlling the UAV using devices like computers, PDAs, and mobile phones, as Bluetooth is commonly found in these devices. Bluetooth is also easy to use, and its low power consumption benefits battery life. The range of Bluetooth devices depends on the power used; at 100mW, the range is 100 meters; at 2.5mW, 22 meters; and at 1mW, it is 6 meters, with 1mW modules being the most common. The maximum range is typically limited to 50 meters. However, Bluetooth has some disadvantages, such as lower data transfer capacity and potential security issues. A Bluetooth device may automatically attempt to connect to other Bluetooth devices, which can be a security concern (Altın, 2013; ArduPilot, 2020).

4.4. Infrared

Infrared technology uses light emitted by an LED to send signals to receiver devices for motion control. Typically, infrared motion control transmitters operate between 32 and 40 KHz. The transmitter communicates with the receiver by sending pulses in binary code via infrared light, which are then decoded by a microprocessor to fulfill the user's commands. The advantages of infrared technology include low power consumption, making it suitable for controlling many devices during the day. It is also inexpensive, integrates easily with other devices or microprocessors, and is generally compact and less affected by signals from other devices. However, infrared technology has limitations. Like television remote controls, infrared transmitters and receivers must have a direct line of sight. Any object, such as a person or wall, blocking the path between the transmitter and receiver can interrupt communication. The range of infrared technology is shorter compared to other technologies, and communication performance decreases with increased distance between the transmitter and receiver. Additionally, environmental factors like sunlight, rain, smoke, and fog can degrade transmission quality between the transmitter and receiver (Altın, 2013).

4.5. Flight control software

To enable a UAV to perform autonomous flight missions, it must be equipped with four fundamental electronic components: an autonomous flight-supporting flight control board, a GPS transmitter and receiver, an IMU for converting

GPS data, and telemetry devices for transmitting this data to other targets. These components are essential for autonomous vehicles, with GPS being mandatory. The hardware and features fully support the selected equipment. During route navigation, maintaining stability can be challenging due to various internal (software or hardware) and external (weather conditions) factors. This challenge is particularly pronounced during manual control. Pre-defined automatic or autonomous flight, where all control is managed by the processor, enhances the stability and performance of the quadcopter.

5. AI based applications

AI has emerged as a transformative technology that imbues machines with intelligence, enabling them to perform tasks with capabilities that can surpass human performance. The integration of AI within UAV networks presents both challenges and opportunities in modern applications (Aliane, 2024). AI methodologies in UAV applications can be categorized into two distinct levels of intelligence. The first level encompasses fundamental methods that enable predictable environmental responses, allowing UAVs to operate according to specific performance metrics. The second level comprises more sophisticated methods that enable UAVs to interact with their environment and make autonomous decisions in unpredictable conditions (S. Rezwan and W. Choi, 2022). This integration of AI into UAVs enhances their communication capabilities, networking efficiency, and flight safety, ultimately improving their service quality in IoT applications (N. Cheng et al., 2023). While AI-based UAV network design is an ongoing research area, AI-based UAV technology focuses on various areas, including:

a) **Security and privacy issues:** Security concerns in UAV systems require a comprehensive approach across multiple levels including hardware, software, communication, and sensor systems (Mekdad et al., 2023). Modern AI-based solutions are being developed to address various security threats, particularly focusing on cyber-physical attack prevention (Sarkar and Gul, 2023).

b) **UAV network design issues:** Despite the advantages of drone technology, significant challenges persist in network implementation. The primary constraints stem from limited payload capacity, affecting power consumption, communication range, and computational capabilities. UAV networks face unique challenges due to their dynamic nature, characterized by high-speed movement and varied maneuverability in obstacle-sparse environments. Traditional ground-based protocols prove inadequate for UAV applications, necessitating AI-based networking and control solutions that leverage advanced deep learning methods and modern computational platforms (Rovira-Sugranes et al., 2022).

c) **Localization and trajectory:** AI-based approaches are crucial for optimizing location and path determination, particularly in addressing the demands of real-time calculations required in dynamic UAV operations (Afifi, 2023).

d) General applications: The application scope of UAV networks continues to expand, encompassing integration with cellular networks, vehicular systems, coverage of high-risk areas, and spectrum utilization optimization (Sarkar and Gul, 2023).

6. Conclusions and Future Directions

This comprehensive review of multirotor UAV systems, with a focus on quadcopters, highlights the rapid advancements and increasing complexity in this field. The paper covers key components and technologies essential for UAV design and operation, including frame types and materials, flight control boards, motors, electronic speed controllers, batteries, propellers, and communication systems. The evolution of UAV technology has led to applications across various sectors, from military and agricultural uses to disaster management and urban planning. The integration of sophisticated sensors, GPS systems, and advanced flight control software has enhanced these systems, allowing for autonomous flight, precise navigation, and complex mission execution. Current challenges in UAV integration include battery technology limitations affecting flight duration, restricted communication ranges, weather-related operational constraints, complex regulatory and certification requirements, and ongoing security and privacy concerns. These factors continue to present significant hurdles for widespread UAV adoption in everyday applications. However, as UAV technology advances, new solutions and opportunities are emerging to address these challenges. As UAV technology continues to evolve, several key areas emerge as focal points for future research and development:

- Energy efficiency technologies such as energy beam-forming and distributed multipoint wireless power transfer.
- Integrating advanced battery applications such as hydrogen fuel cells, improved lithium-ion batteries and solar energy.
- Enhanced autonomous capabilities using onboard computer-vision-based systems.
- Integrating AI and machine learning in terms of battery optimization, route planning, obstacle detection, monitoring, and resource allocation (e.g., computing and battery).
- Using higher communication networks such as 5G and even 6G.
- Improved safety features and fail-safe mechanisms using blockchain and physical layer security.
- Advanced materials for lighter and more durable frames such as glass fiber reinforced polymer, carbon fiber reinforced polymer and Kevlar fiber reinforced polymer.
- More sophisticated sensor technologies integration such as thermal infrared sensors, small unmanned aircraft system-mounted light detection and ranging (sUAS-borne LiDAR), and hyperspectral sensors.
- Development of standardized regulations for UAV operation in various contexts.

The field of UAV technology continues expanding, with new applications and innovations emerging regularly. As these systems become more sophisticated and widely adopted, they will play an increasingly important role in various industries and aspects of modern life. Future research and development in this area will address current limitations and unlock the full potential of UAV technology.

Ethical approval

Not applicable.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgements

This paper's data is sourced from a segment of a PhD thesis, designated as number 782477, at the Institute of Science, Batman University, in Batman, Türkiye.
The authors are thankful to Lecturer Mazlum CENGİZ at the University of Şırnak for his valuable assistance with the style and grammar of this paper.

References

A. Junid, S. A. Zaki, S. Susilawati, and Y. A. Abakr. (2017). Efficiency of brushed and brushless electronic speed control systems and Lithium batteries. 2017 IEEE 15th Student Conference on Research and Development (SCOReD), 332–337.

A. Zul Azfar and D. Hazry. (2011). A simple approach on implementing IMU sensor fusion in PID controller for stabilizing quadrotor flight control. 2011 IEEE 7th International Colloquium on Signal Processing and Its Applications, 28–32.

Al-Haddad, L. A., Jaber, A. A., Giernacki, W., Khan, Z. H., Ali, K. M., Tawafik, M. A. and Humaidi, A. J. (2024). Quadcopter Unmanned Aerial Vehicle Structural Design Using an Integrated Approach of Topology Optimization and Additive Manufacturing. Designs, 8(3), 58.

Aliane, N. (2024). A Survey of Open-Source UAV Autopilots. Electronics, 13(23), 4785.

Altın, C. (2013). Multirotor unmanned aerial vehicle attitude and altitude control [Dört rotorlu insansiz hava aracinin yükseklik ve konum kontrolü]. Bozok University (Master of Science).

Altınışık, N. S. (2019). The investigation of the use of the underwater air vehicle (UAV) in the studies of the renovation of the cadastreal padches: Corum-Osmancik-Karaköy [Kadastro güncelleme çalışmalarında insansız hava aracı (İHA)'nın kullanımının irdelenmesi: Çorum-Osmancık-Karaköy örneği]. Aksaray University (Master of Science)

ArduPilot. (2020). Bluetooth Telemetry radio—Copter documentation. https://ardupilot.org/copter/docs/common-mission-planner-bluetooth-connectivity.html

Asif, G. A., Ariffin, N. H., Aziz, N. A., Mukhtar, M. H. H. and Arsad, N. (2024). True north measurement: A comprehensive review of Carouseling and Maytagging methods of gyrocompassing. Measurement, 226, 114-121.

B B V L, D. and Singh, P. (2016). A survey on design and development of an unmanned aerial vehicle (quadcopter). International Journal of Intelligent Unmanned Systems, 4(2), 70–106.

Balamurugan, C., Revathy, S. and Vijayakumar, P. (2020). Quadcopter based emergency medikit delivery system for hill stations. International Journal of Reconfigurable and Embedded Systems, 9(3), 201.

Başaran, E. (2017). Propeller performance analysis with analytical and numerical methods [Pervane Performansının Analitik ve Sayısal Yöntemlerle Hesabı]. TOBB University of Economics and Technology (Master of Science).

Batmaz, A. U. (2013). Design of multi-rotor unmanned aerial vehicle and optimization of resource allocation in wireless sensor networks [Çok rotorlu insansız hava aracı tasarımı ve kablosuz algılayıcı ağlarda kaynak ataması eniyilemesi]. TOBB University of Economics and Technology (Master of Science).

Bin Junaid, A., Diaz De Cerio Sanchez, A., Betancor Bosch, J., Vitzilaios, N. and Zweiri, Y. (2018). Design and implementation of a dual-axis tilting quadcopter. Robotics, 7(4), 65.

Borah, D. R., Debnath, L. and Gogoi, M. (2016). A review on Quadcopter Surveillance and Control. ADBU Journal of Engineering Technology, 4(1), 116-119.

Bretterbauer, K. and Weber, R. (2003). A primer of geodesy for GIS users. (Vol. 64). Inst. of Geodesy and Geophysics, Dept. of Advanced Geodesy.

Bulut, E. (2019). A study about behavior of four rotors ummanned aerial vehicle (Quadrotor) in the different weather conditions [Dört rotorlu insansız hava aracının (Quadrotor) farklı hava koşullarındaki davranışı üzerine bir inceleme]. Osmaniye Korkut Ata University (Master of Science).

Çabuk, N. and Yıldırım, Ş. (2021). Design, Modelling and Control of an Eight-Rotors UAV with Asymmetric Configuration for Use in Remote Sensing Systems. Journal of Aviation, 5(2), 72–81.

Çakıcı, E. (2019). Development of a brushless motor test system for mini unmanned air vehicles [Mini İnsansız Hava Araçları İçin Bir Fırçasız Motor Test Sistemi Geliştirilmesi]. Eskişehir Osmangazi University (Master of Science).

Carvalho, I. D. de S. B. (2013). Low Reynolds propellers for increased quadcopters endurance. University of da Beira Interior (Master of Science).

Çelebi, Y. and Cengiz, M. (2024). Verification and Validation of UAV Propeller using CFD. 47–59.

Çelebi, Y., Cengiz, M. and Aydın, H. (2024). Propeller Design of UAV Under Low Reynolds Numbers. In Article and Reviews in Engineering Sciences. 407–438. Platanus Publishing.

Çetin, O. (2019). From aerial photographs and different unmanned aerial vehicle images, measurement of land topography, analysis of results and comparison (The study of Haymana Yeşilyurt village) [Hava fotoğrafları ve insansız hava aracı görüntülerinden arazi topoğrafyası ölçümü, sonuçların analizi ve karşılaştırması]. Konya Technical University (Master of Science).

Çetinkaya, Ö. (2017). An experimental and theoretical investigation unmanned air vehicle goes the remotely given coordinates [Uzaktan verilen koordinatlara insansız gidebilen hava araının tasarımı ve deneysel araştırılması]. Trakya University (Doctoral Dissertation).

Çetinsoy, E., Öner, K. T., Kandemir, İ., Akşit, M. F., Ünel, M. and Gülez, K. (2008). Yeni bir insansız hava aracının (SUAVi) mekanik ve aerodinamik tasarımı. 36.

Chen, Z., Yan, J., Ma, B., Shi, K., Yu, Q. and Yuan, W. (2023). A Survey on Open-Source Simulation Platforms for Multi-Copter UAV Swarms. Robotics, 12(2), 53.

Colombo, O. L. and Evans, A. G. (1998). Testing decimeter-level, kinematic, differential GPS over great distances at sea and on land. 1257–1264.

D. A. Gandhi and M. Ghosal. (2018). Novel Low Cost Quadcopter for Surveillance Application. 2018 International Conference on Inventive Research in Computing Applications (ICIRCA), 412–414.

D. Erdos, A. Erdos, and S. E. Watkins. (2013). An experimental UAV system for search and rescue challenge. IEEE Aerospace and Electronic Systems Magazine, 28(5), 32–37.

Elmas, E. E. (2019). An unmanned aerial vehicle realization and its use in detecting and tracking moving objects [Bir insansız hava aracı gerçekleştirme ve hareketli nesnelerin tespit ve takibinde kullanımı]. Gazi University (Master of Science).

Elmeseiry, N., Alshaer, N. and Ismail, T. (2021). A Detailed Survey and Future Directions of Unmanned Aerial Vehicles (UAVs) with Potential Applications. Aerospace, 8(12), 363.

Eugene, C., Lim, J., Nirmal, U. and Lau, S. T. (2019). Battery powered RC boats: A review of its developments for various applications. Current Journal of Applied Science and Technology, 33(5), 1–29.

Filippeschi, A., Schmitz, N., Miezal, M., Bleser, G., Ruffaldi, E. and Stricker, D. (2017). Survey of Motion Tracking Methods Based on Inertial Sensors: A Focus on Upper Limb Human Motion. Sensors, 17(6), 12-57.

Fu, Q., Chen, X.-Y. and He, W. (2019). A Survey on 3D Visual Tracking of Multicopters. International Journal of Automation and Computing, 16(6), 707–719.

G. Özdoğan and K. Leblebicioğlu. (2022). Design, Modeling, and Control Allocation of a Heavy-Lift Aerial Vehicle Consisting of Large Fixed Rotors and Small Tiltrotors. IEEE/ASME Transactions on Mechatronics, 27(5), 4011–4021.

Gajula, R. and Tara, S. (2023). Design and implementation of high efficient UAV quadcopter. AIP Conference Proceedings, 2477(1), 030-052.

Genç, M. S., Özışık, G. and Kahraman, N. (2008). Investigation Of Aerodynamics Performance of Naca0012 Aerofoil With Plain. J. of Thermal Science and Technology, 28(1), 1–8.

Goli, S., Kurtuluş, D. F., Alhems, L. M., Memon, A. M. and Imran, I. H. (2023). Experimental study on efficient propulsion system for multicopter UAV design applications. Results in Engineering, 20, 101555.

Green, C. R. and McDonald, R. A. (2015). Modeling and test of the efficiency of electronic speed controllers for brushless dc motors. 3191.

Gülçat, Ü. (2010). Fundamentals of modern unsteady aerodynamics. (Vol. 2010). Springer.

H. N. P. Wisudawan, A. Nugraha, and A. M. Akmal. (2024). An Efficient Automatic Packet Delivery Using Quadcopter Drone. 2024 4th International Conference on Electronic and Electrical Engineering and Intelligent System (ICE3IS), 170–174.

Hairi, S. M. F. B. S., Saleh, S. J. M. B. M., Ariffin, A. H. and Omar, Z. B. (2023). A Review on Composite Aerostructure Development for UAV Application. In T. Khan and M. Jawaid (Eds.), Green Hybrid Composite in Engineering and Non-Engineering Applications. 137–157. Springer Nature Singapore.

Hell, M., Bolam, R. C., Vagapov, Y. and Anuchin, A. (2018). Design of a portable drone for educational purposes. 2018 25th International Workshop on Electric Drives: Optimization in Control of Electric Drives (IWED), 1–5.

Henderson, J., Condell, J., Connolly, J., Kelly, D. and Curran, K. (2021). Review of Wearable Sensor-Based Health Monitoring Glove Devices for Rheumatoid Arthritis. Sensors, 21(5), 1576.

Hoang, M. and Poon, K. (2013). Final Report Design, Implementationt, and Testing of a UAV Quadcopter.

Kaymak, A. M. (2019). An example of the use of unmanned aerial vehicle (drone) and image processing technologies in fruit gardens [İnsansız hava aracı (drone) ve görüntü işleme teknolojilerinin meyve bahçelerinde kullanım örneği]. Selçuk University (Master of Science).

Kılıç, B. (2014). Dynamic Analysis and Design of Quadcopter [Quadcopter'in Dinamik Analizi ve Tasarımı]. Bulent Ecevit University (Master of Science).

Kumar Nagothu, S., Anitha, G., Siranthini, B., Anandi, V. and Siva Prasad, P. (2023). Weed detection in agriculture crop using unmanned aerial vehicle and machine learning. Materials Today: Proceedings.

Kumar, P., Raj Kumar, A., Anand, S., Ganesh, E. and Prithiviraj, V. (2015). Measurement of Power Radiation in Base Transceiver Station Using Quad Phone and Quadcopter. Journal of Green Engineering, 5, 107–128.

Kutlu, Ö. (2019). Analysis of images obtained by unmanned aerial vehicle by deep learning methods [İnsansız hava aracı ile elde edilen görüntülerin derin öğrenme yöntemleri ile analizi]. Marmara University (Master of Science).

Kuzu, F. (2018). Application of different control methods to unmanned aerial vehicle quadcopter [Dört pervaneli (quadcopter) insansız hava aracına farklı kontrol yöntemlerinin uygulanması]. Fırat University (Master of Science).

M. B. Swedan, A. J. Abougarair, and A. S. Emhemmed. (2023). Stabilizing of Quadcopter Flight Model. 2023 IEEE 3rd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA), 254–260.

M. Varun, M. N. Joel, M. Naveen, and J. V. Haran. (2023). Quadcopter Navigation using Telemetry Data. 2023 International Conference on Computer Communication and Informatics (ICCCI), 1–6.

Magnussen, Ø., Hovland, G. and Ottestad, M. (2014). Multicopter UAV design optimization. 2014 IEEE/ASME 10th International Conference on Mechatronic and Embedded Systems and Applications (MESA), 1–6.

McKelvey, N., Diver, C. and Curran, K. (2019). Drones and Privacy. In I. R. Management Association (Ed.), Unmanned Aerial Vehicles: Breakthroughs in Research and Practice. 540–554.

Metz, B. and Tarpy, D. (2022). Variation in the reproductive quality of honey bee males affects their age of flight attempt. PeerJ, 10, 13859.

Mohsan, S. A., Khan, M. A., Noor, F., Ullah, I. and Alsharif, M. H. (2022). Towards the Unmanned Aerial Vehicles (UAVs): A Comprehensive Review. Drones, 6(6)3 147.

N. Cheng, S. Wu, X. Wang, Z. Yin, C. Li, W. Chen, and F. Chen. (2023). AI for UAV-Assisted IoT Applications: A Comprehensive Review. IEEE Internet of Things Journal, 10(16), 14438–14461.

Neumann, P. P. and Bartholmai, M. (2015). Real-time wind estimation on a micro unmanned aerial vehicle using its inertial measurement unit. Sensors and Actuators A: Physical, 235, 300–310.

Öngül, Y. S. (2017). Variable pitch and variable speed controlled four rotary unmanned air vehiclhe design and production [Değişken hatve ve değişken hız kontrollü dört rotorlu insansız hava aracı tasarımı ve üretimi]. Gebze Technical University (Master of Science).

Özen, E. (2019). Design of unmmanned aerial vehicle and gorund terminal. Gaziantep University (Master of Science).

Özen, E. and Oktay, T. (2022). Effects of Shape Changing of Morphing Rotary Wing Aircraft on Longitudinal and Lateral Flight. Journal of Aviation, 6(3), 251–259.

Özen, E. and Oktay, T. (2024). Maximization of Flight Performance of Eight-Rotor Multirotor with Differentiated Hub Angle. Journal of Aviation, 8(3), 206–213.

Pala, E. (2018). Design, control and manufacturing of a fixed wing vtol aerial vehicle [Dikey kalkış ve iniş yapabilen sabit kanatlı hava aracı tasarımı, kontrolü ve imalatı]. Gebze Technical University (Master of Science).

Peksa, J. and Mamchur, D. (2024). A Review on the State of the Art in Copter Drones and Flight Control Systems. Sensors, 24(11), 33-49.

Podhradsky, M. (2012). Visual Servoing for a Quadcopter Flight Control.: Vol. Independent thesis Advanced level. Lulea University of Technology (Master of Science).

Pütsep, K. and Rassõlkin, A. (2021). Methodology for flight controllers for nano, micro and mini drones classification. 1–8.

Quan, Q. (2017). Introduction to Multicopter Design and Control.

Raimundo, A. S. L. (2016). Autonomous obstacle collision avoidance system for uavs in rescue operations. University Institute of Lisbon (Master of Science).

Romano, S. (2018). Implementation of an Ultralight Autopilot Drone for Service Robotics. Politecnico di Torino (Master of Science).

S. Rezwan and W. Choi. (2022). Artificial Intelligence Approaches for UAV Navigation: Recent Advances and Future Challenges. IEEE Access, 10, 26320–26339.

Scott, M. T. U., Scott, T. J. and Kelly, V. G. (2016). The Validity and Reliability of Global Positioning Systems in Team Sport: A Brief Review. The Journal of Strength & Conditioning Research, 30(5), 1470-1490.

Seidu, I., Olowu, B. and Olowu, S. (2024). Advancements in quadcopter development through additive manufacturing: A comprehensive review. International Journal of Scientific Research in Science, Engineering and Technology, 11(4), 92–124.

Shaeffer, D. K. (2013). MEMS inertial sensors: A tutorial overview. IEEE Communications Magazine, 51(4), 100–109.

Studiawan, H., Grispos, G. and Choo, K.-K. R. (2023). Unmanned Aerial Vehicle (UAV) Forensics: The Good, The Bad, and the Unaddressed. Computers & Security, 132, 103340.

Suparta, W., Basuki, A. and Arsyad, M. (2023). The development of quadcopter using Arducopter APM 2.8 with autopilot for tracking point of drop-off goods. IOP Conference Series: Earth and Environmental Science, 1151(1), 012-032.

T. Dardoize, N. Ciochetto, J. -H. Hong, and H. -S. Shin. (2019). Implementation of Ground Control System for Autonomous Multi-agents using QGroundControl. 2019 Workshop on Research, Education and Development of Unmanned Aerial Systems (RED UAS), 24–30.

T. Kidd, Z. Yu, S. Dobbs, K. R. Anderson, G. Oetting, J. Kim, and M. O'Connell. (2020). UAV Power Management, Generation, and Storage System Principles and Design. 2020 IEEE Conference on Technologies for Sustainability (SusTech), 1–8.

Tomaszewski, D., Rapiński, J. and Pelc-Mieczkowska, R. (2017). Concept of AHRS algorithm designed for platform independent IMU attitude alignment. Reports on Geodesy and Geoinformatics, 104(1), 33–47.

Ural Bayrak, Z., Tanyeri, B. and Uçar, U. U. (2022). The Experimental Study of Attitude Stabilization Control for Programmable Nano Quadcopter. Journal of Aviation, 6(1), 1–11.

URL. (2022a). RC ESC Çeşitleri. ESC ler ne işe yarar. ESC nasıl seçilir. https://www.promodelhobby.com/blog/icerik/rc-esc-ne-ise-yarar-ozellikleri-ve-cesitleri-nelerdir

URL. (2022b). The Differences Between UAV, UAS, and Autonomous Drones—Percepto. https://percepto.co/what-are-the-differences-between-uav-uas-and-autonomous-drones/

URL. (2022c). Wi-Fi—Vikipedi. https://tr.wikipedia.org/wiki/Wi-Fi

Uz, U. (2019). The production of electronic pharmaceutical/irrigation system with an unmanned aerial vehicle in hexacopter structure [Hexacopter yapısında bir insansız hava aracı ile elektronik ilaçlama/sulama sisteminin oluşturulması]. İstanbul Gelişim University (Master of Science).

Velusamy, P., Rajendran, S., Mahendran, R. K., Naseer, S., Shafiq, M. and Choi, J.-G. (2022). Unmanned Aerial Vehicles (UAV) in Precision Agriculture: Applications and Challenges. Energies, 15(1), 217.

Wibisono, A., Piran, Md. J., Song, H.-K. and Lee, B. M. (2023). A Survey on Unmanned Underwater Vehicles: Challenges, Enabling Technologies, and Future Research Directions. Sensors, 23(17), 7321.

Y. Bai, H. Zhao, X. Zhang, Z. Chang, R. Jäntti, and K. Yang. (2023). Toward Autonomous Multi-UAV Wireless Network: A Survey of Reinforcement Learning-Based Approaches. IEEE Communications Surveys & Tutorials, 25(4), 3038–3067.

Yazid, Y., Ez-Zazi, I., Guerrero-González, A., El Oualkadi, A. and Arioua, M. (2021). UAV-Enabled Mobile Edge-Computing for IoT Based on AI: A Comprehensive Review. Drones, 5(4), 148.

Yürek, E. E. (2018). Unmanned aerial vehicle supported vehicle routing problem [İnsansız hava aracı destekli araç rotalama problemi]. Bursa Uludağ University (Master of Science).

Cite this article: Celebi, Y. Aydin, H. (2025). Multirotor Unmanned Aerial Vehicle Systems: An In-Depth Analysis of Hardware, Software, And Communication Systems. Journal of Aviation, 9(1), 225-240.