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Unveiling the Capabilities of an Economical Hexacopter: A Comprehensive Characterization

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Abstract

This paper presents the design and development of a low-cost hexa-copter drone that balances affordability and performance using readily available components and open-source hardware/software. It highlights strategic 3D printing for cost-effective, flexible design and uses cascaded P/PID controllers for precise flight control. A data acquisition system captures flight and environmental data, with room for sensor expansion, supporting citizen science initiatives. The drone excels in applications like videography, mapping, and environmental monitoring, democratizing access to aerial technology. Its modular, open-source design allows for future automation advancements, making it suitable for precision agriculture, infrastructure inspections, and disaster response, while opening new opportunities for intelligent, autonomous aerial systems.

Keywords: Low-cost hexa-copter drone, Multi-purpose applications, Data acquisition system, Affordable aerial technology, Open-source hardware.

1. Introduction

Drone technology has become increasingly popular in recent years, with applications ranging from photography and videography to delivery services. Drones are unmanned aerial vehicles (UAVs) that can be used in various fields such as military, agriculture, surveillance, and photography [1]. They have the potential to provide real-time monitoring, disaster control, traffic detection, logistics, and inspection in civil infrastructure [2]. Additionally, drones can be used for delivery purposes, transporting goods and packages to specific locations [3]. They can also be utilized for medical deliveries, especially in remote areas where access is difficult [3]. However, there are concerns regarding safety and security, such as the risk of power shortages during delivery, potential misuse of recorded customer information, and the possibility of theft [4]. Despite these challenges, drone manufacturers are working on enhancing safety features and improving visual representation for better monitoring. Hexacopter drones are unmanned aerial vehicles (UAVs) with six actuators and six degrees-of-freedom motions. They are highly maneuverable and capable of vertical take-off and landing. Custom hexacopter drones can be designed and manufactured using 3D printing technology and contemporary manufacturing techniques. The use of 3D printing allows for the creation of complex parts and structures, offering design freedom and versatility in manufacturing [5]. The control of hexacopter drones is a critical challenge. A popular open-source autopilot system has been used. The primary control algorithm used is a Proportional-Integral-Derivative (PID) controller. PID controllers are widely used in control systems for stabilizing and regulating the movement of drones and other vehicles. The PID controller adjusts the motor speeds or control surfaces based on the difference between the desired and actual states of the vehicle (e.g., orientation, position) to minimize errors and achieve stable flight. In addition to PID control, the autopilot system also supports advanced control algorithms, such as Model Predictive Control (MPC) and Linear-Quadratic Regulator (LQR), which can offer more sophisticated control strategies for specific applications. In this paper, detailed description from design to manufacturing of a hexacopter drone at a minimum cost is demonstrated. The low-cost hexacopter drone has been developed for various applications such as medical, agriculture, surveillance, security, photogrammetry, and air quality measurement. The drone is designed using open-source hardware and software, and they utilize affordable components available in the market. The use of low-cost controllers, such as Proportional Integral and Derivative (PID), Pole Placement, and Linear Quadratic Regulator (LQR), allows for precise control and stability of the drones [6]. The navigation modules of the drone,

based on GPS and flight controllers, provide accurate positioning data for aerial photogrammetry and environmental measurements [7]. Additionally, the drone is equipped with sensors to monitor air quality, making them portable alternatives to high-cost static monitoring stations. The design and testing of the low-cost hexacopter drone has been carried out to ensure their performance and stability in autonomous flight [8].

2. Methodology

2.1. Part design

The hexacopter was meticulously designed to achieve an optimal balance between performance and cost-effectiveness. Emphasizing simplicity and efficiency, the design prioritizes stability and control. The streamlined frame and strategically positioned propulsion components contribute to reduced drag, enhancing overall flight dynamics. Innovative design features, such as modular frame construction, further underscore the hexacopter's commitment to cost-effective functionality.

2.1.1. Dimensions

The hexacopter boasts precise dimensions tailored to maximize its operational efficiency. Viewed from the top, the hexacopter takes the form of an equilateral hexagon, with each side and vertex measuring 30 cm. This geometric design contributes to optimal stability and aerodynamic performance during flight. The height of the hexacopter is 21 cm, ensuring a compact yet robust structure. With a propeller radius of 10 cm, the hexacopter's propulsion system is finely tuned to balance thrust and efficiency. This configuration not only enhances the overall flight dynamics but also maintains a proportional relationship with the hexacopter's geometric dimensions, ensuring uniform lift distribution and stability during operation. These meticulously calculated dimensions, coupled with the geometric precision of the hexagon and the carefully chosen height and propeller radius, collectively contribute to the hexacopter's exceptional performance and maneuverability across diverse operational scenarios.

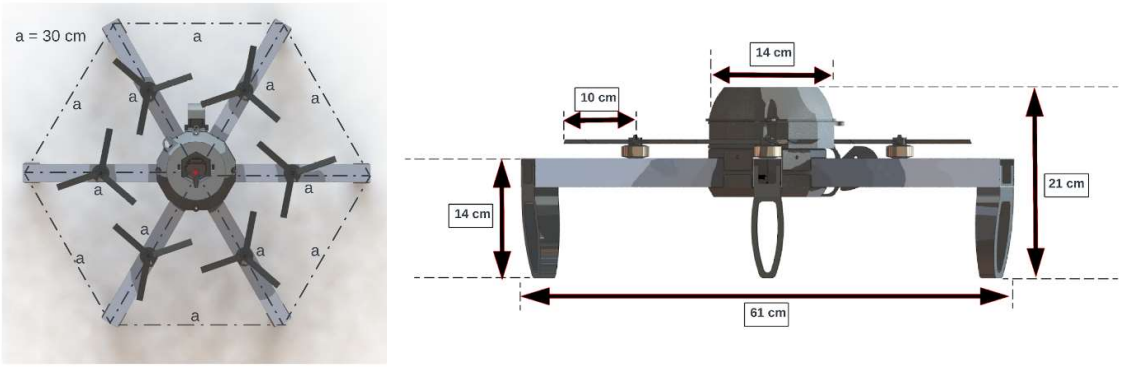


Fig. 1. Dimensions of the hexacopter

2.1.2. Parts

The hexacopter is built with various mechanical elements, each playing a crucial role in its overall functionality. Solid box channels shape the main frame arms, converging at a central body. This design enhances the hexacopter's structural strength and stability during flight. Positioned above the center body, the center hub serves as a housing unit for all electronic parts. This centralized placement streamlines wiring and ensures efficient communication between the flight controller, sensors, and other electronic modules. The center hub is 3D-printed using ABS filament for added protection. Attached to the main frame arms, the motor and propeller assembly ensures balanced thrust distribution. This strategic placement optimizes aerodynamics and contributes to precise control during flight. At the ends of each main frame arm, six 3D-printed landing gears made from TPU filament provide a soft and shock-absorbing landing. This safeguards the hexacopter and any attached payloads during takeoff and landing. Located below the center body, the battery mount maintains the hexacopter's center of gravity for stability in flight. This position also facilitates easy access and quick battery replacement. Affixed to the center body, the camera mount offers a stable platform for imaging equipment. This ensures optimal stability for capturing high-quality aerial footage or conducting surveillance missions. This integrated arrangement of

mechanical elements reflects a considerate design approach, where each part is thoughtfully positioned to enhance the hexacopter's performance and facilitate straightforward maintenance.

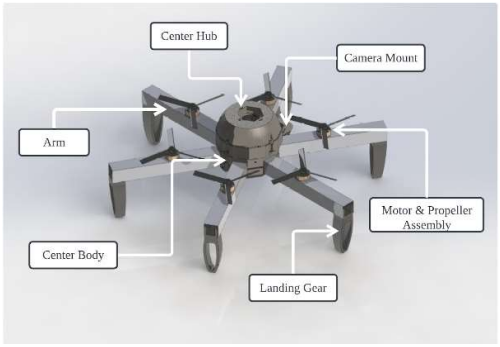


Fig. 2. Parts of the hexacopter

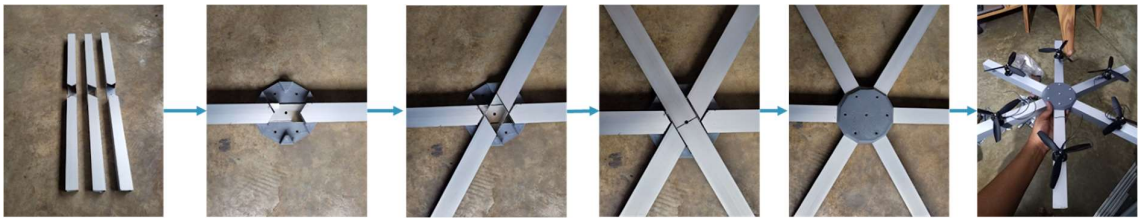


Fig. 3. Assembly process of hexacopter body



Fig. 4. Full assembled hexacopter

2.2 Material selection

The selection of materials for the hexacopter components was a critical consideration in achieving cost-effectiveness. Various materials were evaluated based on factors such as weight, strength, durability, and cost. Each material was chosen with a focus on optimizing its specific properties for the designated part.

2.2.1. Frame main material

The frame, serving as the backbone of the hexacopter, is constructed using lightweight and sturdy aluminum. This material provides excellent structural integrity without compromising weight, ensuring a robust foundation for the entire system. The aluminum frame contributes to the hexacopter's overall durability and stability while maintaining a cost-effective design.

2.2.2. 3D print materials

The central hub housing the electronics is crafted using ABS filament through 3D printing technology. ABS offers a balance of strength and flexibility, providing a resilient enclosure for the electronic components. Its ability to withstand impact and vibrations enhances the protection of crucial hardware, contributing to the hexacopter's overall reliability. The landing gears are 3D printed using TPU filament, known for its excellent elasticity and shock absorption properties. TPU ensures a soft landing and minimizes the impact forces during touchdown, protecting both the hexacopter and any mounted payloads. This choice enhances the hexacopter's durability and extends the lifespan of its components. The combination of aluminum for the frame, ABS for the center hub, and

TPU for the landing gears reflects a thoughtful material selection strategy, taking into account the specific requirements and functional demands of each component. This approach aims to achieve a harmonious balance between performance, durability, and cost-effectiveness in the design of the hexacopter.

2.3. Electronics and control system

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2.3.1. Communication system

The communication system of the drone operates through four distinct carriers/channels, each dedicated to specific functions. **Telemetry 1** operates on the 415 MHz frequency and is responsible for the data collection system, while **Telemetry 2** functions on 933 MHz, facilitating communication between the ground station and the autopilot system. For **manual RC control**, the system uses the 2.4 GHz frequency, ensuring stable and responsive remote control. Additionally, **video transmission** is handled through a 5 GHz channel, providing high-quality, real-time video feeds during flight. This multi-channel communication architecture ensures efficient data transmission, control, and real-time monitoring.

2.3.2. Control system

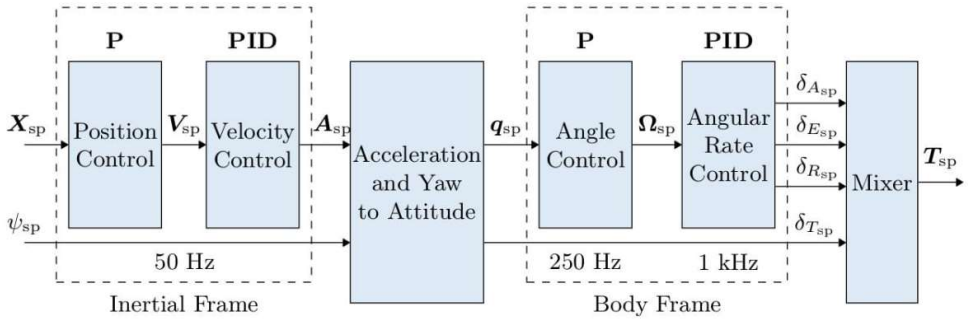


Fig. 5. Control system of the hexacopter

The hexacopter control system is designed using a series of cascaded **Proportional (P) and Proportional-Integral-Derivative (PID)** controllers, which work together to ensure precise and stable flight. At the top level, the **position controller** is a proportional controller that manages the drone's horizontal (X and Y) and vertical (Z) positions. It calculates the desired position relative to the target and generates a **velocity setpoint**, which serves as an input for the PID velocity controller. The **PID velocity controller** then takes this setpoint and calculates the necessary **acceleration** and **rotational motion** needed to achieve the target velocity. This process defines the required **angles** (for pitch, roll, and yaw) and **angular rates** (the rate of change of these angles), which are critical for maneuvering the hexacopter. These angular rates are then fed into the mixer, which determines the appropriate velocity for each of the hexacopter's motors. The mixer adjusts the power sent to each motor, ensuring that the drone maintains stable flight and responds accurately to the control inputs, whether for position changes, hovering, or complex maneuvers. This cascaded control system ensures smooth, responsive, and stable flight behavior.

2.3.3. Power management

The drone is powered by a 14.8V Lithium Polymer (LiPo) battery, which provides stable and efficient energy, ideal for high-performance applications due to its lightweight and high discharge capacity. The battery directly supplies power to the Electronic Speed Controllers (ESCs), which regulate the speed of the motors, allowing for precise control of the drone's flight. To power the more delicate control and communication electronics, such as the flight controller, sensors, and communication modules, the 14.8V is stepped down to 5V using a voltage regulator. These components require lower, stable voltages to function properly without risk of damage. The voltage regulator ensures they receive consistent power, while the motors continue to operate at the higher voltage. By managing the power distribution effectively, the drone ensures that both the high-power motors and the low-power electronics function optimally, contributing to the drone's overall performance and reliability.

2.3.4. Electronic components and specifications

Table 1. Significant components of the hexacopter

Item	Model	Rating / Specifications	Quantity	Price(BDT)
Motor	T-motor Velox 2207	Velocity constant: 2550 KV, Configuration: 12N14P	6	12000
Electronic Speed Controller	Hummingbird Mini	Protocol: DShot 600, Firmware: BLHeli_S, Rating: 30A (cont.) 40A (burst)	6	4800
Power Distribution board	Matek PDB Xt-60	Max input: 16.8V, Regulated outputs: 5V and 12V	1	500
Flight Controller	Pixhawk 6C	Microcontroller : STM32H743 & STM32F103, Clock speed : 480MHz, On-board Sensors: Accelerometer, Gyro, Magnetometer, Barometer	1	19500
Telemetry Module	SiK Telemetry kit	Carrier frequency: 433MHz and 915 MHz, Transmit power: 100mW, Range: 300m	2	17000
RC transmitter and Receiver	FlySky i6-S and FlySky iA-6B	Carrier frequency: 2.4GHz, Channels: 6, Transmit power: 20 dBm	1	5500
Video Camera, Tx and Rx	Caddx Walksnail Avatar HP Pro and VRX	Carrier frequency: 5.8GHz, Transmit power: 30 dBm, Range : 4km	1	24000
GPS Receiver	M9N	Multi-constellation GNSS receiver, ceramic patch antenna, Frequency band: L1, Accuracy: 1.5m CEP	1	4000
Accelerometer	ICM-42688-P BMI055	User selectable Gyro Full-scale range (dps): ±15.6/31.2/62.5/125/250/500/1000/2000	1	1000
			Total	88300

2.4. Data collection system

The data acquisition and processing system employed in the low-cost hexacopter drone is meticulously designed to capture diverse data sets with high accuracy and reliability, while ensuring efficient processing and utilization for successful mission achievement. The system comprises a Sensor Suite and Data Acquisition, Data Processing Techniques, and System Considerations and Implementation.

2.4.1. Sensor suite and data acquisition

The Pixhawk 6c flight controller, at the core of the system, gathers critical flight data using the u-blox M8Q GNSS module for precise positioning, the Invensense MPU-9250 IMU for attitude estimation, and dedicated sensors for velocity and acceleration. Motor controllers track RPM for performance and fault detection, while the battery monitoring system ensures safe operation by tracking power consumption. Environmental data is captured by the Bosch BME 280 sensor, measuring temperature, pressure, and humidity with high accuracy. Additionally, the Walksnail Avatar HD Pro Kit provides high-definition visual data through its Sony Starvis II sensor and H.265 encoding, offering adaptable image acquisition for research and analysis across various fields.

2.4.2. Data processing techniques

Flight data processing involves GPS data enhancement using Kalman filtering, while the MPU-9250 fuses gyroscope, accelerometer, and magnetometer data via a complementary filter for accurate attitude estimation. The Pixhawk autopilot applies geofencing algorithms to restrict flight to designated areas. Environmental data from the BME 280 undergoes calibration for temperature, pressure, and humidity accuracy, with optional data fusion for a comprehensive environmental overview. Visual data may be processed in real-time for object detection or post-processed for photogrammetry and video analysis. Data is either logged on an SD card or transmitted to a ground station, with secure storage protocols ensuring integrity. Interactive visualization tools help analyze collected data, while the system is fully integrated with the drone's control and communication systems for efficient mission execution.

3. Results and Discussion

The versatility of the low-cost hexacopter drone is evident across a wide range of real-world applications, offering capabilities comparable to more expensive drones on the market, but at a fraction of the cost. In **aerial videography**, it sets a new standard for capturing professional-grade footage with its stabilized gimbal and high-resolution camera, featuring adjustable aperture and shutter speed. While high-end drones offer similar video capabilities, this drone provides the same high-quality cinematic shots, such as panoramic cityscapes, close-ups of wildlife, and dynamic tracking of athletes, but with significantly reduced financial investment. Moreover, it excels in **situational awareness** and real-time monitoring of critical infrastructure, such as oil refineries, power plants, and construction sites, where continuous surveillance is necessary. Expensive commercial drones offer this functionality, but the low-cost drone brings it within reach for smaller organizations and industries, offering a more accessible solution for safety and operational monitoring. Its agility also makes it an effective tool for security operations, performing aerial reconnaissance in situations like hostage scenarios or crime scenes, and proving indispensable in **search and rescue missions**, where it can locate missing persons in dense forests or disaster zones with high precision—rivaling the performance of pricier models.
In **mapping** applications, the hexacopter drone excels in spatial analysis, collecting precise data for generating topographic maps, 3D models, and land-use surveys. Similar to costly commercial drones used by professionals in agriculture, environmental monitoring, and urban planning, it can deliver highly accurate land-use maps, monitor the health of vast forests, and assess flood risks after natural disasters. This cost-effective solution provides surveyors, engineers, and researchers with a versatile tool for decision-making, while the performance and precision rival the output of much more expensive platforms available on the market.
The hexacopter also stands out in **environmental data collection**, equipped with advanced sensors to monitor air quality in real-time. As a mobile alternative to conventional ground-based monitoring stations, it can assess pollution levels, track greenhouse gas emissions, identify sources of air pollution in urban areas, and monitor wildfires in real-time. High-end drones used in these environmental applications often come with hefty price tags, yet this low-cost alternative offers similar capabilities, enabling broader access for researchers, governmental agencies, and environmental organizations to gather critical data efficiently.
While premium drones offer extensive functionality, the low-cost hexacopter demonstrates comparable performance across key areas such as videography, mapping, and environmental monitoring. Its affordability and modular design make it an attractive choice for organizations looking for professional-grade drone capabilities without the financial burden, democratizing access to advanced aerial technology that was once cost-prohibitive for many users.

4. Conclusion

The low-cost hexacopter drone democratizes cutting-edge technology, offering an affordable yet powerful aerial platform. Built on open-source platforms, it supports diverse applications, from capturing cinematic footage and enhancing security to generating maps and monitoring environmental conditions. Designed for performance and cost-effectiveness, its streamlined hexagonal frame improves stability, with a modular design that facilitates maintenance. Key mechanical features include solid frame arms, a 3D-printed ABS hub for electronics, shock-absorbing TPU landing gears, and a balanced motor and propeller system. This integration enhances versatility, ease of use, and precision across a range of applications. Future work will focus on incorporating advanced autonomy through AI-powered navigation and inclusion of obstacle avoidance systems. Moreover, we will focus on an optimal and advanced control technique Additionally we will focus on improvements in payload capacity and battery efficiency to expand industrial applications.

5. Acknowledgement

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