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Research Article

Development of Low-Cost Agricultural Sprayer for Hexacopter Drones

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Abstract: As the demand for efficient and sustainable agricultural practices continues to grow, the integration of unmanned aerial vehicles (UAVs) in precision farming has gained significant attention. Hexacopter drones, with their enhanced stability and maneuverability, offer great potential for optimizing agricultural operations. This publication paper presents a comprehensive exploration of a hexacopter drone tailored specifically for agricultural purposes. It delves into crucial aspects such as motor thrust calculation, flight time estimation, hexacopter dynamics, equations of motion, and the electrical integration of an existing drone with a spraying system.

Keywords: Hexacopter drone; dynamics; electronics; thrust

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1. Introduction

Unmanned aerial vehicles, or UAVs, have revolutionized a number of industries, including agriculture (Rejeb et al., 2022). Drones with advanced sensors and smart algorithms have revolutionized precision agriculture by enabling farmers to monitor crops, assess plant health, and distribute resources as effectively as possible (Tsouros et al., 2019). Because of their six rotors, which offer stability, cargo capacity, and mobility, hexacopter drones are an especially beneficial type of unmanned aerial vehicle (UAV). Their characteristics provide them an ideal option for use in agricultural settings (Del Cerro et al., 2021).

This study aims to provide a comprehensive understanding of the mathematical modeling and electrical integration of a hexacopter drone intended mostly for agricultural applications. We begin by going over the crucial portion of motor thrust computation, which determines the lift force generated by each rotor based on several parameters such as propeller characteristics, motor specifications, and external environment. In order to ensure that the drone can carry agricultural equipment and sensors, precise thrust calculation is required to provide optimal flying performance and payload (Xu et al., 2024).

Another important consideration when evaluating the viability and effectiveness of a hexacopter drone for agricultural applications is flight time estimation. We investigate ways to estimate the drone's maximum flying time by taking into account variables including battery capacity, power consumption, payload weight, and flight circumstances (Abeywickrama et al., 2018). Planning missions and guaranteeing continued operation during essential agricultural operations need an understanding of the constraints and optimization of flying time.

Furthermore, this article delves into the dynamics of the hexacopter drone, analyzing its behavior and control mechanisms. We investigate the equations of motion governing the

drone's flight dynamics, considering factors such as aerodynamic forces, rotational motion, and stability (Mueller et al., 2022). A comprehensive understanding of the drone's dynamics is essential for designing effective flight control algorithms and ensuring safe and stable operation in agricultural environments.
Lastly, we explore the integration of an already existing hexacopter drone with a state-of-the-art spraying system. Agricultural spraying plays a vital role in crop protection and nutrient application. By examining the interface between the drone and the spraying system, we highlight the necessary considerations for seamless integration, including communication protocols, payload mounting, and control synchronization. The integration of spraying capabilities enhances the drone's versatility, enabling targeted and precise application of fertilizers, pesticides, and other agrochemicals.
In summary, this publication paper aims to provide a comprehensive overview of a hexacopter drone designed for agricultural applications. By addressing motor thrust calculation, flight time estimation, hexacopter dynamics, and the interface with a spraying system, we lay the groundwork for optimizing the drone's performance and facilitating its integration into precision farming practices. The insights presented here will contribute to the development of efficient and sustainable agricultural practices, ultimately enhancing crop yields and reducing resource wastage.

2. Motor Thrust Calculation

In order to choose a brushless motor for the application, it is required a factor that a motor that can produce a thrust of about twice the weight of the frame and its components (Amici et al., 2021). This weight is usually called the All-Up-Weight (AUW). i.e., Thrust Total ≥ 2 * AUW.

Table 1. Weight specifications of the Hexacopter including its payload

Devices	Quantity	Weight (g)	Each Total (g)
T-Motor 2213/KV920 BLDC motor	6	54	324
Electronics Speed controller	6	26	156
4S LiPo Battery	1	423	423
Flight controller	1	150	150
Telemetry	1	19	19
T9545 propeller	6	16.5	99
Receiver	1	10.9	10.9
Hexacopter frame	1	424	424
Payload including pump, tank, spray	-	1000	1000
Total (AUW)			2,605.9

From this, each motor is required to produce at least a thrust that is equivalent to of the total thrust produced, i.e.,

Thrust Motor = Total Thrust = 2 ∗ AUW/6. Therefore, the required thrust is,

$$Motor\ Thrust = \frac{2 \times AUW}{6} = \frac{2 \times 2605.9}{6} = 868.63g \tag{1}$$

Here the required thrust for each motor should be 868.63 grams. Now it is required to calculate the actual amount of thrust that is going to produce by an individual motor.

The thrust generated by motor is given by following formula (Shen et al., 2017);

$$T = \left[(\eta \times P)^2 \times 2 \times \frac{22}{7} \times r^2 \times Air\ density \right]^{\frac{1}{3}} \tag{2}$$

Where, η = propeller hover efficiency, and let's take as 0.7, P is shaft power which is 211.64w, r is radius of propellers in meters (0.12065meters), and air density is calculated as shown in Equation (3).

$$Air\ Density = \frac{P}{R \times T} \tag{3}$$

where: P is the atmospheric pressure, R is the specific gas constant for dry air and it is approximately 287.05J/(kg \K), T is the temperature in Kelvin at 25 ^{0}C and its value is 25 + 273.15 = 298.15K.

For the sake of illustration, let's assume a standard atmospheric pressure level, which is approximately 101.325KPa. Now, plug these values into the formula:

$$Air\ Density = \frac{101325}{287.05 \times 298.15} \approx 1.1838\, {}^{kg}\!/_{m^3} \tag{4}$$

Now, substitute these values into the formula:

$$T = \left[(0.7 \times 211.64)^2 \times 2 \times \frac{22}{7} \times (0.12065)^2 \times 1.1838 \right]^{\frac{1}{3}} = 13.35N \tag{5}$$

Now, let's convert this thrust value to grams:

Thrust in grams ≈13.35N×101.972g/N = 1,361.33 g

So, with P=211.64W, the estimated thrust is approximately 13.35N or 1361.33grams.

3. Flight Time Estimation of the Hexacopter

To calculate the hexacopter's flying duration with a 1000g average load (Liu et al., 2020). Equation (6) explains the flying time formula as follows:

$$t_f = \frac{Capacity \times discharge}{AAD} \tag{6}$$

Where: capacity is the battery's capacity, measured in either mAh or Ah, and t_f is the hexacopter's flight time in hours. AAD stands for average ampere draw (AAD) of the hexacopter, measured in amperes. It is customary practice never to empty LiPo batteries by more than 80% since they are frequently destroyed if fully exhausted. AAD is computed using Equation (7) as follows:

$$AAD = \frac{AUW \times P}{V} \tag{7}$$

Where: AUW is the hexacopter's all-up weight in kg, as indicated in Table 1, P is the power required to lift a kilogram of the devices in the air, represented as W/kg, and AAD is the average ampere draws in amperes. Furthermore, there's a tendency to choose the cautious estimate of 170 W/kg. A lot of very efficient systems require less like 120 W/kg, V stands for battery voltage, and a 4S battery has 14.8 volts. Therefore, the AAD of the prototype is:

$$AAD = \frac{AUW \times P}{V} = \frac{2.6059kg \times 170\, {}^{W}\!/_{kg}}{14.8v} = 29.93A \tag{8}$$

Then the flying time is:

$$t_f = \frac{Capacity \times discharge}{AAD} = \frac{4.2Ahr \times 0.8}{29.93A} = 6.74Minutes \tag{9}$$

This flight duration comprises 1000g payload; the discharge battery has a capacity of 4.2 Ah and a discharge percentage of 0.8.

4. Modeling of Hexacopter Drone

As seen in Figure 1, a hexacopter is an underactuated aircraft with six rotors at a fixed pitch angle. A vehicle like a hexacopter is difficult to model due to its intricate structure. As seen in Figure 1, a typical hexacopter has six rotors with set angles. These rotors produce six input forces, which are essentially the push that each propeller provides. In comparison to the more acrobatic configuration, an x-configured hexacopter is thought to be more stable.

Two reference systems need to be defined (Alaimo et al., 2013): the hexacopter reference system (Body frame: XB, YB, ZB) and the inertial reference system (Earth frame: XE, YE, ZE). There are numerous approaches to characterize the dynamics of a hexacopter, including quaternion, Euler angle, and direction matrix. To ensure a steady flight, the designed controller must take into account the axis angle when creating attitude stabilization control (Abdelmaksoud et al., 2020). All angle references in each axis of attitude stabilization control must be close to zero, particularly during takeoff, landing, and hovering. It guarantees that when external pressures are applied to the hexacopter body, it remains in a horizontal state at all times. The roll angle (Φ), pitch angle (θ), and yaw angle (ψ) are the three Euler angles that characterize the hexacopter orientation. $\omega_1, \omega_2, \omega_3, \omega_4, \omega_5, \omega_6$ - propeller angular velocity; $T_1, T_2, T_3, T_4, T_5, T_6$: forces produced by the propellers; based on factors such as air density and propeller shape $F_i \propto \omega_i^2$; m denotes the hexacopter's mass; mg denotes its weight; and Φ, θ, ψ stand for the roll, pitch, and yaw angles (Abdelmaksoud et al., 2020).

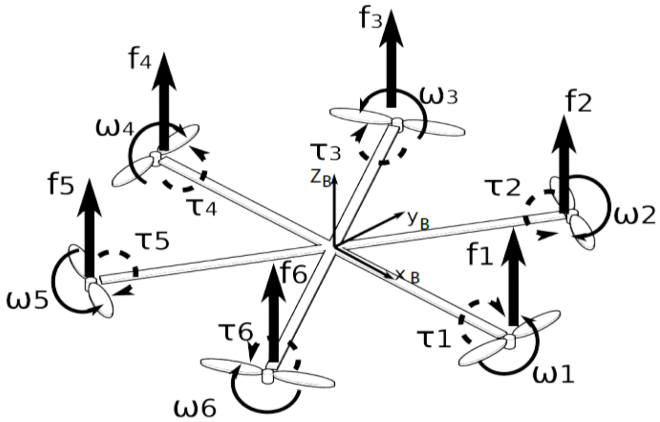

Figure 1 Hardware structure of the hexacopter

The position of the hexacopter is defined in the inertial frame x, y, z- axes with ξ. The attitude, i.e., the angular position, is defined in the inertial frame with three Euler angles η. Pitch angle θ determines the rotation of the hexacopter around the y-axis. Roll angle Φ determines the rotation around the x-axis and yaw angle ψ around the z-axis. Vector q contains the linear and angular position vectors (Morales et al., 2017) (Moussid et al., 2015).

Using ξ, the hexacopter's position is defined in the x, y, and z-axes of the inertial frame. Three Euler angles (η) define the attitude, or angular position, in the inertial frame. The hexacopter's y-axis rotation is determined by its pitch angle, θ. Rotation about the x-axis is determined by roll angle Φ, and rotation around the z-axis by yaw angle ψ. The linear and angular position vectors are contained in vector q.

$$\xi = \begin{bmatrix} x \\ y \\ z \end{bmatrix}, \eta = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix}, q = \begin{bmatrix} \xi \\ \eta \end{bmatrix} \tag{10}$$

The hexacopter's center of mass is where the body reference, or body frame, originates. JB determines the linear velocities and ω determines the angular velocities in the body frame.

$$JB = \begin{bmatrix} Jx,\ \mathrm{B} \\ Jy,\ \mathrm{B} \\ Jz,\ \mathrm{B} \end{bmatrix} \omega = \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{11}$$

From the body frame to the inertial frame, the rotation matrix is;

$$R = \begin{bmatrix} C_\psi C_\theta & C_\psi S_\theta S_\phi - S_\psi C_\phi & C_\psi S_\theta C_\phi + S_\psi S_\phi \\ S_\psi C_\theta & S_\psi S_\theta S_\phi + C_\psi C_\phi & S_\psi S_\theta C_\phi - C_\psi S_\phi \\ -S_\theta & C_\theta S_\phi & C_\theta C_\phi \end{bmatrix} \quad (12)$$

In which Sx = sin(x) and Cx = cos(x). The rotation matrix R is orthogonal thus $R^{-1} = R^T$ which is the rotation matrix from the inertial frame to the body frame. There are 3 types of angular speeds which can describe as the derivative of (Φ, θ, ψ) with respect to time, $\dot{\phi}$ =Roll rate, $\dot{\theta}$ =Pitch rate, $\dot{\psi}$ = Yaw rate. Considering the hovering condition of hexacopter gives 6-equations of forces, directions, moments and rotation speeds. Those are described by following,

- Forces at equilibrium: $\sum_{i}^{6}=1\ T_i = -mg$
- Equilibrium of directions: T 1,2,3,4,5,6||g
- Moments at equilibrium: $\sum_{i}^{6}=1\ M_i = 0$

Rotational speed equilibrium: $((\omega_1+\omega_3+\omega_5)-(\omega_2+\omega_4+\omega_6)=0)$, with $\dot{\phi}=0\ \dot{\theta}=0\ \dot{\psi}=0$ being the result. Through varying the rotational speed of each propeller, the hexacopter is able to do up-and-down movements.

- Flying up: $\sum_{i}^{6}=1\ T_i > -mg$,
- Flying down: $\sum_{i}^{6}=1\ T_i < -mg$, Euler angles and rates are remained 0.

By adjusting the propellers' speed, direction, and moments, the hexacopter's yaw, roll, and pitch equations can be obtained (Moussid et al., 2015).

$$\text{Yaw: } \dot{\psi} = k_y((\omega_2+\omega_4+\omega_6)-(\omega_1+\omega_3+\omega_5))\ \psi = \int \dot{\psi}\, dt$$
$$\text{Roll: } \dot{\phi} = k_R((\omega_2+\omega_4+\omega_6)-(\omega_1+\omega_3+\omega_5))\ \phi = \int \dot{\phi}\, dt \quad (13)$$
$$\text{Pitch: } \dot{\theta} = k_P((\omega_3+\omega_4)-(\omega_1+\omega_6))\ \theta = \int \dot{\theta}\, dt$$

For a hexacopter drone, which has six rotors, the principles of controlling movements are somewhat similar to those of a quadcopter but with additional complexity due to the extra rotors. The control of roll, pitch, and yaw movements can be explained as follows:

Roll Movement: To achieve a roll movement, you can decrease the angular velocities of the rotors on one side (let's say 2nd, 4th, and 6th rotors) while increasing the velocities of the rotors on the opposite side (1st, 3rd, and 5th rotors).

Pitch Movement: To initiate a pitch movement, you can decrease the angular velocities of the rotors on the front side (let's say 1st, 2nd, and 3rd rotors) while simultaneously increasing the velocities of the rotors on the back side (4th, 5th, and 6th rotors).

Yaw Movement: Yaw movement in a hexacopter involves a combination of opposing rotor adjustments. You can increase the angular velocities of one set of opposing rotors (e.g., 1st and 4th rotors) while decreasing the velocities of the other set of opposing rotors (e.g., 3rd and 6th rotors).

It's important to note that the exact configuration may vary depending on the specific design and motor arrangement of the hexacopter. The control algorithms and adjustments can be more complex due to the increased number of rotors, but the fundamental principles of adjusting angular velocities to control roll, pitch, and yaw movements remain consistent.

Equation of Movement: Assuming that k and $F = \sqrt{T}$ are common factors of proportionality, the hexacopter's movement equations are as follows (Moussid et al., 2015):

$$\begin{aligned}
\dot{\psi} &= k((\omega_2+\omega_4+\omega_6-(\omega_1+\omega_3+\omega_5)) = -k\omega_1+k\omega_2-k\omega_3+k\omega_4-k\omega_5+k\omega_6 \\
\dot{\phi} &= k((\omega_4+\omega_5+\omega_6)-(\omega_1+\omega_2+\omega_3)) = -k\omega_1-k\omega_2-k\omega_3+k\omega_4+k\omega_5+k\omega_6 \\
\dot{\theta} &= k((\omega_3+\omega_4)-(\omega_1+\omega_6)) = -k\omega_1+k\omega_3+k\omega_4-k\omega_6 \\
F &= k(\omega_1+\omega_2+\omega_3+\omega_4) = k\omega_1+k\omega_2+k\omega_3+k\omega_4+k\omega_5+k\omega_6
\end{aligned} \tag{14}$$

By using matrices

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \\ F \end{bmatrix} = \begin{pmatrix} -k & -k & -k & k & k & k \\ -k & 0 & k & k & 0 & -k \\ -k & k & -k & k & -k & k \\ k & k & k & k & k & k \end{pmatrix} \begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \\ \omega_5 \\ \omega_6 \end{pmatrix} = k \begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \\ \omega_5 \\ \omega_6 \end{pmatrix} \tag{15}$$

5. Interface of Drone with Spray System

For the agricultural application the drone is interfaced with the spraying system. The spray system is composed of liquid tank, pump, pump interface and nozzles. Figure 2 provides a visual representation of how the spray system interfaces with the drone.

Figure 2. Hexacopter interfaced with spray system

The design considerations on the spray system are:

- Water tank: Lightweight and appropriately sized for the drone's payload capacity.
- Pump: To pressurize and deliver water to the spraying mechanism.
- Nozzles: Depending on the application, choose appropriate nozzles for desired spray patterns.
- Controller and Interface: a control system for the water spray system that can be interfaced with the drone's flight controller. Implement communication protocols for remote control and monitoring.

- Power System: Ensure the power system can support both the drone's flight and the water spray system. Consider power-efficient components to maximize flight time.

5.1. Design of water pump by using 3D printing

The spray system's initial experiment is a 3D printed water pump powered by a BLDC motor. This technique is employed because the motor can be easily interfaced and controlled using an Electronic Speed Controller (ESC). The primary function of an ESC is to manage and control the speed and direction of an electric motor. It interprets signals from a control source (like the receiver) and adjusts the power supplied to the motor accordingly. The ESC essentially acts as an intermediary between the control system and the motor. Figure 3 illustrates a general connection between the battery, ESC, and motor.

Figure 3. Connection between motor, ESC, and battery

The mechanical components of the pump are developed, and 3D printed to fit the motor. Figure 4 shows the pump's 3D printed parts and their attachment to the motor.

Figure 4. 3D printed pump parts and assembly with motor.

5.2. Interfacing of water pump by relay and servomotor drive

To connect a DC motor pump to the drone's receiver, an intermediary system is required due to a mismatch between the receiver's output, which is a PWM signal. To solve the interface difficulty, this study employed a servomotor drive system that communicated with the receiver to operate the relay. Figure 5 shows the system's signal interface.

A micro servo motor typically consists of a small DC motor, a gearbox, a controller chip, and a potentiometer linked directly to the output shaft. Servos are connected through a standard three-wire connection: two wires for a DC power supply and one for control, carrying a pulse-width modulation (PWM) signal. As shown in Figure 5 the servo mechanism will be employed to activate the relay instead of the DC motor upon receiving a command from the receiver. The relay will be utilized to switch on and off the pump motor. A relay is an electrically operated switch that can be controlled by a low-voltage signal. It is used to control high-voltage devices (such as a DC motor or pump) using a low-voltage control circuit providing isolation from the main system.

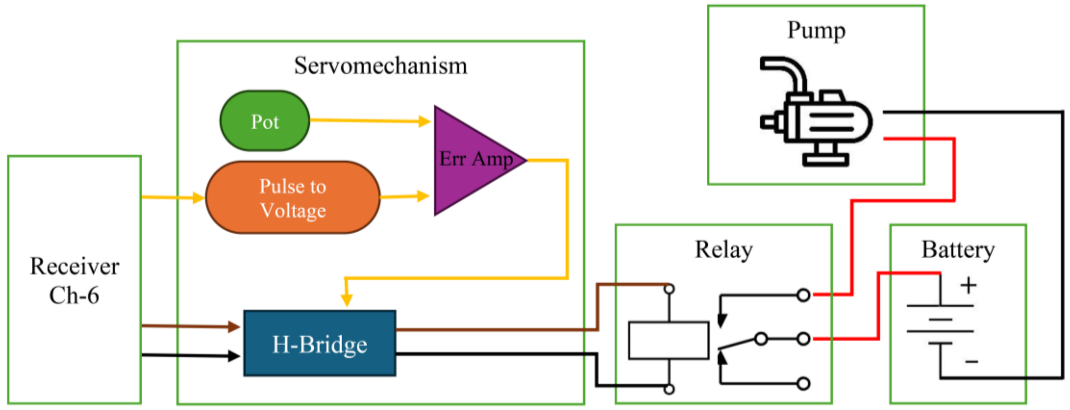

Figure 5. Interface of DC pump with receiver using servo and relay

Figure 6 shows the physical interaction between the micro servo motor drive and the relay.

Figure 6. Physical implementation of the servo interface with relay.

6. Conclusions

In conclusion, this publication paper has provided a comprehensive exploration of a hexacopter drone specifically designed for agricultural applications. By addressing crucial aspects such as motor thrust calculation, flight time estimation, hexacopter dynamics, equations of motion, and the interface with a spraying system, we have laid the foundation for optimizing the drone's performance and facilitating its integration into precision farming practices.

The accurate calculation of motor thrust ensures that the hexacopter drone can generate sufficient lift force to carry agricultural equipment and sensors, enabling precise data collection and monitoring of crops. Additionally, understanding the factors influencing flight time estimation allows farmers to plan missions effectively and maximize the drone's operational efficiency in the field. Furthermore, the exploration of hexacopter dynamics and equations of motion provides insights into the drone's behavior, stability, and control mechanisms. This knowledge is crucial for developing advanced flight control algorithms that enhance the drone's maneuverability and ensure safe operation in agricultural environments. The integration of an existing hexacopter drone with a cutting-edge spraying system presents new opportunities for precision agriculture. By seamlessly interfacing the drone with the spraying system, farmers can achieve targeted and precise application of fertilizers, pesticides, and other agrochemicals, minimizing waste and environmental impact.

The findings and insights presented in this paper contribute to the advancement of agricultural practices by harnessing the capabilities of hexacopter drones. The integration of these drones into precision farming operations enables farmers to make data-driven decisions, optimize resource allocation, and improve overall crop yields. However, it is important to note that further research and development are still required to address challenges such as battery technology advancements for extended flight time, optimization of flight control algorithms for enhanced stability, and the development of advanced sensing capabilities for improved crop monitoring. In conclusion, the hexacopter drone holds significant potential for revolutionizing agriculture by offering efficient and sustainable solutions. By continuously advancing the technology and exploring innovative applications, we can pave the way for a more productive and environmentally friendly future in agriculture.

Conflicts of Interest: The authors declare no conflicts of interest.

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