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DESIGN OF A MECHANICAL SYSTEM FOR A DRONE DELIVERY PACKAGE WITH A CAPACITY OF 2-3 KG

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Abstract
The growing need for fast delivery is driving the development of drones as an alternative logistics solution. However, increasing payload capacity impacts thrust requirements, power consumption, and structural stability, necessitating an integrated mechanical design. This study aims to design a mechanical system for a 2-3 kg package delivery drone with a stable and energy-efficient quadcopter configuration at maximum payload conditions. The method used is a design engineering approach that includes 3D CAD modelling, mass distribution and centre of gravity (CoG) analysis, and thrust and power estimation using momentum theory. Evaluations were conducted on the total system weight, hover thrust requirements, hover power, and peak power, with a thrust-to-weight (T/W) ratio of 1.8-2.0. The results show that at a total mass of ±6.5 kg, a minimum thrust of approximately 1.63 kgf per motor is required for stable hovering. The estimated hover power is around 1.04 kW, while the peak power is close to 3 kW. The 6S 15,000 mAh battery configuration provides approximately 15 minutes of hover time. This design demonstrates technical feasibility for medium-scale logistics drone applications.
Keywords: Design, drone, quadcopter, frame, CAD

INTRODUCTION

The development of uncrewed aerial vehicle (UAV) technology is advancing rapidly, alongside the growing need for a transportation system that is fast, flexible, and adaptable to geographical conditions and infrastructure limitations. (Ahmed & Subbarao, 2016)One type of UAV that is widely developed is the multirotor drone, because it can take off and land vertically (Vertical Takeoff and Landing/VTOL) and hover stably. These characteristics make multirotors relevant for a range of applications, including mapping, inspection, environmental monitoring, and logistics services for package delivery. (Arroyo-Mora et al., 2019).

In the modern logistics sector, the growth of e-commerce and the increasing demand for fast delivery services are driving the development of alternative distribution methods to reduce reliance on land transportation.(Ismail et al., 2023)Drone-based delivery has the potential to reduce travel times, improve access in remote areas, and support emergency deliveries, such as the distribution of medicines and medical supplies (Efendy et al., 2025). However, implementing drones as package delivery vehicles requires a design that excels in control and navigation and also features a strong, stable, and safe mechanical system to carry the load consistently.(Rasyid et al., 2025).

One of the main challenges for package-delivery drones is the increase in payload, which directly affects gross takeoff weight, lift requirements, power consumption, and the structural response to dynamic loads.(Admin et al., 2022)In the 2–3 kg payload range, the payload mass is significant. It can dominate the total system load, thereby increasing the risk of instability if the mass distribution and centre of gravity (CoG) are not properly designed. Furthermore, dynamic forces from acceleration during maneuvers, rotor turbulence, and wind gusts can trigger vibrations and deformations in the frame if the frame design lacks adequate stiffness. This condition can reduce flight stability and increase the control system's workload (R. et al., 2025).

In addition to strength and stability, payload security is a critical aspect of any delivery system. Poorly secured payloads can shift during flight, causing sudden changes in CoG that increase control corrections, energy consumption, and the risk of mission failure. (Pungus, S.Kom, M.T, M.M et al., 2023). Therefore, the mechanical design must include the payload bay and a strapping system capable of holding the package against inertial forces while remaining practical for loading and unloading. (Pranata et al., 2025)On the other hand, placing the load under the frame to maintain stability requires landing gear with sufficient ground clearance, so the landing gear design must balance load protection, structural strength, and weight minimization. (Sarkar & Johnson, 2022).

Given these problems, this research focuses on the mechanical design of a 2–3 kg quadcopter-based package delivery drone. The main contribution of this research is to produce a mechanical design that systematically integrates the frame, arm, payload bay, and landing gear structures, and to evaluate thrust and power requirements at maximum payload conditions as a basis for design feasibility.(Sumartono et al., 2022)The research results are expected to serve as a reference for developing safer, more stable, and more efficient medium-scale logistics drones for package delivery needs(Faisal & Leni, 2025).

METHOD

Research Design

This research uses an engineering design approach to design the mechanical system of a package delivery drone with a payload capacity of 2–3 kg. The methods used include establishing design specifications, conceptual design, 3D modelling, mass distribution analysis, and estimating thrust and power requirements as the basis for evaluating the design's feasibility.(Admin et al., 2022).

Requirements Specifications and Design Parameters

The system's key specifications are defined based on the need for packet delivery over a medium payload range. Design parameters include:

1. Payload capacity: 2–3 kg

2. Drone configuration: multirotor type quadcopter (4 rotors)
3. Stability target: able to hover stably at maximum payload
4. Load placement: centralized under the frame to maintain the centre of gravity (CoG)
5. Ground clearance: sufficient to avoid cargo contact with the ground during takeoff/landing
6. Thrust eligibility criteria: thrust-to-weight (T/W) ratio is targeted ≥ 1.8–2.0 for control margin

Mechanical Design Procedures

The research flow for this study is shown in Figure 1.

Figure 1. Flow chart

The mechanical design stages are carried out as follows:

1. Concept Design

   The structural concept includes the main frame, motor arms, payload bay, and landing gear. The quadcopter configuration was chosen for its simple, easy-to-integrate structure, while still meeting the thrust requirements for a 2–3 kg payload.
2. 3D Modelling and Dimensioning

   The mechanical design is visualized and modelled using CAD software to determine the dimensions of the main components, including:
   a. distance between motor and propeller,
   b. position of heavy components (battery and payload),
   c. payload bay dimensions according to package size,
   d. landing gear height to meet ground clearance.
3. Mass Distribution and CoG Analysis

   A CoG analysis is performed to ensure the drone's stability with maximum payload. The payload is placed as close as possible to the drone's geometric centre, while the battery is placed in the main frame area to maintain mass balance. The design is revised if the CoG shifts significantly from the centre of the frame.

Thrust Estimation and Power Calculation

The design's feasibility is evaluated by calculating the thrust and power requirements at hover and peak conditions.

1. Total Weight Calculation (AUW)

   The total weight of the system is calculated by equations 1 and 2. (Sarkar & Johnson, 2022):

$$m_{total} = m_{payload} + m_{battery}$$

$$W = m_{total} \cdot g$$

   Where:

   m_{total} = Total Weight

   $m_{Payload}$ =Weight Gain

   $m_{battery}$ = Battery Weight

2. Thrust Hover

   The hover condition satisfies Equation 3(Rasyid et al., 2025):

$$T_{total} = W$$

   For quadcopter Equation 4(Zieher et al., 2024):

$$T_{motor} = \frac{T_{total}}{4}$$

   Where:

   T_{motor} = Total thrust in 1 motor

3. Hover Power Estimation

   The ideal induction power is calculated using momentum theory Equation 5(K. Isabella Rani, 2025):

$$P_i = \frac{T^{3/2}}{\sqrt{2\rho A_{tot}}}$$

   Where:

   T = Thrust Force (N)

   ρ = Air Density (Kg/m3)

   A_{tot} = Total area of the rotor

   Where Atot is the total rotor disk area. The power value is corrected using the rotor efficiency (figure of merit/FoM), and the system loss is calculated using equation 6.(Admin et al., 2022):

$$P_{shaft} = \frac{P_i}{FoM}$$

   Where:

   P_{shaft} = Motor shaft power (W)

   P_i = Ideal induction power (W)

FoM = Figure of Merit rotor (aerodynamic efficiency of the rotor, without units)

Moreover, to calculate the actual electrical power required by the system, Equation 7(R. et al., 2025):

$$P_{elec} = P_{shaft}(1 + \eta_{loss})$$

Where:

P_{elec} = Actual electrical power required by the system (W)

P_{shaft} = Motor shaft power (W)

η_{loss} = System loss factor (combined mechanical losses, ESC, cable, and motor efficiency)

4. Peak Power Estimation

Peak power is calculated based on the thrust requirement at a certain T/W ratio Equation 8, K. Isabella Rani, 2025):

$$T_{max} = kW$$

Where:

T_{max} = Total maximum thrust required (N)

K = Thrust-to-weight ratio (T/W), usually 1.8–2.0

W = Total weight of the system (N)

With k set at 1.8–2.0. Peak power is estimated using the relationship equation 9 (Hidayat & Mardiyanto, 2017):

$$P \propto T^{3/2}$$

Where:

P = Power required by the rotor (W)

T = Total thrust (N)

RESULTS AND DISCUSSION

Mechanical System Design Results for 2–3 kg Package Delivery Drone

The mechanical system design of a 2–3 kg package delivery drone shown in Figure 2 was developed using a quadcopter configuration, with a main structure comprising a central frame, four arms, a propulsion system, an elevated landing gear, and a payload bay. Table 1 explains the components and their functions as shown in Figure 2a. This design aims to produce a structure that is statically and dynamically stable, safe during takeoff and landing, and capable of carrying a payload of 2–3 kg, as specified in the design target.

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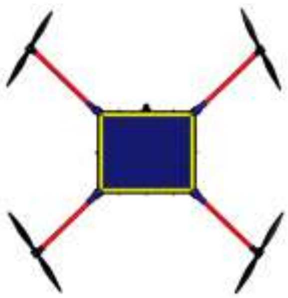
(a)

(b)



(c)

(d)

Figure 2. Drone Design (a) Isometric View, (b) Front View, (c) Top View, and (d) Side View

Table 1. Main Components of a Drone with Functions

No	Component Name	Main Function
1	Propeller	Produces lift (thrust) from motor rotation
2	Brushless Motor	Moving the propeller to produce thrust
3	Drone Arm	Supports the motor and propeller and maintains the distance between the rotors
4	Main Body	Electronic components and battery housing are at the centre of the drone structure
5	Landing Gear	Supports the drone during landing/takeoff and protects the payload
6	Payload Bay	Placement of 2-3 kg packages to ensure stability and safety

Based on the CAD modelling results; the overall mechanical design is shown in Figure 2. The main components are numbered for easy identification and discussion. The propulsion system consists of a propeller and a brushless motor that generates lift (thrust). The motor is mounted at the end of the drone's arm, which is designed symmetrically to maintain an even distribution of lift across all four rotors.

The main frame acts as a central structure that houses the avionics and battery components, while also serving as a distribution point for the load from the arm to the entire frame. To support package delivery operations, this design utilizes elevated landing gear that provides adequate ground clearance, ensuring the load remains safe from direct contact with the ground during takeoff and landing. Furthermore, the package delivery system is supported by a payload bay located at the bottom of the frame, designed to hold the load steady and reduce the risk of shifting during flight.

Overall, the mechanical configuration shown in Figure 2 places the payload below the main frame, resulting in a lower centre of gravity and increased hover stability. This design also allows for more practical loading and unloading of packages without disturbing the main components on top of the frame.

Table 2. Dimensions of Drone

No	Geometric Parameters	Symbol	Mark	Unit	Information
1	Wheelbase (motor diagonal)	WB	850	mm	Diagonal motorcycle distance (front left–rear right)
2	Arm length (centre of frame to motor)	Larm	425	mm	Determine the distance between rotors so that the propellers do not interfere with each other.
3	Landing gear height (ground clearance)	HLG	300	mm	Ground clearance to the bottom frame to protect the payload
4	Payload bay dimensions (L×W×H)	PBay	300×250×200	mm	Package load space dimensions 2–3 kg

Based on three-dimensional modelling using CAD software, the main geometric specifications that determine the drone's stability characteristics and capacity were obtained. A wheelbase of 850 mm was chosen to provide sufficient distance between the motors to accommodate a 15-inch-diameter propeller without interfering with airflow between the rotors. This dimension also contributes to increased lateral and longitudinal stability by increasing the arm moment against roll and pitch disturbances. The arm length of 425 mm is measured from the centre of the frame to the motor mount, and the frame is designed symmetrically to ensure even thrust distribution across all four rotors.

The landing gear height (ground clearance) of 300 mm is designed to provide a safe space between the payload and the ground surface during takeoff and landing. This dimension is important because the payload is placed below the main frame to lower the centre of gravity (CoG) and increase hover stability. Meanwhile, the payload bay dimensions of 300 × 250 × 200 mm are designed to accommodate small-to-medium-scale logistics packages weighing 2-3 kg. The centralised placement of the payload in this cargo space aims to maintain a balanced mass distribution and minimise CoG shifts during flight. Overall, the combination of these geometric parameters yields a stable, safe structural configuration that meets the calculated thrust and power requirements at maximum payload conditions.

Analysis of Mass Distribution and Centre of Gravity (CoG) Stability

The stability of a multirotor drone is significantly influenced by the centre of gravity (CoG) position, especially in systems carrying medium payloads, as in this study. In a quadcopter configuration, the mass distribution relative to the frame's geometric centre determines the magnitudes of the pitch and roll moments that the control system must compensate. Therefore, a CoG analysis was performed using the mass properties feature in CAD software to evaluate changes in the centre of gravity position under various conditions, both with and without the maximum payload.

In this design, the payload is placed as close as possible to the drone's geometric centre to minimize moments caused by an asymmetrical mass distribution. Asymmetrical payload placement can cause lift imbalances, requiring certain motors to work harder to maintain hover. It could increase power consumption and decrease system efficiency.

Table 3. Centre of Gravity (CoG) Coordinates of CAD Output Results on Payload Variations

Condition	Payload (kg)	CoG X (mm)	CoG Y (mm)	CoG Z (mm)
Without payload	0	0	0	-45
With payload	2	0	0	-62
With maximum payload	3	0	0	-78

Based on Table 3, the addition of payload does not shift the X and Y axes (the values remain 0 mm), indicating that the mass distribution remains symmetrical about the frame's geometric centre. It proves that the payload bay design, located directly below the centre of the frame, successfully maintains the system's lateral and longitudinal balance.

However, there was a significant shift in the Z-axis. The CoG position changed from -45 mm in the unloaded condition to -62 mm (2 kg payload) and -78 mm (3 kg payload). This shift indicates that the system's centre of mass decreases as the load increases.

Mechanically, lowering the CoG provides the benefit of increased static stability while hovering. With the CoG below the rotor plane, the system exhibits a pendulum-like behaviour, allowing the drone to return to a stable position when small roll or pitch disturbances occur. It reduces the number of corrections required by the control system.

To maintain CoG consistency during operation, the payload bay is designed using mechanical restraints and a strap/bracket system to prevent load shifting due to inertial forces during translation and changes in direction. At 2-3 kg payloads, CoG control becomes even more critical because the payload mass is large relative to the total takeoff mass, so even small shifts can affect flight stability and power consumption.

The CoG analysis results indicate that the developed mechanical design can maintain a balanced lateral and longitudinal mass distribution while simultaneously improving vertical stability by lowering the centre of mass. It supports the feasibility of the structural configuration under maximum payload conditions.

Strength and Stiffness of Structure against Payload Load

The mechanical structure of a package delivery drone must withstand both static and dynamic loads. Static loads result from the total system weight (frame, battery, avionics, and payload), while dynamic loads arise from acceleration, deceleration, rotor turbulence, and wind disturbances. Under maximum payload conditions, critical load points typically occur at the arm connection to the main frame and at the motor mounts.

To address this issue, the frame design is symmetrical and reinforced at key joints. This reinforcement aims to reduce stress concentrations and increase structural rigidity. Frame stiffness is also related to vibration control. Vibrations from the propulsion system can impair stability and increase sensor noise, so a stiffer structure tends to provide better mechanical stability during load-carrying operations.

To support quantitative proof of arm strength against static hover loads at maximum payload (3 kg), an arm approach is carried out as a cantilever beam. The maximum total mass value in the article is m = 6.5 kg, so that the total weight is:

$$W = m.g = 6{,}5 \times 9{,}81 = 63{,}77\ N$$

Load carried by each arm (assuming even distribution on the quadcopter):

$$F = W4 = 63{,}774 = 15{,}94\ N$$

The arm length from the centre of the frame to the motor (CAD result) is:

$$L = 0{,}425\ m$$

Maximum bending moment at the base of the arm:

$$M = F \cdot L = 15{,}94 \times 0{,}425 = 6{,}77\ N.m$$

The arm profile used is a 20×20 mm hollow aluminium with a thickness of 2 mm, so:

moment of inertia of the cross-section

$$I = 1{,}07 \times 10^{-8}\, m^4$$

outermost fibre distance:

$$c = 0{,}01$$

Maximum bending stress:

$$\sigma = \frac{Mc}{I} = \frac{6{,}77 \times 0{,}01}{1{,}07 \times 10^{-8}} = 6{,}33\ MPa$$

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With the yield stress of aluminium, the safety factor is:$\sigma_y \approx 240\ MPa$

$$SF = \frac{\sigma_y}{\sigma} = 2406{,}33 \approx 37{,}9$$

A safety factor of 37.9 indicates that the drone's arm structure is very safe against bending loads. However, in light UAV design practice, a safety factor of 2 to 3 is commonly used. Therefore, this design still has potential for dimensional optimization to achieve a safety factor of around 2.5, thereby improving mass efficiency without compromising operational safety.

These results indicate the arm has a high safety factor against static hover loads at maximum payload. The results of the drone arm flexibility analysis are shown in Table 4.

Table 4. Drone Arm Flexibility Calculation Results

Parameter	**Symbol**	**Mark**	**Unit**
Total mass	m	6.5	kg
Total weight	W	63.77	N
Load per arm	$F = W/4$	15.94	N
Sleeve length	L	0.425	m
Bending moment	$M = F \cdot L$	6.77	N·m
Moment of inertia of a cross-section	I	1.07×10^{-8}	m^4
Outermost fibre distance	c	0.01	m
Maximum bending stress	$\sigma = Mc/I$	6.33	MPa
Yield stress of the material	σ_y	240	MPa
Safety factor	$SF = \sigma_y/\sigma$	37.9	—

Based on Table 4, the flexural analysis was performed by modelling the drone arm as a cantilever beam that receives a concentrated load at the tip due to the thrust force at the maximum hover payload condition (3 kg). With a total system mass of 6.5 kg, the total weight is 63.77 N. This load is assumed to be evenly distributed across the four arms so that each arm bears a force of 15.94 N. With an arm length of 0.425 m, the maximum bending moment that occurs at the base of the arm is 6.77 N m.

Using a 20×20 mm aluminium hollow profile with a thickness of 2 mm, a cross-sectional moment of inertia of 1.07×10^{-8} m^4, and an outer fibre spacing of 0.01 m, results in a maximum bending stress of 6.33 MPa. This value is much lower than the yield stress of aluminium, which is around 240 MPa. The comparison between the yield stress and the working stress results in a safety factor of 37.9.

A high safety factor indicates that the drone's arm structure is very safe under static hover loads at maximum payload. Even when dynamic loads from maneuvering, rotor turbulence, or wind gusts are considered, the structure still has a significant safety margin. Indicates that the arm design not only meets strength requirements but also provides adequate structural reserves to ensure reliable drone operation in package delivery applications.

Thrust and Power Requirements

The technical feasibility of the mechanical system design under maximum payload conditions is evaluated through a quantitative analysis of thrust and power requirements based on the total system mass and the quadcopter propulsion configuration. This analysis ensures that the force balance is met in hover conditions while verifying the adequacy of the thrust-to-weight ratio (T/W) margin to support stability and dynamic response during maneuvers. The calculation process begins with determining the All-Up Weight (AUW), which is then used to calculate the total thrust and its distribution on each rotor. Hover power and peak power estimates are calculated using the momentum theory formulation as a basic model of rotor performance, with efficiency corrections via figure-of-merit (FoM) parameters and accounting for electrical system losses. This analysis also includes estimates of the energy and battery capacity required to achieve the target hover duration. A summary of the calculation results is presented in Table 5 as a basis for performance evaluation and validation of the design's suitability to the specified operational specifications.

Table 5. Calculation of Thrust and Power Requirements

Counting components	**Symbols/Formulas**	**Substitute numbers from articles**	**Results**
Total mass (AUW)	$(m_{total} = m_{payload} + m_{drone} + m_{battery})$	3.0 + 2.2 + 1.3	6.5 kg
Total weight	$(W = m_{total}, g)$	6.5 × 9.81	63.77 N
Total thrust during hover	$(T_{total} = W)$	= 63.77 N	63.77 N
Thrust per motor (4 rotors)	$(T_{motor} = T_{total}/4)$	63.77/4	15.94 N ≈ 1.63 kgf
Propeller diameter	D	15 inches = 0.381 m	0.381 m
Disc area of 1 rotor	$(A = \pi(D/2)^2)$	π (0.1905) ^2	0.1140 m²
Total disk area of 4 rotors	$(A_{tot} = 4A)$	4×0.1140	0.456 m²
Ideal induction power	$(P_i = T^{3/2}/\sqrt{2\rho A_{tot}})$	$63{,}77^{3/2}\ /\sqrt{2 \times 1{,}225 \times 0{,}456}$	≈ 482 W
Shaft power (FoM=0.6)	$(P_{shaft} = P_i/FoM)$	482/0.6	≈ 803 W
Electrical power (loss 30%)	$(P_{elec} = P_{shaft}(1 + \eta_{loss}))$	803×1.30	≈ 1.04 kW total

Peak power (T/W=2)	$\left(P_{max} \approx 2^{3/2} P_{hover}\right)$	2,828×1,044 kW	≈ 2.95 kW (≈3 kW)
15-minute hover energy	$(E = P_{hover} t)$	1,044 kW × 0.25 hours	261 Wh
Battery capacity (6S 22.2 V)	$(C = E/V)$	261/22.2	11.76 Ah
Safe capacity 80%	$\left(C_{req} = C/0{,}8\right)$	11.76/0.8	14.7 Ah (≈15,000 mAh)

Based on Table 5, the calculation starts with the estimated total system mass (All-Up Weight/AUW), which is the sum of the maximum payload of 3.0 kg, the drone's unladen mass of 2.2 kg, and the battery mass of 1.3 kg, for a total of 6.5 kg. With a gravitational acceleration of 9.81 m/s², the total system weight is 63.77 N. In hover conditions, force balance applies, so the total thrust that must be generated is equal to the total weight. Since the configuration used is a quadcopter with four rotors, the thrust per motor is 15.94 N or approximately 1.63 kgf.

The next power requirement analysis was carried out using the momentum theory approach. With a propeller diameter of 15 inches (0.381 m), the disk area of one rotor is 0.1140 m², and the total disk area of four rotors is 0.456 m². Based on the ideal induction power equation, the induction power requirement is approximately 482 W. After being corrected with a figure of merit (FoM) of 0.6 to consider the aerodynamic efficiency of the rotor, the shaft power increases to approximately 803 W. By taking into account system losses of 30% in the motor, ESC, and cables, the actual electrical power required for hovering is approximately 1.04 kW.

To ensure a control margin during takeoff and maneuvers, a thrust-to-weight (T/W) ratio of 2 is used. Using a nonlinear approach to the relationship between thrust and power, an estimated peak power of approximately 2.95 kW is obtained, for a total of approximately 3 kW. This value is the basis for selecting motor and ESC specifications so that the system can operate within safe current and temperature limits.

Furthermore, the energy analysis shows that to maintain a hover for 15 minutes (0.25 hours), 261 Wh of energy is required. With a 6S battery system with a nominal voltage of 22.2 V, the minimum required capacity is 11.76 Ah. However, given the safe battery discharge limit of 80% to maintain lifespan and voltage stability, the recommended capacity is 14.7 Ah, rounded up to 15,000 mAh. These results indicate that the 6S 15,000 mAh battery configuration is still sufficient to support hover operations for approximately 15 minutes at a maximum payload of 3 kg.

Table 5 shows that, at a maximum payload of 3 kg, the system still meets the thrust, hover power, and energy capacity requirements within safe operational limits. However, to obtain a more comprehensive picture of performance sensitivity to load variations, a comparative analysis between 2 kg and 3 kg payloads is required. This comparison is important because in real logistics applications, drones do not always carry maximum payloads, so evaluating performance across multiple payload levels can provide a more representative picture of thrust changes, power consumption, and flight duration.

By comparing these two conditions, we can analyze how a 1 kg increase in mass affects the lift requirement per motor, the increase in hover power due to the nonlinear relationship between thrust and power, and its implications for flight endurance when battery capacity remains constant. Therefore, the following table compares key parameters for 2 kg and 3 kg payloads to more comprehensively assess the system's operational limits and performance margins.

Table 6. Payload Comparison 2 kg vs 3 kg

Parameter	Payload 2 kg	Payload 3 kg	Information
Total mass (kg)	5.5	6.5	$m = payload + 2{,}2 + 1{,}3$
Total weight (N)	53.96	63.77	$W = m \times 9{,}81$
Thrust per motor (N)	13.49	15.94	$W/4$ (quadcopter)
Total hover power (kW)	0.88	1.04	Momentum theory results
Peak power (kW)	2.49	2.95	$T/W = 2$
Estimated hover duration (minutes)	±18	±15	6S 15,000 mAh battery

Table 6 shows the effects of payload variations on the drone's main performance parameters: total mass, thrust requirement, power consumption, and estimated flight duration. At a 2 kg payload, the total system mass is 5.5 kg, while at a maximum payload of 3 kg, it increases to 6.5 kg. A 1 kg increase in mass (approximately 18%) directly increases the total weight from 53.96 N to 63.77 N.

Because the configuration uses a quadcopter, lift is evenly distributed across the four motors. Therefore, the thrust generated by each motor increases from 13.49 N to 15.94 N. This increase indicates that the propulsion system is working harder as the payload increases.

The most significant impact is seen in the hover power requirement. Based on the momentum theory approach, hover power increases from approximately 0.88 kW at a 2 kg payload to 1.04 kW at a 3 kg payload. This increase occurs because the relationship between thrust and power is nonlinear (proportional to the power of 3/2), so that adding mass results in a proportionally greater increase in power. At peak power conditions with a thrust-to-weight ratio (T/W) = 2, the power requirement increases from 2.49 kW to 2.95 kW, approaching the system's 3 kW limit.

A direct consequence of the increased power is a decrease in flight duration. With a fixed 6S 15,000 mAh battery, the estimated hover time drops from about 18 minutes with a 2 kg payload to about 15 minutes with a 3 kg payload. It demonstrates a trade-off between payload capacity and endurance, where greater payload capacity comes at the cost of higher energy consumption.

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The comparison of 2 kg and 3 kg payloads shows that increasing mass directly increases the thrust requirement per motor and hover power consumption, and decreases flight duration due to limited battery capacity. The nonlinear relationship between thrust and power means that a 1 kg increase in load results in a proportionally greater increase in power, ultimately affecting system endurance. Furthermore, mass distribution and centralized payload placement are proven to play a crucial role in maintaining CoG stability without causing lateral imbalance. These quantitative findings not only illustrate the drone's performance characteristics under varying loads but also demonstrate the methodological consistency of the calculation approach used in this study.

First, the endurance/hover time estimation based on the multicopter's battery system is consistent with the experimentally validated hover time prediction approach by Cho & Han, so the use of power/energy estimation for hover in this study is within the right methodological corridor. (Octonius & Ruseno, 2022)Second, the finding that mass distribution (payload–battery–tare) and CoG position significantly influence feasibility and performance is also consistent with Figliozzi's study, which confirmed the strong impact of mass distribution on drone performance and efficiency.(Figliozzi, 2023)Third, the focus of this research is on optimising the mechanical design (frame/structure) to maintain T/W performance, in line with quadcopter structure studies that emphasise increasing the thrust-to-weight ratio through a lightweight yet strong frame design.(Zieher et al., 2024)Fourth, the context of logistics applications and the technical requirements of package delivery drones are supported by Zieher et al., who formulated the technical requirements for a drone-based parcel delivery system, thereby making the mission assumptions and performance requirements in this study relevant to research trends and applications.(Balayan et al., 2024)Fifth, energy performance modelling and efficiency/endurance estimation are also aligned with the Applied Energy study, which emphasises the importance of energy modelling and state-of-energy estimation for optimising the performance of electric air vehicles.(Abdelkhalek et al., 2025). Thus, the calculations of thrust, hover/peak power, and the payload placement strategy to maintain CoG in this study are consistent with the current literature and support the validity of the design approach.

CONCLUSION

Based on the design and quantitative analysis results, the mechanical system of a 2–3 kg quadcopter package delivery drone is technically feasible for hover operations under maximum payload conditions. At a total mass (AUW) of 6.5 kg, the system weight is 63.77 N, so a minimum thrust of 15.94 N per motor (±1.63 kgf) is required to maintain a stable hover. With a thrust-to-weight (T/W) ratio of 1.8–2.0 as the control margin, the system is estimated to require a peak power of approximately 2.95 kW (approximately 3 kW total) during takeoff and maneuvers. Hover power estimation using the momentum theory approach yields an actual electrical power requirement of approximately 1.04 kW, accounting for the figure of merit (FoM = 0.6) and a 30% system loss. Energy analysis shows that for a 15-minute hover, approximately 261 Wh are required, so a 6S (22.2 V) battery system requires a minimum capacity of 11.76 Ah and is recommended to be around 14.7 Ah or 15,000 mAh, with a safe usage limit of 80%.

In addition to the propulsion and energy aspects, structural analysis shows that the drone arm made of 20×20×2 mm hollow aluminium experiences a maximum bending stress of around 6.33 MPa with a safety factor of ±37.9 against the material yield stress of 240 MPa, so that the structure is in a very safe condition against static hover loads. The symmetrical mass distribution and centralised payload placement are proven to maintain the centre of gravity (CoG), ensuring it remains stable laterally and longitudinally. However, this research remains analytical, based on CAD modelling and theoretical calculations, without flight-test validation or advanced numerical simulations such as FEA or CFD. Therefore, the results obtained represent early-stage design validation and still require experimental testing to verify the system's dynamic response, vibration effects, and actual performance under real operating conditions.

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