Open Conceptual Design Architecture for a Multi-Mission Tactical Quadcopter Using COTS Components

Fulki Shah Jahan[1], Ressa Octavianty[2,*], and Triwanto Simanjuntak[3]

[1]Department of Aviation Engineering, International University Liaison Indonesia (IULI)
[2]Department of Aviation Engineering, International University Liaison Indonesia (IULI); ORCID: `0000-0001-5130-0298`
[3]Department of Aviation Engineering, International University Liaison Indonesia (IULI); ORCID: `https://orcid.org/0000-0002-9009-9889`
[*]Corresponding author: `ressa.octavianty@iuli.ac.id`

Abstract

This paper presents an open conceptual design architecture for a multi-mission tactical quadcopter addressing critical payload limitations in existing commercial loitering munitions. Current tactical quadcopters are limited to 200 g payload capacity, incompatible with standard military ordnance such as the Indonesian GT5-PEA2 defensive grenade (430 g). The design utilizes Components-Off-The-Shelf (COTS) to create a cost-effective platform carrying 400 g to 600 g payloadsa 120 % increase over commercial alternatives. The modular architecture enables three mission profiles: intelligence, surveillance, and reconnaissance (ISR); payload delivery; and kamikaze operations. The compact foldable configuration achieves 180 mm maximum dimensions when stowed, ensuring infantry portability. Performance analysis demonstrates the ISR configuration achieves 30 min endurance and 6790 m range at 387.4 g operating weight, meeting design objectives. Payload missions yield 9.3 min endurance and 2950 m range at 852.6 g maximum take-off mass, with endurance below the 15 min mandatory requirement due to payload-performance trade-offs. Economic analysis reveals 415 to 434 USD component costs with 774 USD unit pricing for 100-unit production, representing 68 % cost reduction versus approximately 2400 USD commercial alternatives. Complete design documentation is made publicly available to democratize tactical UAV technology access and accelerate collaborative development.

Keywords: Loitering munition, COTS components, Multi-mission UAV

This preprint has been submitted to the journal Advances in Military Technology.

1 Introduction

Contemporary military operations are increasingly characterized by urban combat scenarios, driven by global demographic trends that have concentrated over 55 % of the world's population in urban areas, with projections indicating 68 % urbanization by 2050 (Teller, 2021). This shift toward urban-centric conflict represents a fundamental transformation in military operational environments, where traditional tactics developed for open terrain prove inadequate for the complex three-dimensional battlespace of modern cities (Spencer and Geroux, 2022; Glenn, 2002). The dense infrastructure, vertical terrain features, and high civilian population density characteristic of urban environments create unique operational challenges that demand innovative technological solutions (Vautravers, 2010).

Urban warfare fundamentally alters engagement dynamics, reducing typical engagement distances from kilometers to tens of meters while introducing complex vertical dimensions where adversaries can exploit building structures for concealment, ambush, and tactical advantage (Corps, 1998). These constrained operational conditions necessitate precision engagement capabilities that minimize collateral damage while maximizing operational effectiveness. Traditional artillery and air support systems designed for open battlefield conditions often prove unsuitable for urban scenarios due to their limited precision and high collateral damage potential.

Unmanned Aerial Vehicles (UAVs) have emerged as indispensable force multipliers for urban military operations, providing critical capabilities that bridge the gap between strategic air power and tactical infantry operations. UAV systems enable persistent intelligence, surveillance, and reconnaissance (ISR) while minimizing risk to personnel in high-threat environments (Valavanis and Vachtsevanos, 2014). Recent conflicts have demonstrated the transformative impact of tactical UAV systems, with extensive deployment documented in the Nagorno-Karabakh War (2020) and ongoing operations in Ukraine, where loitering munitions have proven particularly effective for precision engagement in urban terrain (Bode and Watts, 2023).

Among various UAV configurations employed in tactical operations, loitering munitionsplatforms that combine reconnaissance and strike capabilities in a single systemhave demonstrated exceptional versatility for urban combat applications. Current operational loitering munitions predominantly utilize fixed-wing configurations, which comprehensive analysis by (Voskuijl, 2022) demonstrates achieve superior range and endurance compared to rotary-wing alternatives. Survey data from (Zhugan and Degtyarev, 2024) indicates that 78 % of operational loitering munitions employ fixed-wing designs, reflecting their advantages for long-range missions and extended loitering operations.

However, the operational advantages of fixed-wing platforms are significantly diminished in urban environments where constrained maneuvering space, complex vertical terrain, and the need for precise hovering capabilities become paramount. Urban combat scenarios frequently require operations in narrow corridors between buildings, precise positioning for target identification, and the ability to launch and recover in confined spaces unavailable for conventional takeoff and landing operations. Multirotor platforms, particularly quadcopters, offer superior capabilities for these demanding operational requirements through their inherent ability to hover precisely, execute vertical takeoff and landing in minimal space, and navigate complex three-dimensional urban terrain (Valavanis and Vachtsevanos, 2014).

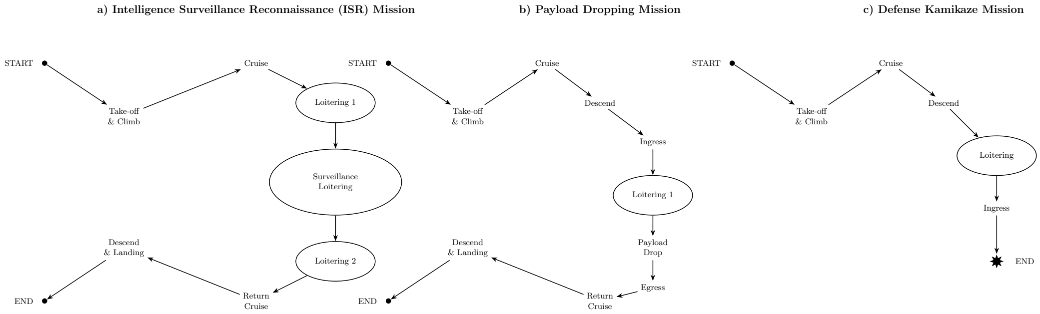

Figure 1: Three operational mission profiles enabled by the multi-mission quadcopter design: (a) Intelligence, Surveillance, and Reconnaissance (ISR) for persistent area monitoring; (b) Payload delivery for precision ordnance deployment; and (c) Kamikaze operations for direct target engagement.

The tactical employment of UAV systems in urban combat is further constrained by the logistical realities of infantry operations. Ground forces operating in urban terrain face stringent equipment weight and volume limitations that directly impact their mobility and combat effectiveness. The U.S. Army Field Manual FM 21-18 establishes maximum load standards of 21.7 kg for combat operations and 32.6 kg for approach marches (Army, 1990). Biomechanical research by (Loverro et al., 2019; Knapik et al., 2004) has demonstrated that loads exceeding these limits significantly increase musculoskeletal injury risk, with female soldiers experiencing disproportionately higher injury rates. These physiological constraints necessitate that any additional equipment, including tactical UAV systems, must be designed with strict adherence to weight and portability requirements while maintaining operational effectiveness.

A critical capability gap exists in current commercial tactical UAV systems regarding payload capacity, particularly for ordnance delivery applications. Market-available tactical quadcopters such as the SpearUAV Viper40 and Defendtex Drone40 are limited to payload capacities of 200 g or less (Voskuijl, 2022). This limitation renders existing commercial platforms incompatible with standard military ordnance, creating a significant operational constraint for infantry units seeking to leverage UAV technology for precision engagement missions.

The payload capacity limitation is particularly problematic for forces equipped with standard defensive grenades, which typically exceed the capacity of available commercial platforms. For example, the Indonesian military's standard-issue GT5-PEA2 defensive grenade has a mass of 430 g (PTP), representing more than double the payload capacity of existing commercial tactical quadcopters. This incompatibility prevents infantry units from utilizing commercially available UAV technology for grenade delivery missions, significantly limiting tactical options in urban combat scenarios where precision ordnance delivery could provide critical operational advantages.

The economic constraints associated with military procurement further compound these technical limitations. Current commercial loitering munitions typically cost approximately 2400 USD per unit, making large-scale procurement challenging for many military organizations. The high cost stems from proprietary design approaches and limited production volumes, creating barriers to widespread adoption of tactical UAV capabilities at the infantry level where they could provide maximum operational impact.

This paper addresses these critical capability gaps through the development of an open conceptual design architecture for a multi-mission tactical quadcopter specifically engineered to overcome existing payload and cost limitations. The design emphasizes three primary objectives: achieving payload capacity of 400 g to 600 g to accommodate standard military ordnance; maintaining compact dimensions and minimal weight for infantry portability; and utilizing Components-Off-The-Shelf (COTS) to minimize cost and enable rapid deployment. Figure 1 illustrates the three distinct mission profiles that the platform is designed to support: ISR operations for persistent surveillance, payload delivery for precision ordnance deployment, and kamikaze operations for direct target engagement.

The open design approach represents a significant departure from proprietary commercial development models, democratizing access to advanced tactical UAV technology and enabling rapid adaptation to specific operational requirements. By making the complete design architecture publicly availableincluding CAD files, technical specifications, performance calculations, and manufacturing guidelinesthis work facilitates collaborative development and accelerates innovation in military robotics applications. This approach enables military organizations with limited research and development resources to rapidly deploy advanced tactical capabilities while fostering continuous improvement through distributed development efforts.

The multi-mission design philosophy provides tactical flexibility essential for dynamic urban combat scenarios. The modular architecture enables rapid reconfiguration between ISR, payload delivery, and kamikaze missions through standardized interfaces and component exchanges. This flexibility maximizes operational utility while minimizing the logistical burden on infantry units that must carry and maintain the systems under combat conditions.

The technical contributions of this work extend beyond the specific platform design to include comprehensive performance modeling methodologies, innovative payload integration approaches, and economic analysis frameworks applicable to broader tactical UAV development programs. The integration of COTS components with custom mechanical interfaces demonstrates a cost-effective approach (Austin, 2010) to achieving military-specific capabilities while leveraging commercial technology advances and established supply chains.

This research directly addresses the evolving requirements of urban warfare while providing a foundation for future tactical UAV development. The successful demonstration of enhanced payload capacity combined with cost-effective manufacturing approaches provides a pathway for transforming infantry-level precision engagement capabilities. The open design methodology ensures that improvements and adaptations can be rapidly implemented and shared across the research communities, accelerating the pace of innovation in this critical area of military technology.

2 Design Requirements and Conceptual Sizing

2.1 Benchmarking Analysis

The initial sizing process began with a comprehensive benchmarking study of existing tactical quadcopter loitering munitions. Two representative commercial platforms were analyzed: the SpearUAV Viper40 and the Defendtex Drone40. These systems represent the current state-of-the-art in tactical multirotor loitering munitions and provide baseline performance metrics for the new design.

Table 1 presents the detailed specifications of both benchmark platforms. A critical limitation identified in both systems is the maximum payload capacity of $\leq 200\,\mathrm{g}$, which is insufficient for standard military ordnance such as the Indonesian military's GT5-PEA2 defensive grenade (430 g). This payload constraint represents a significant operational gap that the proposed design aims to address.

Table 1: Benchmarking of commercial quadcopter loitering munitions.

No.	Specification Parameters	Viper40	Drone40	Units
1	Maximum Take-Off Mass (MTOM)	450	300	g
2	Maximum Operating Empty Mass (MOEM)	250	110	g
3	Payload Mass (m_{pl})	200	190	g
4	Payload Ratio ($f_{\mathrm{pl}} = m_{\mathrm{pl}}/\mathrm{MTOM}$)	0.44	0.63	–
5	Maximum Speed	18	20	m/s
6	Endurance at MTOM	25	30	min
7	Endurance at MOEM	35	60	min
8	Maximum Range at MTOM	1000	20 000	m
9	Maximum Range at MOEM	5000	20 000	m
10	Maximum Length (Folded)	–	180	mm
11	Diameter	40	40	mm

Analysis of the benchmark data reveals an average payload ratio of $f_{\mathrm{pl}} = 0.535$, which serves as a baseline for the new design's mass allocation strategy.

2.2 Design Requirements and Objectives

Based on the operational requirements for Indonesian military applications and the identified gaps in existing commercial platforms, the design requirements and objectives were established as presented in Table 2. The requirements are categorized into mandatory minimum specifications and aspirational goals to guide the design optimization process.

Table 2: Design requirements and objectives.

No.	Design Requirements	Mandatory	Goal	Units
1	Maximum Payload	400	600	g
2	Endurance at MTOM	15	30	min
3	Endurance at MOEM	30	60	min
4	Range at MTOM	1,000	5,000	m
5	Range at MOEM	5,000	10,000	m
6	Maximum Speed	18	21	m/s

The primary design driver is the payload requirement of 400 g to 600 g, which necessitates a significant increase in MTOM compared to existing platforms. This requirement directly supports compatibility with standard military ordnance, particularly the GT5-PEA2 defensive grenade (430 g) used by Indonesian forces.

2.3 Initial Mass Estimation

The initial gross MTOM estimation was derived from the benchmark payload ratio analysis. Using the average payload ratio of $f_{\text{pl}} = 0.535$ and targeting a 430 g payload (GT5-PEA2 grenade), the preliminary MTOM estimate was calculated as:

$$\text{MTOM}_{\text{initial}} = \frac{m_{\text{payload}}}{f_{\text{pl}}} = \frac{430\,\text{g}}{0.535} = 804\,\text{g} \tag{1}$$

Rounding up to account for design uncertainties and additional payload mounting hardware, an initial design MTOM of 850 g was established for subsequent propulsion system sizing.

2.4 Propulsion System Sizing

The total thrust requirement for the quadcopter was determined using a load factor approach. The load factor (l_f) represents the ratio between required thrust force and aircraft weight, providing adequate thrust margin for maneuvering and disturbance rejection. According to (Vu et al., 2019; Cai et al., 2014), typical load factors for small quadcopters range from 2.0 to 2.5, with 2.3 being commonly used for tactical applications.

The total required thrust was calculated as:

$$F_{\text{required}} = l_f \times \text{MTOM} \times g = 2.3 \times 0.85\,\text{kg} \times 9.81\,\text{m/s}^2 = 19.1\,\text{N} \tag{2}$$

Distributing this thrust equally among four propellers:

$$F_{\text{per propeller}} = \frac{F_{\text{required}}}{4} = \frac{19.1\,\text{N}}{4} = 4.78\,\text{N} \tag{3}$$

A 6 in (152.4 mm) diameter propeller with 3 in (76.2 mm) pitch was selected based on market availability and dimensional constraints for the folding configuration. The propeller performance characteristics were estimated using blade element theory, with thrust coefficient $C_T = 0.041$, torque coefficient $C_Q = 0.0036$, and design advance ratio $J = 0.375$.

To generate the required thrust of 4.78 N per propeller, the necessary rotational speed was calculated using the thrust equation:

$$T = \rho n^2 D^4 C_T \tag{4}$$

Solving for rotational speed:

$$n = \sqrt{\frac{T}{\rho D^4 C_T}} = \sqrt{\frac{4.78\,\text{N}}{1.225\,\text{kg/m}^3 \times (0.152\,\text{m})^4 \times 0.041}} = 417/\text{s}\ (25\,020/\text{min}) \tag{5}$$

This rotational speed requirement guided the subsequent motor selection process, ensuring compatibility between propeller characteristics and motor performance capabilities. The calculated thrust-to-weight ratio of 2.3 provides adequate performance margins for hovering with full payload, maneuvering in urban environments with wind disturbances, maintaining stability during rapid directional changes, and compensating for center-of-gravity variations between mission configurations.

2.5 Component-Off-The-Shelf (COTS) Strategy

To minimize development costs and ensure rapid deployment capability, the design philosophy emphasizes the use of COTS components wherever possible. This approach provides several advantages:

1. **Reduced Development Time**: Eliminates need for custom component development
2. **Cost Effectiveness**: Leverages economies of scale from commercial markets
3. **Reliability**: Utilizes proven components with established performance records
4. **Maintainability**: Ensures availability of replacement parts and technical support
5. **Scalability**: Enables rapid production scaling using existing supply chains

The COTS strategy is particularly well-suited for tactical UAV applications where operational deployment timelines often preclude lengthy development cycles. Subsequent sections detail the specific COTS components selected for each subsystem based on the established performance requirements and thrust calculations.

3 System Design and Architecture

3.1 Overall System Architecture

The quadcopter design employs a modular architecture that enables rapid reconfiguration between three distinct mission profiles as illustrated in Figure 1: intelligence, surveillance, and reconnaissance (ISR); payload delivery; and kamikaze operations. The system architecture prioritizes compactness, portability, and operational flexibility while maintaining structural integrity under tactical deployment conditions.

Each mission profile, depicted in Figure 1, presents unique operational requirements and payload configurations. The ISR mission utilizes the quadcopter at minimum weight for maximum endurance and range, carrying only essential sensor equipment. The payload delivery mission incorporates the full grenade mounting system for precise munition deployment at designated targets. The kamikaze mission represents the ultimate force multiplication capability, where the entire platform becomes the delivery mechanism.

The core design philosophy centers on a foldable configuration that minimizes storage volume for infantry transport while providing adequate performance when deployed. The folded configuration achieves maximum dimensions of 180 mm length, facilitating integration with standard military equipment loadouts. Figure 2 illustrates the compact folded configuration optimized for ISR missions at maximum operating empty mass (MOEM). Complete CAD documentation is publicly available at `https://cad.onshape.com/documents/6c9935d65d360fdccf9a8c1d/w/e5a6914356046b56729ae3be/e/969cf05f5bcf11cd731a16e6` to support collaborative development and manufacturing.

3.2 Airframe Design and Materials Selection

The airframe employs a symmetric X-configuration with four foldable arms that rotate about central pivot points. This configuration provides several advantages: uniform load distribution across all four propulsion units, simplified flight control algorithms, and compact folding geometry. The unfolded configuration, shown in Figure 3, achieves a rotor disk diameter of 400 mm with 6 in (152.4 mm) propellers.

Polycarbonate was selected as the primary structural material based on a comprehensive trade study considering strength-to-weight ratio, manufacturing feasibility, and cost constraints. Polycarbonate offers several critical advantages for tactical UAV applications: superior impact resistance compared to alternative polymers essential for tactical deployment scenarios, excellent 3D printing characteristics enabling rapid prototyping (Gao et al., 2015) and low-volume production, favorable density of $1.2\,\mathrm{g/cm^3}$ providing optimal strength-to-weight ratio, resistance to temperature variations and UV degradation typical in field operations, and cost effectiveness through readily available material with established supply chains.

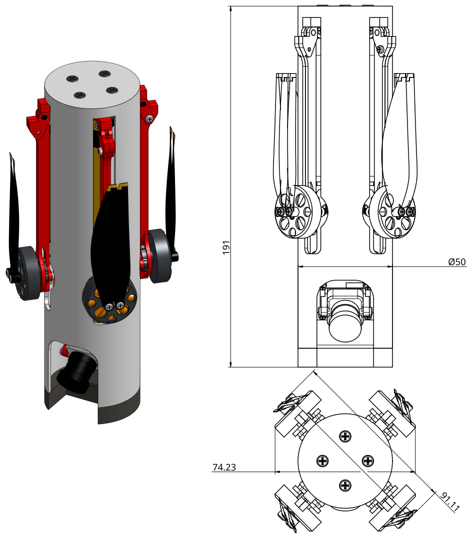

Figure 2: Three-view drawing of quadcopter in folded configuration at maximum operating empty mass (MOEM). Dimensions shown in millimeters.

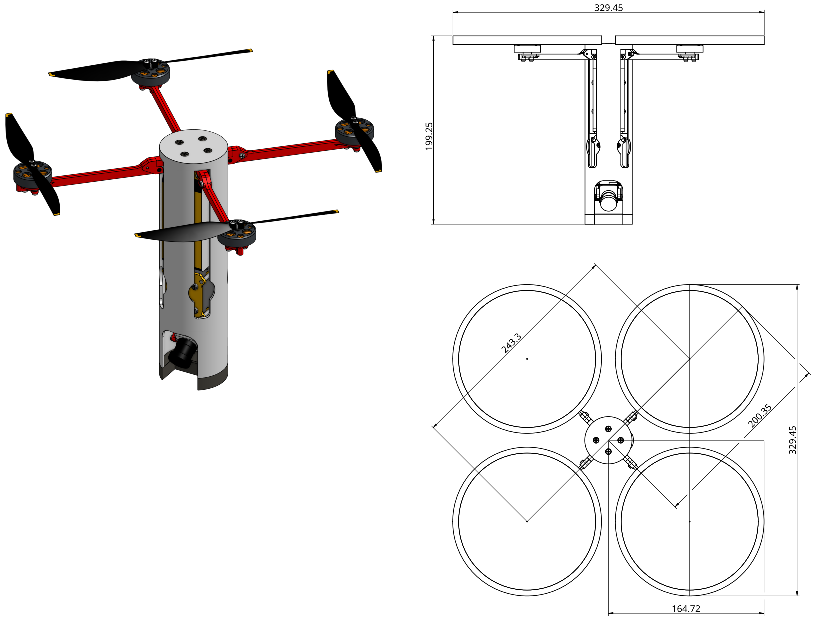

Figure 3: Three-view drawing of quadcopter in deployed configuration at maximum operating empty mass (MOEM). Dimensions shown in millimeters.

The total airframe mass of 109.0 g represents 12.8 % of the maximum take-off mass, indicating efficient structural design. Component thickness varies from 1.5 mm for non-load-bearing panels to 3.0 mm for critical structural joints and motor mounts.

3.3 Component Integration and Layout

Figure 4 illustrates the optimized component layout within the central fuselage. The arrangement prioritizes center-of-gravity control, thermal management, and accessibility for maintenance operations. The battery pack, representing the largest single mass component at 167.0 g, is positioned at the geometric center to minimize CG shift between mission configurations.

The propulsion system consists of four brushless DC motors rated at 16.4 g each, selected to meet the rotational speed requirement of 25 020/min calculated in Section 2.4. The motors are mounted using vibration-isolating elastomeric bushings to minimize structural fatigue and improve flight

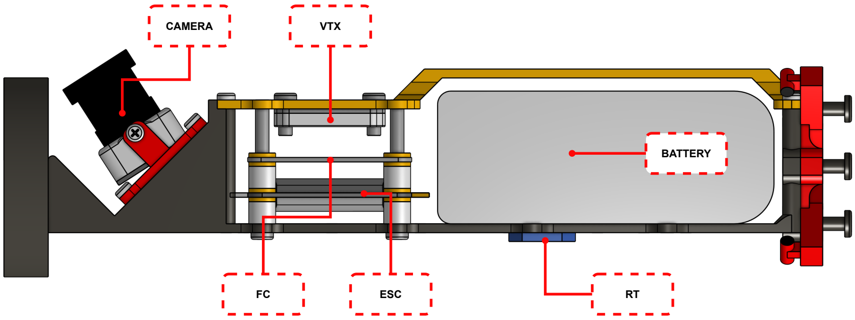

Figure 4: Internal component arrangement showing optimized layout for center-of-gravity control and thermal management.

stability. Each motor-propeller combination generates the required 4.78 N thrust at maximum power settings.

The avionics suite integrates commercial-off-the-shelf components optimized for weight and performance. The T-Motor F7 + F55A PRO II flight controller provides integrated flight control and electronic speed control functionality, while the Matek ELRS 2.4GHz receiver enables secure telemetry and control links. The video system comprises a RunCam Eagle 3 Night Vision camera with T-Motor FT800 video transmitter for real-time ISR capabilities. Power management utilizes a Tattu R-Line 1550mAh 4S 130C battery pack optimized for high discharge rate applications.

3.4 Payload Mounting and Release System

The payload mounting system employs a modular approach that enables rapid reconfiguration between mission types. For payload delivery and kamikaze missions, the GT5-PEA2 defensive grenade (430 g, 50 mm diameter) mounts to the ventral surface via a custom interface shown in Figure 5. The mounting system mass of 35.2 g includes all structural components, release mechanisms, and attachment hardware. The design accommodates center-of-gravity variations between loaded and unloaded configurations while maintaining flight stability margins.

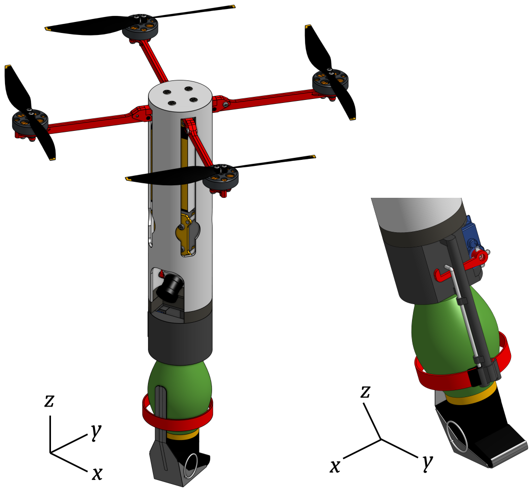

Figure 5: Modular payload mounting system designed for GT5-PEA2 defensive grenade integration.

Figure 6 details the electromechanical release system designed for reliable payload deployment.

The mechanism employs a fail-safe design philosophy where the default state secures the payload, and active servo actuation is required for release. The operating sequence follows four distinct phases: pre-flight preparation where the safety pin is removed and payload secured by safety lever and retention strap; in-flight operation where payload is held by mechanical retention system independent of electrical power; release command execution where servo motor actuates release hook, lifting aluminum retention rod; and payload separation where strap tension releases safety lever, initiating grenade fuse sequence.

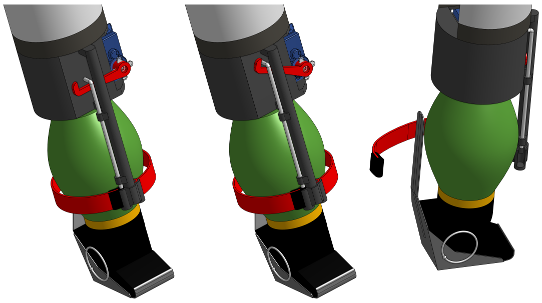

Figure 6: Electromechanical payload release mechanism with fail-safe design architecture.

The release mechanism incorporates multiple safety features to prevent inadvertent activation, including mechanical retention as primary safety system, electrical actuation required for release (fail-safe to secure), physical separation between release mechanism and grenade arming system, and manual safety pin for ground handling operations. This comprehensive safety approach ensures reliable operation under combat conditions while preventing accidental deployment during transport or handling.

3.5 Mission Configuration Analysis

The modular design enables 465.2 g mass reduction when transitioning from payload delivery to ISR configuration, as detailed in Table 3. This significant mass variation between mission profiles demonstrates the flexibility of the modular architecture while highlighting the performance trade-offs inherent in multi-mission design.

Table 3: Detailed mass breakdown by mission configuration.

No.	Component	ISR (g)	Payload (g)	Kamikaze (g))
1	Airframe	109.0	109.0	109.0
2	Flight Controller	7.4	7.4	7.4
3	Electronic Speed Controller	17.5	17.5	17.5
4	Battery	167.0	167.0	167.0
5	Motors (4Œ)	65.6	65.6	65.6
6	Propellers (4Œ)	3.6	3.6	3.6
7	Video Transmitter	7.6	7.6	7.6
8	Radio Receiver	1.2	1.2	1.2
9	Camera	8.5	8.5	8.5
10	Payload Mounting Support	–	35.2	35.2
11	GT5-PEA2 Grenade	–	430.0	430.0
	Total Mass	**387.4**	**852.6**	**852.6**

The modular payload system maintains center-of-gravity within acceptable limits for all mission configurations. The ISR configuration achieves optimal CG positioning with all components concentrated near the geometric center. Payload delivery and kamikaze configurations experience a 12 mm forward CG shift, which remains within the flight control system's compensation capability, ensuring stable flight characteristics across all operational modes.

3.6 Cost Analysis and Economic Feasibility

Table 4 presents the detailed cost analysis for COTS components based on current market pricing. The total component cost ranges from 415.15 to 433.66 USD depending on mission configuration requirements, with the variance primarily attributed to different airframe material requirements for payload mounting systems.

The production cost analysis considers development, tooling, and manufacturing expenses for small-batch production scenarios typical of tactical equipment procurement. Using the methodology from (Nicolai and Carichner, 2010), the development support cost is estimated as:

$$C_{\text{dev}} = 257.75 \times W^{0.63} \times S^{1.3} \times (1+r)^{27} \tag{6}$$

where W is MTOM in kg, S is maximum speed in m/s, and r is the inflation rate. For the design parameters ($W = 0.853$ kg, $S = 21$ m/s, $r = 0.0253$), the development cost is approximately 30 060 USD.

Table 4: Detailed cost analysis for COTS components.

No.	Component	Manufacturer, Product	Price (USD)
1	Camera	RunCam, Eagle 3 Night Vision	69.99
2	Battery Pack	Tattu, R-Line 1550mAh 4S 130C	33.99
3	Communication/Telemetry	Matek, ELRS 2.4GHz Receiver R24S	19.99
4	Video Transmission	T-Motor, FT800	38.90
5	Flight Controller	T-Motor, F7 + F55A PRO II	137.90
6	Motors (4Œ)	T-Motor, F2004 1700KV	83.60
7	Propellers (4Œ)	DJI, Mini Pro Propellers	9.00
8	Airframe Material	Polycarbonate filament	21.80 to 39.29
		Total Component Cost	415.15 **to** 433.66

Manufacturing analysis indicates that 100-unit production requires approximately 265 labor hours, resulting in a unit production cost of 774.26 USD including tooling and overhead. The economic analysis demonstrates significant cost advantages of the COTS-based design approach. For comparison, the DJI Mavic 3 Pro alone costs 2199 USD (DJI, 2025), while the addition of the payload dropping attachment adds 199 USD, totaling approximately 2400 USD for a complete commercial system. This represents a 68 % cost reduction compared to both existing commercial loitering munitions and commercial drone alternatives, providing substantial economic benefits for military procurement programs. The cost analysis demonstrates significant economic advantages of the COTS-based approach through 68 % component cost reduction compared to commercial alternatives, minimized development risk through proven COTS component selection, production scalability enabled by established supply chains, and reduced lifecycle maintenance costs through standard components.

The break-even analysis indicates profitability at production volumes exceeding 50 units, making the design economically viable for military procurement scenarios. This low break-even threshold enables cost-effective production even for specialized military applications with limited procurement quantities, supporting widespread adoption across different military organizations and operational requirements.

4 Performance Analysis

4.1 Performance Analysis Methodology

The performance analysis employs a comprehensive modeling approach that integrates aerodynamic, propulsive, and energy consumption characteristics to predict mission-specific range and endurance capabilities. The analysis considers three distinct flight regimes: hover, low-speed forward flight, and high-speed dash conditions, corresponding to operational requirements for tactical deployment scenarios. Performance calculations were verified using eCalc electric flight calculator (DJI, 2025) to ensure accuracy of the theoretical predictions.

The performance evaluation methodology follows established rotorcraft analysis principles adapted for multirotor configurations (Seddon and Newman, 2011). Key performance metrics evaluated include maximum range (distance achievable at optimal cruise speed for each mission configuration), maximum endurance (flight time achievable at minimum power consumption speed), speed envelope (operational velocity range considering power limitations and mission requirements), and payload-range trade-offs (performance sensitivity to mission configuration variations).

4.2 Aerodynamic and Power Modeling

The total drag force acting on the quadcopter in forward flight consists of parasitic drag from the fuselage and interference effects, plus induced drag from the rotor system operating in edgewise flight conditions. The total drag is modeled as:

$$D_{\text{total}} = D_{\text{parasitic}} + D_{\text{induced}} = \frac{1}{2}\rho V^2 S C_{D_0} + \frac{T^2}{2\rho A V^2} \tag{7}$$

where ρ is air density (1.225 kg/m^3 at sea level), V is forward velocity, S is reference area, C_{D_0} is zero-lift drag coefficient, T is total thrust, and A is rotor disk area. Based on the compact geometry and component arrangement, the equivalent flat plate area was estimated at 0.012 m^2 for the ISR configuration and 0.015 m^2 for payload delivery and kamikaze configurations, accounting for the additional drag from the ventral payload mounting system.

The total power required for sustained flight combines hovering power, climb/descent power, and forward flight power components:

$$P_{\text{total}} = P_{\text{hover}} + P_{\text{climb}} + P_{\text{forward}} + P_{\text{accessories}} \tag{8}$$

The hovering power consumption follows momentum theory with empirical corrections for non-ideal flow effects:

$$P_{\text{hover}} = \frac{T^{3/2}}{\sqrt{2\rho A}} \times \kappa \tag{9}$$

where $\kappa = 1.15$ is the figure of merit accounting for tip losses, non-uniform inflow, and swirl effects typical of small quadcopters (Leishman, 2006). Forward flight power includes additional terms for propulsive efficiency and profile drag:

$$P_{\text{forward}} = \frac{TV}{\eta_p} + \frac{DV}{\eta_p} \tag{10}$$

where $\eta_p = 0.85$ is the propulsive efficiency estimated for the selected propeller-motor combination operating at design conditions.

The battery discharge characteristics significantly influence mission performance, particularly at high discharge rates required for maximum power operation. The available energy is modeled using Peukert's equation modified for lithium polymer chemistry:

$$E_{\text{available}} = E_{\text{nominal}} \times \left(\frac{I_{\text{nominal}}}{I_{\text{actual}}}\right)^{\alpha} \tag{11}$$

where $E_{\text{nominal}} = 91.08$ W h is the nominal battery energy, $I_{\text{nominal}} = 1.55$ A is the 1C discharge rate, and $\alpha = 0.05$ is the Peukert coefficient for high-quality LiPo batteries.

4.3 Mission-Specific Performance Analysis

The ISR mission operates at the minimum system mass of 387.4 g, providing optimal power loading for extended operations. Figure 7 demonstrates that maximum endurance of 30.0 min is achieved at hover or very low forward speeds (<2 m/s). This endurance capability meets the design goal specified in Table 2. Maximum range performance of 6790 m occurs at the optimal cruise speed of 7 m/s, where power required for forward flight is minimized. This represents a 36 % improvement over the mandatory range requirement of 5000 m, providing significant operational margin for tactical scenarios. The power consumption at optimal cruise conditions is approximately 157 W, resulting in a specific energy consumption of 1.73 W h/km, which compares favorably with commercial small UAV platforms of similar size and capability.

Both payload delivery and kamikaze missions operate at the maximum take-off mass of 852.6 g, representing a 120 % increase over the ISR configuration. The additional mass significantly impacts power loading and consequently reduces both range and endurance performance. Maximum endurance for these mission profiles is 9.5 min at low speeds (3 m/s), which falls below the mandatory requirement of 15 min specified in Table 2. However, this still exceeds many tactical mission duration requirements, indicating that mission planning must account for reduced loiter capability when carrying payloads. The maximum range of 2989 m is achieved at a cruise speed of 10 m/s. While this exceeds the mandatory range requirement of 1000 m, it represents a 56 % reduction compared to the ISR configuration, highlighting the significant performance penalty associated with payload carriage.

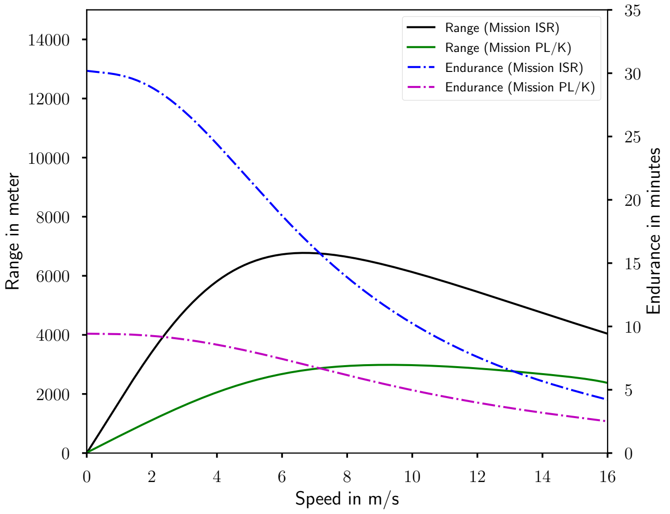

Figure 7: Range and endurance performance envelope for all mission configurations. ISR mission (blue) demonstrates superior performance due to reduced mass, while payload delivery and kamikaze missions (red) show identical performance characteristics due to equivalent MTOM.

4.4 Performance Envelope Characterization

Figure 7 reveals the characteristic relationship between forward speed and endurance for multirotor aircraft. The endurance curves exhibit relatively flat characteristics at low speeds (0 m/s to 5 m/s), where hovering power dominates total consumption. Beyond the minimum power speed, endurance decreases rapidly due to increasing parasitic drag losses. The ISR configuration maintains endurance above 25 min for speeds up to 5 m/s, providing tactical flexibility for slow reconnaissance missions. In contrast, the payload configurations show more rapid endurance degradation, dropping below 8 min at speeds exceeding 8 m/s.

The range curves demonstrate the classic relationship where maximum range occurs at intermediate cruise speeds that balance power consumption with ground speed. For the ISR mission, the optimal cruise speed of 7 m/s provides 15 % better range than hovering flight, while speeds above 12 m/s result in rapidly decreasing range due to parasitic drag penalties. Payload missions show similar trends but with reduced absolute performance. The optimal cruise speed increases to 10 m/s due to higher wing loading, but maximum range remains significantly below ISR capabilities.

Maximum dash speed performance was evaluated to assess tactical maneuvering capabilities. The ISR configuration achieves a maximum speed of 25.3 m/s at full power, exceeding the design goal of 21 m/s. However, this speed can only be maintained for approximately 1.5 min before battery depletion. Payload configurations achieve maximum speeds of 25.3 m/s, exceeding the design goal and providing excellent performance for rapid target engagement or evasive maneuvering scenarios.

4.5 Design Requirements Validation

Table 5 compares the calculated performance results against the design requirements established in Table 2. The analysis demonstrates that the design meets or exceeds mandatory requirements across most performance categories. The payload configuration endurance of 9.3 min falls below the mandatory requirement of 15 min. This deficiency indicates that either battery capacity must be increased or operational procedures must be modified to ensure mission success within the available flight time.

Table 5: Performance validation against design requirements. Performance indicators: △ exceeds design goal, ✓ meets mandatory requirement, × falls below mandatory requirement.

Performance Metric	Design Requirements		Achieved Performance	
	Mandatory	Goal	ISR	Payload
Endurance at MTOM (min)	15	30	–	9.5 ×
Endurance at MOEM (min)	30	60	30.0 ✓	–
Range at MTOM (m)	1000	5000	–	2989 △
Range at MOEM (m)	5000	10 000	6790 ✓	–
Maximum Speed (m/s)	18	21	25.3 △	25.3 △

4.6 Comparative Analysis with Benchmark Platforms

Table 6 presents a comparative analysis of the designed quadcopter against the benchmark platforms (Viper40 and Drone40) across key performance metrics. The design achieves a 120 % increase in payload capacity, enabling compatibility with standard military ordnance, while endurance and range performance are reduced compared to commercial platforms, reflecting the fundamental trade-off between payload capacity and flight performance. The 68 % cost reduction provides significant economic advantages despite performance compromises, and maximum speed performance meets or exceeds commercial benchmarks across all configurations.

Table 6: Performance comparison with benchmark platforms. Performance indicators: Blue indicates improvement, Orange indicates trade-off relative to benchmark average.

Performance Metric	Viper40	Drone40	This Design (Payload)	Improvement vs. Average
Payload Capacity (g)	200	190	430	+120%
Endurance at MTOM (min)	25	30	9.5	-65%
Range at MTOM (m)	1000	20 000	2989	-72%
Maximum Speed (m/s)	18	20	25.3	+26%
Unit Cost (USD)	~2400		774	-68%

4.7 Sensitivity Analysis and Design Optimization

Performance sensitivity to mass variations was evaluated to understand design robustness and optimization potential. A 10 % mass reduction through component optimization would improve endurance by approximately 12 % and range by 8 %, indicating moderate sensitivity to weight optimization efforts. Advanced lithium polymer batteries with 20 % higher energy density would increase endurance to 11.4 min for payload missions, approaching the mandatory requirement. This suggests that battery technology improvements represent the most effective path for performance enhancement.

Propeller optimization studies indicate that custom-designed propellers could improve hovering efficiency by 8 % to 12 %, translating to 1 min to 2 min endurance improvements. However, the additional development cost and complexity may not justify the modest performance gains for tactical applications requiring rapid deployment. The performance analysis demonstrates that the design achieves the primary objective of significantly increased payload capacity while maintaining acceptable flight performance for tactical operations. The identified endurance limitation in payload configuration requires operational consideration but does not fundamentally compromise mission effectiveness for the intended tactical deployment scenarios.

5 Conclusions and Future Work

5.1 Summary of Key Achievements

This paper successfully developed an open conceptual design architecture for a multi-mission tactical quadcopter that addresses critical payload limitations in existing commercial loitering munitions. The design achieved several significant technical milestones that advance the state-of-the-art in tactical UAV systems.

The primary achievement is the successful integration of a 400 g to 600 g payload capacity while maintaining tactical portability and cost-effectiveness. This represents a 120 % increase over existing commercial platforms (Viper40 and Drone40), enabling compatibility with standard military ordnance such as the Indonesian GT5-PEA2 defensive grenade (430 g). The modular design architecture facilitates rapid reconfiguration between three distinct mission profiles: intelligence, surveillance, and reconnaissance (ISR); payload delivery; and kamikaze operations.

The folding configuration achieves maximum dimensions of 180 mm when stowed, meeting infantry portability requirements while providing adequate performance when deployed. The total system mass ranges from 387.4 g for ISR missions to 852.6 g for payload operations, maintaining compatibility with established military load carrying standards.

5.2 Design Validation and Performance Assessment

The performance analysis demonstrates mixed success in meeting the established design requirements. The ISR configuration exceeded performance targets across all metrics, achieving 30.0 min endurance and 6790 m range, both meeting or exceeding the design goals. Maximum speed capability of 25.3 m/s surpassed the target of 21 m/s, providing excellent tactical maneuvering capability.

However, a critical limitation was identified in the payload configuration endurance of 9.5 min, which falls below the mandatory requirement of 15 min. This deficiency represents the fundamental trade-off between payload capacity and flight performance in small multirotor systems. Despite this limitation, the payload delivery range of 2989 m substantially exceeds the mandatory requirement of 1000 m, providing operational flexibility for tactical deployment scenarios.

The propulsion system sizing methodology successfully delivered the required thrust-to-weight ratio of 2.3, ensuring adequate performance margins for hovering with full payload, maneuvering in urban environments, and maintaining stability during rapid directional changes. The Component-Off-The-Shelf (COTS) approach proved effective in balancing performance requirements with cost constraints and development timeline considerations.

5.3 Technical Contributions and Innovation

This work makes several significant technical contributions to the field of tactical UAV design. The open design architecture approach democratizes access to advanced UAV technology, enabling rapid adaptation and customization by military organizations with limited research and development resources. By making all design documentation, CAD files, and performance calculations publicly available, this work facilitates collaborative development and accelerates innovation in military robotics applications.

The modular payload integration system represents a novel approach to multi-mission capability in compact tactical platforms. The electromechanical release mechanism incorporates multiple fail-safe features while maintaining operational simplicity, addressing critical safety requirements for ordnance delivery applications. The mechanical retention system provides reliable payload security independent of electrical power, while the servo-actuated release mechanism enables precise deployment timing.

The comprehensive performance modeling methodology integrates aerodynamic analysis, power consumption modeling, and battery discharge characteristics to provide accurate mission capability predictions. This modeling approach provides a foundation for future design optimization studies and enables systematic trade-off analysis between competing design objectives.

5.4 Economic and Operational Impact

The economic analysis demonstrates significant cost advantages of the COTS-based design approach. The total component cost of 415.15 to 433.66 USD, combined with estimated production costs, yields a unit price of 774.26 USD for 100-unit production runs. This represents a 68 % cost reduction compared to existing commercial loitering munitions and drone alternatives priced at approximately 2400 USD, providing substantial economic benefits for military procurement programs.

The cost effectiveness extends beyond initial acquisition to lifecycle considerations. The use of standard commercial components ensures availability of replacement parts and technical support through established supply chains. This approach minimizes logistical complexity and reduces long-term maintenance costs compared to custom-developed systems requiring specialized support infrastructure.

From an operational perspective, the design addresses critical capability gaps in urban warfare scenarios. The ability to deliver standard military ordnance with precision while maintaining operator safety represents a significant force multiplication capability for infantry units. The compact folding configuration enables integration with existing equipment loadouts without exceeding established weight and volume constraints.

5.5 Limitations and Design Constraints

Several important limitations must be acknowledged in the current design. The most significant constraint is the payload configuration endurance falling below mandatory requirements, limiting operational effectiveness for extended loitering missions. This fundamental trade-off between payload capacity and flight performance reflects the physical constraints of small multirotor systems and represents an area requiring further optimization.

The reliance on COTS components, while providing cost and development time advantages, also introduces limitations in system optimization. Custom-designed components could potentially improve performance efficiency, but at the cost of increased development complexity and higher production costs. The design represents an optimal balance for tactical applications requiring rapid deployment capability.

Environmental limitations include reduced performance at high altitude and in adverse weather conditions typical of tactical deployment scenarios. The current design assumes sea-level operation with standard atmospheric conditions, and performance degradation at operational altitudes requires further investigation.

The release mechanism, while incorporating multiple safety features, requires additional testing and validation to ensure reliable operation under combat conditions. Vibration, shock, and electromagnetic interference effects on the electromechanical actuation system need comprehensive evaluation before operational deployment.

5.6 Future Research Directions

Several promising research directions emerge from this work that could address identified limitations and extend capabilities:

- Battery Technology Integration: Advanced lithium polymer batteries with higher energy density could address the payload configuration endurance limitation. Integration of emerging battery technologies could improve endurance by 15 % to 25 %, potentially meeting mandatory requirements while maintaining payload capacity.
- Propulsion System Optimization: Custom propeller design optimized for the specific operating conditions and motor characteristics could improve hovering efficiency by 8 % to 12 %. Advanced motor technologies with higher power-to-weight ratios could further enhance performance while reducing system mass.
- Autonomous Mission Capabilities: Integration of advanced flight control algorithms enabling autonomous mission execution could significantly enhance operational effectiveness. Waypoint navigation, target recognition, and autonomous engagement capabilities would reduce operator workload and improve mission success probability.
- Swarm Operations: The modular design architecture provides a foundation for developing coordinated swarm capabilities, where multiple units could operate collaboratively to achieve complex mission objectives. Distributed intelligence and communication protocols could enable force multiplication effects beyond individual platform capabilities.
- Payload Diversification: The modular payload interface could accommodate alternative payloads including advanced sensors, communication relays, or non-lethal deployment systems. This flexibility would expand mission applications beyond the current focus on ordnance delivery.
- Environmental Hardening: Development of ruggedized versions capable of operation in extreme environmental conditions, including high altitude, temperature extremes, and electromagnetic warfare environments, would expand operational utility for diverse military applications.

5.7 Concluding Remarks

This research successfully demonstrates the feasibility of developing cost-effective, high-payload-capacity tactical quadcopters using commercially available components and open design principles. The 120 % increase in payload capacity over existing commercial platforms, combined with 68 % cost reduction, represents a significant advancement in tactical UAV capability.

While the identified endurance limitation in payload configuration requires operational consideration, the overall design achieves the primary objective of enabling compatibility with standard military ordnance while maintaining tactical portability and economic viability. The open design approach facilitates continued development and adaptation by the broader research and defense communities.

The technical contributions of this work extend beyond the specific design to include comprehensive performance modeling methodologies, innovative payload integration approaches, and economic analysis frameworks applicable to broader tactical UAV development programs. The publicly available design documentation enables collaborative improvement and accelerates innovation in this critical area of military technology.

Future military operations in urban environments will increasingly rely on tactical UAV systems that provide precision capabilities while minimizing risk to personnel. This design provides a foundation for meeting these evolving operational requirements through cost-effective, rapidly deployable systems that leverage commercial technology advances. The successful integration of enhanced payload capacity with tactical portability requirements demonstrates the potential for transformative improvements in infantry-level precision engagement capabilities.

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