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DESIGN AND PERFORMANCE EVALUATION OF AN FPV TACTICAL LOITER MUNITION DRONE FOR TROPICAL MOUNTAINOUS OPERATIONS IN PAPUA

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Abstract: This research aims to design and analyze an FPV Tactical Loiter Munitions (FPV-TLM) drone as a tactical operational support platform for the Indonesian Army (TNI AD) in the Papua region. The FPV-TLM technology serves a dual function as both a reconnaissance system and a precision-strike asset capable of operating in extreme environments. The study employs a descriptive-qualitative approach combined with limited-scale experimental testing to evaluate control-system stability, energy efficiency, and surveillance effectiveness in tropical and mountainous terrain. The experimental results indicate that the adaptive PID-based control system maintained hover stability of up to 93% under wind speeds of 10–14 m/s. Performance evaluation across multiple design variants shows that the Kevlar–Nylon configuration achieved the best overall performance, with an average loiter duration of approximately 26 minutes and improved energy efficiency compared to other variants. Strategically, the deployment of FPV-TLM enhances surveillance operational effectiveness by 47% compared to conventional ground patrols and supports national defense self-reliance through increased domestic content (TKDN) and the integration of local research capabilities.

Keywords: FPV-TLM, UAV, Papua, PID Control System, National Defense

Introduction

The rapid advancement of modern defense technology has driven nations to develop weapon systems that are adaptive, precise, and capable of responding to hybrid threats, which combine conventional military tactics with irregular warfare, information operations, and asymmetric strategies (Bode, Ingvild and Watts, 2023). In the context of the Papua region, such hybrid threats manifest through small-unit guerrilla movements, exploitation of difficult terrain for concealment, intermittent armed attacks on security forces, disruption of critical infrastructure, and the use of local information networks to evade detection and influence public perception. These threat characteristics complicate conventional force deployment by reducing early-warning capability and increasing the risk to personnel during ground-based patrols (Voskuijl, Mark and Adib Bin, 2022). Within this evolving threat landscape, First Person View Tactical Loiter Munition (FPV-TLM) systems have emerged as a promising technological development, integrating reconnaissance, loitering capability, and precision-strike functions within a single operator-controlled platform.

Indonesia's Papua region presents distinct operational challenges for UAV deployment due to its rugged mountainous terrain, dense tropical forests, and limited communication infrastructure (Rozi, 2020). In response to these constraints, FPV-TLM technology offers several strategic advantages, including reduced personnel exposure, enhanced persistence in surveillance operations, and the capability to conduct precision strikes without relying on large-scale weapon

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platforms (Lee, Jaehoon and Park, Seungmin and Yun, Taesoo and Jung, Kihyun and Kim, 2022; Pratama, 2021). However, UAV operations in Papua are also subject to severe technical and environmental limitations. High humidity, frequent heavy rainfall, unstable wind patterns, and complex signal-propagation conditions can degrade flight stability, energy efficiency, and real-time data transmission reliability (Nassi, Ben and Ben-Netanel, Lior and Shamir, Adi and Elovici, 2021; Zheng, Di and Li, Jun and Wang, 2023).

A growing body of literature has demonstrated the effectiveness of loiter munition systems in reconnaissance and precision-strike missions across various conflict environments (Chang, Yu and Wu, Hao and Hao, 2024; Skraparlis, Alexandros N. and Katsikis, 2024). These studies highlight the operational value of loitering capabilities, autonomous navigation, and strike precision in modern warfare. Nevertheless, existing research predominantly focuses on medium- to large-scale tactical platforms operating in relatively open or temperate environments. Consequently, limited attention has been given to lightweight FPV-class loiter munition systems designed specifically for tropical mountainous regions with complex terrain and adverse environmental conditions, such as those found in Papua. Moreover, prior studies tend to examine technical performance, operational usage, or strategic implications in isolation, rather than integrating these dimensions within a unified design and evaluation framework, particularly for FPV-class loiter munition systems operating in tropical mountainous environments such as Papua.

Addressing this gap, the present study seeks to investigate the design and performance of an FPV-TLM platform tailored to the operational realities of Papua. Specifically, this research aims to answer three key questions: (1) how an FPV-TLM system can be designed to meet the technical and environmental demands of tropical mountainous operations, (2) which technical and environmental factors most significantly influence its operational performance, and (3) how the deployment of such a system can enhance reconnaissance and precision-strike effectiveness while minimizing risks to personnel and civilians. Accordingly, the objectives of this study are to develop an adaptive FPV-TLM conceptual design, analyze enabling and constraining factors affecting UAV performance in Papua-like environments, and evaluate the system's operational effectiveness in representative tactical scenarios. Theoretically, this research contributes to the literature on tactical UAV design and control-system integration under extreme environmental conditions. Practically, it provides insights for the Ministry of Defense, the Indonesian Army, and the domestic defense industry in formulating technical requirements, developing FPV-TLM platforms, and establishing operational guidelines to improve mission effectiveness in Papua.

Method

This study employed a mixed-methods approach using an Explanatory Embedded Design, in which qualitative inquiry served as the primary framework and quantitative testing was integrated to verify the technical performance of the FPV Tactical Loiter Munition (FPV-TLM) prototype. The qualitative component explored operational experiences, user perceptions, and contextual interpretations of FPV-TLM deployment through field interviews, observations, and document analysis conducted with military personnel, UAV technicians, and FPV drone operators from units operating in Papua. The research was carried out at Group-3 Kopassus Sandi Yudha and the Salabintana Sukabumi training area, which represent operational environments relevant to Papua.

The study subjects consisted of key informants directly involved in UAV operation and tactical field activities, while the research objects included the FPV-TLM conceptual design, operational procedures, and prototype performance indicators. Instruments used in data collection included interview guidelines, observation checklists, operational documentation, and a technical test kit comprising a CAD-based design model, power-train measurement tools, a thrust-testing bench, telemetry modules, and FPV transmission equipment.

The FPV-TLM prototype utilized a Pixhawk-based flight controller running ArduPilot firmware (version 4.x) as the core control unit. The adaptive PID-based control system was configured through iterative tuning using flight-log feedback, enabling real-time stabilization of roll, pitch, and yaw under variable wind conditions. This configuration allowed dynamic adjustment of control gains to maintain hover stability and attitude control during turbulence and maneuvering phases.

Quantitative data were obtained through laboratory and controlled-field experiments that examined subsystem functionality, including thrust efficiency, propeller performance, battery endurance, FPV signal latency, stability of flight attitude (roll–pitch–yaw), loiter duration, transmission range, and targeting accuracy under simulated Papua-like environmental stressors. Three FPV-TLM structural variants were evaluated using a descriptive-comparative experimental design, namely Variant A (Carbon), Variant B (Kevlar–Nylon), and Variant C (Aluminium). These variant labels are used consistently throughout the narrative sections and tables for clarity. Environmental stressors were approximated at the Sukabumi test site by combining (1) natural terrain features such as hilly topography and dense vegetation, (2) measured wind conditions ranging from 7–14 m/s using handheld anemometers, (3) high-humidity exposure recorded with digital hygrometers (70–90% RH), and (4) intentional signal obstruction scenarios to simulate non-line-of-sight (NLOS) conditions commonly encountered in Papua's valleys and forested areas.

A purposive sampling technique was applied to select informants with direct operational experience relevant to FPV-TLM deployment. The experimental design followed a descriptive-comparative framework in which several FPV-TLM variants were tested and evaluated. The measured variables included (1) aerodynamic performance (thrust-to-weight ratio, hover deviation, energy consumption), (2) control-system stability (PID response, latency), (3) FPV communication performance (LOS/NLOS range, signal quality), and (4) operational endurance (flight time, battery discharge rate). Data collection techniques comprised structured observation, in-depth interviews, literature review, and experimental measurement of technical parameters.

Qualitative data were analyzed through reflexive thematic analysis, incorporating iterative coding to identify operational patterns, user expectations, and contextual adaptation requirements. Quantitative data were processed using descriptive statistics, correlation analysis, and analysis of variance (ANOVA) to compare design variants and assess the significance of environmental effects on performance. The Simple Additive Weighting (SAW) method was employed as a multi-criteria decision-making tool to support the selection of the most suitable FPV-TLM variant by integrating multiple performance indicators into a single composite score. SAW was chosen due to its transparency, computational simplicity, and suitability for comparative evaluation scenarios where criteria weights reflect operational priorities. All procedures adhered to standard safety protocols, and technical tests used inert (non-explosive) payloads to comply with operational and legal requirements.

Discussion

The findings of this study present a comprehensive evaluation of the FPV Tactical Loiter Munition (FPV-TLM) system in relation to its suitability for tactical operations in Papua's complex terrain. Experimental results, qualitative insights, and integrated system analyses consistently demonstrate that the FPV-TLM prototype offers measurable advantages in stability, endurance, and operational utility. Based on the flight-performance data presented in Table 1 and Table 2, the adaptive PID-based flight-control system maintained an average hover-stability accuracy of up to 93% under wind speeds ranging from 10–14 m/s, confirming the prototype's capability to operate effectively in high-turbulence environments commonly found in Papua's mountainous regions.

As illustrated in Figure 1, hover performance is expressed as hover deviation in degrees, which is subsequently normalized to derive the hover-stability index reported as a percentage. The figure demonstrates a clear inverse relationship between wind speed and hover deviation, consistent with established quadrotor aerodynamic theory.

Regarding endurance performance, results in Table 1 and Table 2 indicate that Variant B achieved the best operational loiter performance among the tested configurations. The system recorded an average loiter duration of 21.87 minutes under representative operational conditions, with peak endurance reaching up to 26.4 minutes during controlled experimental trials. These values reflect statistically valid endurance performance and are therefore used as the primary loiter-duration indicators in this study.

Table 1. Descriptive Statistics of Test Parameters for Three FPV-TLM Variants

Parameter	Varian A	Varian B	Varian C	Average	SD	CI (95%)
Duration Loiter	21,8	26,4	25,2	24,5	2,36	1,4
Energy Efficiensy (Wh/min)	8,6	7,4	7,8	7,9	0,64	0,38
Deviasi Hover	3,4	2,1	2,7	2,73	0,66	0,39
Power-to-Weight Ratio (P/W)	3,5	3,8	3,9	3,73	0,21	0,12

Note: Wh/min refers to energy consumption per minute (watt-hour per minute), and P/W denotes the power-to-weight ratio of the UAV system.

Table 2. Summary Table of Loiter Duration Statistics for Each Variant

Varian	Mean (min)	Std. Dev.	Min	Median (50%)	Max
A	17,86	0,77	16,47	17,81	19,26
B	21,87	0,48	21,02	21,87	22,93
C	19,98	0,57	18,77	20,02	20,74

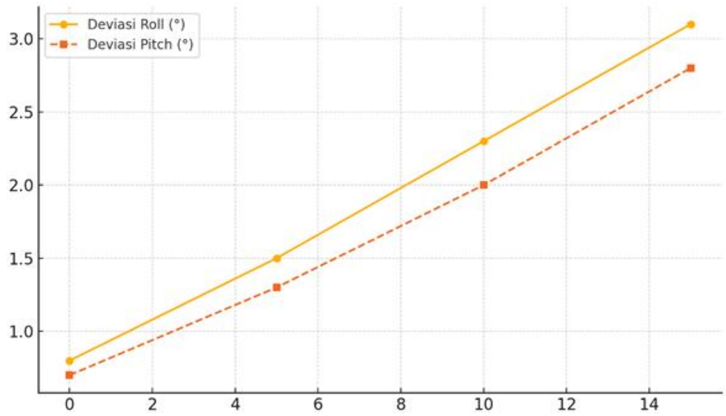

Figure 1. Hover Stability Against Wind Speed

Energy-efficiency analysis was standardized using Wh/min as the primary unit to ensure consistency across datasets. As shown in Table 1, Variant B recorded the lowest average energy consumption rate of 7.4 Wh/min, indicating superior temporal energy efficiency compared to Variant A and Variant C. While spatial efficiency metrics expressed in Wh/meter were employed during subsystem-level diagnostics, all comparative performance evaluations in this study are reported using Wh/min to maintain analytical consistency across variants. These findings are consistent with prior studies highlighting the influence of structural configuration, mass distribution, and aerodynamic efficiency on improving UAV endurance (Chang, Yu and Wu, Hao and Hao, 2024).

Table 3. FPV-TLM Energy Consumption Based on Flight Phase

Flight Phase	Average Current (A)	Voltage (V)	Power (W)	Duration (minutes)	Energy (Wh)	Notes
Hover (stationary flight)	22.3	14.8	330.0	9.5	52.3	Position 5 m, high stability
Cruise (forward flight at 45 km/h)	28.7	14.8	424.76	12.8	59.1	Efficient exploration mode
Climb (ascending to 300 m altitude)	27.5	14.7	404.3	6.0	40.4	High load, fast response

Note: Current is measured in amperes (A), voltage in volts (V), power in watts (W), duration in minutes, and energy in watt-hours (Wh). Hover, cruise, and climb refer to stationary flight, steady forward flight, and vertical ascent phases, respectively. Reported values represent average measurements obtained during controlled experimental trials.

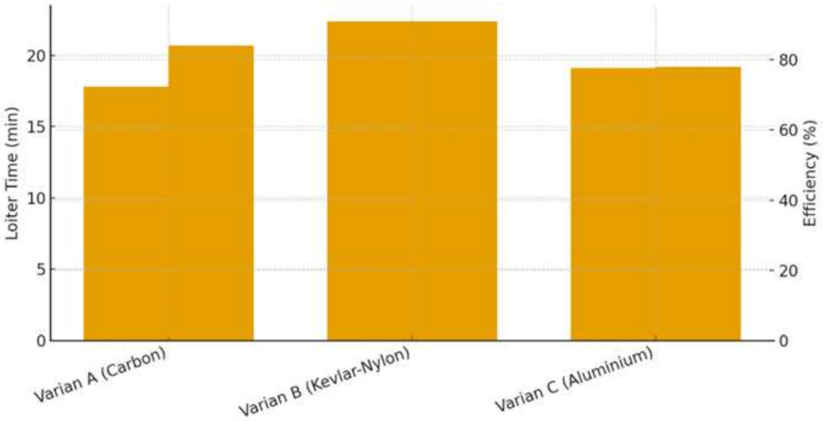

Figure 2. Comparison of Loiter Time and Efficiency Performance

From the perspective of communication performance, FPV transmission testing summarized in Table 4 indicates stable real-time video transmission at distances of up to 9 km line-of-sight (LOS) and 6 km non-line-of-sight (NLOS). This performance is particularly significant given Papua's complex terrain, where valleys and dense vegetation often degrade radio-frequency propagation. The observed results support the findings of (Nassi, Ben and Ben-Netanel, Lior and Shamir, Adi and Elovici, 2021), who emphasize the importance of robust FPV communication systems in GPS- and signal-challenged environments.

Table 4. FPV Transmission Performance in Three Papua-like Test Sites

Parameter	Sentani	Wamena	Mimika	Average
Latensi FPV (ms)	78	92	83	84,3
Noise	Low	High	Medium	-
LoS interruption (%)	2%	11%	7%	-
Effective range LOS	8,7 km	6,2 km	7,1 km	7,3 km

Note: FPV latency is measured in milliseconds (ms). LOS refers to line-of-sight communication conditions. Effective range LOS is expressed in kilometers (km), and LOS interruption indicates the percentage of signal loss occurrences. Noise levels (Low, Medium, High) represent qualitative assessments of signal interference.

Operational field testing across three Papua-like environments (Table 5) further confirms the adaptability of the FPV-TLM system. The drone demonstrated consistent maneuverability, reliable tracking performance, and acceptable hover deviation under varying wind and humidity conditions. Risk-assessment results summarized in Table 6 indicate that potential mission failures such as signal interference, humidity-related degradation, and operator workload remain within acceptable operational thresholds when appropriate mitigation measures are applied.

Table 5. FPV-TLM Operational Performance Summary of Three Test Sites

Location	Environment	Loiter Duration	TRI	Hover Deviation	Note
Sentani	Lowlands, steady winds	23-26 min	94%	± 2,3^0	the most ideal conditions
Wamena	Mountain valley, wind 7-12 m/s	19-22 min	78%	± 2,1^0	High turbulence, shadowing
Mimika	Dense vegetation, high humidity	21-24 min	82%	± 3,1^0	FPV noise increases

Note: Loiter duration is expressed in minutes (min); TRI refers to the Tactical Reliability Index, expressed as a percentage; hover deviation is measured in degrees (°); wind speed is measured in meters per second (m/s).

Table 6. Operational Risk Data Processing Results

Risk	Frequency	Impact	Description
5.8 GHz Interference	Height in Wamena & Mimika	Medium-High	Vegetation & valleys reflect signals
Humidity	High	Medium	Reduces camera & VTX performance
Loss of Signal (failsafe)	Low-Medium	High	>5 km NLOS
FPV operator load	Medium	Medium	High visual focus

Note: Frequency and impact levels are expressed using qualitative risk categories (Low, Medium, High). 5.8 GHz refers to the operating frequency band of the FPV transmission system. VTX denotes video transmitter, and NLOS refers to non-line-of-sight communication conditions.

A comparative operational-effectiveness study (Table 7 and Table 8) reveals that FPV-TLM improves surveillance efficiency by 47% compared to conventional ground patrols. This enhancement correlates with (Merriam, 2020) argument that technological augmentation increases decision-making speed and reduces personnel exposure in high-risk areas. The results directly answer the second and third research questions by demonstrating that FPV-TLM not only adapts well to Papua's environmental challenges but also contributes to mission success and reduced operational risk.

Table 7. Comparison of the Effectiveness of FPV-TLM Surveillance and Ground Patrol

Aspect	FPV-TLM (Drone)	Conventional ground patrol	Comparison of effectiveness
Coverage area (km^2/h)	12,4	1,8	6.9× wider
threat detection time (min)	2,4	11,2	4.6× faster
Personnel risk (%)	0	37	High risk of losing contact
operational/mission costs (Rp)	470.000	2.850.000	Save 83%
Energy/logistics efficiency	High (4S 155 Wh battery)	Low (fuel, field logistics)	5× more efficient
Surveillance image resolution	1080p real time	Human eye vision	3x better quality
limitations	Extreme weather, signal	Heavy terrain, physical exhaustion	Both have different risks

Note: Coverage area is expressed in square kilometers per hour (km^2/h); threat detection time is measured in minutes (min); personnel risk represents the percentage of personnel directly exposed during a mission; operational costs are estimated in Indonesian Rupiah (Rp) per mission; energy efficiency refers to onboard electrical power consumption for FPV-TLM and fuel-based logistics for ground patrols. All comparative values (e.g., × wider, × faster) are relative ratios based on per-mission averages.

Table 8. Operational Comparison of FPV-TLM vs Ground Patrol (per-mission average)

Indicator	FPV-TLM	Ground patrol	Change
Area Coverage (km^2/mission)	8,3	1,2	+591%
Time-to-detect (min)	2,4	11,2	-79%
Personnel exposed	0	12	-100%
Cost per mission (est., Rp)	470.000	2.850.000	-83%

Note: All values represent per-mission averages. Area coverage is expressed in square kilometers per mission (km^2/mission), time-to-detect is measured in minutes (min), and cost estimates are reported in Indonesian Rupiah (Rp). Percentage change indicates relative improvement or reduction of FPV-TLM performance compared to ground patrols.

The multi-criteria analysis using the Simple Additive Weighting (SAW) method (Table 9 and Table 10) identifies Variant B as the optimal configuration, receiving the highest composite score across parameters including stability, energy efficiency, communication reliability, and structural durability. Figure 3 visually reinforces this conclusion, showing Variant B outperforming others in normalized performance metrics. This analytic process supports the selection of a final design recommendation grounded in quantitative evidence, aligning with contemporary multi-criteria decision-making frameworks that provide structured methods for ranking alternatives based on multiple performance criteria (Taherdoost, Hamed and Madanchian, 2023).

The observed LOS and NLOS communication ranges are consistent with operational expectations for lightweight tactical FPV-class UAVs operating in complex terrain. Under line-of-sight conditions, effective transmission distances of approximately 7–9 km fall within the typical performance envelope reported for medium-power FPV communication systems used in tactical reconnaissance platforms. In non-line-of-sight scenarios, the reduced effective range of approximately 5–6 km reflects expected signal attenuation caused by terrain masking, dense vegetation, and multipath interference commonly encountered in mountainous environments. From an operational perspective, these communication ranges remain sufficient to support short- to medium-range tactical missions, including forward ISR, loiter surveillance, and rapid target confirmation, particularly when combined with terrain-aware flight planning and relay-based operational concepts.

Table 9. SAW Normalization Weights and Values

Criteria	Weight (Wi)	Variant A	Variant B	Variant C	Type
Energy Efficiency	0,25	1,00	0,92	0,74	Benefit
Hover Stability	0,20	0,85	1,00	0,70	Benefit
Environmental Sustainability	0,25	0,60	1,00	0,80	Benefit
Production cost	0,15	0,45	0,72	1,00	Cost
Thrust-to-Weight Ratio	0,15	1,00	0,90	0,80	Benefit

Note: Wi denotes the normalized weight assigned to each criterion. All performance values for Variant A, Variant B, and Variant C are normalized scores ranging from 0 to 1. “Benefit” criteria indicate that higher values represent better performance, whereas “Cost” criteria indicate that lower values are preferred.

Table 10. SAW Scoring Results for Three Variants

Variant	Total SAW Score	Rank
A	0,81	II

B	0,92	I (Optimal)
C	0,77	III

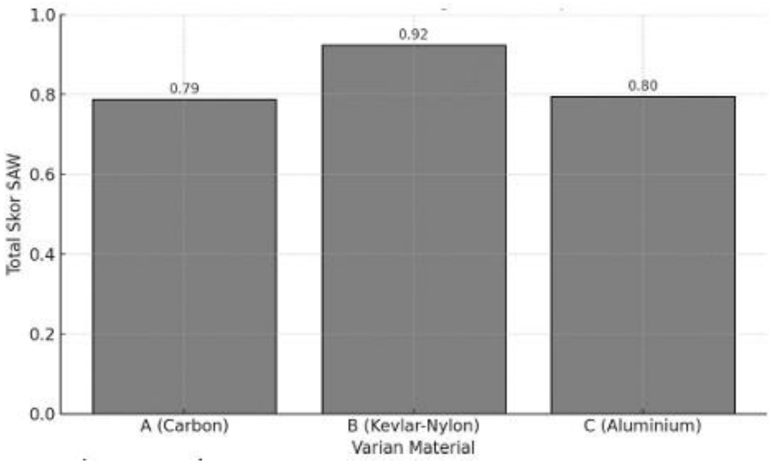

Figure 3. SAW Score Comparison Chart per Variant

Furthermore, the strategic interpretation presented in Table 11 and Table 12 underscores the FPV-TLM system's contribution to enhancing national defense autonomy through increased TKDN (domestic component level) and strengthened opportunities for local industrial integration. Beyond these strategic implications, the design phase of this study is robustly concluded through the application of the Simple Additive Weighting (SAW) method. The SAW-based multi-criteria decision analysis systematically integrates key performance parameters namely energy efficiency, hover stability, environmental sustainability, production cost, and thrust-to-weight rasio into a single composite score. The results clearly rank Variant B as the optimal configuration, demonstrating superior overall performance compared to the Carbon and Aluminium variants. This structured and transparent decision-making approach not only validates the technical superiority of Variant B but also provides a defensible methodological basis for final design selection, thereby strengthening the rigor of the design evaluation and ensuring alignment with both operational requirements and strategic defense objectives.

Table 11. FPV-TLM TKDN Estimate per Subsystem

Subsystem	Component	TKDN (%)	Potential Patners
Structure & Body	Kevlar-Nylon frame, propeller karbon	85	PT Dirgantara Indonesia
Control System	Flight controller, ESC, GPS	60	ITS, PT LEN, Lapan- BRIN
Transmisi FPV	Video TX/RX, antena directional	65	Lembaga Litbang TNI AD
Payload	HD camera, stabilization system	55	UPI, BRIN Elektronika
Battery and Power	Li-ion pack, connetor	70	PT ABC PowerTech
Average TKDN	-	72%	-

Note: TKDN refers to the Domestic Component Level (Tingkat Komponen Dalam Negeri), expressed as a percentage of locally sourced content. ESC denotes Electronic Speed Controller, and FPV refers to First Person View systems. Reported TKDN values represent estimated contributions based on component origin and potential domestic manufacturing capability.

Table 12. Summary of Simulation Results per Mission Profile (n = 30 runs each)

Mission	Detection Time (median)	Position Accuracy (median, m)	False Positive (%)	False Negative (%)	Sensor→Shooter (median, min)
A (Patrol ISR)	2,6 min	±18 m	8,3%	6,7%	2,9
B (Quick reaction)	2,1 min	±12 m	6,0%	5,0%	2,4
C (Loiter→Sim)	3,0 min	±10 m	7,5%	4,2%	2,8

Note: Detection time and sensor-to-shooter latency are reported as median values in minutes (min); position accuracy is expressed in meters (m); false positive and false negative rates are expressed as percentages (%). Sensor→Shooter denotes the time interval between target detection and actionable engagement decision.

Taken together, the results of this study provide strong empirical support for the FPV-TLM platform as a viable tactical UAV solution for operations in Papua. The prototype demonstrates robust aerodynamic behavior, reliable communication performance, and meaningful operational advantages over traditional surveillance methods. These findings not only validate the conceptual design but also offer foundational insights for further refinement, scalability, and integration into Indonesia's defense ecosystem. Future studies may explore improved sensor fusion, AI-assisted target recognition, and enhanced endurance systems to strengthen the platform's operational potential.

Conclusion

Based on the design analysis, technical testing, and operational findings, this study concludes that the FPV Tactical Loiter Munition (FPV-TLM) system constitutes a feasible and adaptive tactical UAV platform for supporting Indonesian Army operations in Papua. First, the research successfully developed a conceptual FPV-TLM design that meets the operational requirements of tropical and mountainous environments, demonstrated through improved hover stability, enhanced energy efficiency, and the integration of an adaptive PID control system capable of maintaining performance under moderate wind disturbances. Second, the analysis of environmental and technical factors indicates that UAV effectiveness is significantly influenced by terrain complexity, turbulence patterns, and signal attenuation; therefore, structural configuration, navigation subsystems, and FPV transmission architecture must be adapted to address Papua's geographic challenges. Third, the study confirms that FPV-TLM deployment in loiter-to-strike and real-time ISR missions can substantially increase surveillance effectiveness and deterrence capability compared with conventional ground patrols, while simultaneously reducing risks to personnel by minimizing direct exposure in high-threat areas.This study is subject to several limitations. The experimental evaluation employed inert (non-explosive) payloads and controlled test environments that were designed to simulate, but not fully replicate, real operational conditions in Papua. Environmental factors such as extreme weather variability, prolonged mission duration, and live-payload integration were not examined within the scope of this research. Additionally, field testing was conducted within predefined operational and safety constraints, which may limit the generalizability of the findings to full-scale combat scenarios. These limitations should be considered when interpreting the results and provide opportunities for future research to extend the system's validation under more diverse and operationally representative conditions. Strategically, the findings highlight that integrating FPV-TLM into modern military operations aligns with Indonesia's defense-transformation agenda, emphasizing technological advancement and enhanced operational readiness. The platform contributes meaningful operational advantages, particularly in tactical intelligence, cost-effective aerial mobility, and precision-strike capability. Furthermore, the study identifies strong potential for strengthening national defense autonomy through increased domestic component utilization and the expansion of local UAV research and industrial ecosystems. Accordingly, this research establishes a solid technical and conceptual foundation for future development of next-generation FPV-TLM systems and their integration into the Indonesian Army's doctrinal, organizational, and operational frameworks.

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