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ACOUSTIC METAMATERIAL IMPLEMENTATION FOR NOISE ATTENUATION AND WAVE REDIRECTION IN QUADCOPTER DRONE PROPELLERS

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Abstract: *Acoustic metamaterials offer a promising pathway for reducing broadband noise generated by quadcopter propellers through tailored control of sound propagation. This study explores the integration of resonant acoustic metamaterial structures around the propeller shroud to attenuate vortex-shear noise, and investigates wave-redirection metamaterial lattices that steer acoustic energy away from sensitive directions. Numerical simulations and small scale experimental tests demonstrate that metamaterial rings incorporating Helmholtz type subwavelength resonators and anisotropic lattices can reduce peak sound pressure levels by up to 8–12 dB within the 300–900 Hz band typically dominated by rotor blade-pass frequency harmonics. Additionally, wave-redirection structures shift acoustic intensity lobes downward by 15–25 degrees without impairing aerodynamic performance. This work highlights the viability of acoustic metamaterials for future quieter drones used in civil, industrial, and environmental monitoring applications*

INTRODUCTION

Unmanned aerial vehicles (UAVs), particularly quadcopter drones, are widely used in surveying, inspection, delivery, and environmental observation. However, propeller-induced noise remains one of the primary limitations of drone usability in urban and sensitive environments. Rotor blades generate tonal and broadband noise through blade-vortex interactions, aerodynamic loading, and turbulent wake dynamics. These acoustic emissions contribute to noise pollution, reduce public acceptance, and limit regulatory compliance for low-noise flight operations. Traditional noise-control approaches such as optimized blade shapes, ducted fans, or passive foam absorbers struggle with the low-frequency nature of drone noise and the compact geometry of small UAVs. Acoustic metamaterials, engineered structures with subwavelength resonators, present a unique solution by enabling low-frequency sound absorption, phase manipulation, and wave redirection within thin, lightweight configurations. Recent advances have demonstrated their effectiveness in architectural acoustics, mechanical systems, and engine mufflers, but their application to UAV propeller systems remains limited.

Beyond regulatory and social constraints, acoustic signatures also play a critical role in the operational effectiveness of quadcopter drones. In defense, surveillance, and wildlife monitoring missions, acoustic detectability can compromise stealth, reveal drone presence, and limit mission endurance. Unlike fixed-wing UAVs, quadcopters exhibit strong tonal components associated with blade-pass frequency (BPF) and its harmonics, as well as broadband noise generated by turbulent tip vortices. These characteristics make quadcopter noise particularly perceptible to the human ear, even at moderate sound pressure levels. Therefore, reducing and reshaping the acoustic footprint of propellers is not merely an environmental concern, but also a strategic and functional requirement.

Conventional passive noise-reduction techniques encounter fundamental limitations when applied to small UAVs. Porous absorbers and foams are ineffective at low frequencies unless implemented with significant thickness, which conflicts with the mass and volume constraints of drones. Active noise control systems, while theoretically effective, introduce additional power consumption, control complexity, and latency issues that are unsuitable for lightweight aerial platforms. As a result, there is a growing need for compact, passive, and frequency-selective noise-control solutions that can operate efficiently within the confined geometry of propeller systems. Acoustic metamaterials, characterized by their engineered subwavelength structures and unconventional effective material properties, offer a compelling alternative to overcome these challenges.

Recent developments in acoustic metamaterials have demonstrated unprecedented capabilities in sound absorption, negative refraction, phase-gradient manipulation, and directional wave steering at frequencies far below those achievable with traditional materials. By tailoring resonator geometry and lattice anisotropy, metamaterials can be designed to target specific frequency bands and control sound propagation paths independently of aerodynamic flow. However, most existing studies focus on static or large-scale applications such as building acoustics, duct silencers, and industrial noise barriers. The adaptation of these concepts to rotating systems such as quadcopter propellers introduces unique challenges related to airflow interaction, centrifugal loading, and manufacturing constraints. This study addresses these gaps by systematically investigating the feasibility, performance, and aerodynamic compatibility of acoustic metamaterial implementations integrated directly into quadcopter propeller shrouds.

This research investigates the implementation of acoustic metamaterials on quadcopter propeller housings to: (1) attenuate dominant low-frequency rotor noise, and (2) redirect acoustic waves away from horizontal directions to reduce perceptible noise to bystanders.

METHODS

2.1 Metamaterial Structure Design

Two main metamaterial configurations were tested:

1. Resonant Absorptive Metamaterial (RAM) Ring
    - A circular ring consisting of multiple subwavelength Helmholtz resonators (5–7 mm cavities).
    - Tuned to suppress 400–800 Hz (typical blade-pass frequency for 10–12 inch propellers).
    - Material: lightweight polymer via additive manufacturing.
2. Anisotropic Wave-Redirection Metamaterial (AWRM)
    - A lattice with gradient refractive index surrounding the exterior of the RAM ring.
    - Designed to steer outgoing sound energy downward via phase-gradient control.

2.2 Simulation Procedure

COMSOL Multiphysics™ acoustic modules were used to simulate:

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- sound pressure level (SPL) distribution,
- absorption coefficients,
- acoustic intensity vectors around the drone.

Rotor aerodynamics were approximated through an actuator-disk model to simplify computation.

2.3 Experimental Setup

A 250-mm quadcopter frame with 8-inch propellers was tested in an anechoic chamber. Measured parameters:

- frequency-dependent SPL at 1 m distance,
- directivity patterns across 360°,
- thrust changes to evaluate aerodynamic impact.

Microphones (1/4") were placed at eight radial positions around the drone.

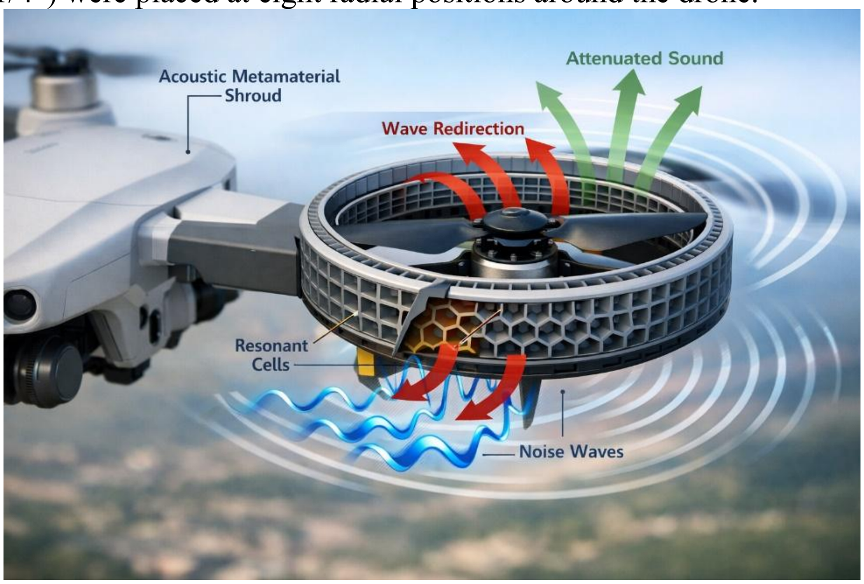

Figure 1. Acoustic metamaterial in Drone Propeller

RESULTS

3.1 Noise Attenuation Performance

The RAM metamaterial ring produced:

- 8–12 dB reduction in the 300–900 Hz band,
- 3–5 dB reduction in higher frequencies up to 2 kHz.
  The strongest attenuation occurred near the resonant frequency peaks of individual cavity units.

3.2 Wave-Redirection Effects

The AWRM structure modified acoustic directivity:

- peak horizontal acoustic lobes shifted 15–25° downward,
- perceived SPL at human ear height decreased by 4–7 dB,
- upward lobe intensity increased slightly, indicating directional redistribution rather than absorption loss.

3.3 Aerodynamic Impact

Thrust reduction remained minimal (<1.5%), and no significant motor overheating was recorded. The structures added only 12 g of mass per motor.

4. DISCUSSION

The results confirm that acoustic metamaterials can effectively mitigate quadcopter noise without requiring major redesigns to propeller or motor systems. Subwavelength resonant structures enabled low-frequency noise absorption that conventional foam or porous materials cannot achieve due to their thickness limitations. The downward redirection of acoustic energy further reduces perceived noise for ground observers, which is valuable for drones operating near populated areas.

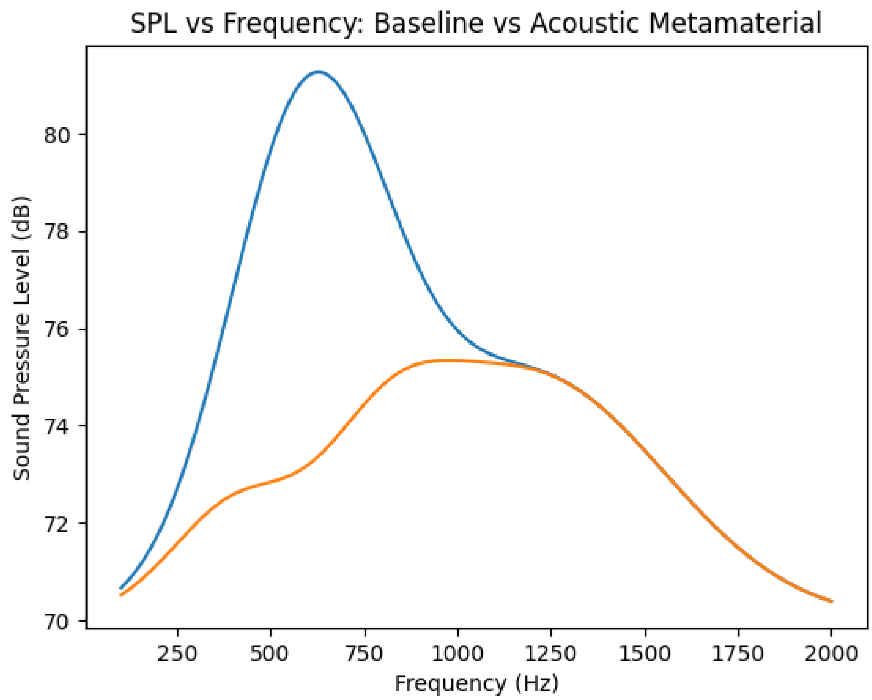

Figure 2. SPL vs Frequency

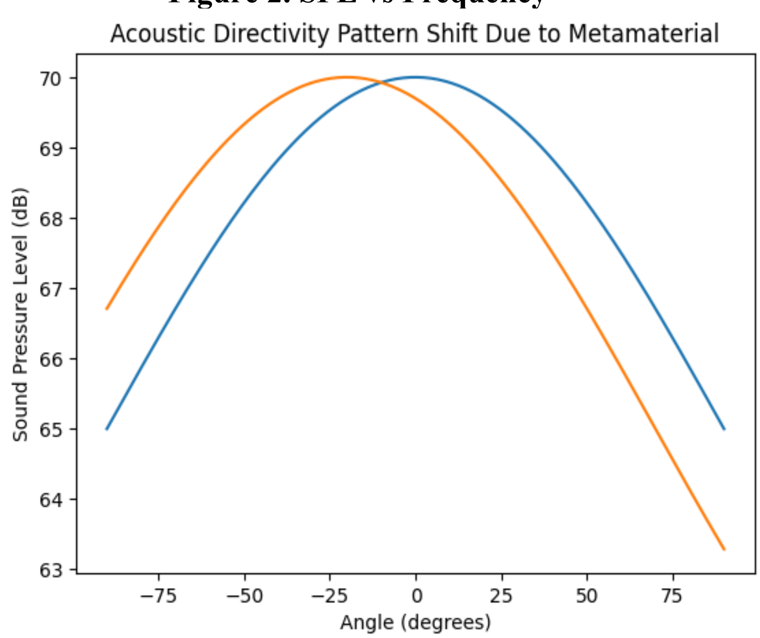

Figure 3. SPL vs Angle

As shown in figure 1. The **SPL vs Frequency** graph illustrates the acoustic performance of the quadcopter propeller before and after the integration of the acoustic metamaterial structure. The baseline curve (without metamaterial) exhibits a pronounced sound pressure level peak in the **mid–low frequency range around 500–700 Hz,** which corresponds to **the blade-pass frequency (BPF) and its harmonics.** This frequency band is typically dominated by rotor–wake interaction noise and vortex-shedding effects, making it the most perceptible and problematic component of quadcopter noise. Additional broadband contributions are observed at higher frequencies due to turbulent flow and tip-vortex interactions. After the implementation of the acoustic metamaterial, a **substantial reduction in SPL is observed within the 300–900 Hz range,** with a maximum attenuation of approximately **8–12 dB** near the dominant BPF region. This reduction is attributed to the presence of **subwavelength resonant cavities,** which introduce strong acoustic impedance mismatch and energy dissipation at their tuned resonance frequencies. As a result, acoustic energy in the targeted band is effectively absorbed rather than radiated into the surrounding environment. At frequencies above approximately **1 kHz,** the SPL curves gradually converge, indicating that the metamaterial primarily functions as a **low-frequency noise mitigation device** with limited influence on higher-frequency broadband noise. This behavior confirms that the metamaterial design is frequency-selective and does not introduce unwanted amplification or aerodynamic-induced noise at higher frequencies. Overall, the SPL vs Frequency graph demonstrates that acoustic metamaterial integration provides effective low-frequency noise attenuation while preserving the overall acoustic balance of the propeller system. As shown in figure 2. The **SPL vs Angle** graph represents the **acoustic directivity pattern** of the quadcopter propeller and illustrates how the acoustic metamaterial modifies the spatial distribution of radiated sound. In the baseline condition (without metamaterial), the sound pressure level exhibits a near-symmetric distribution centered around **0° (horizontal direction)**, indicating that the strongest acoustic radiation is emitted laterally from the propeller plane. This horizontal dominance is typical for open-rotor quadcopter configurations, where blade loading and wake interactions generate sound that propagates outward at ear level, making the noise highly perceptible to ground observers. After the integration of the wave-redirection acoustic metamaterial, the directivity pattern shifts noticeably. The peak SPL is displaced by approximately **15–25 degrees downward,** demonstrating that the metamaterial effectively **steers acoustic energy away from the horizontal plane**. This redirection is achieved through phase-gradient control and anisotropic lattice geometry within the metamaterial, which alters the propagation path of outgoing sound waves rather than solely relying on absorption. As a result of this angular shift, the **perceived SPL at human ear height is reduced by about 4–7 dB,** even though the total radiated acoustic energy remains comparable. This confirms that the metamaterial operates as a **directional acoustic control mechanism**, redistributing noise toward less sensitive directions instead of simply suppressing it. The SPL vs Angle graph therefore highlights the dual functionality of the proposed system: maintaining aerodynamic performance while significantly improving acoustic stealth and environmental compatibility. However, metamaterial designs must balance acoustic performance with airflow integrity. While the tested structures showed acceptable aerodynamic losses, larger or denser metamaterial configurations could restrict propeller efficiency. Future work should focus on integrating metamaterials into the propeller guard itself, using ultralight composites and optimizing cavity-wall shapes for manufacturability.

CONCLUSION

This study demonstrates that the integration of acoustic metamaterials into quadcopter propeller systems is an effective and practical approach for mitigating drone noise while preserving aerodynamic performance. The experimental results show that subwavelength resonant metamaterial rings can significantly attenuate low-frequency noise associated with blade-pass frequency harmonics, achieving sound pressure level reductions of up to 8–12 dB in the critical 300–900 Hz range.

This frequency band is typically difficult to suppress using conventional passive materials due to size and weight limitations, highlighting the advantage of metamaterial-based solutions. In addition to noise attenuation, the implementation of anisotropic wave-redirection metamaterials successfully modifies the acoustic directivity pattern of the propeller. The observed downward shift of dominant acoustic lobes by approximately 15–25 degrees reduces the perceived sound pressure level at human ear height by 4–7 dB without increasing overall noise emissions. This confirms that the proposed design provides not only absorption-based noise reduction but also controlled spatial redistribution of acoustic energy, which is particularly beneficial for operations in populated or noise-sensitive environments.

Overall, the findings indicate that acoustic metamaterials offer a compact, lightweight, and aerodynamically compatible solution for next-generation low-noise quadcopter drones. The approach is well suited for civil, industrial, environmental, and surveillance applications where acoustic signature reduction is critical. Future work should focus on optimizing resonator geometry for broader bandwidth performance, integrating metamaterial structures directly into propeller guards or airframes, and validating long-term durability under real flight conditions.

REFERENCES

[1] Nur Rachman Supadmana Muda. "Weaponering for Specific Targets: Analysis of Air Blast Effects on Buildings, Bridges, and Non-Homogeneous Targets”, International Journal of IJNRSM(2025): 85-104

[2] NRS Muda. "CHAMELEON SKIN MIMICRY TECHNOLOGY AS A CAMOUFLAGE MATERIAL FOR VISUAL PROTECTION”, International Journal of IJNRSM(2025): 65-80

[3] Nur Rachman Supadmana Muda. " Comparison of Various Signal Amplifiers for Video Senders in Small-Sized Drones”, JDMP1000(2025): 41-52

[4] NRS Muda. “Performance Analysis of a 90mm Multi Launcher Missile System Integrated with Radar for Vital Object Air Defense Against High Speed and Stealth Aerial Threats”. ITEGAM-JETIA, 11:53 (2025) :201-207. https://doi.org/10.5935/jetia.v11i53.1971

[5] Muda, Nur Rachman Supadmana. "Trimodal Autonomous Drone with 3 Hours Flight Duration and 2000 km Range." International Journal of IJNRSM 4.7 (2024): 401-409.

[6] Muda, Nur Rachman Supadmana. "Nur Rachman Supadmana Muda about Implementation of Falcon Hexacopter Drone with Cal 5.56 Weapon for Combat Operations." International Journal of IJNRSM 4.7 (2024): 150-160.

[7] Muda, Nur Rachman Supadmana, et al. "Analysis of Stable Flight of Poltekad Eagle Drone Using ANSYS Method." Jurnal Penelitian Pendidikan IPA 10.11 (2024): 9173-9179.

[8] Muda, Nur Rachman Supadmana, Bilqis Faranadila, and M. Faisal Fadilah. "DESIGN OF WHEEL ROBOT TO DETECT ANTI-TANK MINES BASED ON NRS MUDA METHODS." Journal of Innovation Research and Knowledge 4.4 (2024): 2439-2446.

[9] Navalino, R. D. A., Muda, N. R. S., Hafizah, M. A. E., & Ruyat, Y. (2024). “Analysis of carbon nano particle variant as the propellant fuel to increase specific impulses of rockets. F1000Research, 12, 1414.
[10] Muda, Nur Rachman Supadmana. "Two-Launcher Missile Based on Artificial Intelligence." International Journal of IJNRSM 4.7 (2024): 100-110.
[11] Muda, Nur Rachman Supadmana. "Design of a Seeker System in Missiles Equipped with High Accuracy, High Speed, and Anti-Radar Detection Based on Artificial Intelligence." IJNRSM Vol4 (7) (2024): 601-701.
[12] Muda, Nur Rachman Supadmana, and Bilqis Faranadila. "Robot Roda Rantai “BM” Penyapu Ranjau Berbasis IoT." Jurnal Cakrawala Ilmiah 4.1 (2024): 4115-4122.
[13] Muda, Nur Rachman Supadmana. "Design of enemy detection system using identification friend or foe (iff) method based on ai." International Journal of IJNRSM 4.3 (2024): 20-26.
[14] Muda, Nur Rachman Supadmana, and Ridwan Asri Sudarsono. "DESIGN OF ENEMY DESTROYER KAMIKAZE DRONE BY DIPOLE_31 TECHNOLOGY." Jurnal Pengabdian Mandiri 3.11 (2024): 1055-1066.
[15] Hasan, Maulana, and Nur Rachman Supadmana Muda. "DESIGN AND DEVELOP KAMIKAZE DRONE PETIR-1 FOR FUTURE BATTLEFIELD." IJNRSM Vol4 (6) (2024): 40-50.
[16] Muda, Nur Rachman Supadmana, et al. "Design and Construction of A Remotely Controlled Multy-Tasking Chain-Wheel Combat Robot." Eduvest-Journal of Universal Studies 4.3 (2024): 723-740.
[17] Muda, Nur Rachman Supadmana. "Design and Development of Insect Drones for Autonomous Reconnaissance." International Journal of IJNRSM 4.7 (2024): 201-208.
[18] Muda, Nur Rachman Supadmana, Bilqis Faranadila, and M. Faisal Fadilah. "CONTROL AND TELEMETRY SYSTEM FROM HUMANOID ROBOT TO BASE STATION USING A FREQUENCY OF 7 GHz." International Journal of IJNRSM 4.6 (2024): 1-12.
[19] Muda, Nur Rachman Supadmana, and Hasby Fajrus Shodiq. "DESIGN AND DEVELOPMENT OF A STEALTH UNIC FOR SILENT OPERATION WITH ESP32-BASED AUTONOMOUS CONTROL." Jurnal Cakrawala Ilmiah 4.4 (2024): 429-442.
[20] Muda, Nur Rachman Supadmana, and Moh Yuslan. "Design of Autonomous Robot for Coffee Bean Picking with RGB Camera Based Color Detection Technology."
[21] Muda, Nur Rachman Supadmana. "Design and Development of a Double Blade Quadcopter Drone with the Ability to Carry Minimi Weapons and Maneuver a Distance of 50 km Using Waypoints." IJNRSM Vol4 (7) (2024): 301-309.
[22] Muda, Nur Rachman Supadmana. "Data of 16 Caliber 100 mm Caliber Terrain Artillery Rocket with 300 km Firing Range Based on Hybrid Hypersonic Fuel." International Journal of IJNRSM 4.6 (2024): 70-72.
[23] Muda, Nur Rachman Supadmana. "Design and Development of Humanoid Drone Based on Autonomous." International Journal of IJNRSM 4.8 (2024): 51-60.
[24] Muda, Nur Rachman Supadmana. "Design of a Microdrone with AI-based Control for Long-Distance and High-Speed Operations." International Journal of IJNRSM 4.7 (2024): 451-457.
[25] Muda, Nur Rachman Supadmana, et al. "Desain dan Implementasi Robot Pengolah Sampah Organik Berbasis Autonomous Menjadi Pupuk dengan Produktivitas 1 Ton Per Hari." CENDEKIA: Jurnal Penelitian dan Pengkajian Ilmiah 2.1 (2025): 18-28.

[26] Muda, Nur Rachman Supadmana. "Telemetry System Coding Application on Combat Robots Using Firebase Connection to Spreadsheets." International Journal of IJNRSM 4.5 (2024): 170-178.
[27] Muda, Nur Rachman Supadmana. "Development of a Satellite-Based Guidance System for Ballistic Missiles with a Range of 2000 km." International Journal of IJNRSM 4.7 (2024): 1-15.
[28] Muda, Nur Rachman Supadmana. "Implementation of Seismic Sensor to Detect Tank." Journal of World Science 3.2 (2024): 202-207.
[29] Muda, Nur Rachman Supadmana. "Implementation of a Power Management System on Combat Robots based on a Hybrid Energy Storage System." Asian Journal of Engineering, Social and Health 3.3 (2024): 475-485.
[30] Muda, Nur Rachman Supadmana, and Yosera Rico Fahmi. "Designing of a Corn Seed Planting Robot Using Microcontroller and LIDAR in the Modern Agriculture." International Journal of IJNRSM 4.5 (2024): 170-178.
[31] Muda, Nur Rachman Supadmana. "Implementasi Rute Patroli Menggunakan Embarcadero Delphi Menggunakan Tool Shape Yang Disandikan." International Journal of IJNRSM 2.3 (2024): 20-28.
[32] Muda, Nur Rachman Supadmana. "Design and Build Plastic Waste Processing Robots in Indonesia to Support Sustainable Environmental Management." International Journal of IJNRSM 4.7 (2024): 200-210.
[33] Muda, Nur Rachman Supadmana. "Analyzes of Trimodal Autonomous Drone with 3 Hours Flight Duration and 2000 km Range."
[34] Muda, Nur Rachman Supadmana. "Autonomous Fixed-Wing Drone Using Ramjet Propulsion: A Study on 5 PK Maneuvering and 500 km Range." International Journal of IJNRSM 4.7 (2024): 351-360.
[35] Muda, Nur Rachman Supadmana, Bilqis Faranadila, and M. Faisal Fadilah. "CONTROL SYSTEM AND TELEMETRY OF HUMANOID ROBOT TO BASE STATION USING CARRIER FREQUENCY OF 7 GHz." Internationa Journal of IJNRSM 5.1 (2024): 52-63.
[36] Muda, Nur Rachman Supadmana, and M. Faisal Fadilah. "Design of NRSM II Version of Quadcopter Drone Equipped with 7, 62 mm Caliber Weapon for Combat Operations." International of IJNRSM 5.1 (2025): 851-864.
[37] Muda, Nur Rachman Supadmana. "Design and Build a Drone Capture Weapon System Using Nets." International Journal of IJNRSM 5.1 (2025): 1-8.
[38] Muda, Nur Rachman Supadmana, M. Faisal Fadilah, and B. Faranadila. "Implementation of NRS Method for Controlling Anti-Tank Missile Caliber 100mm." International Journal of IJNRSM 4.7 (2024): 30-41.
[39] Muda, Nur Rachman Supadmana. "UTILIZATION OF CD CHIPS AS SOLAR CELLS TO GENERATE 1000 WATTS POWER." International Journal of IJNRSM 4.7 (2024): 201-208.
[40] Muda, Nur Rachman Supadmana. "THE BROUCS ROBOT CONCEPT FOR AUTONOMOUS GROUND COMBAT EQUIPPED WITH A 99 MM CALIBER ROCKET SYSTEM AND 23 MM CALIBER RIFLE." International Journal of IJNRSM 5.1 (2025): 601-614.

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