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CONTENTS

Experimental Analysis of Propeller Geometry Effects on Aerodynamic Efficiency <i>Adam Gani, Zainol Abidin Awang Sa, Haryatti Mohd Arif & Nurul Najwa Abd Rahman</i>	147 - 155
Aerodynamic Performance of a Folding Wing Air-Launched Glider <i>Syamimi Mohd Yusoff, Ermira Junita Abdullah & Adi Azriff Basri</i>	156 - 165
Design and Experimental Evaluation of Solar-Integrated UAV Wings Under Shadowing and Tilt Effects <i>Norliza Ismail, Muhammad Danial Haiqal, Zulhilmy Sahwee, Shahrul Ahmad Shah, Sabarina Abdul Hamid, Nadhiya Liyana Mohd Kamal & Nurhakimah Norhashim</i>	166 - 178
A Review of Satellite-Based LoRa and LoRaWAN for IoT Applications <i>Shihab Abdelaziz Mohamed Elhassan, Nadhiya Liyana Mohd Kamal*, Nurhakimah Norhashim, Zulhilmy Sahwee, & Shahrul Ahmad Shah</i>	179 - 187
Evolution of the GNSS Threat Environment: The Increasing Operationalisation of Jamming and Spoofing <i>Dinesh Sathyamoorthy, Nurul Syafiqah Afiq Rosli & Nurul Ayni Mat Pauzi</i>	188 - 207
Evaluation of the Effect of Narrowband Interference on GNSS Performance <i>Dinesh Sathyamoorthy, Nurul Syafiqah Afiq Rosli, Nurul Ayni Mat Pauzi & Nursharlini Borhan</i>	208 - 216
Development of a MATLAB / Simulink-Based Predictive Mobility Model for Tactical Small Unmanned Ground Vehicles <i>Mohammad Syafiq Mohammad Rafi, Aizul Fazli Suhaimi, Nur Naajihah Ab Rahman, Muhammad Ramdhan Mohd Suhaili, Mohd Azim Md. Burhanuddin, Ezza Nur Adzlilliya Azali, Shaiful Bahri Zainal, Muhammad Nur Annuar Mohd Yunos, Noratikah Alawi & Haizeiq Hazaruul Yusoff</i>	217 - 229
Real-Time LiDAR-Based SLAM and RRT Path Planning for Mobile Robots <i>Nilabh Pandey, Kishore Bingi, Aizul Fazli Suhaimi & Mohammad Syafiq Mohammad Rafi</i>	230 - 238
Make-or-Buy Evaluation for High Mobility Multipurpose Vehicle (HMMV) Component Selection <i>Ezza Nur Adzlilliya Azali, Fadzli Ibrahim, Termizi Muhamad, Adzrai Aziz Ibrahim, Shamsul Akmar Ab Aziz, Siti Rozanna Yusuf, Mohammad Syafiq Mohammad Rafi, Muhammad Nur Annuar Mohd Yunos, Mohd Moesli Muhammad & Azrain Mohammad</i>	239 - 251
CFD-Based Optimisation of a C-D Rocket Nozzle Using Response Surface Methodology for Exhaust Plume Characteristics and Thrust Performance <i>Izzat Najmi Yaaacob, Norkhairunnisa Mazlan, Kamarul Arifin Ahmad, Na'im Abdullah, Ain Umaira Md Shah, Nurhana Mohdmd Rouyan & Fikri Rasih</i>	252 - 265
Effect Of Soil Barrier Shape and Arrangement on Blast Wave Mitigation <i>Jestin Jelani, Zuliziana Suif, Nordila Ahmad, M.F. Abdullah & Suraya Shahedi</i>	266 - 275
Analysis of Physical and Mechanical Properties Affecting Water Penetration in Coated Fabrics <i>Noreen Farzuhana Mohd Zulkifli, Tengku Muhammad Harith Tengku Hasan, Mohamad Ridzuwan Mohd Rahimi & Farah Liyana Khairulaman</i>	276 - 285
A Review of Biosensor Technologies for Airborne Microorganism Detection <i>Ahmad Razi Mohamed Yunus, Lini Idris, Sharifah Nur Amiera Syed Fazal, Harshaan Arumagam & Nurul Arianna Ahmad Yuhidan</i>	286 - 300



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The next edition of the journal (Vol. 20, Num. 1) is expected to be published in April 2027. The due date for submissions is 6 January 2027. **It is strongly iterated that authors are solely responsible for taking the necessary steps to ensure that the submitted manuscripts do not contain confidential or sensitive material.**

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Contents of abstract.

Keywords: *Keyword 1; keyword 2; keyword 3; keyword 4; keyword 5.*

1. TOPIC 1

Paragraph 1.

Paragraph 2.

1.1 Sub Topic 1

Paragraph 1.

Paragraph 2.

2. TOPIC 2

Paragraph 1.

Paragraph 2.



Figure 1: Title of figure.

Table 1: Title of table.

Content	Content	Content
Content	Content	Content
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Equation 1

(1)

Equation 2

(2)

REFERENCES

Long lists of notes of bibliographical references are generally not required. The method of citing references in the text is 'name date' style, e.g. 'Hanis (1993) claimed that...', or '...including the lack of interoperability (Bohara *et al.*, 2003)'. End references should be in alphabetical order. The following reference style is to be adhered to:

Books

Serra, J. (1982). *Image Analysis and Mathematical Morphology*. Academic Press, London.

Book Chapters

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Jang, B.K. & Chin, R.T. (1990). Analysis of thinning algorithms using mathematical morphology. *IEEE T. Pattern Anal.*, **12**: 541-550.

Online Sources

GTOPO30 (1996). *GTOPO30: Global 30 Arc Second Elevation Data Set*. Available online at: <http://edcwww.cr.usgs.gov/landdaac/gtopo30/gtopo30.html> (Last access date: 1 June 2009).

Unpublished Materials (e.g. theses, reports and documents)

Wood, J. (1996). *The Geomorphological Characterization of Digital Elevation Models*. PhD Thesis, Department of Geography, University of Leicester, Leicester.

EXPERIMENTAL ANALYSIS OF PROPELLER GEOMETRY EFFECTS ON AERODYNAMIC EFFICIENCY

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ABSTRACT

Propeller geometry, particularly diameter and pitch, plays a critical role in determining aerodynamic performance and propulsion efficiency in unmanned aerial systems (UAS). This study presents an experimental analysis of the performance characteristics of three propellers with varying diameter and pitch configurations (30 in $\times$ 23°, 32 in $\times$ 23°, and 32 in $\times$ 20°) driven by a Limbach L550 EF internal combustion engine under controlled static test conditions. The experimental testing focused on key performance parameters of thrust, torque, power, and fuel consumption, which were measured across a rotational speed range of 3,000 - 6,000 RPM using an instrumented test rig with real-time data acquisition. In order to enable a more rigorous aerodynamic evaluation, the measured data were further analysed using non-dimensional performance coefficients, namely thrust coefficient (C_T) and power coefficient (C_P). The results indicate that increasing propeller diameter significantly enhances thrust generation due to increased disc area, while higher pitch leads to elevated aerodynamic loading, resulting in increased torque and power demand. Among the tested configurations, the 32 in $\times$ 20° propeller demonstrated the most favourable balance between thrust production and power consumption, achieving the highest thrust-to-power ratio. The findings highlight the importance of matching propeller geometry with operating conditions to optimise propulsion efficiency. However, the study is limited to static conditions, and further experimental testing under forward flight conditions is recommended to fully characterise propeller performance.

Keywords: *Propeller geometry; aerodynamic performance; propulsion efficiency; thrust coefficient; power coefficient.*

1. INTRODUCTION

Propeller performance remains a cornerstone of modern aerospace applications, particularly with the rapid rise of electric vertical takeoff and landing (eVTOL) aircraft and unmanned aerial vehicles (UAVs). Propellers convert rotational energy into thrust, and their performance is dictated by fundamental design parameters, such as diameter, pitch and rotational speed (Kaygan, 2024; Adam *et al.*, 2025). Recent experimental studies emphasise that increasing the propeller diameter expands the swept area and enhances static thrust, a critical factor for hovering efficiency in multirotors, even though it introduces higher profile drag, torque requirements and overall power consumption (Adam *et al.*, 2025). Conversely, optimising the pitch angle, especially through advanced variable-pitch control mechanisms, allows for significantly better aerodynamic performance and efficiency matching across broad flight envelopes and high speed cruise regimes, though it demands strict management of aerodynamic resistance and transient power consumption (Liu *et al.*, 2025; Zhang *et al.*, 2025).

In order to improve propulsion efficiency, recent research has increasingly focused on geometric and structural optimisation. Blade aspect ratio, specialised aerofoil profiles and biomimetic features, such as

leading-edge tubercles, may help delay stall, reduce unsteady aerodynamic loads and lower noise (Ali *et al.*, 2025). Lightweight carbon fibre reinforced polymers (CFRP) also offer high specific strength, but their anisotropy and structural flexibility can cause deformation under aerodynamic loading, altering the effective blade pitch and reducing performance if not properly controlled (Möhren *et al.*, 2023; He *et al.*, 2023).

High fidelity computational fluid dynamics and fluid–structure interaction methods are increasingly used to assess these effects (Kim & Shin, 2025). More recent approaches also incorporate machine learning-based surrogate models to predict flow separation, blade pressure distribution and unsteady aerodynamic behaviour more efficiently (Etewa *et al.*, 2024; Sun *et al.*, 2025). These methods support the evaluation of trade-offs between propeller geometry, structural deformation and aerodynamic performance while reducing computational effort (Crona *et al.*, 2024).

Experimental validation nevertheless remains essential. Numerical and experimental studies have shown that propeller thrust and efficiency are strongly influenced by diameter, pitch, rotational speed and advance ratio (Brandt & Selig, 2011; Czyż *et al.*, 2022; Kaygan *et al.*, 2024). Recent investigations have further confirmed that propeller geometry significantly affects UAV aerodynamic performance and that CFD predictions can show good agreement with measured thrust data (Zhang *et al.*, 2023; Chen *et al.*, 2025).

This study compares the thrust, torque, power and fuel consumption characteristics of different propeller configurations with varying diameter and pitch to evaluate their aerodynamic performance. The findings contribute to improved understanding of the influence of propeller geometry on aerodynamic performance, and support propeller selection and engine–propeller matching for UAV and aerospace propulsion systems.

2. METHODOLOGY

2.1 Experimental System Design

The experimental system for assessing propeller aerodynamic performance, as designed and presented in this paper, is capable of collecting data on propeller speed, single thrust, fuel consumption and propeller torque. Manual operation via remote control is required to adjust the blade's rotational speed. The experimental system developed in this study assesses propeller aerodynamic performance by measuring propeller rotational speed, thrust, torque, fuel-flow rate and cylinder-head temperature. Total fuel consumption during each test is determined by integrating the measured fuel-flow rate over the test duration. Propeller rotational speed is adjusted manually using a remote controller. The system comprises two principal subsystems: the experimental test subsystem and the measurement and control subsystem. Figure 1 illustrates the functional connections and data flow between the system components, whilst Figure 2 shows their physical arrangement on the experimental propeller test rig.

The experimental test subsystem is constructed on a rigid steel frame and comprises the Limbach L550EF internal combustion engine, the propeller, the load-cell assembly and the fuel-delivery system. As shown in Figure 2, the engine and propeller are mounted on the upper section of the frame and aligned with the load-cell assembly to enable the forces generated during operation to be measured. The steel structure provides mechanical support and maintains the alignment of the engine, propeller and measuring apparatus throughout each test. The fuel-delivery system comprises a fuel pump, fuel filter and SLF3S-4000B liquid-flow sensor. As indicated by the red flow path in Figure 1, fuel is delivered by the pump through the filter and flow sensor before entering the engine. The SLF3S-4000B measures the instantaneous fuel-flow rate and transmits the measurement to the Arduino Mega.

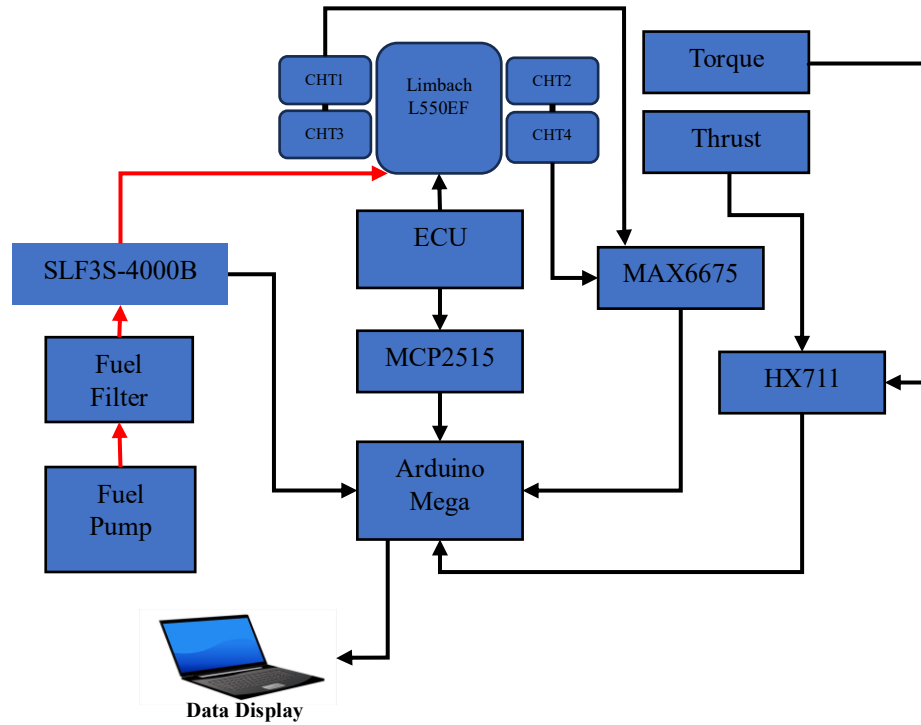


Figure 1: Block diagram of the propeller aerodynamic performance test system.

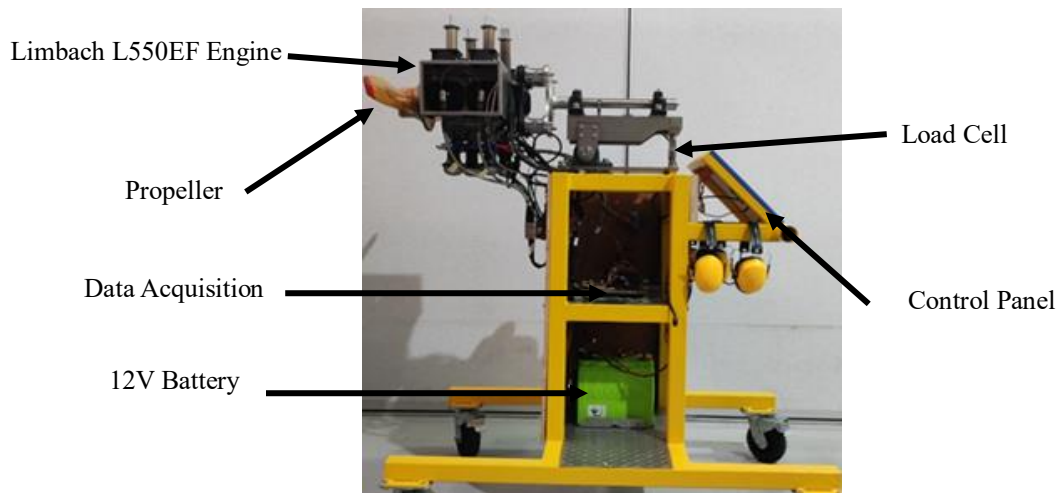


Figure 2: Experimental propeller mount test rig.

The measurement and control subsystem comprises the sensors, signal-conditioning modules, engine control unit (ECU), Arduino Mega data-acquisition unit, control panel, 12 V battery and computer-based data-display system. Four cylinder-head temperature sensors, designated CHT1–CHT4, monitor the operating temperatures of the engine cylinders. Their thermocouple signals are processed by MAX6675 interface modules before being transmitted to the Arduino Mega. The thrust and torque generated by the engine–propeller assembly are measured by the corresponding load-cell arrangements. Their outputs are amplified and digitised by HX711 load-cell interface modules before being sent to the Arduino Mega. Engine operating data, including rotational speed, are communicated from the ECU to the Arduino Mega through the MCP2515 Controller Area Network (CAN) interface module.

As shown in Figure 2, the data-acquisition equipment is housed within the central section of the steel frame, whilst the 12 V battery is located in the lower compartment. The battery provides the primary electrical supply for the fuel pump, ECU and measurement system, with appropriate voltage regulation provided for the low-voltage electronic components. The control panel is positioned on the side of the rig to provide convenient access to the operating controls. The Arduino Mega functions as the central data-acquisition device by collecting and synchronising the fuel-flow, cylinder-temperature, thrust, torque and rotational-speed measurements. The acquired data are subsequently transmitted to a computer for real-time display, monitoring and storage.

2.2 Propeller Configurations

Three propeller configurations with varying diameter and pitch ($30\text{ in} \times 23^\circ$, $32\text{ in} \times 23^\circ$, and $32\text{ in} \times 20^\circ$) were tested to assess performance under increasing operational conditions. Two propellers maintain a consistent pitch angle of 23° , while two propellers have a fixed diameter of 32 in. The specifications of the tested propellers are presented in Table 1. The thrust (N), torque (Nm), power (W), and fuel consumption (L/hr) were recorded at various RPM levels ranging from 3,000 to 6,000 RPM. The data were plotted to observe trends and compare performance.

Table 1: Specifications of tested propellers.

Propeller	Diameter (in)	Pitch ($^\circ$)
30x23	30	23
32x23	32	23
32x20	32	20

2.3 Non-Dimensional Performance Parameters

In order to enable more rigorous aerodynamic assessment and facilitate comparison with existing literature, the experimental results were further analysed using non-dimensional performance coefficients, namely the thrust coefficient (C_T), power coefficient (C_P), advance ratio (J) and propeller efficiency (η). The thrust and power coefficients are defined as:

$$C_T = \frac{T}{\rho \eta^2 D^4} \quad (1)$$

$$C_P = \frac{P}{\rho \eta^3 D^5} \quad (2)$$

where T is thrust (N), P is power (W), ρ is air density (kg/m^3), η is rotational speed (rev/s), and D is propeller diameter (m). As the present study was conducted under static conditions ($V = 0$), propeller efficiency is expressed as:

$$\eta = \frac{TV}{P} \quad (3)$$

which approaches zero under static testing conditions, indicating that efficiency trends must be interpreted indirectly through the thrust and power characteristics.

3. RESULTS AND DISCUSSION

3.1 Thrust Characteristics and Diameter Effect

The thrust performance results of the tested propellers shown in Figure 3 demonstrate that the 32 in $\times$ 20° propeller consistently produces the highest thrust across all RPM levels, followed by the 32 in $\times$ 23° propeller, while the 30 in $\times$ 23° propeller generates the lowest thrust. The lower thrust produced by the 32 in $\times$ 23° configuration suggests that the smaller propeller diameter limits aerodynamic force generation due to reduced disc area. Meanwhile, although the 32 in $\times$ 23° propeller shares the same diameter as the 32 in $\times$ 20° configuration, it demonstrates slightly lower thrust, indicating that increasing pitch may negatively affect thrust generation at a given RPM due to increased aerodynamic resistance.

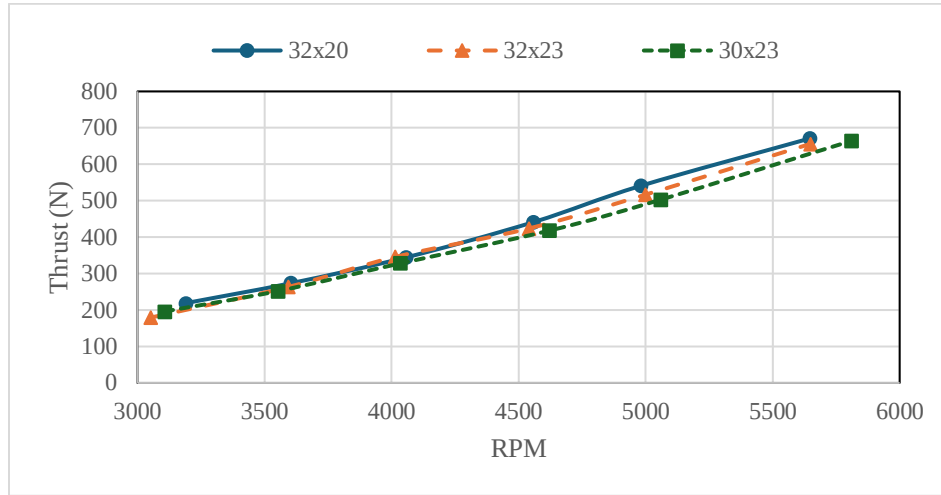


Figure 3: Thrust performance of the tested propellers.

When normalised using the thrust coefficient (C_T), the larger diameter propellers maintain superior thrust coefficients, confirming that thrust generation is strongly influenced by propeller disc area. From momentum theory, thrust can be approximated as:

$$T = 2\rho A v_i^2 \quad (4)$$

where A is the propeller disc area, and v_i is the induced velocity. An increase in propeller diameter increases the disc area, thereby reducing the induced velocity required to generate a given thrust. This improves aerodynamic loading and reduces induced losses. The lower thrust performance of the 30 in $\times$ 23° propeller is thus attributed to its reduced disc area, which limits its ability to accelerate airflow effectively at comparable rotational speeds.

3.2 Influence of Pitch on Aerodynamic Loading

The torque performance of the tested propellers results shown in Figure 4 demonstrate that torque requirements increase with RPM for all the tested propeller configurations. The 32 in $\times$ 23° configuration exhibits the highest torque demand due to its increased pitch, requiring greater power to sustain rotational speed. In contrast, the 32 in $\times$ 20° propeller demonstrates a slightly lower torque requirement, suggesting improved efficiency in converting power into thrust while minimising torque load. The 30 in $\times$ 23° propeller exhibits the lowest torque requirement but also demonstrates the lowest thrust production efficiency.

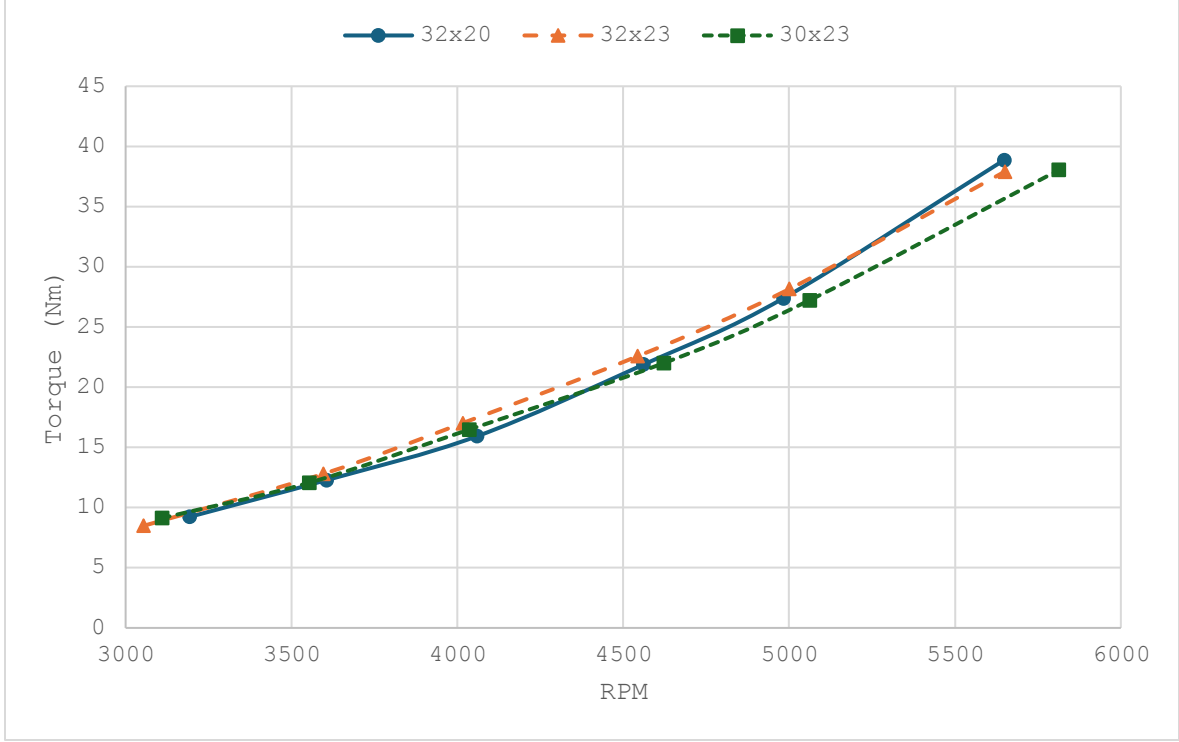


Figure 4: Torque performance of the tested propellers.

Despite sharing the same diameter, the 32 in $\times$ 23° propeller produces lower thrust than the 32 in $\times$ 20° configuration, indicating a strong influence of pitch on aerodynamic behaviour. A higher pitch increases the blade angle of attack relative to the rotational plane, which under static conditions leads to increased aerodynamic loading, higher drag forces, and potential flow separation at low advance ratios. This reduces the lift-to-drag ratio and lowers effective thrust generation. Consequently, although higher pitch may be advantageous during forward flight, it becomes less effective under static or low-speed operating conditions, explaining the lower thrust observed for the 32 in $\times$ 23° configuration.

3.3 Power Consumption and Propeller Efficiency

The power performance of the tested propellers results shown in Figure 5, follows a similar trend to the torque characteristics, with the 32 in $\times$ 23° propeller demanding the highest power due to its increased torque load. However, the 32 in $\times$ 20° propeller demonstrates a better balance between power input and thrust output, indicating improved energy efficiency. In contrast, although the 30 in $\times$ 23° propeller consumes the least power, its lower thrust performance highlights a trade-off between energy consumption and propulsion efficiency.

The torque measurements indicate that the 32 in $\times$ 23° propeller exhibits the highest torque requirement, followed by the 32 in $\times$ 20° and 30 in $\times$ 23° configurations. This trend is further reflected in the power coefficient (C_P), which increases with both propeller diameter and pitch. The higher torque demand for the 32 in $\times$ 23° propeller can be attributed to increased blade loading, higher aerodynamic resistance, and greater energy required to maintain rotational speed. This relationship is expressed as:

$$P = 2\pi nQ \quad (5)$$

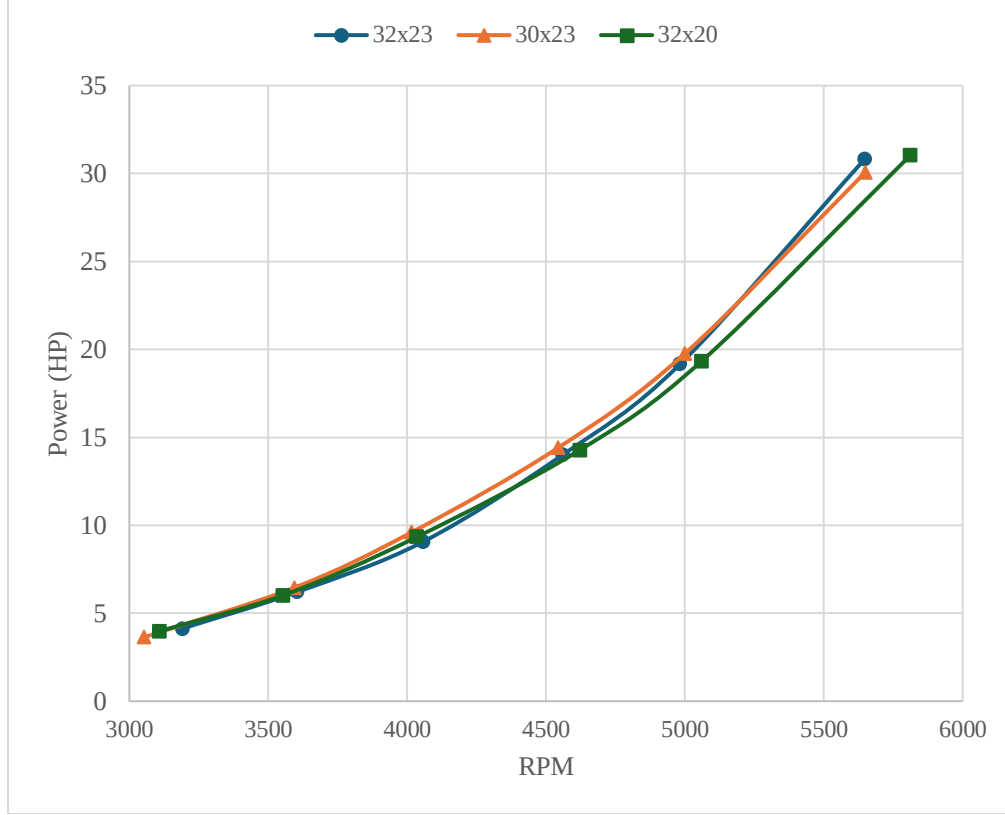


Figure 5: Power performance of the tested propellers.

where Q is torque and η is true propulsive efficiency. As pitch increases, the blade encounters greater resistance, requiring higher torque and consequently higher power input. In contrast, the 32 in $\times$ 20° propeller demonstrates a more balanced C_P , indicating a more efficient conversion of mechanical power into useful aerodynamic work.

Although true propulsive efficiency (η) cannot be directly evaluated under static conditions, the thrust-to-power ratio (T/P) provides a useful indication of relative aerodynamic efficiency. The 32 in $\times$ 20° propeller exhibits the most favourable thrust-to-power ratio, indicating superior aerodynamic efficiency. This suggests that the propeller operates closer to its optimal loading condition, minimising both induced and profile losses. In contrast, the 32 in $\times$ 23° propeller experiences excessive aerodynamic loading, while the 30 in $\times$ 23° propeller is under-loaded due to its reduced disc area. These findings reflect the trade-off between propeller diameter and pitch in achieving efficient propulsion performance under static operating conditions.

3.4 Fuel Consumption and Engine–Propeller Matching

The fuel consumption performance of the tested propellers, as shown in Figure 6, further reinforces the aerodynamic findings. The 32 in $\times$ 23° propeller exhibits the highest fuel consumption, consistent with its increased torque demand and elevated power requirement. From a propulsion system perspective, this indicates a mismatch between engine operating characteristics and propeller loading, where the higher pitch imposes excessive load on the engine, increasing fuel consumption without proportional gains in thrust. In contrast, the 32 in $\times$ 20° propeller demonstrates a more favourable balance between thrust generation and fuel efficiency, indicating improved engine–propeller matching and more efficient propulsion performance.

Although the 30 in $\times$ 23° propeller consumes the least fuel, its lower thrust output reduces its suitability for applications requiring higher propulsion efficiency.

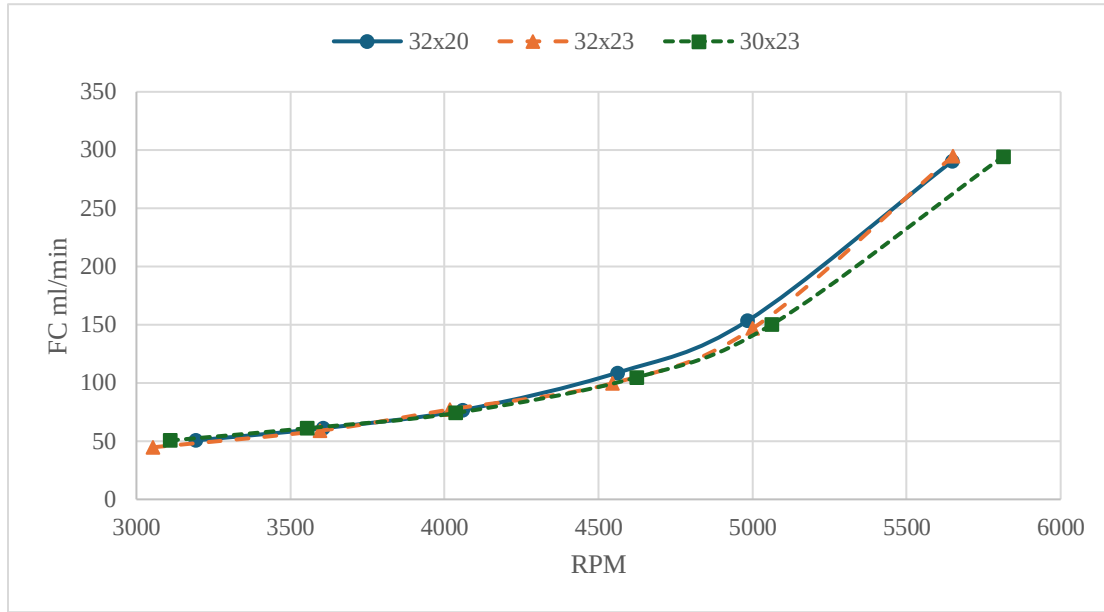


Figure 6: Fuel consumption performance of the tested propellers.

3.5 Limitations of Static Testing

The present study is limited to static testing conditions (advance ratio, $J = 0$), which do not fully represent actual flight conditions. In forward flight, the advance ratio is defined as:

$$J = \frac{V}{\pi D} \quad (6)$$

where V is the freestream velocity. Under forward flight conditions, higher pitch propellers are expected to operate more efficiently, while flow separation effects are reduced and overall propulsive efficiency increases. Therefore, although the present findings provide valuable insight into static thrust performance, further investigation under controlled airflow conditions, such as wind tunnel testing, is required to fully characterise propeller behaviour across different operational regimes.

4. CONCLUSION

The experimental investigation demonstrated that propeller diameter and pitch significantly influence aerodynamic performance under static operating conditions. Among the tested configurations, the 32 in $\times$ 20° propeller consistently produced the highest thrust across the evaluated RPM range while maintaining a more favourable balance between torque demand, power consumption, and fuel efficiency. In contrast, the 32 in $\times$ 23° propeller exhibited higher aerodynamic loading due to its increased pitch, resulting in greater torque and power requirements as well as elevated fuel consumption. Although the 30 in $\times$ 23° propeller required the lowest power and fuel consumption, its reduced diameter limited thrust generation due to the smaller propeller disc area. The analysis using thrust and power coefficients further confirmed that propeller diameter strongly affects thrust generation and aerodynamic loading characteristics.

The findings also highlighted the importance of appropriate engine–propeller matching in achieving efficient propulsion performance. The 32 in × 20° configuration demonstrated the most favourable thrust-to-power ratio, indicating improved aerodynamic efficiency and more balanced operating characteristics under static test conditions. Nevertheless, the present study is limited to static testing conditions, which do not fully represent actual flight environments where inflow velocity and advance ratio influence propeller behaviour. Consequently, further investigations under controlled airflow conditions, such as wind tunnel testing or dynamic flight evaluation, are recommended to fully characterise propeller performance across wider operational regimes.

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AERODYNAMIC PERFORMANCE OF A FOLDING WING AIR-LAUNCHED GLIDER

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ABSTRACT

Whilst folding wing aerodynamics has been widely investigated, the aerodynamic characterisation of progressive wing deployment for air-launched unpowered gliding vehicles remains limited. This study investigates the aerodynamic performance of a folding wing glider comprising a fixed inboard wing section and a deployable outboard wing section across three deployment states, namely stowed wing (SW), half deployed wing (HDW) and fully deployed wing (FDW). Two deployment methods were considered: dihedral- and sweep-based deployments. Aerodynamic performance was evaluated using the vortex lattice method (VLM) implemented in the VSPAero computational environment, with the results assessed in terms of lift coefficient (C_L), drag coefficient (C_D), drag polar characteristics and lift-to-drag ratio (L/D). The results obtained show that wing deployment configuration and deployment method significantly influence aerodynamic performance. The fully deployed configurations achieved the highest lift coefficients, whilst the stowed sweep configuration exhibited aerodynamic characteristics distinct from the remaining deployment states. For the dihedral-based deployment method, aerodynamic efficiency improved progressively with deployment stage, with peak L/D increasing from approximately 22 for SW_D to 35 for FDW_D . In contrast, the sweep-based deployment method exhibited a reduction in L/D as deployment progressed from SW_S to FDW_S . Among the configurations investigated, FDW_D demonstrated the most favourable combination of lift generating capability and aerodynamic efficiency. The findings highlight the importance of deployment kinematics in folding wing glider design and provide useful aerodynamic insights for the preliminary development of air-launched unpowered gliding vehicles.

Keywords: Air-launched glider; folding wing aircraft; wing deployment; aerodynamic performance; vortex lattice method (VLM).

1. INTRODUCTION

Air-launched gliding vehicles are unpowered aerial platforms that rely entirely on aerodynamic lift to sustain flight following release from a carrier aircraft. Owing to the absence of onboard propulsion, these vehicles offer reduced weight, lower system complexity and lower acquisition costs as compared to powered alternatives, making them attractive for expendable applications (Jung *et al.*, 2024; Jia *et al.*, 2025). One such application is the air-launched expendable aerial target, which must maintain a stable and predictable glide trajectory to fulfil its role as a radar or infrared target (Jia *et al.*, 2025). For such platforms, aerodynamic efficiency, commonly expressed by the lift-to-drag ratio (L/D), is a primary determinant of glide range and overall mission effectiveness (Jung *et al.*, 2024).

The operational requirements of air-launched systems impose additional design constraints. In order to ensure compatibility with aircraft external store suspension systems, the vehicle must be carried in a compact configuration during captive flight. Folding-wing designs address this requirement by allowing the wing to be stowed during carriage and deployed after release. Upon deployment, the wing transitions

from a compact storage configuration to an aerodynamically efficient lifting surface capable of sustaining unpowered flight.

Unlike powered aircraft, expendable gliding vehicles possess limited capability to compensate for deployment deficiencies. Wing deployment is typically achieved using simple passive mechanisms to minimise weight, cost, and system complexity. Consequently, incomplete deployment resulting from mechanical interference, aerodynamic loading, or deployment system variability may significantly reduce aerodynamic performance. Since propulsion is unavailable to compensate for reduced aerodynamic efficiency, the ability of the vehicle to sustain an effective glide is strongly dependent on the aerodynamic characteristics achieved at each deployment stage.

Various folding wing and morphing-wing concepts have been investigated in the literature. Smart-material-based wing morphing systems have demonstrated the feasibility of modifying wing geometry to influence aerodynamic performance (Abdullah *et al.*, 2009; Bil *et al.*, 2013). Folding wing configurations have also been developed for compact storage and deployment in unmanned aerial vehicles (UAVs) and constrained launch environments (Karatzas *et al.*, 2026; Telleria Serra, 2025). At the aerodynamic level, previous studies have shown that wing folding alters lift generation, drag characteristics and spanwise aerodynamic behaviour (Bae *et al.*, 2005; Huang *et al.*, 2023; Healy *et al.*, 2022; Güler & Nikbay, 2026). Other investigations have focused on deployment dynamics and deployment reliability (Zhang & Yang, 2018; Qian *et al.*, 2026).

Despite these advances, existing studies have primarily focused on fully deployed wing configurations (Bae *et al.*, 2005; Healy *et al.*, 2022; Huang *et al.*, 2023; Güler & Nikbay, 2026), as well as on deployment mechanisms and deployment dynamics (Zhang & Yang, 2018; Cheng *et al.*, 2019; Qian *et al.*, 2026). Limited attention has been given to the aerodynamic performance of intermediate deployment states, particularly for air-launched unpowered gliding vehicles where aerodynamic efficiency directly determines mission performance. To the authors' knowledge, no study has systematically characterised the aerodynamic efficiency of a two-section folding wing glider comprising a fixed inboard wing section and a deployable outboard wing section across progressive deployment stages.

The vortex lattice method (VLM) provides a computationally efficient approach for evaluating the aerodynamic performance of variable wing geometries. Previous studies have demonstrated the suitability of VLM-based tools for predicting lift and drag characteristics, as well as for conducting rapid parametric investigations involving geometric variations (Cheng *et al.*, 2019; Mariën, 2021; Sahraoui *et al.*, 2024). This capability makes VLM particularly suitable for evaluating the aerodynamic implications of progressive wing deployment.

Accordingly, this study investigates the aerodynamic performance of a folding wing glider across three deployment configurations ranging from fully stowed to fully deployed. Two deployment methods are considered, namely dihedral-based deployment and sweep-based deployment. Using the VLM-based VSPAero computational environment, the study evaluates the resulting lift, drag and lift-to-drag characteristics to establish the aerodynamic efficiency envelope associated with progressive wing deployment and to support the preliminary design of air-launched unpowered gliding vehicles.

2. METHODOLOGY

2.1 Scope of Analysis and Flight Scenario

The present aerodynamic analysis considers only the stable, quasi-steady low-subsonic glide phase that follows wing deployment, as this is the condition that governs the glider's aerodynamic performance; the preceding captive-carry, release, free-fall and deceleration phases are not modelled. The analysis was conducted at a representative altitude of 3,000 m AMSL, corresponding to the anticipated glide envelope. Under International Standard Atmosphere (ISA) conditions, this altitude gives an ambient

temperature of 268.66 K, a pressure of 70,121 Pa and an air density of 0.9093 kg/m³. A glide airspeed of 94.6 km/h (26.29 m/s) was adopted, consistent with the detectability requirements of a representative fighter-aircraft fire-control radar, giving a chord-based Reynolds number of 3.51×10^5 that lies within the low-subsonic validity range of the VLM employed in this study.

2.2 Wing Geometry

The wing geometry of the air-launched folding wing glider was developed in OpenVSP, and the principal geometric parameters are summarised in Table 1. The overall vehicle configuration in the fully deployed wing (FDW) state is illustrated in Figure 1. The vehicle is designed as a lightweight expendable platform with a gross vehicle weight of approximately 8 - 12 kg, consistent with the intended operational role and the physical constraints of standard aircraft external store suspension systems.

Table 1: Wing geometry parameters of the air-launched folding-wing glider across stowed wing (SW), half deployed wing (HDW) and full deployed wing (FDW) configurations.

Parameter	Unit	SW (0%)	HDW (50%)	FDW (100%)
Total Span	m	0.597	1.194	2.388
Root Chord	m	0.249	0.249	0.249
Tip Chord	m	0.249	0.249	0.249
Mean Aerodynamic Chord (MAC)	m	0.249	0.249	0.249
Aspect Ratio	-	0.60	2.40	9.59
Airfoil Section	-	NACA 0010	NACA 0010	NACA 0010

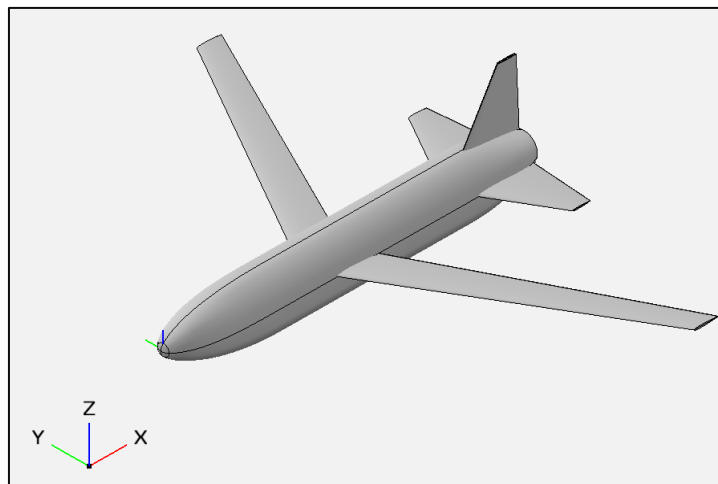


Figure 1: Generic configuration of the air-launched folding-wing glider in FDW shown in isometric view

2.2.1 Wing Section Features

The wing is modelled as a two-section assembly in OpenVSP, comprising a fixed inboard section (Section 1) and a deployable outboard section (Section 2), as illustrated in Figure 2. Section 1 constitutes the inboard half of the wing, spanning 0.597 m from the root, and remains geometrically fixed across all deployment configurations, serving as the structural backbone of the wing assembly. Section 2 constitutes the outboard deployable panel, spanning 1.194 m from Section 1 tip to the wing tip, and undergoes geometric transformation to represent progressive wing deployment. Both sections share identical chord dimensions of 0.249 m at the root and tip, leading-edge sweep of 15° and NACA 0010 airfoil profile, ensuring geometric continuity across the section interface.

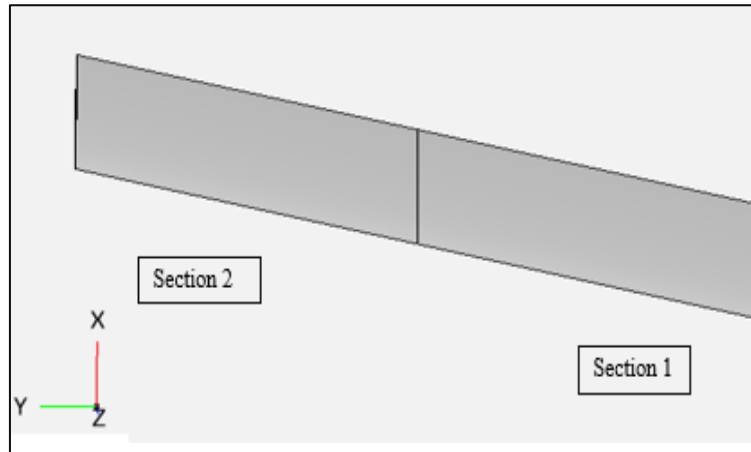


Figure 2: An asymmetrical wing model showing Sections 1 and 2 as modelled in OpenVSP, representing the starboard wing of the symmetric full-span configuration (top view).

2.2.2 Wing Deployment Configurations

Two distinct geometric methods were employed to model the wing deployment in Section 2 within the OpenVSP environment, representing two physically realisable deployment kinematics applicable to folding-wing glider configurations. The first method modulates the dihedral angle of Section 2 to simulate deployment in the z-direction, whilst the second method modulates the leading-edge sweep angle of Section 2 to simulate deployment in the x-direction. Both methods produce three discrete deployment configurations designated as SW, HDW and FDW, representing 0, 50 and 100% wing deployment respectively.

In the dihedral-based deployment method, Section 2 rotates from a fully vertical orientation at 90° dihedral in the SW configuration, representing the wing panel stowed perpendicular to the horizontal plane, through an intermediate dihedral angle of 45° in the HDW configuration, to a fully horizontal orientation at 0° dihedral in the FDW configuration, consistent with a planar wing geometry. Section 1 maintains a fixed dihedral of 0° across all configurations.

In the sweep-based deployment method, Section 2 transitions from a highly swept orientation at 60° leading-edge sweep in the SW configuration, representing the wing panel folded rearward in the horizontal plane, through an intermediate sweep angle of 30° in the HDW configuration, to a fully extended orientation at 15° leading-edge sweep in the FDW configuration, consistent with the nominal wing sweep of Section 1. Section 1 maintains a fixed leading-edge sweep of 15° across all configurations.

The geometric parameters defining both deployment methods across all three configurations are summarised in Table 2, and the corresponding OpenVSP models are illustrated in Figures 3 and 4 respectively. For graphical presentation and comparative analysis, each deployment configuration is assigned a compact designation comprising of the configuration abbreviation and a deployment method

subscript. Configurations simulated using the dihedral-based deployment method are denoted with the subscript D, whilst configurations simulated using the sweep-based deployment method are denoted with the subscript S. The resulting designations are SW_D , HDW_D , and FDW_D for the dihedral method, and SW_S , HDW_S , and FDW_S for the sweep method. These designations are adopted consistently across all figures and graphical results presented in the subsequent sections.

Table 2: Wing deployment configuration parameters.

Configuration	Designation	Deployment (%)	Section 2 Dihedral Method (°)	Section 2 Sweep Method (°)
Stowed wing	SW	0	90.00	60.00
Half deployed wing	HDW	50	45.00	30.00
Fully deployed wing	FDW	100	0.00	15.00

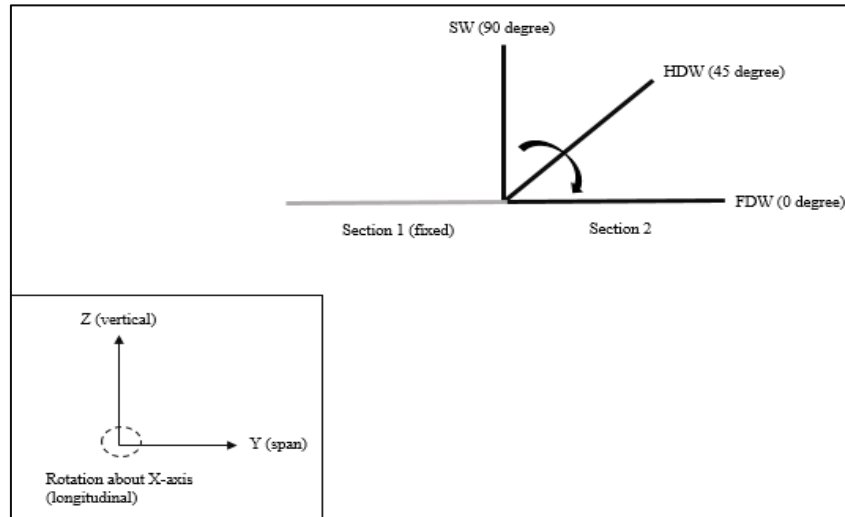


Figure 3: Wing deployment via dihedral variation and rotation about the x-axis, with Section 2 movement occurring in the yz-plane (front view).

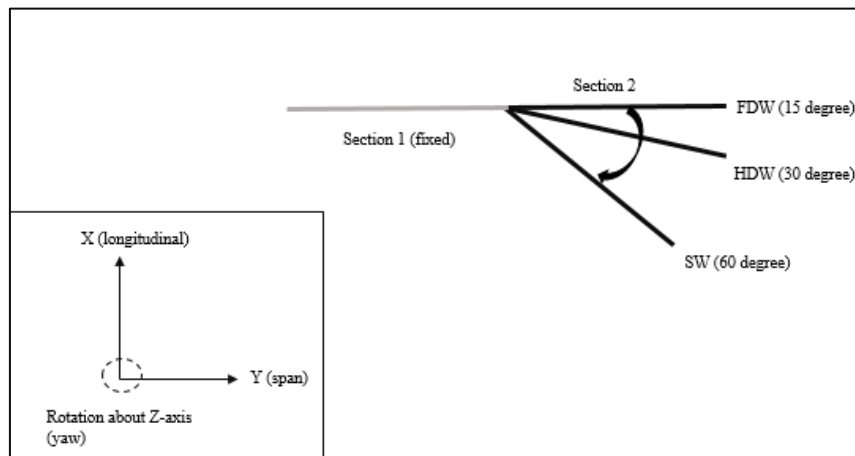


Figure 4: Wing deployment via sweep variation and rotation about the z-axis, with Section 2 movement occurring in the xy-plane (top view).

2.3 VSPAero Solver Configuration

The aerodynamic analysis was performed using VSPAero, the VLM solver integrated within the OpenVSP computational environment. The Thin Surface formulation was selected, consistent with the VLM assumption of infinitely thin lifting surfaces operating at low angles of attack with attached flow conditions. The solver was configured with a fixed wake model using three wake iterations and a relaxation factor of 1.000, consistent with the default convergence settings recommended for low-subsonic VLM analysis. The angle of attack was swept from -10 to 15° at discrete increments, encompassing the aerodynamically efficient glide regime within which the vehicle is expected to operate during the stable glide phase, and consistent with the small angle of attack validity domain of the VLM solver. The freestream Mach number was set to 0.080, consistent with the low subsonic glide condition at 3,000 m altitude, and the chord-based Reynolds number was set to 3.51×10^5 . The solver reference parameters were defined based on the FDW geometry, representing the maximum wing span and reference area configuration, as summarised in Table 3.

Table 3: VSPAero solver configuration parameters.

Parameter	Value
Solver Type	Vortex lattice method (VLM)
Wake Model	Fixed wake
Wake Iterations	3
Relaxation Factor	1.000
Alpha Start	-10.0°
Alpha End	15.0°
Mach Number	0.080
Reynolds Number (Re)	3.51×10^5
Reference Area (S_{ref})	0.594 m^2
Reference Span (b_{ref})	2.388 m
Reference Chord (c_{ref})	0.249 m

2.4 Aerodynamic Performance Parameters

The primary aerodynamic performance metric evaluated in the present study is the lift-to-drag ratio (L/D), which governs the aerodynamic efficiency of an unpowered gliding vehicle. The lift coefficient (C_L) and drag coefficient (C_D) were extracted directly from the VSPAero output for each angle of attack and wing deployment configuration. The lift-to-drag ratio was subsequently computed as:

$$\frac{L}{D} = \frac{C_L}{C_D} \quad (1)$$

The variation of C_L , C_D and L/D with angle of attack was evaluated for each of the six deployment configurations, namely SW_D , HDW_D , FDW_D , SW_S , HDW_S and FDW_S , to characterise the aerodynamic performance associated with progressive wing deployment. The maximum L/D attained within the analysed angle of attack range was identified for each configuration and used as the primary indicator of aerodynamic efficiency.

It is acknowledged that the VLM solver primarily captures lift-induced aerodynamic effects and does not fully account for viscous profile drag. Consequently, the computed L/D values should be interpreted as representative indicators of aerodynamic performance rather than absolute performance predictions. Therefore, the relative comparison of C_L , C_D and L/D among the deployment configurations forms the primary basis for aerodynamic assessment in the present study.

3. RESULTS AND DISCUSSION

The aerodynamic performance of the six wing deployment configurations, namely SW_D , HDW_D , FDW_D , SW_S , HDW_S and FDW_S , was evaluated across an angle of attack (α) range of -10 to 15° at 3,000 m AMSL. The results are presented in terms of the drag polar, lift coefficient (C_L), drag coefficient (C_D) and lift-to-drag ratio (L/D), as illustrated in Figures 5 - 8.

3.1 Drag Polar

Figure 5 presents the drag polar for all six configurations, plotting C_L against C_D over the analysed angle-of-attack range. The SW_S configuration occupies a distinctly separate aerodynamic regime, achieving a maximum C_L of approximately 0.60 at a comparatively low C_D of approximately 0.040. This behaviour is attributed to the substantially reduced effective aerodynamic span of the stowed-sweep configuration.

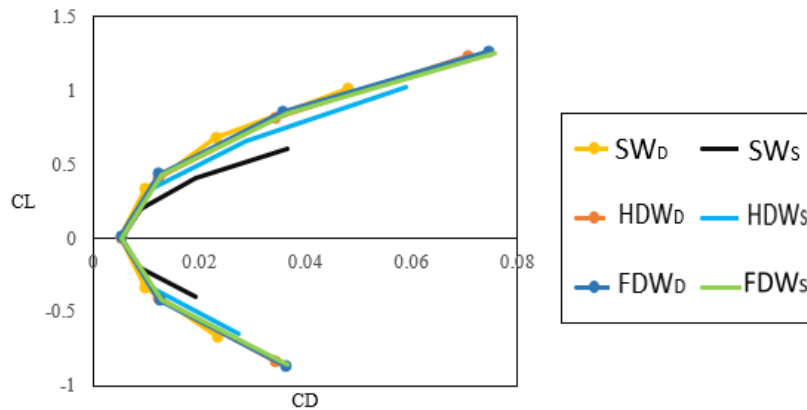


Figure 5: Comparison of drag polar characteristics for the six wing deployment configurations.

The remaining configurations, namely SW_D , HDW_D , FDW_D , HDW_S and FDW_S , exhibit broadly similar drag polar characteristics, converging towards a maximum C_L of approximately 1.25 at C_D values approaching 0.075. These results indicate that the partially and fully deployed configurations provide significantly greater lift-generating capability than the stowed sweep configuration while maintaining comparable drag characteristics. Overall, the drag polar demonstrates that the SW_S configuration behaves distinctly from the other deployment states, whereas the remaining configurations exhibit broadly similar aerodynamic characteristics.

3.2 Lift Coefficient (C_L)

Figure 6 presents the variation of C_L with α for all six configurations. All configurations exhibit an approximately linear C_L - α relationship throughout the analysed range, consistent with attached flow behaviour and the validity range of the VLM solver.

The FDW_D , FDW_S and HDW_S configurations attain the highest C_L values of approximately 1.25 at $\alpha = 15^\circ$, reflecting the larger effective aerodynamic span available for lift generation. The HDW_S configuration exhibits lift characteristics comparable to the fully deployed configurations, indicating that the outboard wing section continues to contribute substantially to lift generation even at the intermediate sweep angle.

The HDW_D and SW_S configurations produce intermediate C_L values of approximately 1.00 at $\alpha = 15^\circ$, while the SW_D configuration yields the lowest C_L of approximately 0.65. For the dihedral-based deployment method, C_L increases progressively with deployment stage, confirming that wing deployment enhances the lift-generating capability of the vehicle by increasing the effective aerodynamic span.

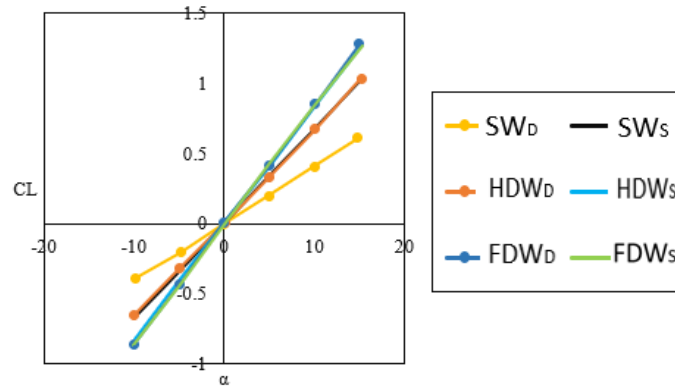


Figure 6: Lift coefficient (C_L) versus angle of attack (α) for the six wing deployment configurations.

3.3 Drag Coefficient (C_D)

Figure 7 presents the variation of C_D with α for all six configurations. The minimum drag for all configurations occurs in the vicinity of $\alpha = 0^\circ$, consistent with the symmetric NACA 0010 airfoil section and zero-camber wing geometry. The SW_S configuration exhibits the lowest C_D throughout much of the positive α range, corresponding to its relatively low lift generation. Conversely, the fully deployed configurations of FDW_D and FDW_S exhibit the highest C_D values, reaching approximately 0.073 at $\alpha = 15^\circ$. This increase in drag is accompanied by a corresponding increase in lift generation. The C_D values of the dihedral-based and sweep-based configurations at equivalent deployment stages are generally comparable, indicating that deployment method exerts a relatively minor influence on drag characteristics compared with the overall degree of wing deployment.

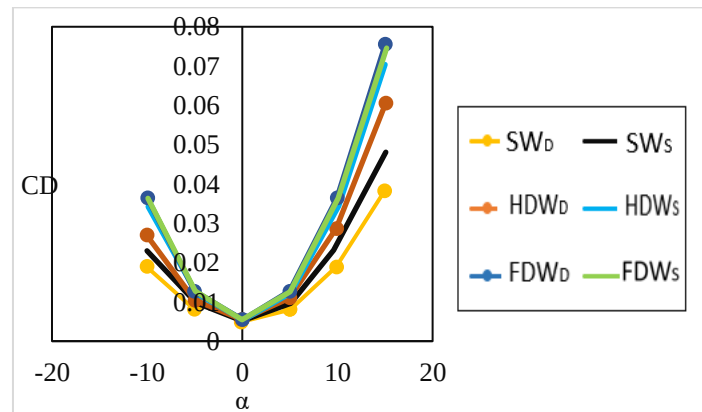


Figure 7: Drag coefficient (C_D) versus angle of attack (α) for the six wing deployment configurations.

3.4 Lift-to-Drag Ratio

Figure 8 presents the variation of L/D with α , which represents the primary aerodynamic performance metric for the unpowered gliding vehicle. All configurations attain their peak L/D at approximately $\alpha = 5^\circ$.

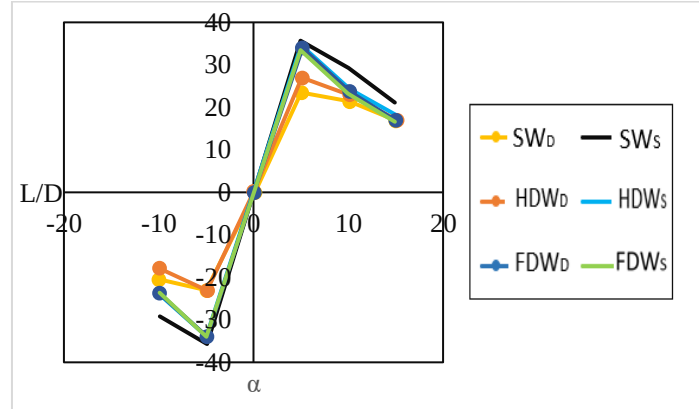


Figure 8: Lift-to-drag ratio (L/D) versus angle of attack for the six wing deployment configurations.

The SW_S configuration achieves the highest peak L/D , reaching approximately 33 - 35. However, despite its favourable L/D value, this configuration also exhibits the lowest lift generating capability among the six configurations, as reflected by its comparatively low C_L values. Consequently, L/D alone may not be sufficient to assess the practical aerodynamic suitability of the configuration.

For the dihedral-based deployment method, peak L/D increases progressively with deployment stage, from approximately 22 for SW_D to 27 for HDW_D and 35 for FDW_D. This trend indicates that progressive deployment of the outboard wing panel improves aerodynamic efficiency while simultaneously increasing lift-generating capability.

The sweep-based deployment method exhibits a different trend. Although the SW_S configuration attains the highest L/D , the aerodynamic efficiency decreases as deployment progresses to HDW_S and FDW_S. This behaviour suggests that the sweep-based deployment geometry influences the aerodynamic characteristics differently from the dihedral-based approach, resulting in a less favourable L/D progression despite comparable lift and drag performance at the fully deployed state.

Overall, the results indicate that the dihedral-based deployment method provides a more consistent improvement in aerodynamic efficiency throughout the deployment process. Among the configurations investigated, FDW_D exhibits the most favourable combination of lift generating capability and aerodynamic efficiency, making it the preferred configuration for sustained gliding performance.

4. CONCLUSION

This study investigated the aerodynamic performance of an air-launched folding-wing glider across six wing deployment configurations using the VLM. The results demonstrate that both wing deployment configuration and deployment method significantly influence aerodynamic performance. The fully deployed configurations achieved the highest lift coefficients, whilst the drag polar analysis showed that SW_S exhibits aerodynamic characteristics distinct from the remaining deployment states.

For the dihedral-based deployment method, aerodynamic efficiency improved progressively with deployment stage, with peak L/D increasing from approximately 22 for SW_D to 27 for HDW_D and 35 for FDW_D. In contrast, the sweep-based deployment method exhibited a reduction in L/D as deployment

progressed from SW_S to FDW_S. Among the configurations investigated, FDW_D demonstrated the most favourable combination of lift generating capability and aerodynamic efficiency. For the wing geometry considered in this study, the results indicate that the dihedral-based deployment approach provides more favourable aerodynamic performance than the sweep-based deployment approach for air-launched unpowered gliding vehicles. These findings provide useful aerodynamic insights for the preliminary design and development of folding wing gliders intended for expendable aerial applications.

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DESIGN AND EXPERIMENTAL EVALUATION OF SOLAR-INTEGRATED UAV WINGS UNDER SHADOWING AND TILT EFFECTS

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ABSTRACT

Unmanned aerial vehicles (UAVs) are increasingly utilised in defence operations for reconnaissance, surveillance and extended missions. Integrating solar panels into UAV wings can extend flight duration, but power losses caused by shadowing and UAV orientation effects remain a challenge. This study involves the design, fabrication and experimental evaluation of a solar-integrated UAV wing to investigate power degradation caused by shading and tilt effects. Using Wing Helper software, a fixed-wing UAV was designed to fit solar cells while maintaining aerodynamic performance. Experimental tests were conducted on two cell sizes (12.4 cm × 12.4 cm and 12.4 cm × 6.2 cm) to evaluate power output under angular tilt (0 - 90°), localised shadowing along x- and y-axes, as well as simulated wing roll during flight. The results demonstrated a significant power degradation of up to 93% at high tilt angles and full shadow coverage. Larger solar cells retained higher power output under tilt conditions, while smaller cells exhibited improved tolerance to partial shading and greater integration flexibility. Vertical (y-axis) shadowing consistently caused greater power loss than horizontal (x-axis), highlighting the need for strategic solar panel orientation and structural layout. In wing roll tests, roll angles beyond 50° resulted in substantial reduction in power output, with losses reaching up to 85% at 90°, demonstrating the strong influence of UAV attitude on solar energy capture. This highlights the need for careful solar panel placement, stable flight conditions and optimised design to reduce power loss. The study provides useful insights into the development of more reliable solar-powered UAVs for long endurance missions in the future.

Keywords: Solar-integrated UAV wing; tilt angle; partial shading effects; wing roll; power degradation.

1. INTRODUCTION

Unmanned aerial vehicles (UAVs), commonly known as drones, have become essential to modern defence and security applications due to their versatility, cost-effectiveness and ability to perform a wide range of tasks. These applications include surveillance, reconnaissance, target acquisition and landmine detection, among others. UAVs are designed with advanced technology, lightweight materials and advanced aerodynamics to ensure optimal performance in challenging environments. Their ability to operate autonomously or be remotely piloted makes them suitable for high-risk and politically sensitive operations (Mohsan *et al.*, 2022; Criollo *et al.*, 2024; Jayakumar *et al.*, 2024).

However, an ongoing challenge in electric UAVs is their limited flight duration. While lithium batteries are popular because of their lightweight characteristics, their limited capacity reduces UAV endurance, which is a serious issue for defence missions such as extended surveillance operations and border patrol missions (Abdulrahman *et al.*, 2025). In order to solve this problem, using renewable energy, especially solar panels, has become an effective and eco-friendly option. Solar-powered UAVs can harness sunlight during flight, either to supplement the onboard battery or, in some designs, serve as the primary source of energy, thus significantly extending airborne operation (Sahwee *et al.*, 2023). Prior research

has demonstrated this potential: for example, the Zephyr UAV developed by Airbus set a world record by remaining airborne for over 25 days, relying entirely on solar energy during daylight and battery storage at night (Westbrook & Rostvik, 2018). NASA's Pathfinder and Helios UAV programs also showed that solar-powered UAVs can fly at high altitudes for long periods (Dhafari *et al.*, 2024).

In response to the growing interest in advanced solar-powered UAV systems, the Unmanned Aerial System (UAS) Research Cluster at University Kuala Lumpur Malaysian Institute of Aviation Technology (UniKL MIAT) has contributed several studies related to solar-powered UAV development. Sahwee *et al.* (2019) introduced an encapsulation process using epoxy resin and advanced composite techniques to enhance the durability and efficiency of solar cells installed on UAV wings. Shah *et al.* (2021) conducted a comparative evaluation of Maximum Power Point Tracking (MPPT) and Pulse Width Modulation (PWM) solar charge controllers within UAV systems, demonstrating that the MPPT controllers provide more consistent voltage regulation and slightly higher energy conversion efficiency. Sahwee *et al.* (2022) evaluated various motor-propeller combinations suitable for solar-powered UAVs, optimising propulsion efficiency under solar-integrated configurations. Earlier work by Sahwee *et al.* (2012) focused on automating photovoltaic cell performance monitoring during flight, enabling real-time health assessment of solar arrays aboard UAVs. Complementing these experimental efforts, the team also developed solar-integrated wing designs using the Wing Helper software, built early-stage hybrid solar-powered UAV prototypes tailored for Malaysian conditions, and created a solar simulation platform for modelling UAV energy systems, each contributing to the incremental advancement of solar UAV technologies at UniKL MIAT (Sahwee *et al.*, 2023; Hakimi & Sahwee, 2025).

Despite these advancements, a major obstacle to the use of solar power in UAVs remains the effect of shadowing on performance. Shadowing has significant impact on the performance and efficiency of solar-powered UAVs by limiting solar energy intake and potentially disrupting communication systems. This effect can be caused by many factors, including the UAV structure, environmental features such as terrain and buildings, as well as atmospheric conditions such as cloud cover. One common issue is airframe shadowing, where parts of the UAV, such as wings and payloads, cast shadows over solar panels or block communication lines. This leads to power loss and degraded signal quality. Another issue is partial shading of solar panels, typically caused by environmental factors such as clouds and obstacles. This can result in multiple peaks in the power-voltage curve of the photovoltaic system, making it harder for standard MPPT algorithms to locate the actual maximum power point (Mazumdar *et al.*, 2024; Zhang *et al.*, 2025).

Reducing shadowing problems in solar-powered UAVs requires smart flight control, good energy management and careful aircraft design. Licea *et al.* (2023) found that adjusting the UAV's flight path and position using models based on flight speed and angle can reduce shadow effects by helping the UAV avoid shadowed areas during flight. Nguyen (2015) demonstrated through simulation that the number of shaded modules directly correlates with power loss, regardless of their specific position in the array. These findings stress the need for more adaptive MPPT techniques in solar UAV systems. In order to reduce the impact of shadowing, some UAVs are designed with larger solar panels, even if it affects their shape and flight performance. This helps them to collect more energy in different lighting conditions. Dinca *et al.* (2023) noted that balancing aerodynamics and solar panel size can lead to a more robust and energy-efficient UAV design, especially for long missions or shaded environments.

This research aims to improve solar-powered UAVs by optimising wing designs to minimise shadow effects and maximise energy generation. This study focuses on designing and building a UAV wing with integrated solar panels using the Wing Helper software. This software helps create accurate and aerodynamic wing structures that support solar panel integration. The main goal is to maximise solar energy capture during flight without affecting the UAV's performance or structural integrity. By running simulations and field tests, the study looks at how wing shape, panel position and materials influence shading and energy output. The results offer useful guidance for creating UAVs that can fly longer and work more reliably in defence and security missions.

2. MATERIALS AND METHODS

2.1 Wing Design Using Wing Helper

The UAV wing was designed using Wing Helper 1.7.1, a specialised 3D modelling software for fixed-wing aircraft. The design focused on integrating five monocrystalline solar cells ($12.4\text{ cm} \times 6.2\text{ cm}$) while maintaining aerodynamic efficiency and structural stability. The wingspan was determined based on the total surface area required for solar cell placement. The chord length and aspect ratio were selected to balance lift and drag. A NACA 4412 airfoil was chosen due to its reliable lift characteristics and efficiency at low speeds, which are typical in small UAV operations. The wing design included a moderate dihedral angle for lateral stability and a slight sweep angle to support aerodynamic control during manoeuvres.

Internally, the wing structure comprised ribs, spars and leading / trailing edges, arranged to ensure both strength and accommodation for solar panels. The rib spacing was optimised to provide open sections where solar cells could be mounted without interference. Iterative modifications were made to align the structural components with electrical integration needs. Figure 1 illustrates the design environment within Wing Helper 1.7.1, showcasing the skeletal wing structure, including the placement of structural members and empty bays designated for solar cell installation. Once finalised, the digital model was exported as a Drawing Exchange Format (DXF) file (Figure 2) to enable laser-based fabrication of plywood parts. This ensured precise translation from digital design to physical assembly.

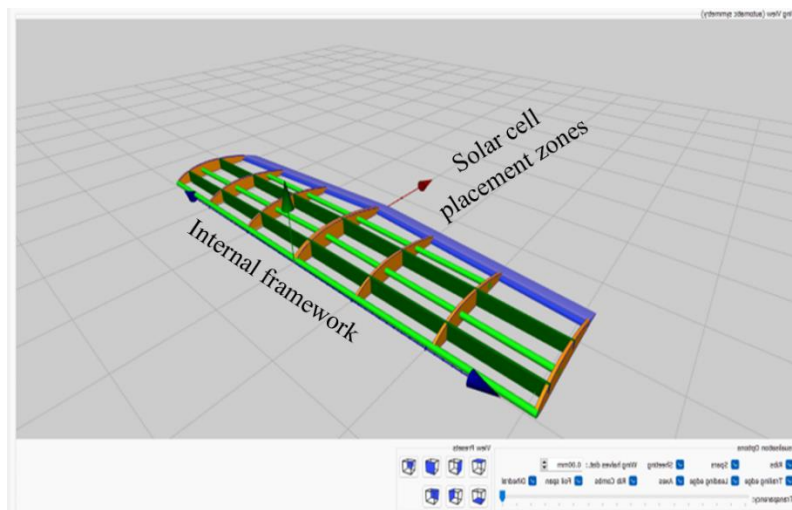


Figure 1: Wing structure designed using Wing Helper 1.7.1, showing internal framework and solar cell placement zones.

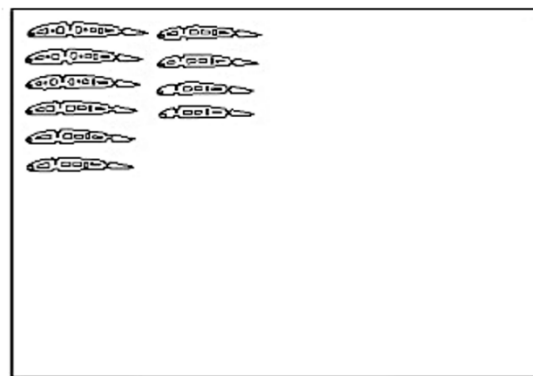


Figure 2: Wing structure design for laser cutting.

2.2 Fabrication of UAV Wing and Solar Integration

The fabrication of the UAV wing was carried out using a rib-and-spar construction method designed for lightweight strength and efficient solar integration. The process began with laser cutting of the wing components from plywood sheets using a computer numerical control (CNC) laser cutter, as shown in Figure 3(a). All ribs and spars were precisely shaped according to the DXF files exported from the design phase to ensure accuracy and fitment.

Following the cutting process, the individual structural components were manually assembled into the wing frame. Each rib was slotted along the spar and aligned to maintain the aerodynamic contour, with adhesive applied to secure all joints, as depicted in Figure 3(b). After curing, the structure underwent surface sanding to smoothen joints and eliminate any irregularities. Next, a transparent heat-shrink laminate film was applied to the outer surface using a heat-sealing iron, shown in Figure 3(c). This film served both as the aerodynamic skin and a protective layer that allows sunlight to pass through to the solar cells mounted underneath. Care was taken during lamination to avoid thermal deformation of the balsa and plywood structure. For solar integration, half-cut monocrystalline solar cells ($12.4\text{ cm} \times 6.2\text{ cm}$) were mounted between the internal ribs to maintain the structural integrity and minimise shadowing from the framework. Electrical wiring was embedded within the structure to connect the solar cells in series, and the entire module was tested for continuity and alignment, as illustrated in Figure 3(d).

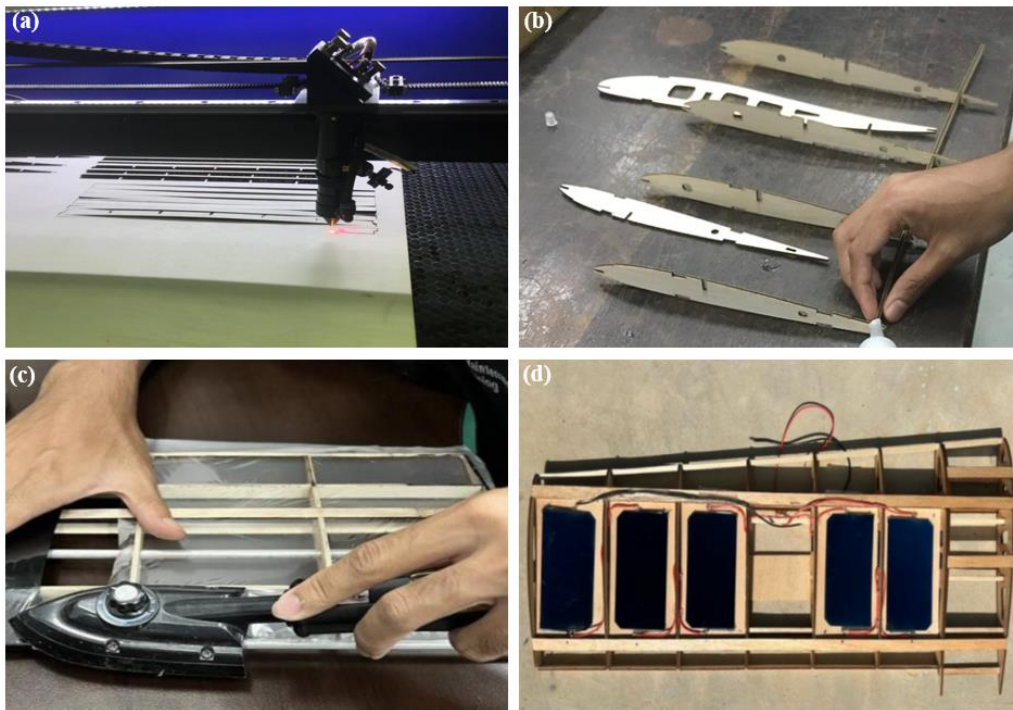


Figure 3: Fabrication stages of the rib-and-spar UAV wing with integrated solar cells: (a) CNC laser cutting of rib and spar components from plywood. (b) Manual assembly of interlocked wing structure. (c) Application of transparent heat-shrink lamination for aerodynamic surface and photovoltaic exposure. (d) Completed wing with integrated half-cut monocrystalline solar cells ($12.4\text{ cm} \times 6.2\text{ cm}$) mounted between ribs.

2.3 Solar Cell Shadow Testing

In order to evaluate the performance of individual solar cells under varying shadow conditions, angle and layer shadow tests were conducted. Two monocrystalline solar cell sizes of $12.4\text{ cm} \times 12.4\text{ cm}$ (large) and $12.4\text{ cm} \times 6.2\text{ cm}$ (small) were tested to evaluate the impact of surface area on power output

under varying conditions. Both tests were performed under consistent environmental conditions, with solar irradiance maintained at or above 1,000 W/m², as verified using a solar power meter. This ensured accurate data collection under standard sunlight conditions.

For the angle shadow test, solar cells were positioned outdoors on a platform exposed to direct sunlight, with a digital angle meter used to gradually adjust the panel orientation from 0 to 90° in 10° increments to simulate the varying incidence angles encountered during UAV flight manoeuvres. Figure 4 illustrates the tilt angle configuration for the solar cell test setup.

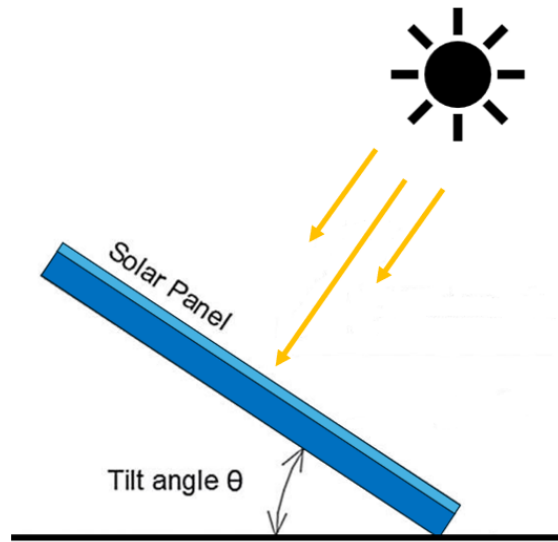


Figure 4: Simple illustration of tilt angle (θ) for the solar cells.

At each angle, the main electrical parameters were measured: voltage using a voltmeter, current using a DC clamp meter, and power output, which was calculated using the following equation

$$P = V \times I \quad (1)$$

where P is power output, V is voltage and I is current. Power was calculated at a fixed load resistance of 0.9 Ω . In order to quantify the performance loss caused by angle-induced shadowing, a loss percentage was calculated using the following formula:

$$\text{Loss Percentage} = [(\text{Power at } 0^\circ - \text{Power at Angle}) / \text{Power at } 0^\circ] \times 100\% \quad (2)$$

In addition to evaluating different tilt angles, a layer shadow test was conducted to examine the effect of localised shading on power output. Each solar cell surface was divided into 10 equal parts along the x -axis (horizontal) and y -axis (vertical). Both solar cells were exposed to full sunlight, and each segment was sequentially covered with black paper to simulate partial shading caused by UAV structural components and environmental obstacles. Figure 5 shows the test setup, where the divided sections facilitated controlled and repeatable shading conditions.

At each step of shading, voltage, current and power were measured to evaluate how the performance dropped as more shadow was added. By comparing the results in both directions, the test evaluated whether the solar cell reacted differently to shadows from different sides. This helps in determining the optimal position and orientation of the solar cell.

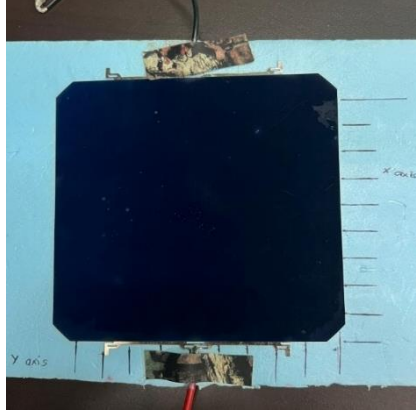


Figure 5: Solar cell segmented into 10 layers along the x- and y-axes for the layer shadow test.

3. RESULTS AND DISCUSSION

3.1 Angle Shadow Test

As shown in Figure 6, the larger solar cell demonstrated a significant drop in performance with increasing tilt angle. At 0° , the cell achieved maximum power output of 3.42 W, with current of 5.7 A. However, at 90° , the current dropped to 0.4 A, reducing power to just 0.24 W, with loss of approximately 93%. Throughout the angle range, the voltage output remained constant at 0.6 V, confirming that current reduction due to light incidence is the primary cause of power loss. The results showed that power output declined progressively with increasing tilt angle, indicating that tilt-induced shadowing rapidly reduces irradiance on the active surface. This suggests that UAV roll or pitch movement during flight significantly impacts real-time solar energy collection. (Li *et al.*, 2022).

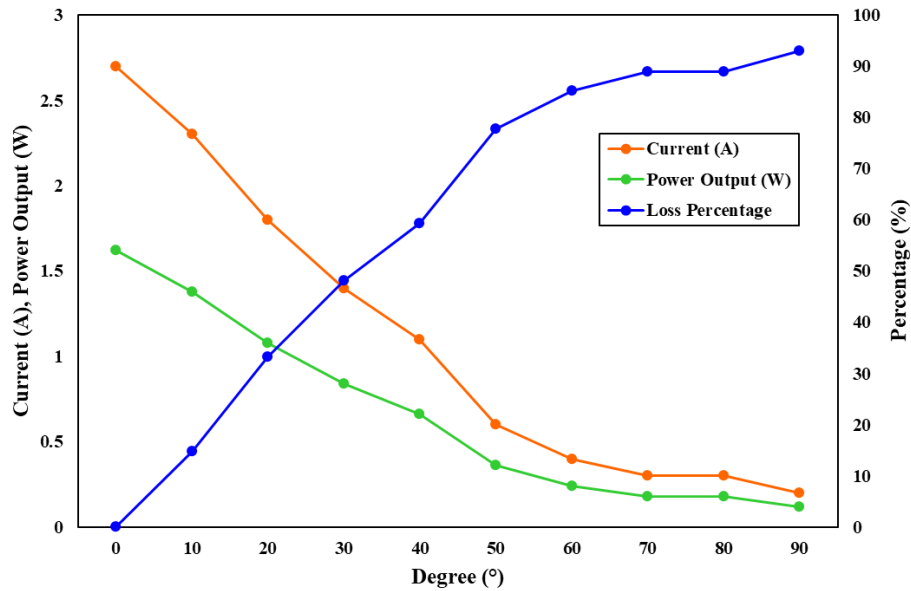


Figure 6: Variation of current, power output and power loss percentage of the $12.4 \text{ cm} \times 12.4 \text{ cm}$ solar cell at different tilt angles under irradiance level $1,210 \text{ W/m}^2$. The voltage output remained approximately constant at 0.6 V throughout the test.

As shown in Figure 7, the smaller solar cell followed a similar trend in performance degradation with increasing tilt. At 0°, it produced current of 2.7 A with power of 1.62 W. At 90°, the output dropped sharply to 0.12 W (0.2 A), representing a 93% loss, matching the larger cell's final loss. However, a key difference was observed at lower tilt angles: the smaller cell lost 14.8% of its power at just 10°, compared to only 5.3% for the larger cell. This indicates that smaller cells are more sensitive to tilt-induced shading. This performance gap is mainly due to the smaller surface area, which reduces photon capture more quickly as the angle shifts from the optimal position (Sharma Ruchpaul & Shamachurn, 2020). In UAV applications, this highlights a compromise between the benefits of lightweight, compact solar cells and the stability of energy output during flight. Both solar cell sizes exhibited a clear inverse relationship between tilt angle and power output. Larger cells provided better power retention under angular deviations but at the cost of size and weight. The results emphasise the need for UAV designs that maintain level flight or incorporate automatic attitude adjustments to optimise solar exposure.

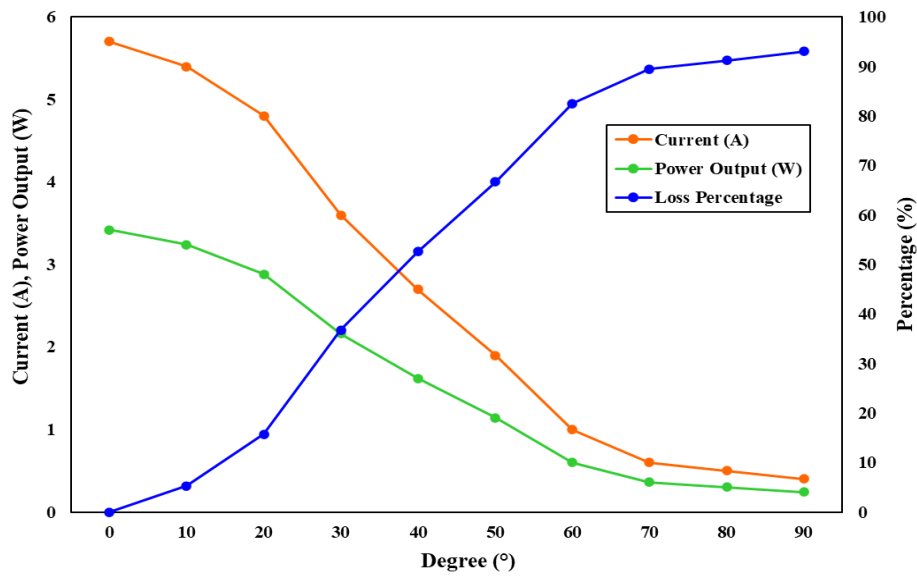


Figure 7: Variation of current, power output and power loss percentage of the 12.4 cm × 6.2 cm solar cell at different tilt angles under irradiance levels of approximately 1,210 W/m². The voltage output remained approximately constant at 0.6 V throughout the test.

Solar cell performance is highly sensitive to tilt angle, with small deviations causing significant power loss, especially in smaller or segmented cells. Photovoltaic module output depends strongly on tilt, with optimal angles varying by location, season, and design, but power loss rates also depend on cell size, segmentation, and internal connections, not just surface. While total power loss at extreme tilts (e.g., 90°) may be similar across cell sizes, smaller or half-cut cells show steeper initial drops at low tilts, likely due to electrical configuration and shading sensitivity (Yunus Khan *et al.*, 2020). Shading resistance and tilt sensitivity are influenced by both physical and electrical design factors. Most experiments use fixed loads, but real-world applications in UAVs face variable loads, altering tilt-related power loss patterns (Rezk *et al.*, 2020).

3.2 Layer Shadow Test

Layer shadow testing was conducted to evaluate the power degradation characteristics of monocrystalline solar cells under partial shading applied incrementally along both the x-axis (horizontal) and y-axis (vertical). Figures 8 and 9 show the power degradation trends for the two solar cell sizes under different shading directions.

As shown in Figure 8, for the full-size cell ($12.4 \text{ cm} \times 12.4 \text{ cm}$), shading along the y -axis resulted in significantly higher power losses as compared to the x -axis. At 50% shadow coverage, y -axis shading caused approximately 65% power loss, while x -axis shading led to about 50% loss. This difference can be attributed to the orientation of the internal series connections of the solar cells. Vertical shading (y -axis) disrupts more of the current flow pathways in series-connected cells, leading to a steeper drop in power output. As shadow coverage increased to 100%, the power output from both axes converged to zero, as expected. This confirms that full-size cells are highly sensitive to vertical shading and thus require careful orientation and placement to minimise energy loss in real-world applications.

In contrast, as shown in Figure 9, the half-cut solar cell ($12.4 \text{ cm} \times 6.2 \text{ cm}$) demonstrated improved tolerance to shading effects. At 50% coverage, y -axis shading resulted in only 45% power loss, while x -axis shading caused about 35% loss. The segmentation inherent in half-cut cells appears to reduce the severity of shading impact, allowing unaffected segments to maintain power generation even when part of the cell is covered. This design significantly enhances shading resilience, particularly in dynamic environments such as UAV flight where the orientation to sunlight is constantly changing. The reduced shading sensitivity of the half-cut cell also implies improved thermal performance and reduced risk of hotspots, which contributes to overall system reliability.

The results show that y -axis shading reduces power more than x -axis shading, especially in full-size cells. These findings are important for improving the design of solar-powered UAVs. Structural elements such as spars, ribs and wiring that create vertical shadows across the solar cell surface should be minimised or repositioned to reduce energy losses. Additionally, selecting half-cut or segmented solar cells for UAV wings offers significant benefits in terms of shading tolerance and energy consistency (Bocullo *et al.*, 2023). Improved performance under y -axis shading makes these cells particularly attractive for UAV designs that operate in varying altitudes and angles relative to the sun. Overall, the shadow analysis provides insight into how solar cells perform under uneven light and supports the design of more efficient and reliable solar UAVs.

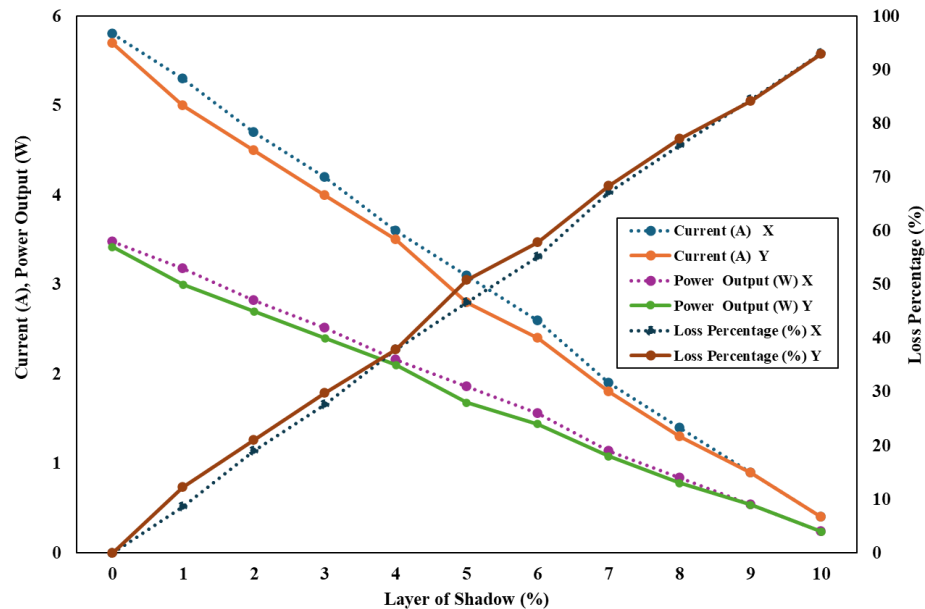


Figure 8: Effects of partial shading along the x - and y -axes on current, power output and power loss percentage for the $12.4 \text{ cm} \times 12.4 \text{ cm}$ solar cell.

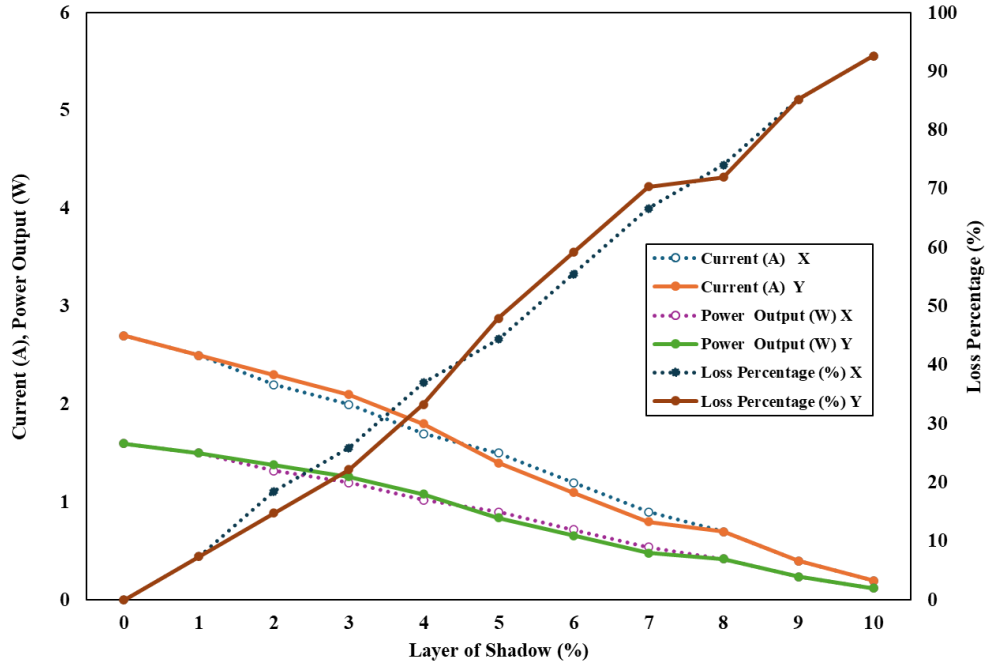


Figure 9: Effects of partial shading along the x- and y-axes on current, power output and power loss percentage for the 12.4 cm × 6.2 cm solar cell.

3.3 Wing Roll Simulation

In order to evaluate the real-world performance of the solar-integrated UAV wing during dynamic flight conditions, a simulated wing roll test was conducted. This test aimed to analyse how roll angles commonly experienced during UAV manoeuvres such as turning or side wind correction affect solar energy capture. The fabricated wing, embedded with the half-cut 12.4 cm × 6.2 cm monocrystalline solar cell, was gradually rolled from 0 to 90° in both left and right directions. The half-cut solar cell was used as it matches the cell size integrated into the UAV wing prototype and provides a realistic representation of actual operating conditions. The setup was evaluated under full sunlight with consistent irradiance above 1,000 W/m².

Figure 10 presents the variation in power output with roll angle, demonstrating a nonlinear decrease in power generation as the tilt angle increased. At the neutral position (0°), the left and right solar panels achieved their maximum power outputs of approximately 3.76 and 3.60 W respectively, confirming optimal solar exposure and alignment. As the roll angle increased, a gradual reduction in power output was observed up to 50°. Beyond this angle, the power output decreased significantly. At 70°, the power loss reached approximately 59 and 56% for the left and right roll directions respectively. At 90°, the recorded power outputs were only 0.12 and 0.09 W corresponding to losses of approximately 80% and 85% respectively. This reduction can be attributed to the decrease in effective solar irradiance incident on the panel surface as the panel orientation deviates from the direct solar path. The results from both left and right roll directions exhibited similar overall trends, indicating consistent shading effects across both wings.

The most pronounced reduction in power output occurred beyond 50°, highlighting the critical influence of roll manoeuvres on solar energy harvesting. These findings confirm that UAV attitude directly influences solar energy capture, particularly during roll manoeuvres. In practical applications, this highlights the importance of stabilising the UAV during solar charging or cruise phases. It also supports the need for intelligent flight path planning and adaptive MPPT systems to compensate for temporary shading or misalignment (Wang *et al.*, 2023).

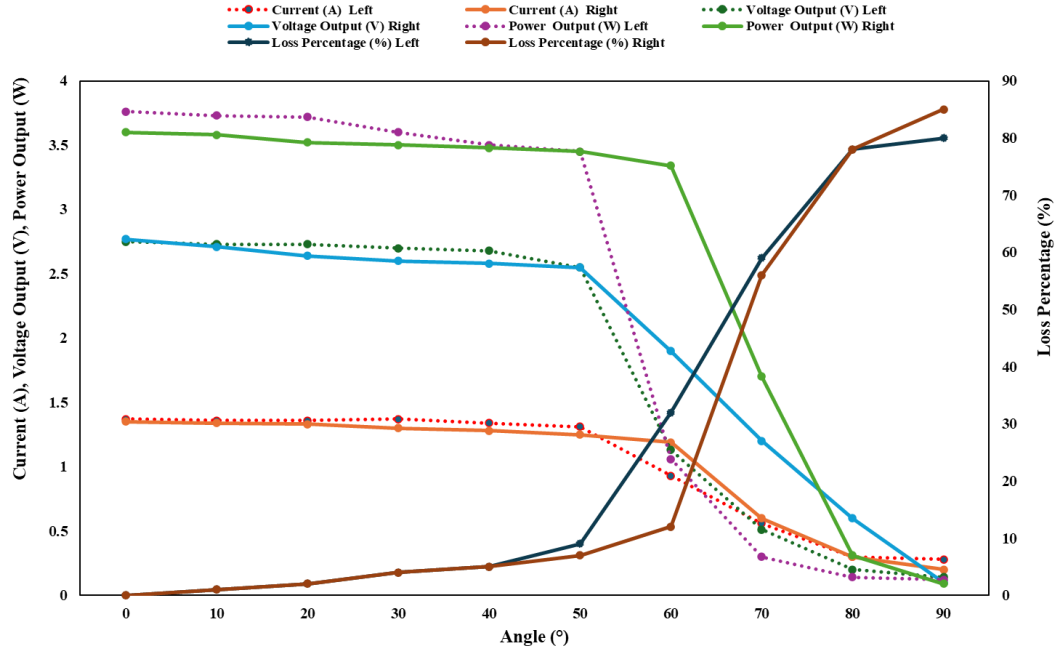


Figure 10: Comparison of current, voltage, power output and power loss percentage during left- and right-wing roll angles (0 - 90°) under full sunlight conditions.

3.4 Comparative Efficiency Summary

For a comprehensive assessment of the impact of shading and tilt angles on solar cell performance, a summary comparison of maximum power output and power under maximum shadow was compiled for all the main experimental conditions: angle shadow testing (for both large and small solar cells) and wing roll simulation. The results are presented in Figure 11, which compares the maximum power output, power under maximum shading conditions, as well as corresponding power loss for the angle shadow, layer shadow, and wing roll tests. The angle shadow test for the 12.4 cm × 12.4 cm solar cell showed a significant drop in power from 3.42 W at 0° to 0.24 W at 90°, indicating a 93% loss. Similarly, the smaller 12.4 cm × 6.2 cm solar cell experienced a drop from 1.62 W to 0.12 W, also reflecting a 93% efficiency loss. Although both cells showed the same loss rate, the larger cell produced more power and was slightly more stable at mid-range angles. The layer shadow test exhibited a similar degradation pattern, with maximum power losses of approximately 93.1 and 92.6% for the 12.4 × 12.4 cm and 12.4 × 6.2 cm solar cells respectively, highlighting the severe impact of progressive surface obstruction on photovoltaic performance. The wing roll simulation, which mimics actual flight behaviour of the UAV during turning manoeuvres, revealed a comparable trend. The solar-integrated UAV wing delivered peak output of 3.42 W at level position (0°), which decreased to 0.30 W at 90° roll, resulting in a 91% power loss. This simulation shows that the UAV's position during flight, especially during turns or when affected by wind, strongly affects how much solar energy it can collect (Wei *et al.*, 2023).

These findings confirm that shadowing and UAV orientation are critical limiting factors in solar energy collection for flight applications. While the use of larger cells can provide more total power, they are also more prone to partial shading if not carefully placed. On the other hand, smaller or half-cut cells offer better integration flexibility and potentially less severe performance drops under localised shading, especially when combined with advanced energy management systems.

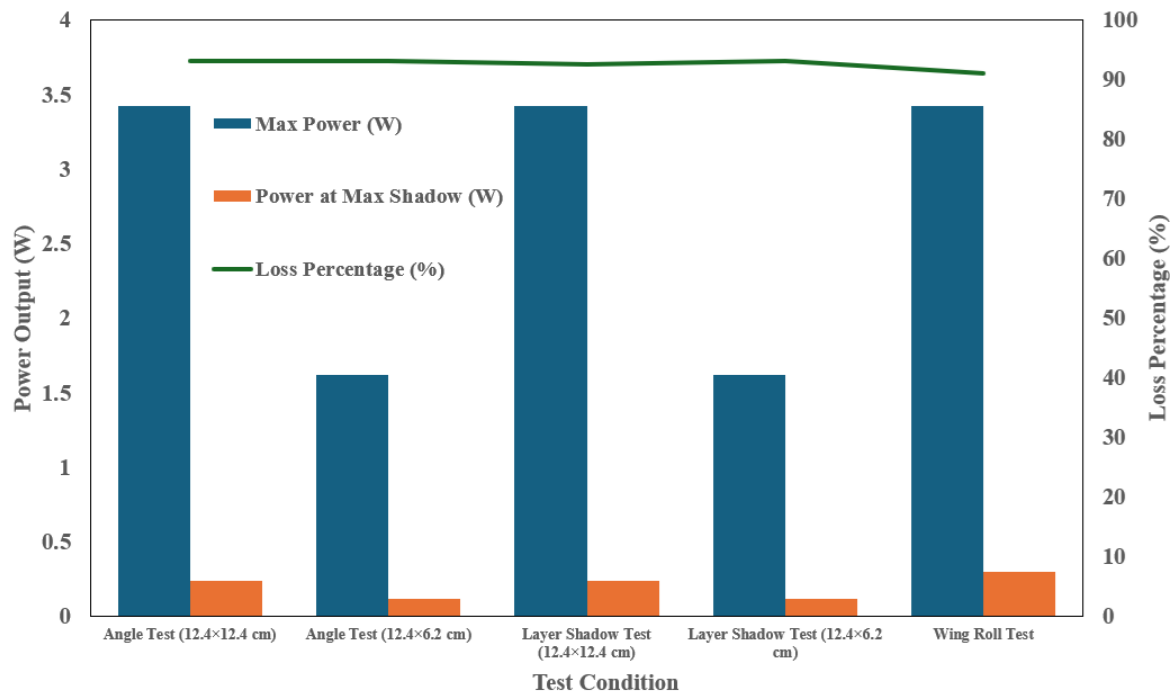


Figure 11: Comparative efficiency summary of angle shadow layer shadow, and wing roll tests.

4. CONCLUSION

This study investigated power loss mechanisms in solar-powered UAV wings, focusing on the effects of shadowing and tilt angles. The results obtained showed that both factors greatly reduce solar panel performance, with power losses reaching up to 93% under extreme conditions. These results offer useful guidance for improving UAV design and flight strategies to boost energy efficiency. Solar cell size and placement were found to significantly impact performance. Larger cells (12.4 cm × 12.4 cm) performed better under tilt conditions, but power output decreased significantly as the tilt angle increased, with losses approaching 93% at 90° for both cell configurations. Shadows from the y-axis (vertical) caused more power loss than those from the x-axis (horizontal), showing the importance of smart panel placement to avoid obstacles from parts such as ribs and cables. The wing roll test showed that power output decreased gradually up to 50° and dropped sharply at higher roll angles, reaching losses of approximately 80 - 85% at 90°, confirming that UAV attitude strongly affects solar energy capture. While larger cells provide higher power output, smaller cells demonstrate better tolerance to partial shading. A combination of both configurations may help balance power generation and shading resilience. In summary, improving solar-powered UAV performance requires careful solar panel placement to minimise shading, stable flight conditions during energy collection, and consideration of hybrid solar panel layouts. These improvements can enhance UAV endurance and operational reliability, particularly for defence, surveillance and environmental monitoring missions. Future work should apply these findings to real UAV platforms operating under long duration flight conditions.

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A REVIEW OF SATELLITE-BASED LORA AND LORAWAN FOR IOT APPLICATIONS

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ABSTRACT

Satellite-based Internet of Things (IoT) systems have emerged as a promising solution for extending connectivity beyond the limitations of conventional terrestrial networks, particularly in remote and underserved regions. The Internet of Space Things (IoST) further expands this concept by integrating satellites, communication networks, and sensing platforms into a unified framework for data collection, communication, and information exchange. Among the communication technologies available for IoT applications, Long Range (LoRa) and LoRa wide area network (LoRaWAN) have gained significant attention due to their long communication range, low power consumption and cost-effective deployment. By integrating LoRa and LoRaWAN technologies with Low Earth orbit (LEO) satellites, global IoT connectivity can be achieved in areas where terrestrial infrastructure is unavailable or impractical to deploy. This paper reviews current trends in satellite-based IoT communications, including emerging architectures and enabling technologies. Particular emphasis is placed on LoRa and LoRaWAN technologies, as well as their features, applications, and suitability for satellite-based IoT and IoST deployments. Existing satellite LoRa implementations, key technical challenges and future research directions are also discussed.

Keywords: *Satellite-based Internet of Things (IoT); Internet of Space Things (IoST); Long Range (LoRa); LoRa wide area network (LoRaWAN); low Earth orbit (LEO) satellites.*

1. INTRODUCTION

The development of satellite technology has transformed global communications, navigation and Earth observation, enabling a wide range of civilian, commercial and scientific applications. In recent years, the rapid growth of the space economy and increasing participation from private organisations have accelerated the deployment of satellite systems and expanded access to space-based services (NASA, 2013; World Economic Forum, 2024). Among these developments, satellite-based Internet of Things (IoT) communications have emerged as a promising paradigm for extending connectivity beyond the limitations of conventional terrestrial networks.

The Internet of Space Things (IoST) extends the concept of IoT into the space domain by integrating satellites, communication networks, sensing platforms, and data processing systems into a unified framework. Through the convergence of satellite systems, communication protocols, and data analytics, IoST enables seamless connectivity and information exchange between terrestrial and space-based assets. As a result, IoST has attracted considerable attention for applications requiring wide-area coverage, including environmental monitoring, transportation, agriculture and remote sensing (Priyadarshini *et al.*, 2022; Shutao, 2024).

Despite significant advances in terrestrial communications, many regions continue to experience limited or unreliable connectivity due to geographical constraints, sparse population distribution or insufficient communication infrastructure. Conventional communication networks may thus be unable to support large-scale IoT deployments in remote and hard-to-access environments. Consequently, satellite-based IoT architectures have emerged as a promising solution for extending connectivity to regions where terrestrial communication infrastructure is unavailable, unstable, or prohibitively expensive to deploy (Dlamini & Vilakati, 2021; Deng *et al.*, 2023).

Low Earth Orbit (LEO) satellites are particularly attractive for satellite IoT applications due to their lower propagation losses and shorter communication delays as compared with MEO and geostationary Earth orbit (GEO) satellites. In addition, modern LEO constellations and CubeSat platforms provide cost-effective opportunities for extending communication coverage on a global scale. These satellite systems can serve as communication gateways, collecting data from geographically distributed IoT devices and relaying the information to central processing facilities (Colavolpe *et al.*, 2019; Qin *et al.*, 2025).

Among the various communication technologies available for IoT applications, Long Range (LoRa) has gained significant attention due to its long communication range, low power consumption, and cost-effective deployment. LoRa is commonly used together with the LoRa wide area network (LoRaWAN) protocol, which provides the networking architecture and communication framework required for large-scale IoT deployments. By integrating LoRa and LoRaWAN technologies with satellite platforms, particularly LEO satellites, it becomes possible to provide connectivity for IoT devices operating in remote, rural, and infrastructure-limited environments. This approach enables data collection and transmission in locations where terrestrial LoRa gateways are unavailable or impractical to deploy (Temim, 2022).

Recent research has explored a range of technologies and architectures to support satellite-based IoT communications. These include grant-free random access (GF-RA) frameworks for LEO satellite IoT networks (Guo *et al.*, 2023), collaborative LEO satellite architectures for secure and energy efficient Internet of Remote Things (IoRT) deployments (Yue *et al.*, 2023), space-terrestrial integrated IoT frameworks (Fraire *et al.*, 2022), experimental platforms for evaluating LoRa satellite communications (Colombo *et al.*, 2022), and advanced multiple-access techniques for satellite LoRa networks (Zhang *et al.*, 2022). Collectively, these developments demonstrate the growing maturity of satellite-based IoT and the increasing role of LoRa technologies in enabling global IoT connectivity.

Building upon these developments, this paper reviews current trends in satellite-based IoT communications, including emerging architectures and enabling technologies. Particular emphasis is placed on LoRa and LoRaWAN technologies, their characteristics, applications, and suitability for satellite-based IoT and Internet of Space Things (IoST) deployments. The paper further examines existing satellite LoRa implementations, key technical challenges and future research directions.

2. EMERGING SATELLITE-BASED IOT ARCHITECTURES

2.1 Grant-Free Random Access (GF-RA) LEO Framework

This framework introduces a novel GF-RA architecture characterised by low latency and minimal signalling overhead. Such an approach is particularly beneficial for connectivity in remote areas, as it enables active IoT devices to transmit data directly to LEO satellites without requiring prior access requests. One of the framework's major contributions is the development of a joint device and data detection algorithm specifically designed for large-scale GF-RA in LEO satellite IoT networks. By detecting active devices and recovering their associated data, the algorithm improves overall communication efficiency. Extensive simulations demonstrate that the proposed method performs well under challenging conditions, including low signal-to-noise ratios, limited antenna availability, short codeword lengths, and a high number of active devices. Furthermore, compared with conventional

algorithms such as approximate message passing (AMP) and orthogonal matching pursuit (OMP), the proposed technique achieves superior detection performance. Consequently, the algorithm shows strong potential for application in LEO satellite IoT systems (Guo *et al.*, 2023).

2.2 Collaborative LEO Satellites for Secure and Green IoRT

This framework employs multiple collaborative LEO satellites to enhance the performance of the IoRT. By combining signals received by several satellites, the system improves communication reliability and efficiency while addressing challenges associated with high mobility and limited energy resources in remote IoRT deployments. The collaborative approach significantly increases the signal-to-noise ratio through the integration of uplink signals received by multiple satellites. This improvement reduces the transmit power requirements of energy-constrained terminals, thereby enhancing system efficiency and sustainability. To compensate for phase differences between satellites, the framework utilises a modified version of the SUMPLE algorithm. This approach improves the overall signal combining gain and is particularly effective for direct sequence spread spectrum (DSSS) communications. Simulation results indicate that the proposed method achieves superior combining gain as compared with the conventional SUMPLE technique (Yue *et al.*, 2023). The term SUMPLE is taken from its predecessor, the SIMPLE (semi-implicit method for pressure-linked equation) algorithm, which achieves array coherence using a simple pairwise correlation of antenna signals. However, SUMPLE adds together a number of antenna signals before performing the correlation procedure (Rahman *et al.*, 2022).

2.3 Space-Terrestrial Integrated Internet of Things

Fraire *et al.* (2022) proposed STEREO, a space-terrestrial integrated IoT architecture that enables both direct and indirect satellite access for ground-based IoT devices. The objective of this architecture is to integrate terrestrial and space networks into a unified framework capable of providing global IoT connectivity, particularly in regions lacking terrestrial communication infrastructure. STEREO serves as a reference architecture for the convergence of space and terrestrial networks by leveraging existing technologies, protocols, and operational practices from both domains. With a focus on satellite IoT communications, the authors examine a range of technologies suitable for future integrated networks and identify LoRa / LoRaWAN and narrowband IoT (NB-IoT) as promising solutions for space-terrestrial IoT applications.

2.4 Low-Cost SDR-Based Tool for Evaluating LoRa Satellite Communications

Colombo *et al.* (2022) proposed a low-cost experimental platform for evaluating LoRa satellite communications using software-defined radio (SDR) technology and LEO satellite scenarios. The platform enables controlled introduction of channel impairments and adverse propagation effects, allowing researchers to assess the suitability of LoRa for satellite-based communications. As the proprietary details of LoRa modulation are not publicly available, the platform relies on reverse-engineered implementations of the LoRa physical layer.

A key focus of the study is the simulation of Doppler effects, which are critical in satellite communications due to the high relative velocity between satellites and ground devices. In order to emulate realistic satellite communication conditions, the baseband signal is modified to introduce Doppler-induced frequency shifts after validating the LoRa transceiver implementation and achieving a low packet error ratio (PER) using a commercial LoRa receiver. The study further demonstrates that time-on-air (ToA), orbital altitude, and communication parameters influence the severity of Doppler effects, with lower orbits and longer ToA values increasing susceptibility to dynamic Doppler variations.

Experimental results indicate that LoRa communications exhibit strong resilience to static Doppler shifts, whereas dynamic Doppler effects result in increased transmission errors. The authors suggest that future work should focus on improving resistance to dynamic Doppler effects and investigating the causes of frame losses observed even under otherwise ideal operating conditions.

2.5 Orthogonal LoRa Multiple Access Algorithm for Satellite IoT

Zhang *et al.* (2022) proposed a low-complexity orthogonal LoRa multiple access (OLMA) algorithm to enhance the multiple-access performance of satellite-based LoRa IoT networks. The algorithm exploits the orthogonality of LoRa symbols in the fractional domain, enabling multiple users to share the same frequency bandwidth efficiently. In order to minimise mutual interference caused by collisions, OLMA partitions the fractional bandwidth into distinct regions through the use of address codes. Users assigned different address codes occupy separate bandwidth segments for data transmission.

The multiple access capability of the system can be dynamically adjusted by modifying the length of the address code according to application requirements. Theoretical analysis and simulation results demonstrate that the OLMA algorithm can significantly increase both network capacity and overall transmission bit rate without requiring modifications to existing LoRa modulation parameters or processes. Although the proposed approach assumes a common spreading factor among users, future work will investigate support for users operating with different spreading factors (Zhang *et al.*, 2022).

2.6 Internet of Space Things (IoST)

IoST is a cyber-physical framework that integrates satellite and terrestrial systems to support a wide range of sensing, communication, and data processing applications. The architecture employs software-defined networking (SDN) and network function virtualisation (NFV) to manage networks comprising CubeSats and ground-based sensing devices. Within this framework, SDN and NFV provide flexible network control, improved resource utilisation and simplified management of space-based network assets. Constellations of LEO CubeSats provide both communication infrastructure and sensing capabilities, enabling seamless integration with terrestrial communication and sensing networks. The architecture supports multiband wireless communications across microwave, millimetre-wave and terahertz frequency bands. In addition, compact transceiver front-ends and electronically reconfigurable antennas enhance network capacity and support emerging applications such as Internet connectivity in remote and underserved regions, global transportation management and large-scale sensing networks (Georgia Institute of Technology, 2020; Priyadarshini *et al.*, 2022).

3. LORA TECHNOLOGY

LoRa is a wireless modulation technology based on chirp spread spectrum (CSS) modulation. It transmits information using chirp signals, providing high sensitivity, robustness against interference, and long communication ranges. LoRa is particularly suitable for IoT applications that require the transmission of small amounts of data at low bit rates over extended distances. Compared with conventional wireless technologies such as Wireless Fidelity (Wi-Fi), Bluetooth and ZigBee, LoRa offers significantly greater communication range while maintaining low power consumption, making it well suited for battery-powered sensors and actuators. LoRa operates primarily in licence-free industrial, scientific and medical (ISM) frequency bands, including 433, 868 and 915 MHz. It can also operate in the 2.4 GHz band, which provides higher data rates but generally at the expense of reduced communication range. Depending on the selected communication parameters, LoRa supports payload sizes ranging from 2 to 255 octets, while channel aggregation techniques can achieve data rates of up to 50 kbps (Augustin *et al.*, 2016; The Things Network, 2024).

3.1 LoRaWAN

LoRaWAN is an open low power wide area network (LPWAN) protocol developed and maintained by the LoRa Alliance®, an international non-profit consortium that promotes interoperability and standardisation within the LoRa ecosystem. The protocol is designed to provide low power wireless connectivity for battery-operated devices across local, regional and global networks while supporting key IoT requirements such as bidirectional communication, end-to-end security, mobility and geolocation services. Operating within the unlicensed ISM spectrum, LoRaWAN defines the communication protocol and system architecture that utilise the LoRa physical layer. The standard ensures interoperability between devices and network infrastructure from different manufacturers, facilitating large-scale IoT deployments. LoRaWAN has also been recognised by the International Telecommunication Union (ITU) as a standard LPWAN technology. Semtech develops the underlying LoRa chipsets, while the LoRa Alliance oversees the continued development and harmonisation of the LoRaWAN protocol. LoRaWAN is particularly suitable for applications involving the transmission of small payloads, such as sensor measurements and status information, over long distances. The combination of long communication range, low power consumption and low deployment cost makes LoRaWAN an attractive technology for IoT and IoST applications (Augustin *et al.*, 2016; The Things Network, 2024).

3.2 Features of LoRa and LoRaWAN

LoRa and LoRaWAN offer several features that make them attractive for IoT and IoST applications. One of their primary advantages is long range communication capability, which can extend to tens of kilometres in rural environments while maintaining reliable connectivity in dense urban areas and indoor environments. In addition, their low power consumption enables battery-powered devices to operate for several years, significantly reducing maintenance requirements and operating costs. LoRaWAN incorporates multiple security mechanisms, including AES-128 encryption, mutual authentication, data integrity protection and confidentiality safeguards. The technology also benefits from global standardisation, enabling interoperability between devices and network infrastructure from different vendors while supporting worldwide deployment. Additional features include geolocation capabilities that enable device tracking without reliance on Global Navigation Satellite System (GNSS) receivers, support for mobility applications and high network scalability capable of accommodating large numbers of connected devices. Furthermore, the relatively low infrastructure and operational costs make LoRaWAN an economically attractive solution for large-scale IoT deployments (Dasiga *et al.*, 2020; Bougaddou *et al.*, 2024).

Despite these advantages, LoRa and LoRaWAN face several limitations. As network density increases, spectrum congestion and interference may affect communication performance. In addition, the technology is designed primarily for low data rate applications and thus supports only relatively small payload sizes, limiting its suitability for bandwidth-intensive applications (Fernandez *et al.*, 2020; Petty, 2021).

3.3 Applications of LoRa and LoRaWAN

LoRaWAN has been adopted across a wide range of IoT applications owing to its long communication range, low power consumption and economical deployment. Of particular relevance to this study is the use of satellites to provide global LoRaWAN connectivity, enabling communication in remote, rural and infrastructure-limited environments where terrestrial networks are unavailable. Beyond satellite communications, LoRaWAN has been successfully applied in numerous sectors. In healthcare logistics, LoRaWAN sensors are used for vaccine cold chain monitoring to ensure that temperature-sensitive medical products remain within specified temperature limits during transportation and storage (Bose *et al.*, 2022). In wildlife conservation, LoRaWAN-based tracking devices are employed to monitor

endangered species such as Black Rhinos and Amur Leopards. Other notable applications include smart agriculture, water resource management, food safety monitoring, waste management, airport asset tracking and wearable monitoring devices for individuals with dementia (Yadav *et al.*, 2023; The Things Network, 2024). The versatility of these applications demonstrates the suitability of LoRaWAN as a communication technology for both terrestrial IoT systems and emerging satellite-enabled IoT deployments.

4. LORA SATELLITE DEPLOYMENT

4.1 Existing Implementations

The satellite IoT market is experiencing rapid growth, driven by advances in satellite communications and increasing demand for global connectivity, particularly in remote and underserved regions. As conventional terrestrial networks often fail to provide reliable coverage in sparsely populated or geographically challenging areas, LEO satellites have emerged as an attractive solution, offering lower latency and improved coverage compared with traditional satellite systems (Vizzarri, 2026).

The success of LoRaWAN in terrestrial IoT deployments has encouraged its adoption in satellite communications. Direct-to-satellite LoRaWAN enables IoT devices to communicate with satellites operating in the same ISM frequency bands commonly used by terrestrial LoRa networks. This approach extends IoT connectivity beyond the reach of terrestrial gateways while maintaining the low power and low-cost characteristics of LoRa technology. Several organisations, including Lacuna Space and Plan-S, have demonstrated satellite-enabled LoRaWAN services, enabling global connectivity for IoT devices operating in remote environments such as oceans, deserts, forests and agricultural regions (LoRa Alliance, 2025).

The performance of satellite-based LoRa networks depends on several factors, including satellite altitude, communication range, link budget and channel conditions. Compared with terrestrial deployments, direct-to-satellite communications involve significantly greater transmission distances, requiring careful consideration of antenna gain, receiver sensitivity and transmission power. LEO satellites are particularly attractive for LoRa-based IoT applications due to their lower propagation losses and shorter communication delays as compared with MEO and GEO satellites. However, communication opportunities are typically limited to periods during which a satellite is visible to a ground terminal. Consequently, satellite constellation design plays a critical role in ensuring adequate coverage, reducing communication latency and improving data delivery performance (Vizzarri, 2026).

4.2 Challenges and Future Research Directions

Despite its potential, LoRa-LEO integration faces several technical challenges. One of the most significant is the Doppler effect, which arises from the high relative velocity between satellites and ground terminals. The resulting frequency shifts can affect signal synchronisation and decoding performance, particularly during long-duration transmissions (Asad *et al.*, 2024). Furthermore, various Doppler emulation and compensation techniques have been proposed to improve communication reliability in satellite LoRa systems (Subramanian *et al.*, 2023).

The Doppler shift may be estimated as follows:

$$f_d = \frac{vf_o}{c} \quad (1)$$

where f_d = Doppler shift (in Hz), v = relative velocity of the satellite (in m/s), f_o = transmitted frequency (in Hz) and c = speed of light (3×10^8 m/s) (Subramanian *et al.*, 2023).

To better understand the impact of Doppler effects on satellite communications, three scenarios may be considered during a satellite pass. As the satellite approaches the ground terminal, positive Doppler shift is observed ($f_d(t) > 0$). When the satellite is directly overhead ($t = 0$), Doppler shift becomes zero. As the satellite moves away from the terminal, a negative Doppler shift occurs ($f_d(t) < 0$) (Asad *et al.*, 2024). As the satellite approaches the ground terminal, a positive Doppler shift is observed, which decreases to zero near closest approach and becomes negative as the satellite moves away. The Doppler rate is greatest near closest approach and decreases towards zero near the horizon.

In addition to Doppler effects, satellite-based LoRa systems face limitations related to payload size, spectrum sharing, and network scalability. LoRa was originally designed for low-data-rate applications and therefore supports only relatively small payloads. While this limitation is acceptable for many IoT applications involving sensor measurements and status messages, it restricts the transmission of large datasets and may limit the suitability of LoRa for bandwidth-intensive applications. Furthermore, increasing numbers of devices sharing the same spectrum may lead to collisions and reduced network performance, particularly in large-scale deployments. Future research should focus on addressing the challenges associated with direct-to-satellite LoRa communications. Key areas include advanced Doppler compensation techniques, adaptive modulation and coding schemes, satellite-aware LoRaWAN protocols, and efficient multiple-access mechanisms for large-scale IoT deployments. Additional research is also required to evaluate the performance of satellite LoRa systems under diverse operating conditions and to develop integrated terrestrial-satellite architectures capable of providing seamless global IoT connectivity (Fernandez *et al.*, 2020; Petty, 2021).

5. CONCLUSION

Satellite-based IoT systems have emerged as a promising solution for extending connectivity beyond the limitations of conventional terrestrial networks. This paper reviewed current developments in satellite-based IoT communications, including GF-RA frameworks, collaborative LEO satellite architectures, space-terrestrial integrated IoT systems, and satellite LoRa communication platforms. Particular emphasis was placed on LoRa and LoRaWAN technologies, whose long communication range, low power consumption, and cost-effective deployment make them well suited for satellite-enabled IoT and IoST applications.

Despite their potential, satellite-based LoRa systems continue to face challenges related to Doppler effects, limited payload capacity, spectrum sharing and network scalability. Therefore, future research should focus on improving communication reliability through advanced Doppler compensation techniques, efficient multiple-access mechanisms and integrated terrestrial-satellite architectures. As satellite technologies and LEO constellations continue to mature, LoRa and LoRaWAN are expected to play an increasingly important role in extending IoT connectivity to remote, underserved, and infrastructure-limited regions worldwide.

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EVOLUTION OF THE GNSS THREAT ENVIRONMENT: THE INCREASING OPERATIONALISATION OF JAMMING AND SPOOFING

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ABSTRACT

Global Navigation Satellite Systems (GNSS) have become an essential component of modern positioning, navigation and timing (PNT) infrastructure, supporting a wide range of civil, commercial and military applications. However, increasing dependence on GNSS has heightened exposure to interference threats, particularly jamming and spoofing. While these vulnerabilities have long been recognised, recent developments indicate a significant evolution in the threat environment. Jamming and spoofing have progressed from isolated technical phenomena and experimental demonstrations to operationally deployed capabilities affecting users across large geographic areas and multiple sectors. This paper reviews the contemporary GNSS threat landscape, examining the mechanisms, characteristics and operational impacts of jamming and spoofing, as well as recent developments that have contributed to their increasing operational significance. Particular attention is given to the transition from signal level vulnerability to system level risk, where interference can affect not only individual receivers but also interconnected systems, critical infrastructure and operational decision making processes that depend on GNSS-derived PNT information. The paper further reviews contemporary mitigation and resilience frameworks, including receiver level countermeasures, anti-jamming and anti-spoofing technologies, multi-constellation and multi-frequency operation, hybrid PNT architectures, timing resilience, monitoring, detection and adaptive response mechanisms, as well as structured test and evaluation programmes. The review highlights a broader shift from protecting GNSS signals alone towards ensuring continuity of operations under degraded and contested conditions. As jamming and spoofing become enduring features of the contemporary electromagnetic environment, resilience, empirical validation, operational preparedness and cross-sector coordination will play increasingly important roles in sustaining trustworthy PNT capabilities.

Keywords: *Global Navigation Satellite System (GNSS); jamming; spoofing; positioning, navigation and timing (PNT) resilience; interference mitigation.*

1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) have become a foundational component of modern positioning, navigation and timing (PNT) infrastructure, supporting a wide range of applications across civil, commercial and military domains. These include aviation navigation, maritime operations, land transportation, telecommunications, financial systems and critical infrastructure. The widespread adoption of GNSS has enabled unprecedented levels of accuracy, efficiency and automation, while simultaneously introducing a high degree of systemic dependency on satellite-based services (DOT, 2024; Critchley-Marrows & Verspieren, 2025; Orbán, 2025; Prezelj & Juvan, 2026).

Despite these benefits, GNSS signals are inherently vulnerable due to their extremely low received power levels, typically in the range of -160 to -130 dBm. This makes them highly susceptible to radio frequency interference (RFI), whether intentional or unintentional. Among the most significant threats are jamming and spoofing, which can respectively deny access to GNSS signals or manipulate them to produce misleading positioning and timing information. While these vulnerabilities have long been

recognised in the literature, recent developments indicate a fundamental shift in the nature, scale and operational significance of the threat environment, particularly as interference events increasingly affect wide geographic areas, civil infrastructure and safety critical operations (Burbank *et al.*, 2024; Rados *et al.*, 2024; Jiang *et al.*, 2025; Meheretu *et al.*, 2025).

In earlier reviews (Dinesh, 2009, 2013), these vulnerabilities were examined with emphasis on the technical feasibility of interference and the implications for civilian users. The analysis focused on signal fragility, receiver exposure, and the need for practical countermeasures at the receiver and system levels. These assessments anticipated that expanding GNSS reliance would amplify both the sophistication and operational reach of interference threats, while increasing the potential for disruption to affect interconnected systems and critical infrastructure.

In recent years, GNSS interference has evolved beyond isolated or short duration events into a persistent and geographically scalable threat. Documented cases across regions such as the Eastern Mediterranean, Black Sea and parts of the Middle East indicate that disruption to GNSS services now occurs on a routine basis, affecting both military and civilian users. This transition from episodic disruption to sustained interference challenges long standing assumptions regarding GNSS availability, integrity and reliability, particularly for safety critical applications that may need to operate under degraded GNSS conditions (Intertanko, 2025; EASA, 2026; FAA, 2026; RIN, 2026).

Furthermore, the impact of GNSS interference extends beyond the signal level, affecting entire system architectures and operational processes that rely on GNSS-derived inputs. Modern platforms often integrate GNSS into multiple subsystems, including navigation, surveillance, guidance and control functions. As a result, disruption to GNSS signals can propagate through interconnected systems, leading to cascading effects that degrade overall system performance. In the case of spoofing, the risk is particularly significant because plausible but incorrect outputs may affect navigation displays, surveillance data and operational decision making without immediately indicating a loss of signal (Rados *et al.*, 2024; Orbán, 2025; Trýb & Hospodka, 2025; Prezelj & Juvan, 2026).

The increasing complexity of GNSS interference scenarios has highlighted the limitations of traditional mitigation approaches. Techniques such as multi-constellation and multi-frequency reception can improve robustness under nominal conditions, but may not fully address coordinated or wideband interference. Similarly, conventional detection mechanisms may be insufficient against sophisticated spoofing attacks that mimic legitimate signals. These limitations have shifted attention towards broader resilience-based approaches that combine receiver level countermeasures, hybrid PNT architectures, timing resilience, monitoring, detection and adaptive response mechanisms, as well as structured test and evaluation programmes. Such approaches recognise that resilience cannot be assumed from design specifications alone, but must be demonstrated through controlled laboratory simulation and field exercises conducted under representative jamming and spoofing conditions (Rados *et al.*, 2024; Critchley-Marrows & Verspieren, 2025; Jiang *et al.*, 2025; Meheretu *et al.*, 2025; Yao *et al.*, 2025).

This paper reviews the evolving GNSS jamming and spoofing threat landscape, focusing on their technical characteristics, operational impacts and implications for PNT resilience. It synthesises findings from recent studies, operational reports and large scale testing initiatives to examine how GNSS interference has progressed from a signal level vulnerability into a system level operational risk. In doing so, the paper provides an integrated perspective on the operationalisation of GNSS interference and the broader shift from protecting GNSS signals alone towards ensuring continuity of operations in increasingly contested electromagnetic environments.

2. GNSS JAMMING

GNSS jamming is the primary method of denying access to satellite-based PNT services. It involves transmitting radio frequency (RF) energy that interferes with the reception of legitimate GNSS signals. By increasing the noise floor within the receiver bandwidth, jamming reduces the carrier-to-noise

density ratio (C/N_0), degrading signal tracking performance and, under severe interference, preventing signal acquisition. From a signal processing perspective, jamming lowers the signal-to-noise ratio (SNR), reducing the receiver's ability to detect and track satellite signals. As interference increases, receivers experience progressive degradation, including higher pseudorange noise, intermittent satellite loss of lock and eventually failure of the navigation solution. Under sufficiently strong interference, the receiver front end or automatic gain control (AGC) may become saturated, rendering the receiver inoperative, as illustrated in Figure 1 (Burbank *et al.*, 2024; Rados *et al.*, 2024; Jiang *et al.*, 2025; Meheretu *et al.*, 2025).

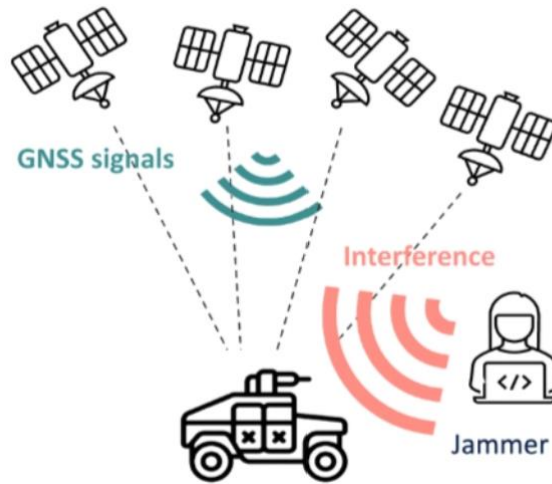


Figure 1: GNSS jamming scenario in which legitimate satellite signals are overpowered and disrupted by RFI from a terrestrial jammer.
(zSource: SBG Systems, 2025)

Jamming signals can take several forms, including continuous wave (CW), narrowband, swept and wideband interference. Their impact depends on spectral characteristics and overlap with GNSS frequency bands. Narrowband interference may disrupt specific frequencies, whereas wideband jamming can affect multiple constellations and frequency bands simultaneously. Modern jamming systems increasingly target several frequencies at once, reducing the resilience normally provided by multi-frequency and multi-constellation receivers and representing a shift from earlier scenarios where disruption was typically limited to a single frequency or constellation (Rados *et al.*, 2024; Jiang *et al.*, 2025; Meheretu *et al.*, 2025; Yao *et al.*, 2025).

The effects of jamming are reflected in observable changes in receiver behaviour. Initial indicators include reduced C/N_0 , increased measurement noise and unstable tracking loops. As interference intensifies, receivers progressively lose lock on individual satellites, degrading satellite geometry and positioning accuracy. Under severe conditions, receivers may be unable to acquire or re-acquire satellite signals, resulting in complete loss of PNT services (Burbank *et al.*, 2024; Rados *et al.*, 2024; Bačić *et al.*, 2025; Jiang *et al.*, 2025).

The operational impact of jamming depends on how deeply GNSS is integrated within the host system. In aviation, GNSS degradation may result in the loss of area navigation (RNAV) and required navigation performance (RNP) capabilities, requiring aircraft to revert to conventional navigation aids and rely more heavily on air traffic control (ATC). In maritime operations, degraded or unavailable GNSS signals can affect electronic chart display and information systems (ECDIS), automatic identification systems (AIS) and integrated bridge systems, reducing situational awareness and increasing navigational uncertainty. Beyond navigation, jamming may also disrupt timing-dependent functions in communications, surveillance and data processing systems, producing secondary effects that extend beyond positioning alone (DOT, 2024; Intertanko, 2025; EASA, 2026; FAA, 2026; RIN, 2026).

The spatial extent of jamming depends on transmitter power, antenna gain, propagation conditions, terrain, as well as the geometry between the jammer and receiver. Low power jammers generally create localised interference, while high power systems deployed on elevated terrain or airborne platforms can disrupt GNSS reception across much larger areas. Consequently, receivers operating within the same region may experience different levels of degradation, making jamming effects difficult to predict and mitigate. Although multi-constellation reception, signal redundancy and integration with inertial navigation systems (INS) can improve robustness, their effectiveness decreases under high power or coordinated jamming, while INS performance remains limited by accumulated drift during prolonged GNSS outages (Burbank *et al.*, 2024; Rados *et al.*, 2024; Jiang *et al.*, 2025; Yao *et al.*, 2025).

A major development since earlier review articles is the transition of GNSS jamming from isolated local interference to coordinated, large scale electronic warfare (EW) operations. Earlier studies primarily focused on personal privacy devices (PPDs), malfunctioning transmitters and isolated denial events. In contrast, contemporary jamming is increasingly associated with military operations and geopolitical tension, with effects extending over broad geographic areas and spilling over into civilian aviation and maritime domains. This trend is illustrated in Figure 2, which shows elevated GNSS interference on 8 July 2026 across several conflict-affected and geopolitically sensitive regions, including the Baltic region, Eastern Europe, Black Sea, Eastern Mediterranean, Middle East, South Asia and mainland Southeast Asia. These developments demonstrate that GNSS jamming has evolved from a receiver level vulnerability into an operational capability with significant implications for infrastructure resilience, spectrum governance and national security (Orbán, 2025; Critchley-Marrows & Verspieren, 2025; Tryb & Hospodka, 2025; Prezelj & Juvan, 2026).

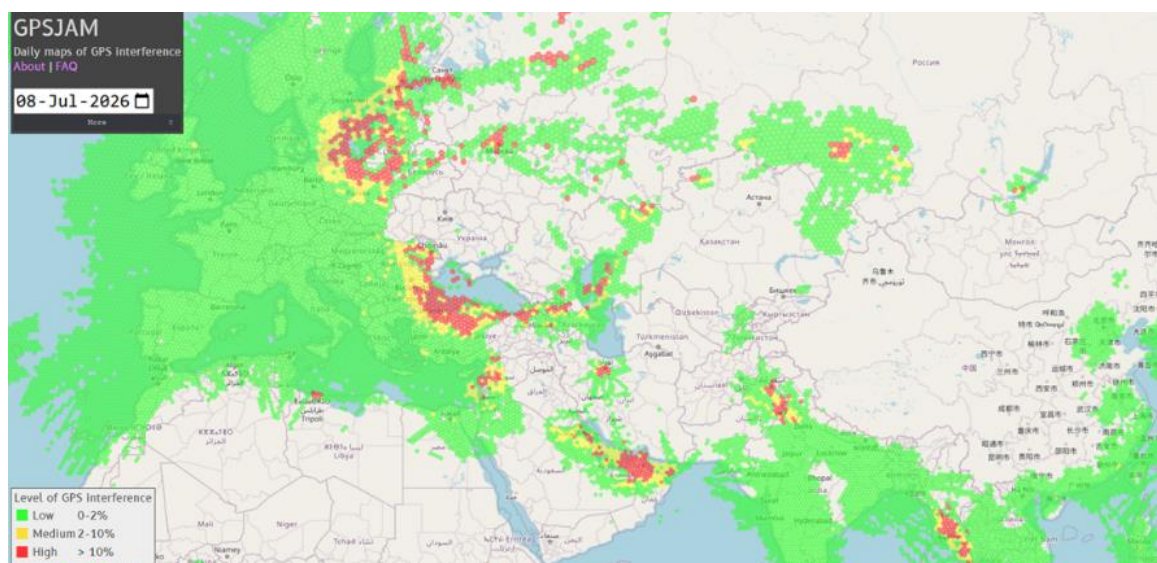


Figure 2: GNSS interference map for 8 July 2026, showing low, medium and high levels of interference across Europe, the Middle East/Gulf and parts of Asia based on aircraft ADS-B GPS accuracy reports over a 24 hour period.
(Source: gpsjam.org)

These developments underscore the need to evaluate GNSS jamming within a broader resilience framework. The consequences of interference depend not only on receiver performance but also on system architecture, operational procedures, as well as the availability of complementary navigation and timing sources. As GNSS becomes increasingly integrated into critical infrastructures, distinguishing between signal level degradation and system level consequences is essential for assessing operational risk and developing effective resilience strategies (DOT, 2024; Critchley-Marrows & Verspieren, 2025; Tryb & Hospodka, 2025; Prezelj & Juvan, 2026).

3. GNSS SPOOFING

Unlike jamming, which denies access to GNSS signals, spoofing is a deceptive form of interference that manipulates receivers into computing incorrect PNT solutions while maintaining the appearance of normal operation. By transmitting counterfeit signals that mimic authentic satellite transmissions, spoofing exploits the receiver's trust in received signals, compromising data integrity rather than signal availability (Burbank *et al.*, 2024; OPSGROUP, 2024; Rados *et al.*, 2024; Meheretu *et al.*, 2025). The basic mechanism of GNSS spoofing is illustrated in Figure 3, where counterfeit signals generated by a spoofing transmitter cause the receiver to compute a false navigation solution while authentic satellite signals remain present.

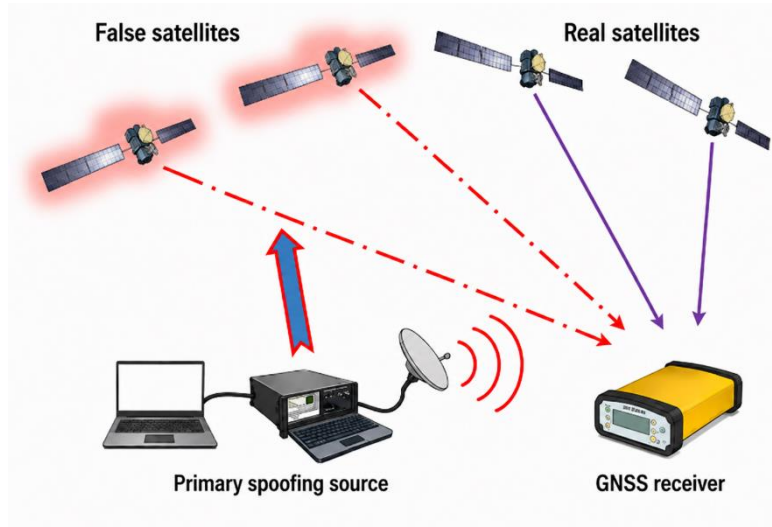


Figure 3: Schematic illustration of a GNSS spoofing scenario in which counterfeit signals from a spoofing source cause the GNSS receiver to compute a false position while authentic satellite signals remain present.

(Source: Li *et al.*, 2023)

Spoofing can be implemented through a range of techniques, varying in sophistication and level of control over the target receiver. At the simplest level, unsophisticated spoofer may broadcast static or pre-recorded GNSS signals, resulting in fixed position offsets or limited disruption. More sophisticated spoofer generate counterfeit signals that are synchronised in time, frequency and code phase with authentic GNSS signals, allowing the receiver to transition gradually from authentic to counterfeit signals without losing lock. This technique, commonly known as carry-off spoofing, has become more accessible due to the increasing availability of software-defined radio (SDR) platforms and open source signal generation tools, which have lowered the technical and financial barriers to conducting spoofing attacks (Burbank *et al.*, 2024; Rados *et al.*, 2024; Jiang *et al.*, 2025; Meheretu *et al.*, 2025).

A common operational approach to spoofing involves the use of jamming to first disrupt legitimate GNSS signals, followed by the introduction of counterfeit signals during the reacquisition phase. This increases the likelihood that the receiver will reacquire counterfeit signals instead of authentic ones. Once control is established, the spoofer can manipulate the receiver's computed position or time in a controlled manner while maintaining internally consistent navigation outputs. Unlike jamming, which normally produces signal loss or obvious degradation, spoofing may yield a seemingly valid but incorrect navigation solution. This "false normal" condition makes spoofing especially difficult to detect because standard indicators such as signal strength and satellite tracking may continue to appear normal (Burbank *et al.*, 2024; OPSGROUP, 2024; Rados *et al.*, 2024; Meheretu *et al.*, 2025).

Recent operational reports indicate that spoofing has evolved from a largely experimental threat into an operationally deployed capability affecting maritime and aviation users. Documented incidents in regions such as the Black Sea, Port of Shanghai and Strait of Hormuz have involved sudden vessel position displacements, structured false tracks and anomalous navigation outputs, often while receivers continued to indicate normal operation. These incidents demonstrate how spoofing can affect multiple users across critical maritime corridors, producing coherent but incorrect position solutions that influence situational awareness and operational decision making (OPSGROUP, 2024; Intertanko, 2025; RIN, 2026; EASA, 2026).

One of the most critical characteristics of spoofing is its potential to contaminate receiver state information. During an attack, counterfeit navigation data and manipulated position, velocity and timing information may influence the receiver’s navigation solution and internal state. As a result, even after the spoofing signal is removed, the receiver may continue to produce erroneous outputs until the corrupted data is cleared or overwritten. This can lead to delayed or intermittent errors that persist beyond the immediate interference event, complicating both detection and recovery (Rados *et al.*, 2024; Critchley-Marrows & Verspieren, 2025; Jiang *et al.*, 2025; Meheretu *et al.*, 2025).

The operational effects of spoofing depend strongly on the level of system integration and reliance on GNSS-derived inputs. In maritime operations, spoofed position data may affect navigation displays, collision avoidance systems and vessel tracking, resulting in incorrect situational awareness and increased operational risk (OPSGROUP, 2024; EASA, 2026; FAA, 2026; RIN, 2026). As illustrated in Figure 4, spoofed GNSS-derived position information can create discrepancies between GNSS-derived positioning and other bridge navigation systems, including radar, AIS and ECDIS, resulting in misaligned navigation displays.

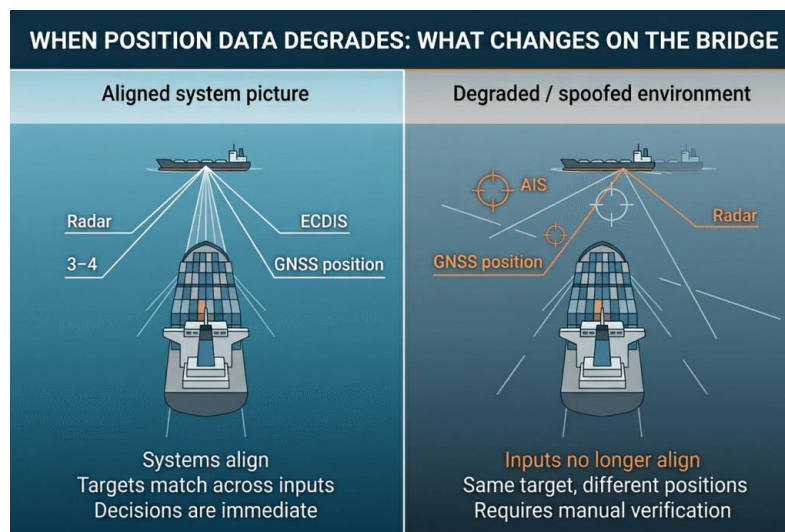


Figure 4: Comparison of normal and spoofed bridge navigation displays, illustrating discrepancies between GNSS-derived positioning and integrated navigation systems.
(Source: Ifrah, 2026)

In aviation, spoofed or corrupted GNSS-derived information may propagate into flight management systems (FMS), automatic dependent surveillance-broadcast (ADS-B), terrain awareness and warning systems (TAWS), and area navigation procedures. Reported effects include unexpected position jumps, erroneous navigation indications and discrepancies between onboard navigation systems and surveillance data. An example is shown in Figure 5, where aircraft operating near Seoul, South Korea, were reportedly spoofed to false positions over the ocean. These developments have prompted aviation authorities and industry organisations to emphasise pilot awareness, cross-checking of navigation sources and contingency procedures (EASA, 2026; FAA, 2026; OPSGROUP, 2024; RIN, 2026).

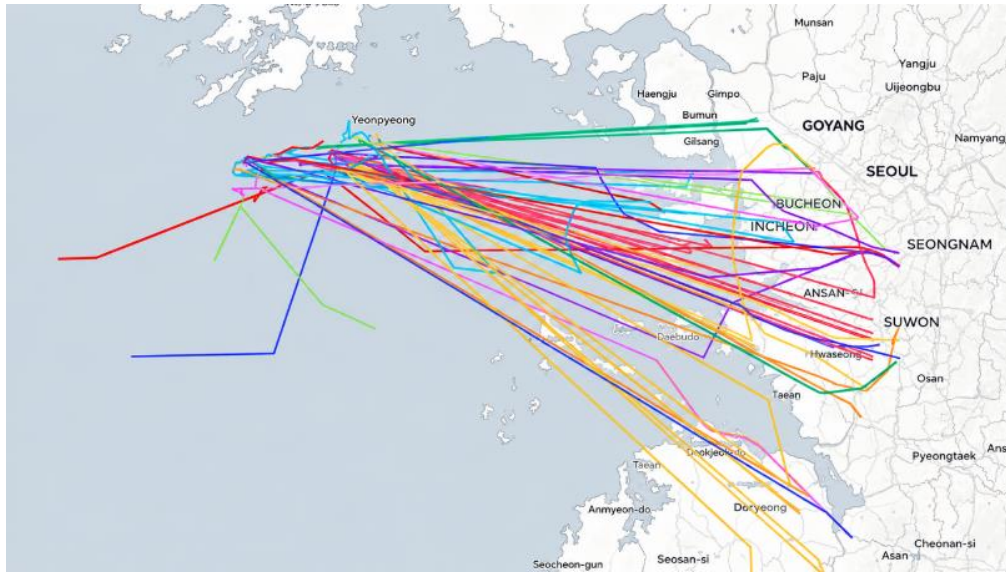


Figure 5: Aircraft operating near Seoul, South Korea, reportedly spoofed to false positions over the ocean between 28 and 30 May 2024.
(Source: Goward, 2024)

Unlike jamming, where degradation is often immediately apparent, spoofing may remain undetected until inconsistencies emerge between GNSS-derived information and other sources. Indicators of spoofing may include unexpected position shifts, discrepancies between independent navigation systems, abnormal Doppler behaviour or inconsistencies in timing information. However, none of these indicators is conclusive, particularly in environments where alternative reference systems are limited or degraded. This challenge is further increased when spoofing affects multiple receivers simultaneously within a given area, causing affected systems to report consistent but incorrect solutions and reducing the effectiveness of cross-checking between platforms (OPSGROUP, 2024; Rados *et al.*, 2024; Jiang *et al.*, 2025; Meheretu *et al.*, 2025).

The increasing sophistication of spoofing techniques has highlighted limitations in conventional detection and mitigation strategies. Methods based on signal strength monitoring or simple consistency checks may be insufficient against well executed attacks that preserve nominal signal characteristics. While approaches such as multi-constellation comparison, angle-of-arrival discrimination and cryptographic authentication can improve resilience, their effectiveness varies depending on implementation and operational conditions. As a result, spoofing mitigation increasingly requires layered detection, cross-validation and system level resilience measures rather than reliance on a single countermeasure (Rados *et al.*, 2024; Critchley-Marrows & Verspieren, 2025; Jiang *et al.*, 2025; Meheretu *et al.*, 2025).

Beyond navigation, spoofing also presents risks to GNSS-dependent timing applications. Telecommunications networks, financial transaction systems, electrical power infrastructure and other critical services frequently rely on GNSS-derived timing as a primary synchronisation source. Manipulation of timing information may not be immediately visible to operators, but can propagate through dependent systems and affect network synchronisation, event timestamping and system coordination (DOT, 2024; Critchley-Marrows & Verspieren, 2025; Trýb & Hospodka, 2025; Prezelj & Juvan, 2026).

Overall, spoofing is particularly challenging because it can produce plausible but incorrect position or timing information without immediately indicating failure. Its consequences may include inappropriate system responses, false alerts, suppression of valid warnings and unsafe operational decisions. The deceptive nature of spoofing, together with the increasing scale and sophistication of recent attacks, makes it a significant operational risk, particularly in high workload or low visibility conditions (OPSGROUP, 2024; EASA, 2026; FAA, 2026; RIN, 2026).

4. MITIGATION AND RESILIENCE FRAMEWORKS

GNSS interference mitigation has evolved from isolated receiver level protection towards a broader resilience framework that combines technical, architectural, operational and institutional measures. As jamming and spoofing increasingly affect wider geographic areas and interconnected systems, effective mitigation requires more than suppressing interference at the signal level. It must also include receiver level countermeasures, hybrid PNT sources, timing resilience, monitoring, detection and adaptive response mechanisms, structured testing and evaluation, as well as broader operational and institutional measures. Figure 6 summarises the main categories of GNSS interference mitigation and resilience measures discussed in this section.



Figure 6: GNSS interference mitigation and resilience framework.

4.1 Receiver Level Countermeasures

Modern GNSS receivers increasingly incorporate defensive capabilities against both denial and deception, forming the first layer of protection against interference. These capabilities are primarily implemented through enhancements in signal processing and antenna design, aimed at improving robustness under degraded conditions.

4.1.1 Anti-Jamming Technologies

Contemporary anti-jamming measures include the use of adaptive antenna arrays and controlled radiation pattern antennas (CRPA), which enable spatial discrimination between legitimate satellite signals and interference sources. The use of antenna-array-based methods with spatial processing and correlation analysis enables anomalies to be detected in received signals from spatially separated antennas (Noah & Elmusrati, 2025). Figure 7 illustrates how a CRPA antenna can provide high gain towards legitimate GNSS satellite signals while attenuating interference from jammers and other

terrestrial sources. In addition, techniques such as beamforming and null steering allow receivers to suppress interference by dynamically adjusting antenna gain patterns, while spatial filtering and polarisation discrimination further enhance the ability to isolate and improve reception of desired signals. In the signal processing domain, time-frequency filtering techniques are employed to attenuate interference energy within specific spectral regions. Collectively, these approaches are designed to suppress interfering signals while preserving the integrity of authentic GNSS transmissions (Li *et al.*, 2023; Singh & Bodade, 2024; Jiang *et al.*, 2025; Ren *et al.*, 2025).

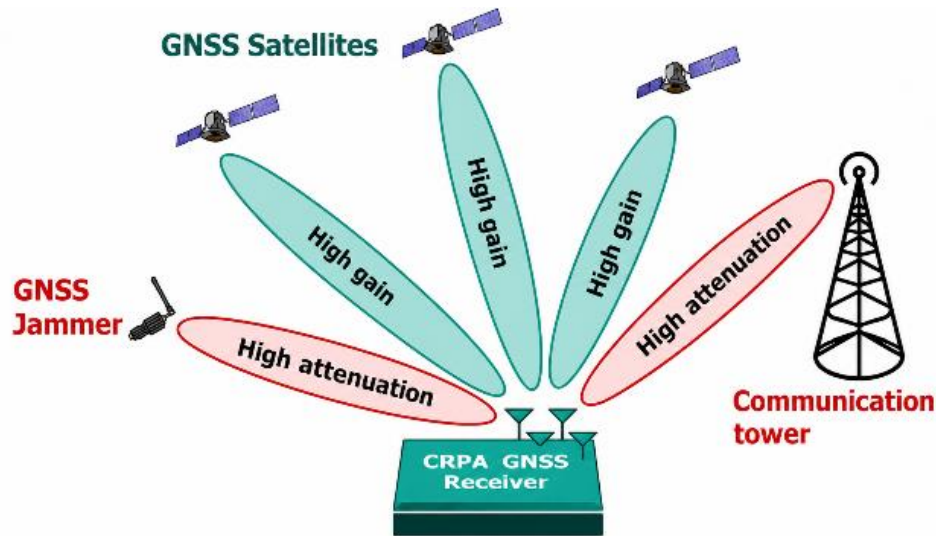


Figure 7: Illustration of CRPA antenna gain pattern, showing high gain towards GNSS satellites and high attenuation towards interference sources.
(Source: Inside GNSS, 2022)

High end systems incorporating these technologies are capable of maintaining operation in contested electromagnetic environments. However, their deployment is often constrained by cost, size, power consumption and system complexity, limiting their widespread adoption in civilian applications. Furthermore, their effectiveness may be reduced in scenarios involving high-power, wideband, or multi-source interference, where suppression capabilities can be exceeded (Li *et al.*, 2023; Jiang *et al.*, 2025; Ren *et al.*, 2025; Yao *et al.*, 2025).

4.1.2 Anti-Spoofing Technologies

In contrast to anti-jamming measures, anti-spoofing techniques focus on detecting inconsistencies in received signals rather than their absence. These techniques include monitoring signal quality and identifying distortions that deviate from expected GNSS characteristics, as well as detecting anomalies in received power levels. Multi-antenna configurations enable time-of-arrival (ToA) and angle-of-arrival discrimination, allowing receivers to differentiate between signals arriving from expected satellite directions and signals originating from improbable directions. Figure 8 shows an example of an antenna-based spoofing mitigation system. Additional safeguards include consistency checks across multiple constellations and frequencies, as well as cross-validation with inertial navigation systems (INS) to detect discrepancies between independent navigation solutions (Chen *et al.*, 2024; Rados *et al.*, 2024; Jiang *et al.*, 2025; Meheretu *et al.*, 2025). Signal robustness can also be improved through integration with additional sensors, cross-correlation with secure receivers or trusted reference stations, and specialised hardware for measuring absolute signal power (Psiaki *et al.*, 2013; Noah & Elmusrati, 2025).

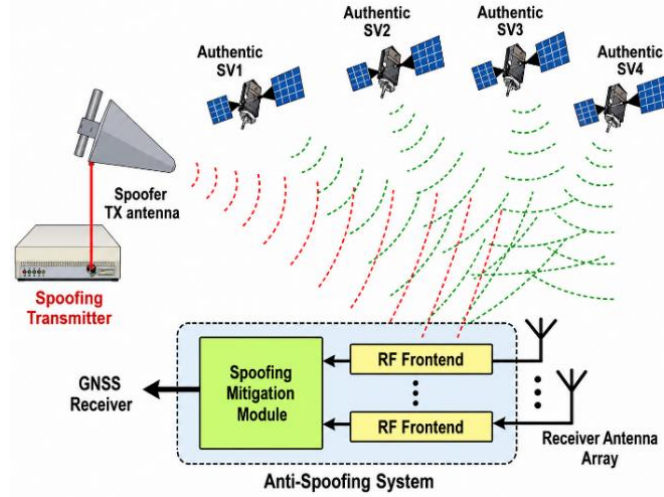


Figure 8: Antenna-based GNSS spoofing mitigation system using spatial discrimination to distinguish authentic GNSS signals from spoofing signals.
(Source: Farhadi *et al.*, 2017)

The introduction of cryptographic signal authentication in modernised GNSS services provides an additional layer of protection by enabling receivers to verify the authenticity of transmitted navigation data and, in some cases, the signal itself. Examples of cryptographic approaches include spread spectrum security codes (SSC), navigation message authentication (NMA), signal authentication sequences and anti-replay mechanisms (Noah & Elmusrati, 2025), which typically incorporate encrypted spreading codes, digital signatures and authentication features into signal structures and messages. Systems such as Galileo’s Open Service Navigation Message Authentication (OSNMA) aim to mitigate spoofing by allowing receivers to detect unauthorised signal generation or manipulation through cryptographic validation. However, the effectiveness of these mechanisms depends on receiver capability, processing latency and the specific authentication scheme employed, with adoption remaining uneven across constellations and user equipment. Moreover, authentication does not fully address threats such as signal replay, meaconing and sophisticated implementation level attacks, underscoring the need for complementary detection and resilience measures (Rados *et al.*, 2024; Burbank *et al.*, 2024; Critchley-Marrows & Verspieren, 2025; Galan *et al.*, 2025).

4.2 System Level and Hybrid PNT Architectures

Operational experience indicates that reliance on a single satellite-based PNT source introduces systemic exposure. As interference becomes more persistent and geographically extensive, mitigation strategies increasingly focus on diversifying sources of positioning and timing information and reducing single-point dependency.

4.2.1 Multi-Constellation and Multi-Frequency Operation

The simultaneous use of multiple GNSS constellations, such as GPS, GLONASS, Galileo and BeiDou, in combination with multi-frequency reception, improves signal availability and robustness under nominal conditions. Figure 9 illustrates the signal bands used by major global and regional navigation satellite systems, highlighting the frequency diversity available for multi-constellation and multi-frequency operation. This diversity enhances the likelihood of maintaining sufficient satellite visibility and signal redundancy in the presence of localised interference. Access to multiple constellations also improves satellite geometry and increases the probability of retaining an operational navigation solution when individual signals or frequencies are degraded (Rados *et al.*, 2024; Jiang *et al.*, 2025; Meheretu *et al.*, 2025; Yao *et al.*, 2025).

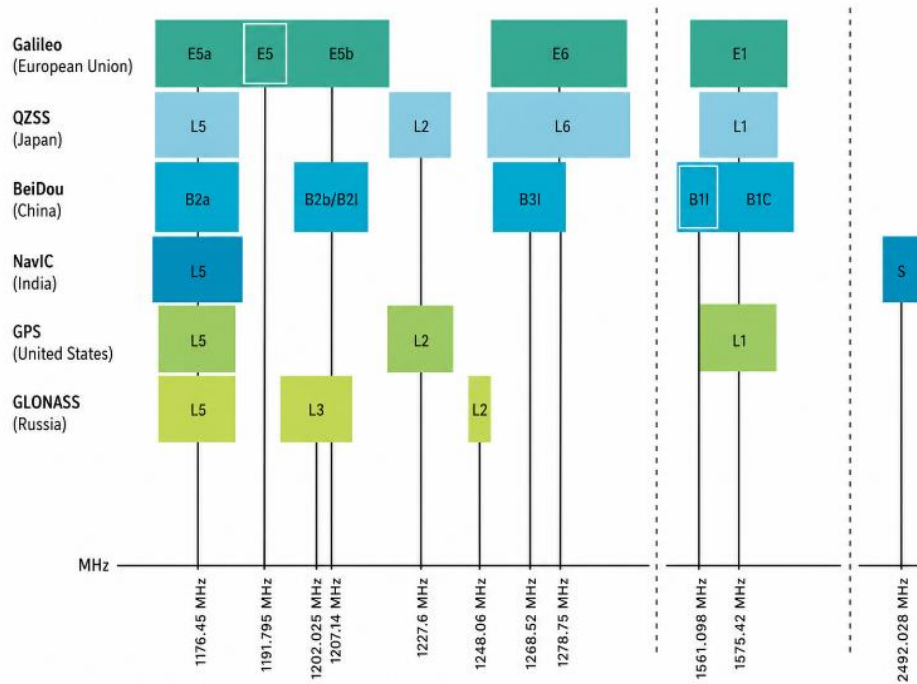


Figure 9: GNSS signal bands across major global and regional navigation satellite systems, illustrating the frequency diversity available for multi-constellation and multi-frequency positioning.
(Source: NovAtel, 2026)

However, the benefits of diversity should not be overstated. Coordinated interference targeting multiple constellations or frequency bands can still result in significant degradation, particularly when interference affects common frequency allocations or receiver front end processing. Therefore, multi-constellation and multi-frequency reception enhance robustness but do not eliminate vulnerability, highlighting the limitations of relying solely on GNSS-based diversity as a resilience measure. (DOT, 2024; Critchley-Marrows & Verspieren, 2025; Jiang *et al.*, 2025; Yao *et al.*, 2025).

4.2.2 Hybrid PNT

In order to address these limitations, hybrid PNT architectures integrate GNSS with complementary systems, including INS, multi-sensor fusion, terrestrial positioning solutions, alternative timing references and emerging low Earth orbit (LEO)-based PNT concepts. Figure 10 illustrates the broader hybrid PNT ecosystem, where GNSS is complemented by alternative PNT sources, sensor fusion, anti-jam capabilities and signals-of-opportunity to improve resilience under degraded GNSS conditions. Such integration provides layered redundancy, enabling systems to maintain functionality even when GNSS performance is degraded. By combining independent sources, hybrid architectures support cross-validation of navigation solutions and reduce reliance on any single technology (DOT, 2024; Critchley-Marrows & Verspieren, 2025; Yao *et al.*, 2025; Prezelj & Juvan, 2026).

An important advantage of hybrid architectures is their ability to support graceful degradation, whereby system performance is progressively reduced rather than failing abruptly following GNSS disruption. Although alternative PNT sources may not provide equivalent accuracy or coverage under all conditions, they can maintain essential operational functions and improve overall resilience. However, the contribution of LEO-based PNT and signals of opportunity may be constrained by high deployment costs, limited standardisation and vulnerability to wideband interference. Consequently, hybrid PNT remains an important component of resilience strategies, provided that these practical limitations are addressed in system design and implementation (DOT, 2024; Critchley-Marrows & Verspieren, 2025; Orbán, 2025; Trýb & Hospodka, 2025).

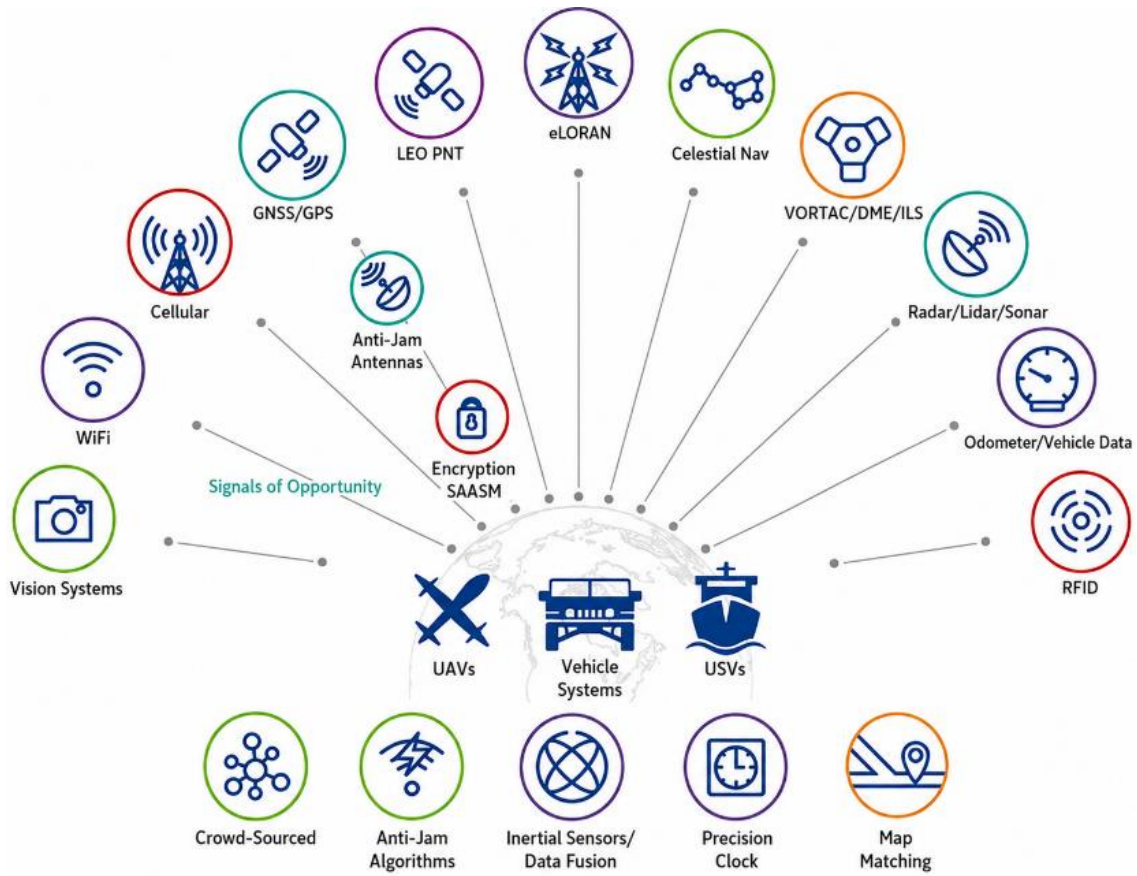


Figure 10: Hybrid PNT ecosystem for resilient operation under degraded GNSS conditions.
(Source: Abbott, 2023)

4.2.3 Timing Resilience

In applications where precise timing is critical, such as telecommunications and financial systems, resilience extends beyond positioning to include protection against timing disruption and manipulation. Techniques such as the use of holdover oscillators, atomic clocks and disciplined timing architectures enable systems to maintain accurate time synchronisation during short term GNSS outages. In addition, timing resilience can be strengthened through the use of diverse and complementary time synchronisation sources, including direct two-way satellite time transfer, GNSS assurance, fibre-based precision time protocol (PTP), terrestrial radio time signals and internet-based time services (Figure 11). These sources provide different levels of timing accuracy and resilience, and may be combined depending on the criticality and performance requirements of the application (DOT, 2024; Critchley-Marrows & Verspieren, 2025; Trýb & Hospodka, 2025; Prezelj & Juvan, 2026).

Unlike positioning errors, timing disruptions may not be immediately visible to operators but can propagate through dependent systems and affect wider network performance. Loss or manipulation of GNSS-derived time can degrade synchronisation in telecommunications networks, financial transaction systems, power grid monitoring, surveillance systems and other critical infrastructure. For this reason, timing resilience requires not only backup clocks and alternative timing sources, but also monitoring, holdover performance assessment, anomaly detection and procedures for controlled re-synchronisation once reliable timing sources are restored (DOT, 2024; Rados et al., 2024; Trýb & Hospodka, 2025; Prezelj & Juvan, 2026).

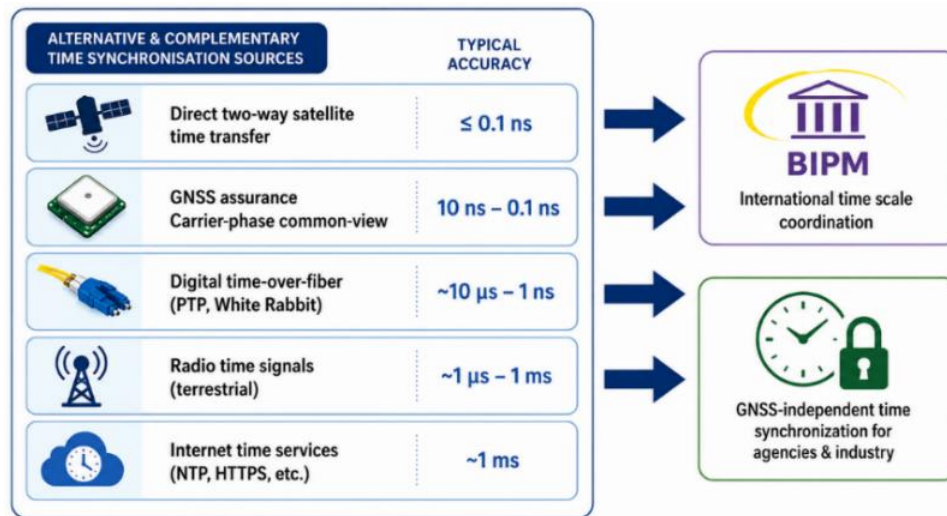


Figure 11: Alternative and complementary time synchronisation sources for timing resilience, showing typical accuracy levels.
(Source: Patla, 2021)

4.3 Monitoring, Detection and Adaptive Response

The persistence of interference has driven the development of structured monitoring systems capable of detecting, characterising and localising jamming and spoofing sources, as well as facilitating appropriate responses according to the type and severity of interference encountered. These systems play an important role in both real time operational response and long term resilience planning. Modern monitoring approaches combine distributed spectrum monitoring stations, direction finding systems and crowdsourced GNSS receiver reports to identify interference sources and assess their operational impact across wide geographic areas. In aviation, dedicated GNSS reliability reporting mechanisms further support the identification of affected airspace and the dissemination of warnings to operators to support timely operational action. By integrating data from multiple sources, these monitoring networks enable the correlation of anomalies across regions, facilitating the identification of coordinated or wide area interference patterns. This enhances situational awareness, and supports more effective mitigation, response and resilience strategies for safety critical operations (van der Merwe *et al.*, 2023; DOT, 2024; Rados *et al.*, 2024; Critchley-Marrows & Verspieren, 2025).

Artificial intelligence (AI) and machine learning (ML) are among the emerging techniques increasingly being explored to enhance the detection, classification and mitigation of GNSS interference. As GNSS environments become more complex, with multiple constellations, frequencies and signal authentication mechanisms operating simultaneously, conventional rule-based approaches may have limited effectiveness in identifying subtle or previously unseen interference patterns. AI-based methods can analyse large volumes of signal, receiver and network level data to identify anomalous behaviour, improving sensitivity to sophisticated jamming and spoofing attacks, while reducing reliance on fixed thresholds and manually defined detection rules (van der Merwe *et al.*, 2023; Rados *et al.*, 2024; Suseelan, 2024; Esfandabadi *et al.*, 2026). Figure 12 illustrates an example of an ML-based GNSS interference monitoring pipeline, where potentially interfered signals are captured by sensor nodes, stored in a central database, analysed for detection and classification, and subsequently visualised or localised using AI-based methods.

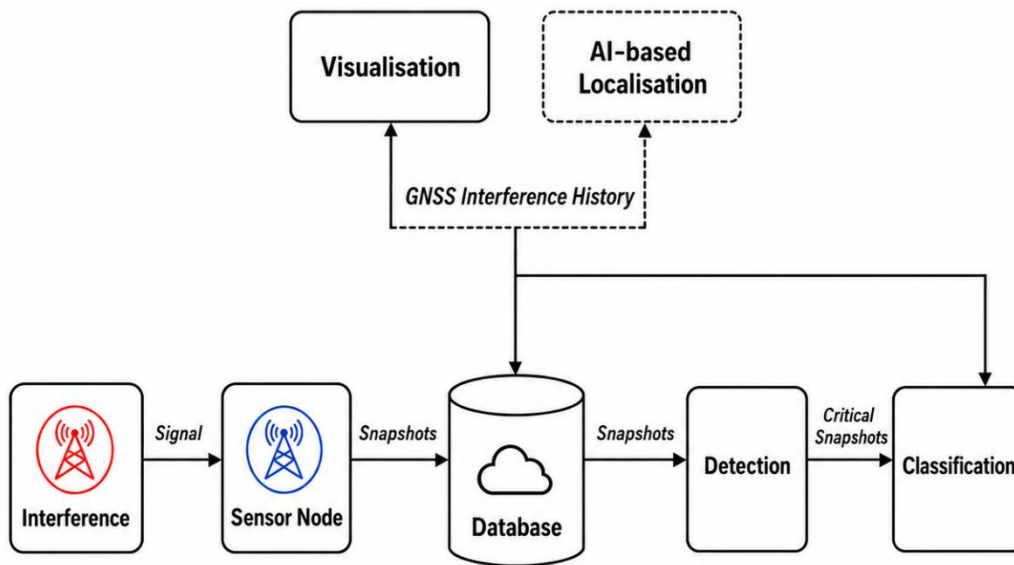


Figure 12: ML-based GNSS interference monitoring pipeline for detection, classification, visualisation and AI-based localisation of potentially interfered GNSS signals.
(Source: van der Merwe *et al.*, 2023)

At the network level, AI-enabled systems can analyse spatial and temporal patterns across distributed receivers to detect correlated anomalies indicative of wide area interference. At the receiver level, ML algorithms can classify interference types, detect abnormal signal behaviour and support adaptive mitigation strategies, including dynamic signal selection, interference aware tracking, and transition to alternative or hybrid PNT sources when GNSS integrity is compromised. Recent research has also explored the use of AI to enhance interference localisation, spectrum monitoring and situational awareness by combining information from multiple sensors and data sources. These capabilities are particularly relevant in environments where interference may be intermittent, geographically distributed or difficult to distinguish from normal signal variations. Emerging approaches include the use of crowdsourced data from commercial GNSS receivers and smartphones, enabling interference monitoring and localisation across large geographic areas while complementing dedicated monitoring infrastructure (Rados *et al.*, 2024; Suseelan, 2024; Esfandabadi *et al.*, 2026; Tegedor *et al.*, 2026).

Despite these potential benefits, AI-enabled approaches introduce additional complexity and potential vulnerabilities. ML models may be susceptible to adversarial manipulation, biased training data and reduced performance when operating outside the conditions represented in their training datasets. They may also impose significant computational demands on embedded and real time platforms, as well as produce false alarms or missed detections in dynamic and non-stationary RF environments. Therefore, ensuring robustness, transparency, explainability and rigorous validation remains essential before AI-driven techniques can be relied upon in safety critical or security sensitive applications. Consequently, AI should be viewed as a complement to, rather than a replacement for, established GNSS resilience measures and operational procedures (Burbank *et al.*, 2024; Rados *et al.*, 2024; Suseelan, 2024; Esfandabadi *et al.*, 2026).

4.4 GNSS Test and Evaluation: Structured Stress Testing of Resilience

A significant development in the contemporary GNSS resilience landscape is the institutionalisation of structured interference testing at national and international levels. While earlier assessments of GNSS vulnerability were largely analytical or based on laboratory simulations, current approaches increasingly rely on controlled, large scale testing designed to replicate realistic interference conditions. These testing frameworks recognise that resilience cannot be inferred solely from design specifications or theoretical analysis. Although analytical studies and laboratory simulations remain important for

analysing, characterising, mapping and developing mitigation methods, field evaluation is also essential for assessing the impact of real interference on civilian and military grade receivers. Therefore, system performance must be empirically validated under representative electromagnetic stress conditions, including scenarios involving multiple interference sources, dynamic platforms and complex propagation environments (DOT, 2024; Quinn *et al.*, 2024; Critchley-Marrows & Verspieren, 2025; Gerrard *et al.*, 2026).

Norway's Jammertest programme (Figure 13) represents a structured national effort to evaluate the impact of GNSS jamming and spoofing on civilian infrastructure. Conducted within controlled environments and coordinated with affected stakeholders, these exercises assess the effects of sustained interference on aviation navigation, maritime operations, emergency services and critical infrastructure systems. The resulting data provides valuable insight into system behaviour under real world conditions, informing contingency planning, procurement decisions and resilience assessments. Beyond its technical findings, Jammertest reflects a broader recognition that GNSS disruption must be treated as a credible operational condition rather than a hypothetical scenario, providing empirical evidence to support resilience planning across multiple sectors (Gerrard *et al.*, 2026).

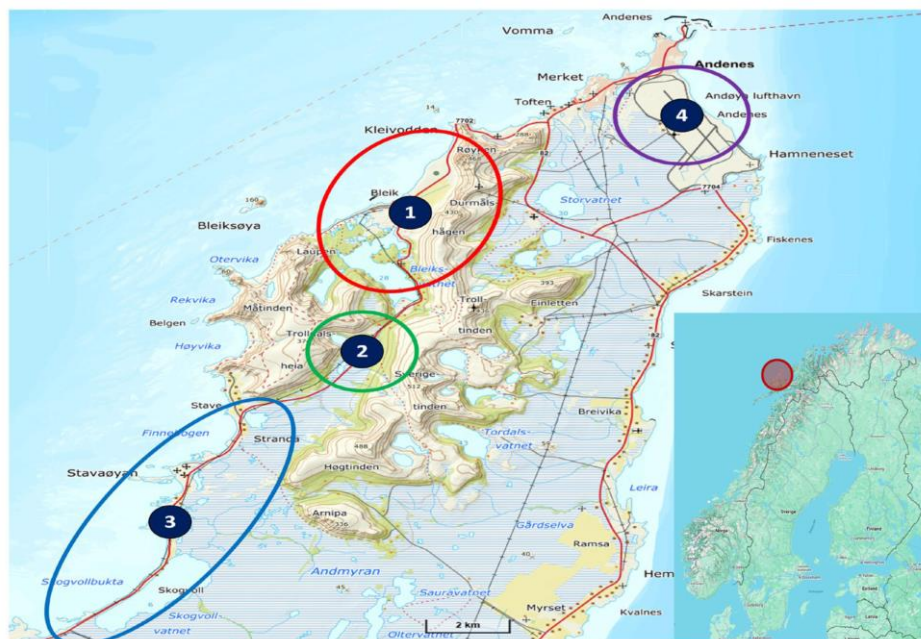


Figure 13: Jammertest interference test areas in Andøya, Norway.
(Source: Gerrard *et al.*, 2026)

In the US, Navigation Festival (NAVFEST) and related navigation warfare exercises provide controlled environments for evaluating platform performance under both jamming and spoofing conditions. These exercises enable validation of anti-jamming and anti-spoofing technologies, assessment of integrated navigation systems and evaluation of operational procedures. In addition, they facilitate coordination between agencies and support interoperability across different platforms and systems. Such activities illustrate a shift from theoretical assurance towards empirical verification, where resilience is demonstrated through realistic testing rather than assumed through compliance-based evaluation (Quinn *et al.*, 2024).

In addition to field evaluations, structured simulation environments and controlled laboratory testing are increasingly used to assess the vulnerability of timing infrastructure, critical services and multi-domain GNSS dependence. High fidelity simulation platforms enable the injection of controlled interference scenarios into representative system architectures without disrupting live operations. These test environments support policy development, infrastructure risk modelling and quantitative assessment of resilience by allowing system behaviour to be evaluated under repeatable and carefully controlled conditions. Such capabilities complement field-based testing programmes by providing a

flexible environment for investigating complex interference scenarios, validating mitigation measures and examining the potential consequences of GNSS disruption across interconnected systems (Bi & Yuan, 2021; Sathish Nayak *et al.*, 2023; Luccio, 2024; DOT, 2024).

The Science and Technology Research Institute for Defence (STRIDE) conducts a range of GNSS resilience assessments using both simulation- and field-based evaluation approaches. These studies have examined the effects of GNSS jamming and spoofing on receiver performance, as well as the resilience of unmanned aerial vehicles (UAVs), high precision GNSS systems and alternative PNT solutions under degraded GNSS conditions (Figure 14) (Dinesh *et al.*, 2010; 2012a, b; 2017; 2020; 2023a, b; 2024; 2025; 2026). Collectively, these activities demonstrate the value of combining GNSS simulation and field evaluation to support resilience assessment, capability development and operational preparedness. These efforts also contribute to a broader understanding of GNSS vulnerabilities and support the development of practical resilience measures through empirical evaluation of both system performance and mitigation approaches.



Figure 14: GNSS jamming and spoofing tests conducted by the Geospatial Technology Unit, STRIDE, through (a) GNSS simulation and (b) field evaluation.

4.5 From Protection to Resilience: A Systems Perspective

The operational characteristics of GNSS interference demonstrate that disruption can be persistent, geographically extensive and strategically employed. As a result, mitigation strategies must move beyond preventing interference towards ensuring continuity of operations under degraded conditions. Effective resilience requires a layered approach that integrates receiver level protections, signal authentication, hybrid PNT architectures, monitoring networks, structured testing programmes and coordinated operational procedures. By combining these elements, systems can reduce reliance on any single source and maintain functionality through graceful degradation rather than abrupt failure (Burbank *et al.*, 2024; DOT, 2024; Rados *et al.*, 2024; Critchley-Marrows & Verspieren, 2025).

GNSS resilience is no longer confined to equipment level enhancements, but has become an infrastructure level requirement embedded within aviation, maritime operations, telecommunications, energy systems and autonomous platforms. This shift reflects the recognition that interference is an operational reality rather than an exceptional event. As dependence on GNSS-derived positioning and timing information continues to increase, disruption has the potential to produce cascading effects across multiple interconnected systems and sectors. Consequently, resilience planning increasingly extends beyond individual platforms to encompass critical infrastructure, operational continuity and cross-sector dependencies (DOT, 2024; Critchley-Marrows & Verspieren, 2025; Trýb & Hospodka, 2025; Prezelj & Juvan, 2026).

Sustained resilience requires not only technical and operational measures, but also appropriate governance, regulatory and organisational frameworks. The transboundary nature of GNSS interference highlights the importance of coordination between governments, regulators, infrastructure operators and international organisations, particularly where disruption affects users across multiple jurisdictions. Increasingly, national resilience strategies incorporate monitoring networks, structured testing programmes, alternative PNT capabilities and information sharing mechanisms to support preparedness and response. These developments reflect a growing recognition that effective PNT resilience depends on the integration of technical, operational and institutional measures within a coherent resilience framework (DOT, 2024; Critchley-Marrows & Verspieren, 2025; EASA, 2026; FAA, 2026).

Therefore, future GNSS security should be addressed as a system wide resilience requirement rather than through signal protection alone. This requires security measures to be integrated across the wider PNT ecosystem and aligned with broader cybersecurity, infrastructure protection and organisational preparedness frameworks.

5. CONCLUSION

This paper has reviewed the evolving GNSS threat environment, highlighting the transition of jamming and spoofing from isolated technical vulnerabilities to persistent and operationally significant challenges affecting modern PNT systems. Recent developments demonstrate that GNSS interference is no longer confined to localised denial or experimental deception scenarios, but has become an increasingly operational and geographically scalable capability affecting aviation, maritime operations, critical infrastructure and other GNSS-dependent services. As reliance on GNSS-derived positioning and timing information continues to grow, the consequences of interference extend beyond signal degradation to encompass system level effects, operational disruption and risks associated with the integrity of navigation, surveillance and timing information. These developments underscore a broader shift from viewing GNSS interference as a receiver level problem towards recognising it as a resilience challenge affecting interconnected systems and critical infrastructure.

In response, contemporary mitigation strategies increasingly emphasise resilience rather than protection alone. Effective resilience requires a layered approach that combines receiver level countermeasures, multi-constellation and multi-frequency operation, hybrid PNT architectures, timing resilience, monitoring, detection and adaptive response mechanisms, as well as coordinated operational procedures. The increasing use of AI- and ML-assisted monitoring approaches further reflects the need to detect, classify, localise and respond to interference events across wider operational environments, while structured test and evaluation, including GNSS simulation and field evaluation, remains essential for validating system performance under representative interference conditions.

Overall, the operationalisation of GNSS jamming and spoofing marks a significant change in the PNT risk landscape. As interference becomes an enduring feature of the contemporary electromagnetic environment, future GNSS security must move beyond protecting signals in isolation towards sustaining trustworthy PNT services under degraded and contested conditions. This will require continued investment in resilient system architectures, alternative and complementary PNT sources, monitoring networks, empirical validation, governance frameworks and cross-sector coordination. In this context, resilience, operational preparedness and evidence-based evaluation will remain central to ensuring the continuity and trustworthiness of PNT-dependent systems.

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EVALUATION OF THE EFFECT OF NARROWBAND INTERFERENCE ON GNSS PERFORMANCE

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ABSTRACT

Global Navigation Satellite System (GNSS) receivers are vulnerable to radio frequency interference (RFI) because GNSS satellite signals are extremely weak. While wideband interference has been extensively studied, many real-world sources produce narrowband interference that is harder to detect and mitigate. This study evaluates the effects of continuous wave (CW) and sweep interferences on GNSS performance through controlled GNSS simulation and live sky field evaluation using a consumer grade Garmin GPSMAP 66sr and a high precision Trimble DA2. Interference was generated within the GNSS L1 / E1 band and progressively increased in power. The results show that receiver response depends on interference characteristics, receiver architecture and operating conditions. For CW interference, simulation and field results were broadly consistent: GPSMAP 66sr exhibited progressive degradation and eventual loss of lock, while DA2 maintained stable positioning. Under sweep interference, both receivers showed differences between GNSS simulation and field evaluation. DA2 maintained positioning throughout the evaluated range, although the degradation pattern differed between environments. For GPSMAP 66sr, the difference was more pronounced, with relatively stable positioning under GNSS simulation but greater variability and pronounced error spikes under field evaluation. These findings indicate that controlled GNSS simulation is useful for reproducing general degradation trends associated with steady narrowband interference, while field evaluation remains important for characterising the more variable effects of frequency varying interference. Overall, DA2 demonstrated greater resistance to the evaluated narrowband interferences than GPSMAP 66sr, reflecting differences in receiver architecture and processing.

Keywords: *Global Navigation Satellite System (GNSS); narrowband interference; positioning accuracy; signal degradation; receiver architecture.*

1. INTRODUCTION

Global Navigation Satellite System (GNSS) receivers operate using extremely weak satellite signals, typically in the range of -160 to -130 dBm, rendering them inherently vulnerable to radio frequency interference (RFI) from both intentional and unintentional sources. This vulnerability has been widely documented, with interference capable of degrading signal tracking, reducing carrier-to-noise density (C/N_0), and ultimately leading to positioning errors or complete loss of navigation solutions (Rados *et al.*, 2024; Meheretu *et al.*, 2025; Orbán, 2025; Trýb & Hospodka, 2025). Past works have demonstrated how elevated noise floors adversely affect GNSS tracking loops and positioning accuracy (Dinesh *et al.*, 2010, 2012, 2017, 2020, 2023a, 2023b, 2025).

However, many real-world interference events are not wideband in nature, but instead manifest as narrowband interference arising from RF emitters such as communication systems, radar and other electronic equipment operating within or near GNSS frequency bands. Such narrowband interference can introduce localised spectral distortion while remaining difficult to detect and mitigate using conventional approaches (Obiols-Bernaus *et al.*, 2023; Qiao *et al.*, 2023; Calatrava *et al.*, 2025; Chen *et al.*, 2025).

Two forms of narrowband interference frequently encountered in operational environments are continuous wave (CW) and sweep interferences. CW interference typically manifests as a single tone signal within the GNSS band and may originate from sources such as spurious emissions, local oscillator leakage and unintended transmissions. In contrast, sweep interference consists of frequency varying signals that traverse portions of the GNSS spectrum and are commonly associated with radar systems, frequency agile transmitters and scanning equipment. These interference types are representative of real-world threats encountered across a wide range of applications, including aviation, maritime operations, surveying and critical infrastructure systems (Obiols-Bernaus *et al.*, 2023; Qiao *et al.*, 2023; Calatrava *et al.*, 2025; Chen *et al.*, 2025).

Given their prevalence and operational relevance, this study evaluates the impact of CW and sweep interferences on GNSS performance through both controlled GNSS simulation and live sky field evaluation. Two receivers with distinct architectures - a consumer grade Garmin GPSMAP 66sr (Garmin, 2021) and a high precision Trimble DA2 (Trimble, 2023) - are used to investigate how receiver design influences susceptibility to these interference types. The findings contribute towards improving the understanding of GNSS resilience to narrowband interference under both laboratory and operational environments.

2. METHODOLOGY

This study evaluates the effect of narrowband interference on GNSS positioning accuracy using a two-phase experimental approach, comprising of GNSS simulation and field evaluation. The interference signals employed throughout the study are generated using a DS Instruments SG6000L signal generator (DS Instruments, 2022) and transmitted via a Hyperlog 60180 directional antenna (Aaronia, 2009). Two forms of narrowband interference are evaluated: 1) CW interference at 1575.42 MHz; 2) Sweep interference centred at 1575.42 MHz, sweeping across a 2 MHz bandwidth covering the GPS L1 C/A signal spectrum. A Spectran HF-60105 spectrum analyser (Aaronia, 2015) is used to verify the absence of external interference signals during the experiments.

In the GNSS simulation phase, GNSS signals are generated using an Aeroflex GPSG-1000 GNSS simulator (Aeroflex, 2010) within STRIDE's semi-anechoic chamber (A. Faridz *et al.*, 2010), following the methodology described in Dinesh *et al.* (2023a). This setup enables controlled and repeatable evaluation of receiver behaviour under varying interference conditions.

In the field evaluation phase, GNSS receivers operate under live sky conditions where satellite geometry, multipath propagation and environmental RF noise vary naturally. The field evaluation follows the methodology described in Dinesh *et al.* (2023b, 2025).

For GNSS simulation, the tests are conducted using the GPS L1 coarse acquisition (C/A) signal, with the Trimble DA2 receiver operating in standalone mode only. For field evaluation, the tests are conducted using GNSS L1 / E1 signals, with the Trimble DA2 receiver operating in both standalone mode and precise point positioning (PPP) using Trimble Catalyst (Trimble, 2024). The interference signal is initially transmitted at a low power level and progressively increased in increments of approximately 3 dBm. Horizontal positioning errors for both GNSS receivers are recorded at each interference power level.

3. RESULTS & DISCUSSION

Figures 1 to 4 present the positioning accuracy of both GNSS receivers under increasing levels of CW and sweep interferences for both GNSS simulation and field evaluation. The absolute accuracy metrics among receivers cannot be directly compared owing to variations in internal processing, filtering techniques and error modelling. Accordingly, the analysis focuses on relative trends in positioning accuracy degradation as interference power increases.

3.1 CW Interference

Under CW interference (Figures 1 and 2), GNSS simulation and field evaluation show broadly consistent behaviour for both GNSS receivers. Across both environments, GPSMAP 66sr exhibits progressive degradation in positioning accuracy as interference power increases, followed by abrupt escalation in positioning error and eventual loss of lock at higher interference levels. In several instances, large positioning error spikes are observed immediately prior to signal loss, indicating strong susceptibility to steady narrowband interference.

In contrast, DA2 maintains stable positioning performance across a broader range of interference levels for both GNSS simulation and field evaluation. In standalone mode, positioning accuracy degrades only gradually with increasing interference power, with no abrupt loss of lock observed within the tested range. Similarly, under field conditions, the PPP mode maintains consistently high positioning accuracy with only minor variation despite increasing interference levels.

The generally uniform behaviour noted between GNSS simulation and field assessment suggests that GNSS simulation can replicate the overall degradation patterns linked to persistent narrowband interference. This behaviour is expected, as CW interference introduces a continuous and spectrally fixed disturbance within the GNSS band, resulting in relatively deterministic receiver responses that are less dependent on surrounding environmental conditions.

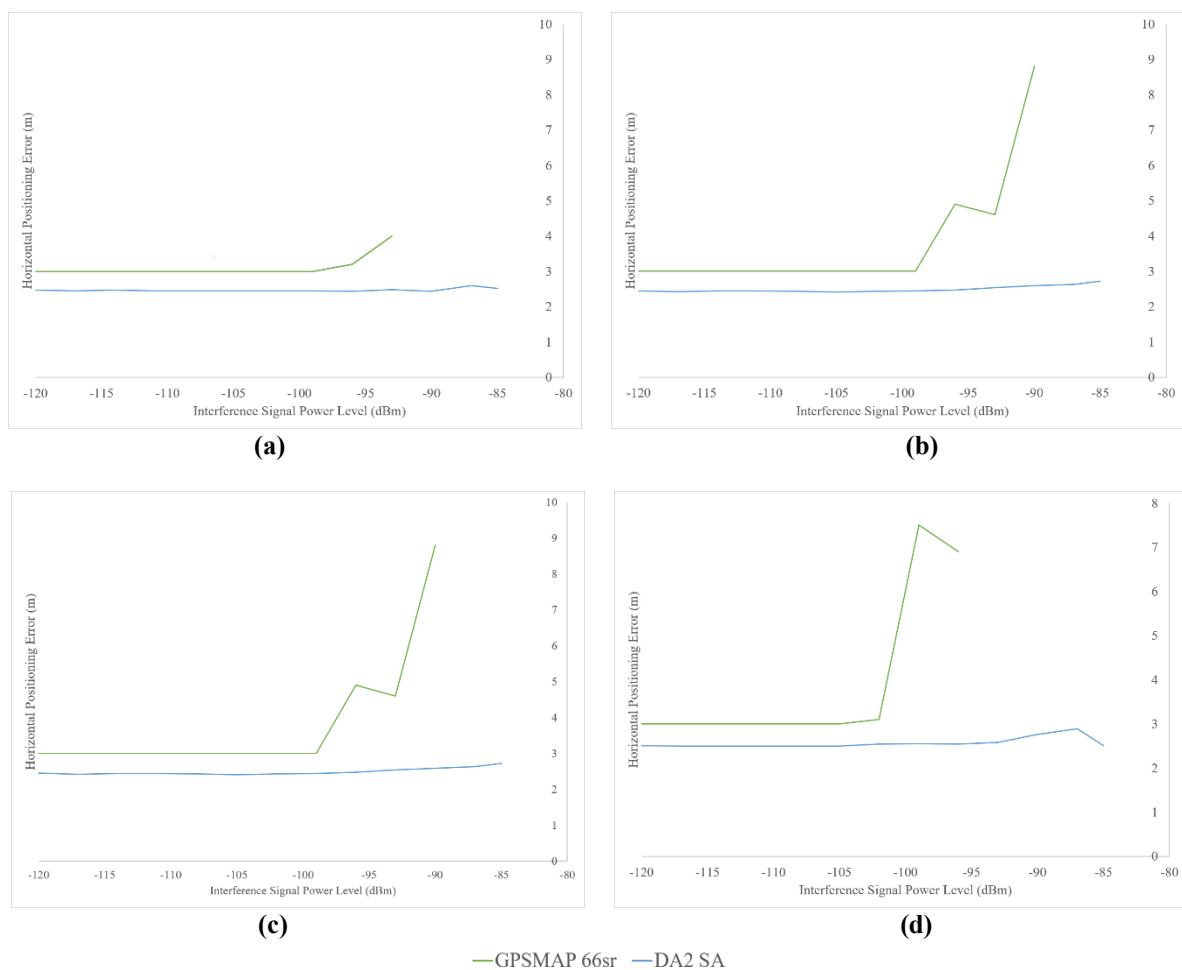


Figure 1: Effect of CW interference on horizontal positioning error for GNSS simulation:
(a) Reading 1 (b) Reading 2 (c) Reading 3 (d) Reading 4.

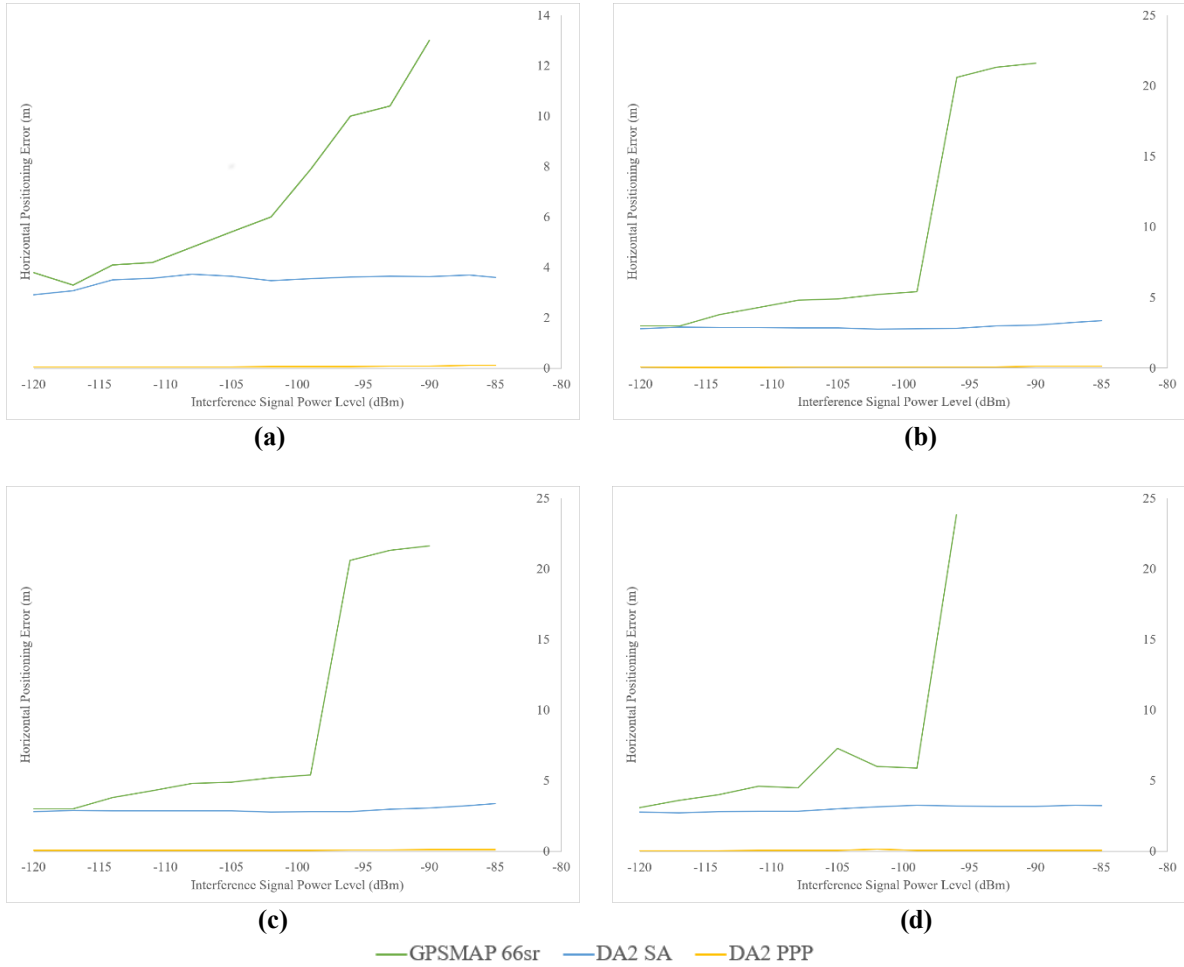


**Figure 2: Effect of CW interference on horizontal positioning error for field evaluation:
(a) Reading 1 (b) Reading 2 (c) Reading 3 (d) Reading 4.**

The superior performance of DA2 may be associated with differences in receiver architecture and processing as compared with GPSMAP 66sr. While the internal designs of the receivers are not directly evaluated in this study, the observed results indicate that DA2 is better able to maintain stable positioning under steady narrowband interference. Within the DA2 configurations, PPP consistently achieves substantially higher positioning accuracy than standalone mode while exhibiting comparable robustness under increasing CW interference, indicating that the improvement in positioning accuracy does not appear to reduce receiver stability.

3.2 Sweep Interference

Under sweep interference (Figures 3 and 4), both receivers exhibit differences between GNSS simulation and field evaluation, although the magnitude and pattern of these differences vary between the receivers. For DA2, positioning is maintained throughout the evaluated interference range in both environments, with no loss of lock observed. Under GNSS simulation, the standalone solution remains relatively stable at lower interference levels before showing a more pronounced increase in positioning error at the highest interference levels. Under field conditions, the degradation is generally more gradual, with the standalone solution remaining comparatively stable and the PPP solution maintaining sub-metre positioning accuracy.

For GPSMAP 66sr, the difference between simulated and field conditions is more pronounced. Under GNSS simulation, the receiver maintains relatively stable positioning performance across most of the evaluated interference range, with only slight variation as interference power increases. In contrast, under field conditions, positioning errors increase more noticeably at higher interference levels and culminate in pronounced error spikes. These results indicate that the response of GPSMAP 66sr to sweep interference is considerably more variable under live sky conditions than under controlled GNSS simulation.

The differing responses observed for both receivers indicate that the effects of sweep interference are influenced not only by the characteristics and power of the interference signal, but also by the surrounding operating environment. Controlled GNSS simulation provides relatively stable and repeatable signal conditions, whereas field evaluation introduces additional variability associated with satellite geometry, multipath propagation, atmospheric effects, environmental RF noise and real-world signal conditions. These factors may alter the available signal margin and consequently influence receiver response as the sweep interference traverses the GNSS signal band.

The contrast between CW and sweep interference further supports this observation. CW interference introduces a steady and spectrally fixed disturbance, resulting in degradation patterns that are comparatively more consistent between GNSS simulation and field evaluation. In contrast, sweep interference produces frequency varying disturbances that move across portions of the GNSS spectrum over time. Receiver response to these transient disturbances appears to be more sensitive to the surrounding operating conditions, resulting in greater differences between controlled simulation and live sky evaluation.

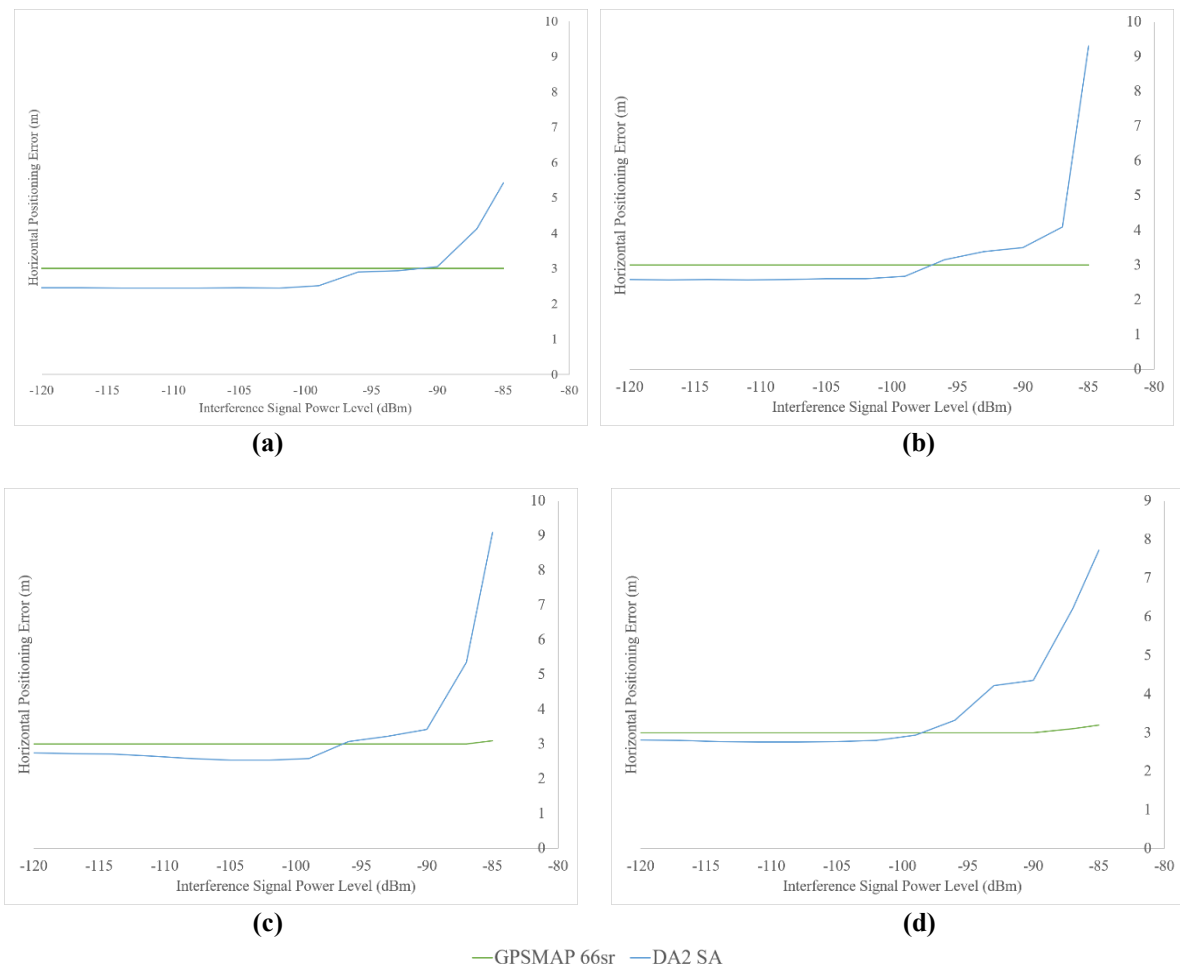


Figure 3: Effect of sweep interference on horizontal positioning error for GNSS simulation:
(a) Reading 1 (b) Reading 2 (c) Reading 3 (d) Reading 4.

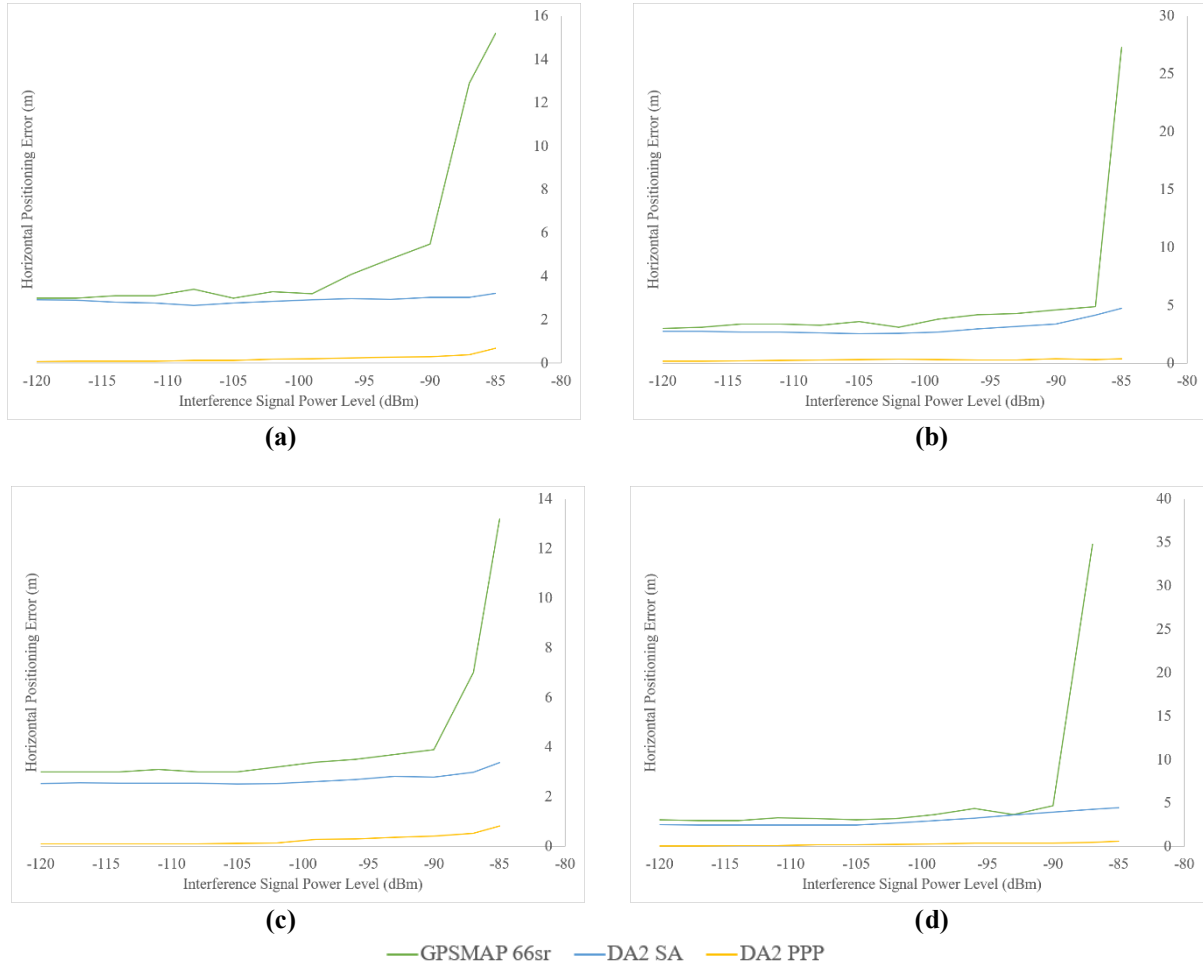


Figure 4: Effect of sweep interference on horizontal positioning error for field evaluation:
(a) Reading 1 (b) Reading 2 (c) Reading 3 (d) Reading 4.

The results further indicate that sweep interference can produce greater positioning variability than CW interference under both GNSS simulation and field conditions, although the effect differs between receivers. Under simulation, the standalone DA2 mode exhibits more pronounced degradation at the highest sweep interference levels, while under field conditions GPSMAP 66sr shows substantial increases in positioning error and pronounced error spikes. This behaviour is consistent with the frequency varying nature of sweep interference, where the disturbance traverse portions of the GNSS signal spectrum rather than remaining fixed at a single frequency. Therefore, the results suggest that the effects of sweep interference may be more variable and less predictable than those associated with steady CW interference.

Within DA2 configurations, the PPP mode consistently maintains substantially better positioning accuracy than the standalone mode during the field sweep interference tests, with positioning errors remaining at sub-metre levels throughout the tested range. Although the standalone and PPP modes differ considerably in absolute positioning accuracy, both remain operational across the complete range of interference levels. This indicates that DA2 maintains a usable positioning solution under the tested sweep interference conditions, while PPP provides substantially higher positioning accuracy.

3.3 Discussion

Across both interference types, clear differences in receiver susceptibility are observed. DA2 generally maintains more stable positioning performance across the evaluated interference range, whereas GPSMAP 66sr exhibits greater degradation and, under some conditions, pronounced increases in positioning error. These results indicate that receiver architecture plays an important role in determining susceptibility to narrowband interference. However, as the internal receiver architectures are not directly evaluated, the observed differences should be interpreted as reflecting differences in overall receiver design and processing rather than being attributed to specific internal mechanisms.

The comparison between GNSS simulation and field evaluation further shows that the degree of agreement between controlled and operational environments depends strongly on the characteristics of the interference signal. For CW interference, the laboratory and field results exhibit broadly consistent degradation behaviour, indicating that controlled GNSS simulation is capable of reproducing the general effects of steady narrowband interference. In contrast, sweep interference produces more noticeable differences between simulation and field evaluation for both receivers. For DA2, the degradation pattern differs between the two environments despite positioning being maintained throughout the evaluated interference range, while for GPSMAP 66sr the difference is more pronounced, with substantially greater positioning variability and error spikes observed under live sky conditions.

These findings indicate that the impact of narrowband interference is not solely dependent on interference power but is also influenced by the spectral and temporal characteristics of the interfering signal, receiver architecture and surrounding operating conditions. The comparatively consistent response to CW interference reflects the steady and spectrally fixed nature of the disturbance. In contrast, sweep interference repeatedly traverses portions of the GNSS spectrum, producing transient disturbances whose effects appear to be more dependent on receiver and environmental conditions. Consequently, sweep interference exhibits greater variability between GNSS simulation and field evaluation, and may be less predictable than steady CW interference.

Variations in positioning error between test runs are also expected due to the dynamic nature of GNSS satellite constellations and the resulting changes in satellite geometry. Positioning accuracy is influenced by dilution of precision (DOP), with variations in satellite geometry contributing to fluctuations in positioning performance (DOD, 2020; Ding *et al.*, 2025; Zuo *et al.*, 2025). Under field conditions, additional factors such as multipath propagation, atmospheric effects, environmental RF noise and real-world signal variability may further influence receiver response. These factors may alter the available signal margin and contribute to the differences observed between GNSS simulation and field evaluation. Therefore, the results highlight the importance of complementing GNSS simulation with field evaluation when assessing GNSS performance under frequency-varying interference.

Several limitations of this study should be acknowledged. First, the evaluation is confined to the GNSS L1 / E1 band, whereas modern receivers increasingly operate across multiple frequencies and constellations. As such, the results may not fully capture the resilience provided by multifrequency and multi-constellation processing. Second, the interference scenarios are limited to CW and sweep signals, and do not encompass the full range of narrowband interference encountered in operational environments, such as pulsed and multi-tone interference. Third, the analysis is based on only two receivers and thus reflects specific receiver implementations rather than broader receiver classes. In addition, the differing behaviour observed between GNSS simulation and field evaluation under sweep interference indicates that controlled simulation may not fully reproduce all operational effects associated with frequency varying narrowband interference under live sky conditions. Future work should extend the study to multifrequency and multi-constellation configurations, a wider range of interference types with different spectral and temporal characteristics, as well as a larger set of receivers. This approach will facilitate a more thorough evaluation of GNSS resilience under realistic operating conditions.

4. CONCLUSION

This study evaluated the impact of CW and sweep narrowband interferences on GNSS performance through both controlled GNSS simulation and live sky field evaluation. The results demonstrate that receiver response is strongly dependent on the characteristics of the interference signal, receiver architecture and surrounding operating conditions.

For CW interference, broadly consistent behaviour is observed between GNSS simulation and field evaluation. GPSMAP 66sr exhibits progressive degradation in positioning accuracy followed by abrupt loss of lock at higher interference levels, indicating greater susceptibility to steady narrowband interference. In contrast, DA2 maintains stable positioning performance across the evaluated interference range, with gradual degradation observed in standalone mode and consistently higher positioning accuracy maintained under the PPP mode.

For sweep interference, both receivers exhibit differences between GNSS simulation and field evaluation, although the magnitude and pattern of these differences vary. DA2 maintains positioning throughout the evaluated interference range in both environments, but shows a more pronounced increase in positioning error at the highest interference levels under GNSS simulation as compared with the more gradual degradation observed under field evaluation. For GPSMAP 66sr, the difference is more pronounced, with relatively stable positioning under GNSS simulation but substantially greater positioning variability and pronounced error spikes under field evaluation. These findings indicate that the effects of sweep interference are more dependent on receiver and operating conditions than those of steady CW interference.

Overall, the results demonstrate that CW interference produces comparatively consistent degradation patterns between controlled and live sky environments, whereas sweep interference produces more variable and less predictable responses. Therefore, GNSS simulation is useful for reproducing general degradation trends associated with steady narrowband interference, but field evaluation remains important for characterising the effects of frequency varying interference under realistic operating conditions. The results also show that DA2 is generally more resistant to the evaluated narrowband interferences than GPSMAP 66sr, reflecting differences in receiver architecture and processing.

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DEVELOPMENT OF A MATLAB / SIMULINK-BASED PREDICTIVE MOBILITY MODEL FOR TACTICAL SMALL UNMANNED GROUND VEHICLES

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ABSTRACT

This study presents the development of a MATLAB / Simulink-based predictive mobility model for evaluating the mobility and energy performance of tactical small unmanned ground vehicles (UGVs) operating under varying terrain and slope conditions. The proposed framework integrates terrain characterisation, vehicle dynamics modelling, powertrain analysis and battery performance evaluation to estimate key performance parameters, including required torque, motor speed, power consumption, current draw, battery efficiency, speed efficiency and battery state of charge. Two simulation scenarios were conducted to investigate the effects of terrain type, vehicle mass and slope angle on vehicle performance. Straight line mobility analysis was performed on asphalt, sandy and rocky terrains for vehicle masses of 3, 6 and 9 kg, while inclined terrain analysis evaluated asphalt slopes ranging from 10 to 40°. The results revealed that terrain condition and vehicle mass significantly influence drivetrain loading and energy consumption, with higher terrain resistance and vehicle mass increasing torque, power and current requirements under straight line conditions. Furthermore, slope angle was identified as the dominant factor affecting mobility performance, where the maximum wheel torque reached 1.208 Nm while power demand approached 330 W and 27.5 A under the most demanding operating condition of a 9 kg vehicle on a 40° slope. The developed framework provides a practical engineering tool for motor selection, motor driver sizing, drivetrain optimisation and battery performance assessment, thereby supporting the design and development of terrain aware and energy efficient tactical UGV systems for defence and security applications.

Keywords: Unmanned ground vehicle (UGV); MATLAB / Simulink; mobility prediction; terrain traversability; drivetrain optimisation.

1. INTRODUCTION

The rapid advancement of robotics and autonomous systems has significantly transformed modern military operations, particularly in missions involving reconnaissance, surveillance, intelligence gathering, explosive hazard assessment and operations in high-risk environments. Among these technologies, unmanned ground vehicles (UGVs) have emerged as important force multipliers by reducing personnel exposure to threats while improving situational awareness and operational effectiveness. For tactical applications, small UGVs are particularly valuable because they can operate in confined, hazardous and terrain-challenging environments where direct human intervention may be unsafe or impractical (Ni *et al.*, 2020; Gans *et al.*, 2021; Muda *et al.*, 2026).

Small tactical UGVs commonly adopt skid-steer wheel configurations due to their mechanical simplicity, compact structure and high manoeuvrability in confined or unstructured environments. By independently controlling the rotational speed of the left and right wheel pairs, skid-steer vehicles can perform directional control without a dedicated steering mechanism (Khan *et al.*, 2020; Kratky *et al.*, 2021; Al-Baiti *et al.*, 2025). However, their mobility performance is strongly influenced by vehicle mass, wheel geometry, terrain condition, slope gradient and available energy. These factors directly affect traction requirement, power consumption, current demand, battery usage and mission endurance (Baril *et al.*, 2020; Zhou *et al.*, 2022).

Terrain mobility remains one of the main challenges in tactical UGV development. Unlike conventional road vehicles, military UGVs may operate on paved roads, sandy surfaces, rocky terrain and sloping paths. These terrain conditions introduce different levels of rolling resistance and wheel-terrain interaction, which increase torque demand and energy consumption (Czapla *et al.*, 2022; Kivekäs *et al.*, 2024). In addition, slope inclination imposes gravitational resistance that must be overcome by the drivetrain, resulting in higher power requirements and faster battery depletion. Therefore, terrain type and slope gradient must be considered during the early design stage to ensure that the selected motor, drivetrain and battery system can meet the intended operational requirements (Agrawal *et al.*, 2023; Ding *et al.*, 2025).

Predictive modelling provides an effective approach for evaluating UGV mobility performance before physical prototype fabrication. Previous studies have used mathematical and simulation-based methods to analyse vehicle dynamics, wheel-terrain interaction, energy consumption and traversability. Zhou *et al.* (2022) developed a dynamic model for skid-steered UGVs, and demonstrated the influence of slippage and terrain interaction on vehicle performance, while Trivedi *et al.* (2024) proposed a probabilistic motion model for skid-steer robots operating on off-road terrain. Other studies have also shown that vehicle mass, speed, terrain condition and drivetrain efficiency significantly affect energy consumption and mission endurance (Touzout *et al.*, 2021; Vantsevich *et al.*, 2023).

Although existing studies have addressed navigation, control systems, terrain traversability and energy consumption, there remains a need for an integrated simulation framework that combines mobility prediction, torque estimation, power consumption analysis, current demand and battery related performance for tactical small UGV design (Mohamadi *et al.*, 2024; Ramirez *et al.*, 2025). In practice, UGV development often depends on iterative prototyping and field testing to determine suitable motor specifications, wheel dimensions, battery capacity and drivetrain configuration. This approach can be costly and time-consuming during the early stages of system development (de Carvalho Pinheiro, 2023).

Therefore, this study develops a MATLAB / Simulink-based predictive mobility model for tactical small UGVs by integrating vehicle dynamics, rolling resistance modelling, terrain-dependent mobility analysis and battery performance prediction within a unified simulation environment. The model uses key design and operational parameters, including battery voltage and capacity, discharge rate, vehicle mass, wheel radius and diameter, target speed, terrain type, as well as slope angle, to estimate critical mobility and energy indicators such as required torque, motor rotational speed, power consumption, current demand, battery efficiency and state of charge. By enabling quantitative assessment under flat ground straight line conditions across asphalt, sandy and rocky terrain, as well as inclined terrain conditions up to 40°, the proposed framework provides practical decision support for early stage motor selection, motor driver sizing, drivetrain optimisation and battery performance assessment prior to prototype fabrication.

2. METHODOLOGY

2.1 Research Framework

The proposed framework integrates four main components: terrain characterisation, vehicle dynamics modelling, powertrain analysis and battery performance evaluation, as illustrated in Figure 1. The

simulation begins with the definition of key design and operational parameters, including vehicle mass, battery voltage, battery capacity, battery discharge rate, wheel radius, wheel diameter, target speed, terrain type and slope angle. The selected terrain type is then assigned a corresponding rolling resistance coefficient to represent different operating surfaces, including asphalt, sandy and rocky terrain. These components are implemented within a unified simulation environment to estimate key mobility and energy parameters during the early design stage.

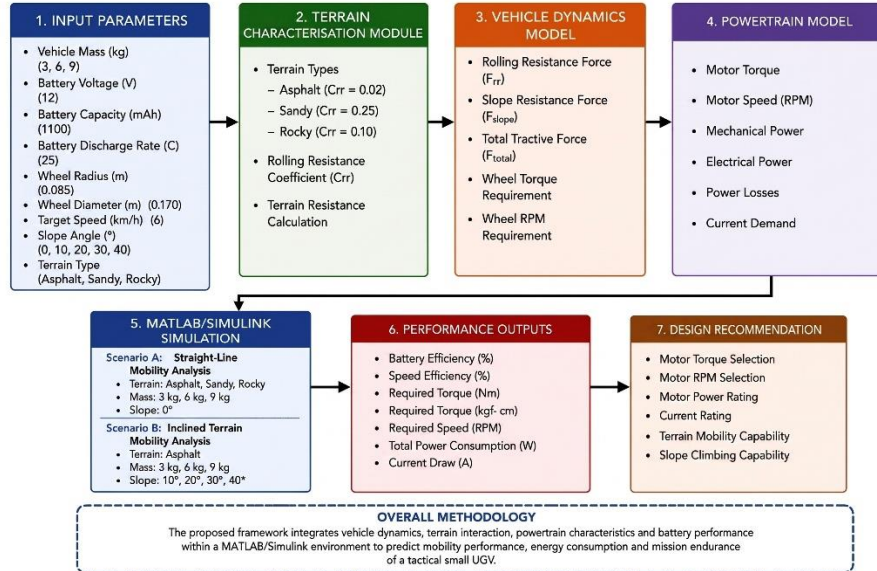


Figure 1: Proposed MATLAB / Simulink-based predictive mobility modelling framework integrating terrain characterisation, vehicle dynamics modelling, powertrain analysis and battery performance evaluation.

The vehicle dynamics model uses these inputs to calculate rolling resistance force, slope resistance force, total tractive force, wheel torque requirement and wheel rotational speed. These outputs are then used by the powertrain model to estimate mechanical power, electrical power consumption and current demand. Battery characteristics are also incorporated to assess battery efficiency and energy utilisation under different operating conditions.

The developed model is evaluated using two simulation scenarios. The first scenario assesses straight line mobility on asphalt, sandy and rocky terrain under flat ground conditions for vehicle masses of 3, 6 and 9 kg. The second scenario evaluates inclined terrain mobility on asphalt terrain at slope angles of 10, 20, 30 and 40° for the same vehicle masses. This framework provides a systematic basis for assessing the influence of terrain type, vehicle mass and slope angle on UGV drivetrain and energy performance.

2.2 Tactical UGV System Architecture

The tactical UGV considered in this study adopts a four-wheel skid-steer configuration, which is suitable for compact robotic platforms operating in confined and unstructured environments. This configuration enables directional control through differential wheel speeds between the left and right sides of the vehicle, thereby eliminating the need for a dedicated steering mechanism and reducing mechanical complexity.

The proposed UGV architecture consists of four independently driven wheels powered by DC geared motors, as illustrated in Figure 2. The propulsion system is supplied by a rechargeable battery pack, while a motor driver unit regulates the electrical power delivered to each motor. A mobility control subsystem generates the required wheel speed commands based on the desired operating conditions, while a terrain interaction subsystem represents the effect of surface conditions on vehicle mobility.

The physical STRIDE tactical UGV platform used as the reference system for this study is shown in Figure 3.

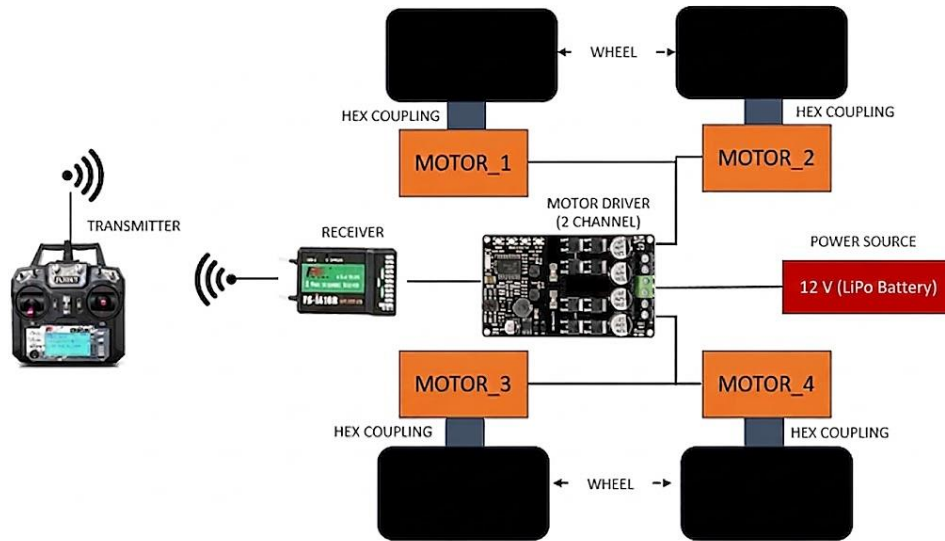


Figure 2: Tactical UGV powertrain system architecture showing the battery pack, motor driver, DC geared motors and wheel-drive configuration.



Figure 3: STRIDE tactical UGV platform used as the reference system for the predictive mobility model.

Vehicle motion is achieved by controlling the rotational speed of the wheel pairs. Forward and reverse motions occur when all wheels rotate at the same speed, while turning manoeuvres are produced by introducing a speed difference between the left and right wheel pairs. This steering approach eliminates the need for dedicated steering actuators, reducing system weight, maintenance requirements and mechanical complexity. Consequently, skid-steer platforms are widely adopted for small tactical UGVs deployed in military, security and search-and-rescue operations (Sharma, 2022).

The system architecture forms the foundation for the terrain characterisation, vehicle dynamics modelling, powertrain analysis and battery performance models implemented in MATLAB / Simulink. The interaction between these subsystems enables the predictive assessment of mobility performance and drivetrain requirements for tactical small UGV design.

2.3 Simulation Input Parameters

The predictive mobility model evaluates vehicle performance using several operational and design parameters that significantly influence mobility, power consumption, and endurance. The selected input parameters are presented in Table 1.

Table 1: Simulation input parameters for the predictive mobility model.

Parameter	Input Value
Battery Voltage	12 V
Battery Capacity	1,100 mAh
Battery Discharge Rate	25 C
Vehicle Mass	3, 6 and 9 kg
Wheel Radius	0.085 m
Wheel Diameter	0.170 m
Target Speed	6 km/h
Terrain Type	Asphalt, Sandy, Rocky
Slope Angle	0 - 40°

Terrain type is incorporated to account for varying wheel-terrain interaction characteristics. Each terrain is assigned a rolling resistance coefficient based on values commonly reported in off-road mobility studies (Vantsevich *et al.*, 2023; Hua *et al.*, 2025).

Table 2: Terrain classification and rolling resistance coefficients used in the simulation.

Terrain Type	Rolling Resistance Coefficient (C_{rr})
Asphalt	0.02
Sandy	0.25
Rocky	0.10

2.4 Vehicle Mobility Modelling

The mobility model is developed based on fundamental vehicle dynamics principles. The total tractive force required to propel the UGV is determined by considering terrain rolling resistance and gravitational forces induced by slope inclination

The rolling resistance force is calculated as:

$$F_{rr} = C_{rr}mg \cos \theta \quad (1)$$

where:

F_{rr} = rolling resistance force (N)

C_{rr} = rolling resistance coefficient

m = vehicle mass (kg)

g = gravitational acceleration (9.81 m/s²)

θ = slope angle (°)

The slope resistance force is calculated as:

$$F_{slope} = mg \sin \theta \quad (2)$$

Therefore, the total traction force required for vehicle motion is expressed as:

$$F_{total} = F_{rr} + F_{slope} \quad (3)$$

This modelling approach enables the prediction of terrain-dependent mobility performance under various operational conditions (Zhou *et al.*, 2022; Lopatka *et al.*, 2023).

2.5 Torque and Wheel Speed Modelling

The required wheel torque is determined based on the total traction force and wheel radius:

$$T = F_{total}r \quad (4)$$

where:

T = wheel torque (Nm)

r = wheel radius (m)

The rotational speed required to achieve the desired vehicle velocity is calculated using:

$$RPM = \frac{v}{2\pi r} \times 60 \quad (5)$$

where:

v = vehicle velocity (m/s)

The torque and wheel speed calculations provide the basis for motor selection and drivetrain sizing during the conceptual design stage.

2.6 Power Consumption and Current Demand Modelling

The mechanical power required to propel the UGV is estimated from the calculated torque and angular velocity.

$$P_{mech} = T\omega \quad (6)$$

where:

ω = angular velocity (rad/s)

The electrical power demand is subsequently determined based on the motor efficiency and drivetrain characteristics.

The current required by the system is estimated using:

$$I = \frac{P}{V} \quad (7)$$

where:

I = current (A)

P = electrical power (W)

V = battery voltage (V)

The energy modelling approach adopted in this study is consistent with energy consumption frameworks reported for autonomous robotic systems and off-road vehicles (Touzout *et al.*, 2021; Vantsevich *et al.*, 2023).

2.7 Simulation Scenarios and Performance Metrics

In order to evaluate the mobility and energy performance of the proposed tactical UGV, two simulation scenarios were conducted using the MATLAB / Simulink-based predictive mobility model. The simulations were designed to assess the effects of terrain condition, vehicle mass and slope inclination on key mobility and powertrain performance indicators. This simulation-based approach is consistent with previous studies that have used predictive modelling to evaluate vehicle-terrain interaction, mobility performance and energy consumption in autonomous ground vehicles operating in unstructured environments (Zhou *et al.*, 2022; Vantsevich *et al.*, 2023; Hua *et al.*, 2025).

Two simulation scenarios were considered for vehicle masses of 3, 6 and 9 kg. The first scenario, referred to as straight line mobility analysis, evaluated vehicle performance on three representative terrain types, namely asphalt, sandy and rocky surfaces. These terrain conditions were selected to represent different levels of rolling resistance commonly encountered during tactical reconnaissance and off-road operations. The simulations were conducted under flat ground conditions at 0° slope.

The second scenario, referred to as inclined terrain mobility analysis, evaluated the influence of slope gradient on vehicle performance. In this scenario, the UGV operated on asphalt terrain at slope angles of 10, 20, 30 and 40°. This scenario was used to assess the effect of increasing gravitational resistance on tractive force requirement, drivetrain loading and energy consumption.

For both simulation scenarios, the target vehicle speed was maintained at 6 km/h, while the battery voltage, capacity and discharge rate, as well as wheel radius and diameter were kept constant throughout the study. The simulation outputs include battery efficiency (%), speed efficiency (%), required torque (Nm), required motor speed (rpm), total power consumption (W), current draw (A) and battery state of charge (%). These performance indicators provide the basis for evaluating mobility capability, drivetrain requirements, motor selection criteria and battery loading under different operating conditions.

3. RESULTS & DISCUSSION

3.1 Straight Line Mobility Analysis

The simulation cases for straight line mobility analysis are summarised in Table 3. As battery voltage, capacity and discharge rate, target speed, as well as wheel radius and diameter were kept constant as specified in Table 1, only terrain type and vehicle mass were varied. All straight line simulations were conducted under flat ground conditions at 0° slope.

Table 3: Simulation cases for straight line mobility analysis.

Leg	Terrain Type	Mass (kg)
1	Asphalt	3
2	Sandy	3
3	Rocky	3
4	Asphalt	6
5	Sandy	6
6	Rocky	6
7	Asphalt	9
8	Sandy	9
9	Rocky	9

The straight line mobility analysis was conducted to evaluate the effects of terrain type and vehicle mass on the mobility and energy performance of the proposed tactical UGV. Three representative terrain types, namely asphalt, sandy and rocky surfaces, were considered for vehicle masses of 3, 6 and 9 kg, while the target speed was maintained at 6 km/h.

The simulation results in Table 4 indicate that both terrain condition and vehicle mass influence the mobility characteristics of the UGV. For all vehicle masses, asphalt terrain produced the lowest torque requirement, power consumption and current draw. In comparison, sandy and rocky terrains increased drivetrain loading due to greater wheel-terrain interaction and mobility resistance.

Table 4: Simulation results for straight line mobility analysis.

Leg	Battery Efficiency (%)	Speed Efficiency (%)	Required Torque (Nm)	Required Torque (kgfcm)	Required Speed (rpm)	Total Power (W)	Required Current (A)
1	94.99	99.86	0.01451	0.1480	191	1.509	0.1258
2	94.94	97.43	0.06796	0.6930	187.3	7.248	0.604
3	94.93	97.98	0.08435	0.8601	220.3	8.946	0.7455
4	94.98	99.89	0.0237	0.2417	191	2.465	0.2054
5	94.88	97.53	0.1305	1.3307	187.3	13.9	1.159
6	94.86	98.03	0.1641	1.6733	220.3	17.39	1.449
7	94.97	99.89	0.03289	0.3354	191.1	3.423	0.2852
8	94.83	97.57	0.193	1.9680	187.2	20.55	1.713
9	94.78	98.05	0.2438	2.4860	220.3	25.84	2.153

For the 3 kg vehicle configuration, the required torque increased from 0.0145 Nm on asphalt terrain to 0.0680 and 0.0844 Nm on sandy and rocky terrains respectively. The corresponding power consumption increased from 1.509 to 7.248 and 8.946 W, while current demand increased from 0.1258 to 0.6040 and 0.7455 A. This demonstrates the direct relationship between terrain resistance and drivetrain loading.

As vehicle mass increased, higher torque, power and current were required across all terrain types. For the 9 kg vehicle operating on rocky terrain, the required torque reached 0.2438 Nm, while power consumption increased to 25.84 W and current demand reached 2.153 A. This indicates that the combined effect of vehicle mass and terrain resistance has a significant influence on mobility performance.

Battery efficiency remained relatively stable across all straight line scenarios, ranging from 94.78 to 94.99%, while speed efficiency remained above 97%. This suggests that, under flat ground conditions, terrain resistance and vehicle mass were the dominant factors affecting drivetrain loading, while the battery system remained within an efficient operating range.

Overall, the straight line mobility results show that the proposed model can quantify the effects of terrain type and vehicle mass on torque demand, power consumption and current draw. These findings are consistent with previous studies which identified wheel-terrain interaction and rolling resistance as important factors affecting UGV traversability and off-road mobility performance (Beycimen *et al.*, 2023; Hua *et al.*, 2025).

3.2 Inclined Terrain Mobility Analysis

The simulation cases for inclined terrain mobility analysis are summarised in Table 5. Since battery voltage, capacity and discharge rate, target speed, as well as wheel radius and diameter were kept constant as specified in Table 1, only vehicle mass and slope angle were varied. Asphalt terrain was used for all the inclined terrain simulations.

Table 5: Simulation cases for inclined terrain mobility analysis.

Leg	Mass (kg)	Slope Angle (°)
1	3	10
2	3	20
3	3	30
4	3	40
5	6	10
6	6	20
7	6	30
8	6	40
9	9	10
10	9	20
11	9	30
12	9	40

The inclined terrain mobility analysis was conducted to investigate the effect of slope angle and vehicle mass on the mobility performance and energy requirements of the proposed tactical UGV. The simulations were performed on asphalt terrain at slope angles of 10, 20, 30 and 40° for vehicle masses of 3, 6 and 9 kg, while the target speed was maintained at 6 km/h.

The simulation results in Table 6 show that slope angle has strong influence on vehicle performance. As the slope angle increased, the gravitational resistance opposing vehicle motion also increased, resulting in higher tractive effort, torque requirement, power consumption and current draw. For the 3 kg vehicle configuration, the required torque increased from 0.1208 Nm at 10° to 0.4063 Nm at 40°. Over the same slope range, power consumption increased from 12.70 to 330 W, while current demand increased from 1.058 to 27.5 A.

Table 6: Simulation results for inclined terrain mobility.

Leg	Battery Efficiency (%)	Speed Efficiency (%)	Required Torque (Nm)	Required Torque (kgfcm)	Required Speed (rpm)	Total Power (W)	Required Current (A)
1	94.98	98.81	0.1208	1.2318	191.1	12.7	1.058
2	94.8	97.66	0.2236	2.2800	191	23.78	1.982
3	94.71	96.32	0.3197	3.2600	191.2	34.51	2.876
4	92.25	95	0.4063	4.1430	178.3	330	27.5
5	94.79	98.84	0.2363	2.4096	191	24.83	2.069
6	94.61	97.69	0.4418	4.5050	191.1	46.99	3.916
7	94.43	96.35	0.6341	6.4659	191	68.35	5.696
8	92.25	95	0.8073	8.2320	179.4	330	27.5
9	94.69	98.84	0.3518	3.5873	191	36.97	3.081
10	94.42	97.7	0.6601	6.7310	191.1	70.2	5.85
11	94.15	96.36	0.9485	9.6719	191.1	102.3	8.526
12	92.25	95	1.208	12.3180	179.8	330	27.5

A similar trend was observed for the 6 and 9 kg vehicle configurations. For the 9 kg vehicle, the required torque increased from 0.3518 Nm at 10° to 1.2080 Nm at 40°. Power consumption increased from 36.97 to 330 W, while current demand increased from 3.081 to 27.5 A. These results indicate that the required tractive effort is influenced by both vehicle mass and slope angle.

An important observation is that all vehicle configurations reached the same maximum power consumption of 330 W and current draw of 27.5 A at slope angle of 40°. This corresponds to the maximum power delivery capability of the battery system. Based on a battery voltage of 12 V, battery capacity of 1,100 mAh, and discharge rate of 25 C, the maximum available current is:

$$I_{max} = C_{bat} \times C_{rate} = 1.1 \text{ Ah} \times 25 \text{ C} = 27.5 \text{ A} \quad (8)$$

Therefore, the maximum available electrical power is:

$$P_{max} = V \times I_{max} = 12 \times 27.5 = 330 \text{ W} \quad (9)$$

This indicates that battery discharge capability becomes the limiting factor under the most demanding inclined terrain condition. Although higher vehicle mass and slope angle increase the torque requirement, the electrical power output is constrained by the battery specification.

The required wheel speed remained relatively constant at approximately 191 rpm for slope angles between 10 and 30°. However, at 40°, the required wheel speed decreased to approximately 178 - 180 rpm, while speed efficiency reduced to 95%. This suggests that the vehicle begins to experience power limited operation as the available battery power approaches its maximum output.

Battery efficiency also decreased slightly from approximately 95% at lower slopes to 92.25% at 40°. This reduction is associated with increased current demand and higher electrical loading under steep-slope operation. Overall, the results show that slope angle is a critical design consideration for tactical UGV mobility, particularly in relation to motor torque capacity, motor driver sizing and battery discharge capability.

3.3 Engineering Implications for Tactical UGV Design

The simulation results demonstrate that terrain condition, vehicle mass and slope angle directly influence the drivetrain and energy requirements of tactical small UGVs. In straight line operations, terrain resistance and vehicle mass primarily affect torque demand, power consumption and current draw. Under inclined terrain conditions, slope angle becomes the dominant factor, with the 40° slope cases reaching the battery discharge limit of 27.5 A and maximum available power of 330 W.

These findings show that motor selection, motor driver sizing, drivetrain configuration and battery specification should be considered together during the early design stage. A motor with sufficient torque alone may not be adequate if the battery and motor driver cannot supply the required current under steep slope or high load conditions. Similarly, increasing vehicle mass may significantly reduce mobility margin, especially on uneven terrain or slopes.

Overall, the developed MATLAB / Simulink-based predictive mobility model provides a practical decision support tool for evaluating drivetrain loading and energy demand before prototype fabrication. By estimating torque, speed, power and current requirements under different operating conditions, the framework can support more informed design decisions for tactical small UGV development.

4. CONCLUSION

This study developed a MATLAB / Simulink-based predictive mobility model for evaluating the mobility and energy performance of a tactical small UGV under varying terrain and slope conditions. The proposed framework integrates terrain characterisation, vehicle dynamics modelling, powertrain analysis and battery performance evaluation to estimate key parameters, including required torque, motor speed, power consumption, current draw, battery efficiency and state of charge, as well as speed efficiency. +

The simulation results demonstrated that terrain condition, vehicle mass and slope angle significantly influence the mobility performance and drivetrain requirements of tactical small UGVs. Under straight line conditions, increasing terrain resistance and vehicle mass resulted in higher torque, power and current requirements, while battery efficiency remained relatively stable. Under inclined terrain conditions, slope angle became the dominant factor affecting mobility performance, with the 40° slope cases reaching battery discharge limit of 27.5 A and maximum available power of 330 W.

These findings confirm the usefulness of the proposed model as an early stage simulation tool for assessing whether the selected drivetrain and battery configuration can meet the intended operating conditions. By providing quantitative estimates of mobility and energy requirements before physical testing, the model can help reduce design uncertainty and support more efficient tactical UGV development. Future work will focus on validating the simulation results using a physical UGV platform and extending the model by incorporating wheel slip behaviour, terrain deformability and advanced terramechanics models to improve prediction accuracy under real-world operating conditions.

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REAL-TIME LIDAR-BASED SLAM AND RRT PATH PLANNING FOR MOBILE ROBOTS

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ABSTRACT

Deploying autonomous mapping on low cost robotic platforms remains a practical challenge, particularly when hardware constraints such as the absence of wheel encoders limit the available sensor modalities. This paper documents the implementation and evaluation of a simultaneous localisation and mapping (SLAM) system built around AlphaBot2-Pi, a Raspberry Pi-based differential-drive robot, using a 2D RPLiDAR A1 sensor and the Hector SLAM algorithm within the ROS Noetic framework. The robot was manually teleoperated through a custom cardboard maze while laser scan data was incrementally processed to produce a 2D occupancy grid map, visualised in real time via RViz. The resulting map was subsequently converted into a binary obstacle grid and used as input to a rapidly exploring random tree (RRT) path planner, which computed a collision-free route with 32 waypoints spanning approximately 1,600 grid units. Testing revealed that the lack of wheel encoders prevented autonomous path execution, as Hector SLAM relies solely on scan matching and cannot draw on odometry feedback. Despite this constraint, the work confirms the viability of SLAM-based mapping and motion planning on budget hardware and provides a replicable software foundation for future encoder-enabled autonomous navigation.

Keywords: *Hector simultaneous localisation and mapping (SLAM); rapidly exploring random tree (RRT); mobile robot; LiDAR mapping; indoor navigation.*

1. INTRODUCTION

Autonomous robots must construct a spatial representation of their surroundings while simultaneously estimating their position within that environment. This dual requirement is addressed through simultaneous localisation and mapping (SLAM), a fundamental capability in mobile robotics that reduces reliance on pre-existing maps or Global Navigation Satellite System (GNSS) infrastructure (Hensel *et al.*, 2022; Li *et al.*, 2024). SLAM has been applied across numerous domains, including warehouse logistics, disaster response, agricultural inspection and planetary surface exploration, particularly where robots must operate in unfamiliar environments (Rajapakshe & Hettiarachchi, 2022; Jiang *et al.*, 2025).

Most published SLAM studies focus on well resourced platforms equipped with high-end LiDAR sensors, graphics processing units and multi-sensor fusion systems (Pang *et al.*, 2024; Ren *et al.*, 2025). Such configurations may be impractical for educational platforms and early stage prototypes. This raises the question of how effectively SLAM can be implemented using a low cost robot, a budget sensor and open source middleware, as well as the extent to which hardware limitations affect the system's capabilities (Kassem & Asem, 2024; Sui *et al.*, 2025).

This study investigates the implementation of Hector SLAM on AlphaBot2-Pi, a Raspberry Pi 3-powered differential drive robot equipped with a Slamtec RPLiDAR A1 sensor (Waveshare, 2025). ROS Noetic provides the middleware for sensor integration, inter-process communication and real-time map visualisation. Hector SLAM was selected because it can operate without wheel-encoder input, making it suitable for a platform that does not provide wheel-based odometry (Kohlbrecher *et al.*, 2011).

The study makes three main contributions. First, a complete robot operating system (ROS)-based SLAM pipeline is implemented and evaluated on a low cost mobile robot, from sensor integration to real-time map generation. Second, the resulting occupancy grid is used for offline rapidly exploring random tree (RRT) path planning, demonstrating the potential link between environmental mapping and route generation (LaValle, 1998). Third, the study examines the absence of wheel encoders as the principal limitation of the platform, explaining its effect on autonomous path execution and identifying the hardware modification required for future development (Kiran *et al.*, 2022; Barbadekar *et al.*, 2023).

The remainder of the paper is organised into six sections. Sections 2 and 3 describe the hardware platform, system architecture and software framework. Section 4 outlines the experimental setup and procedure, while Section 5 presents the mapping and path-planning results. Section 6 discusses the main findings and limitations, followed by the conclusion and future work in Section 7.

2. SYSTEM DESCRIPTION

The experimental platform comprises an AlphaBot2-Pi mobile robot equipped with an RPLiDAR A1 sensor and connected to a host computer through a local wireless network. The main hardware components and system architecture are described below.

2.1 AlphaBot2-Pi Platform

The AlphaBot2-Pi is a circular, two-wheeled differential drive robot developed by Waveshare for educational and prototyping applications (Waveshare, 2025). It consists of an AlphaBot2 base, which houses the drive system, and an upper board that supports the Raspberry Pi and peripheral interfaces, as shown in Figure 1. The robot is driven by two geared motors controlled through a dual H-bridge driver, while a Raspberry Pi 3 Model B serves as the main processor. The platform does not include wheel encoders and thus cannot provide wheel-based odometry for closed-loop motion control (Termizi *et al.*, 2024; Kahar *et al.*, 2025).



Figure 1: The AlphaBot2-Pi mobile robot platform showing its two layer construction and differential drive configuration.

2.2 RPLiDAR A1 Sensor

A Slamtec RPLiDAR A1M8 2D laser scanner was mounted on the upper layer of the robot, with its 360° scanning field kept unobstructed, as shown in Figure 2. The sensor operates at approximately 10 Hz, has a maximum range of 12 m, and communicates with the Raspberry Pi through a USB serial connection.

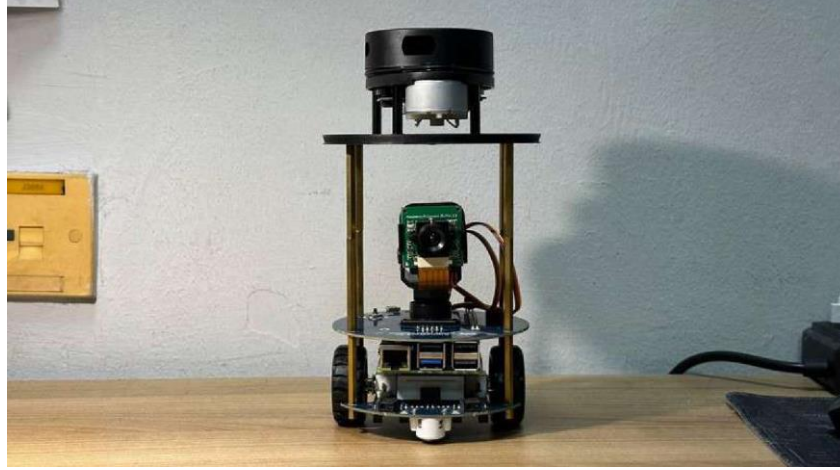


Figure 2: AlphaBot2-Pi mobile robot with RPLiDAR A1 sensor mounted on the top layer.

2.3 Overall System Architecture

The system operates across two computing nodes linked over a local Wi-Fi network, as shown in Figure 3. The AlphaBot2-Pi, running ROS Noetic on Ubuntu 20.04, acts as the primary robot node, and hosts the LiDAR driver, SLAM process and motor controller. A host PC on the same ROS distribution connects via SSH, and handles visualisation in RViz and keyboard teleoperation. The ROS master runs on the Raspberry Pi and manages communication between the nodes (Borthakur & Panja, 2024).

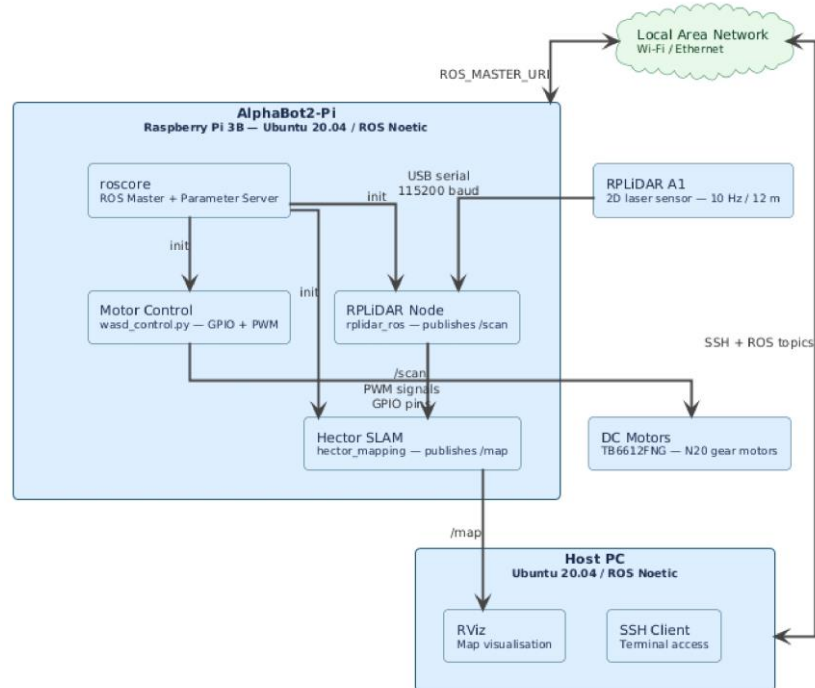


Figure 3: System architecture showing the two node ROS network: the AlphaBot2-Pi robot node and the host PC operator interface.

3. SOFTWARE ARCHITECTURE

3.1 ROS Environment, Sensor Integration and SLAM Configuration

The software system was developed using ROS Noetic on Ubuntu 20.04, with the required packages installed in a catkin workspace on the Raspberry Pi (Borthakur & Panja, 2024). The RPLiDAR A1 was integrated using the `rplidar_ros` package, which publishes laser scan data to the `/scan` topic.

Hector SLAM subscribes to the laser scan data and generates the occupancy grid map. It was selected because it can estimate the robot's pose without wheel-based odometry, making it suitable for the encoder free platform used in this study (Kohlbrecher *et al.*, 2011). The resulting map can subsequently be exported for analysis and path planning.

3.2 ROS Node Architecture and Motor Control

During mapping, the main ROS nodes comprise the LiDAR driver, Hector SLAM, map-export, RViz visualisation and teleoperation nodes. These nodes exchange laser scan, occupancy grid, pose and map saving messages, as illustrated in Figure 4 (Borthakur & Panja, 2024). The robot was manually controlled using a custom Python-based keyboard teleoperation script, which translated directional commands into motor control signals through the Raspberry Pi.

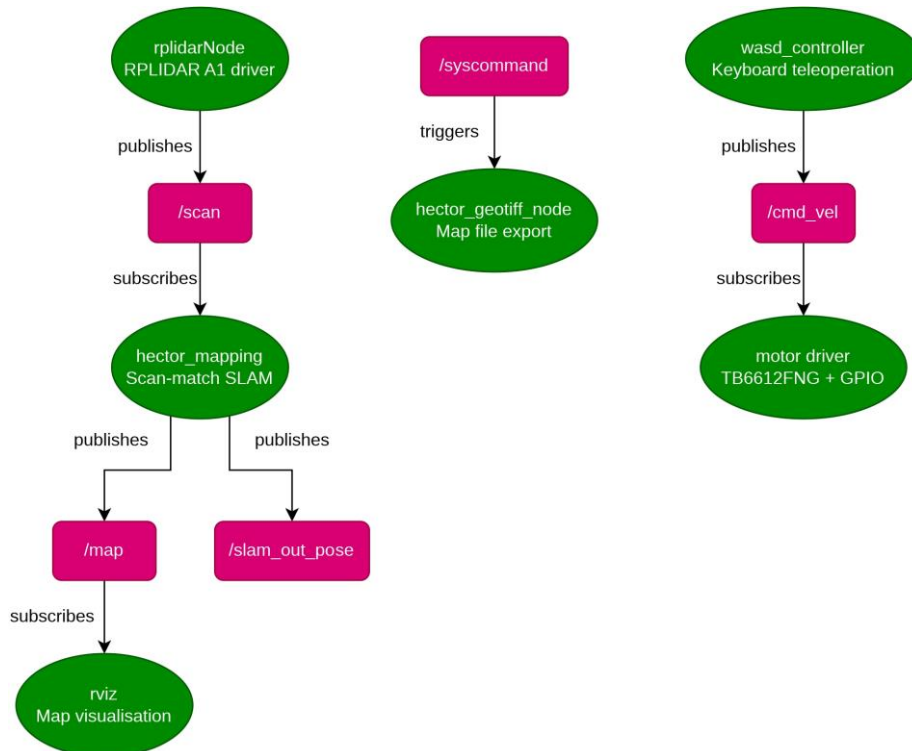


Figure 4: ROS node graph illustrating the communication topology during a SLAM mapping session.

4. EXPERIMENTAL SETUP

4.1 Custom Test Environment

A controlled test environment was constructed from a large corrugated cardboard box fitted with vertical partition walls to form interior corridors and corners. The layout was kept compact enough to stay within the RPLiDAR's usable range while offering sufficient geometric variations, including straight runs, turns and narrow gaps, for the scan-matching process. The robot started each trial from a fixed position near the top left corner of the enclosure. Figure 5 shows the constructed maze, including the partition walls and corridors mapped during each trial.



Figure 5: Custom built cardboard maze used as the experimental environment for SLAM evaluation.

4.2 System Initialisation Sequence

Before each session, the ROS master, RPLiDAR driver, motor control script and Hector SLAM node were launched on the Raspberry Pi. The host computer was connected through SSH and used to run RViz for real-time visualisation of the generated occupancy grid. Sensor communication and system status were verified before the mapping began.

4.3 Mapping Procedure

With all nodes running and RViz displaying an empty initial grid, the robot was driven through the maze using the WASD interface. The robot was moved in short intervals with brief pauses between movements to maintain stable scan matching. It traversed the full perimeter and internal passages of the enclosure before the completed map was saved.

4.4 Path Planning Simulation

Hector SLAM does not include a built-in path planner, while direct integration with the ROS navigation stack was not feasible because the platform lacked the required odometry. Therefore, path planning was conducted separately using an online motion planning visualiser. The occupancy grid from RViz was manually reproduced as a binary obstacle map in the tool to match the wall layout of the SLAM output. The RRT algorithm (LaValle, 1998) was then run on that grid to determine a collision free route from user-defined start and goal points.

5. RESULTS

5.1 SLAM Map Output

Hector SLAM produced a coherent occupancy grid during the mapping run. As shown in Figure 6, detected walls are represented by solid black lines, while free corridors are shaded grey and unscanned regions remain white. The robot trajectory is indicated by the green line, with the pose axes showing its current orientation. The final map closely resembled the physical layout of the test environment, with no major visible drift, wall duplication or distortion.

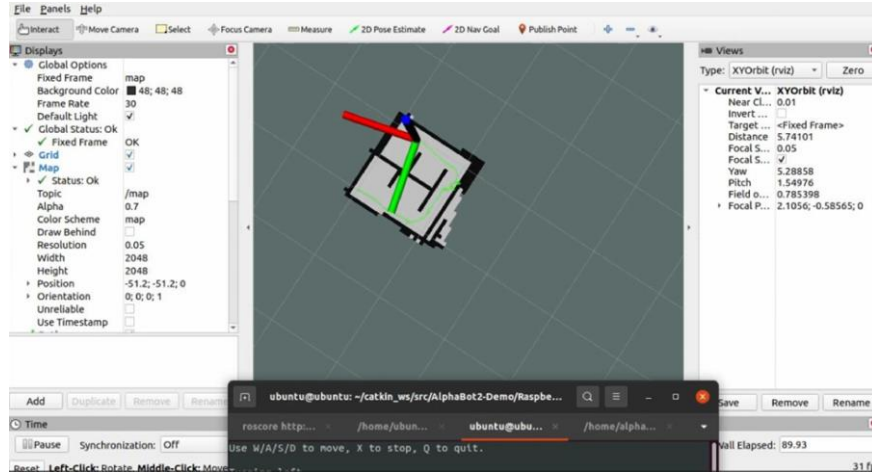


Figure 6: 2D occupancy grid map generated by Hector SLAM, visualised in RViz. Black lines indicate detected walls, grey regions represent free space, while green trace shows the robot trajectory.

5.2 RRT Path Planning Result

The RRT planner was assigned with start coordinates of (634, 463) and goal coordinates of (641, 162) in the grid frame. The algorithm generated a collision free route comprising of 32 waypoints and covering approximately 1,600 grid units, as shown in Figure 7. The yellow branches indicate the selected route, while the red branches represent the remaining explored nodes. The generated route passed through the corridor structure and avoided the obstacle cells.



Figure 7: RRT path planning result on the binary occupancy grid derived from the SLAM map. Yellow branches indicate the computed path (32 waypoints, ~1,600 grid units), while red branches show the explored tree.

6. DISCUSSION

6.1 Impact of Encoder Absence on SLAM Performance

The absence of wheel encoders was the principal hardware limitation encountered during the experiments. Without encoder-based odometry, the system relied primarily on LiDAR scan matching for pose estimation, which limited mapping stability during continuous movement.

Hector SLAM estimates the robot pose by aligning incoming laser scans with the evolving map representation (Kohlbrecher *et al.*, 2011). When movement between successive scans remained small, sufficient geometric overlap was maintained for stable scan matching. However, continuous movement, produced visible wall shear and map distortion during the initial trials. Moving the robot in short intervals with brief pauses reduced these effects and produced a more coherent map. Similar sensitivity to irregular motion has been reported in other low-cost robotic platforms without encoder feedback (Kassem & Asem, 2024; Tamsin *et al.*, 2024).

6.2 Path Execution Constraint

A valid path was generated, but the robot could not execute it autonomously. Waypoint tracking requires closed-loop control, in which the robot estimates its current position, compares it with the target waypoint and adjusts the motor commands accordingly (Qu *et al.*, 2024). Without encoder-based odometry, the platform could not reliably measure the distance travelled or compensate for wheel slip, inertia and variations in motor response. Consequently, autonomous movement could deviate from the planned route without continuous positional feedback (Tamsin *et al.*, 2024; Ren *et al.*, 2025). Table 1 summarises the functional differences between the existing AlphaBot2-Pi configuration and an encoder equipped platform.

Table 1: Comparison between AlphaBot2-Pi motor and DC motor with encoder.

Criterion	No Encoder	With Encoder
Feedback Control	None	Real-time position / speed
Odometry Support	Not supported	Encoder pulse count
Path Following	Cannot track	Reliable waypoints
Pose Estimation	Scan match only	Dead reckoning + fusion
Navigation Accuracy	Low	High
Path Execution	Not supported	Supported
Cost	Lower	Slightly higher

6.3 Feasibility Assessment

The results indicate that the software architecture provides a suitable foundation for SLAM-based mapping and path planning. The occupancy grid generated by Hector SLAM corresponded closely with the physical layout of the test enclosure, while the RRT planner successfully produced a valid route through the mapped environment. The ROS-based architecture also supports the future integration of localisation, global and local planning, as well as obstacle avoidance functions (Borthakur & Panja, 2024; Sui *et al.*, 2025). However, achieving autonomous navigation would require further hardware and software integration, particularly encoder-based odometry, closed-loop motor control and real-time path execution. Therefore, replacing the existing motors with encoder-equipped alternatives would provide an important basis for further development towards full autonomy.

7. CONCLUSION

This study demonstrated the feasibility of real-time 2D mapping using Hector SLAM on a low cost mobile robot without wheel encoders. Under controlled, slow movement conditions, the system generated an occupancy grid that closely represented the test environment. The resulting map was subsequently used for offline RRT path planning, which produced a collision free route. However, the robot was unable to execute the planned route because the platform lacked the odometry and motion feedback required for closed loop waypoint tracking.

The findings indicate that the existing ROS-based architecture provides a suitable foundation for further development towards autonomous navigation. Future work should focus on integrating rotary encoders for wheel-based odometry, fusing encoder and inertial measurement unit data for more robust pose estimation, implementing adaptive Monte Carlo localisation and ROS navigation stack for real-time path execution, as well as developing a lightweight web interface for remote monitoring and control.

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MAKE-OR-BUY EVALUATION FOR HIGH MOBILITY MULTIPURPOSE VEHICLE (HMMV) COMPONENT SELECTION

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ABSTRACT

Component sourcing decisions made during the preliminary design of military vehicles influence development cost, integration complexity, lifecycle supportability and long-term operational availability. This paper presents an inference-based framework for evaluating make-or-buy strategies for a high mobility multipurpose vehicle (HMMV) programme under information-limited conditions. The methodology combines functional system decomposition, analysis of observable donor platform characteristics, qualitative component classification and a weighted decision matrix to assess technical, economic, operational and strategic considerations without relying on proprietary design or cost data. The framework is demonstrated through application to the HMMV suspension system. The results indicate that most suspension components favour a Make (outsource) strategy because they require project specific adaptation, while the suspension-mount insert is classified as Modify and the stabiliser bar as Buy. No component is identified for complete in-house development. The findings show that preliminary sourcing decisions can be developed systematically using engineering judgement and system level understanding, while directing internal research and development toward application specific integration, mounting structures and structural optimisation. The framework provides a practical decision support tool for early stage military vehicle development, and should be further validated using detailed technical, supplier, cost and lifecycle data.

Keywords: Make-or-buy; component selection; high mobility multipurpose vehicle (HMMV); donor platform; decision matrix.

1. INTRODUCTION

Make-or-buy decisions are a fundamental consideration in vehicle engineering and manufacturing because they determine whether components and subsystems should be developed internally, procured from external suppliers or adapted from existing solutions. Decisions made during the preliminary design stage are particularly important because they establish constraints that influence development cost, schedule, system integration, lifecycle supportability and future upgrade potential (Potts *et al.*, 2020; Dullen *et al.*, 2021; Wöhr *et al.*, 2023). Although make-or-buy evaluations have traditionally focused on production cost, economies of scale and supplier competitiveness, sourcing decisions must also consider technical and strategic factors, including component complexity and system integration requirements (Aspeteg *et al.*, 2025) as well as internal engineering capability, intellectual property, supplier availability and supply chain risk (Reitsma *et al.*, 2025). Therefore, a comprehensive evaluation should balance economic efficiency with technical feasibility and the need to retain control over strategically important capabilities (Messerschmidt, 2026).

These considerations are especially significant in military vehicle development. Military platforms are generally produced in relatively low volumes, must satisfy mission specific performance requirements and are expected to remain operational for extended service periods. Their development must thus

account for reliability, maintainability, adaptability, obsolescence management, export controls and dependence on foreign suppliers. While standard or non-critical components may be procured externally, components that require substantial customisation may require project specific design or modification (Dattathreya, 2025), while components that contribute to safety-critical and functional requirements require careful consideration of their architecture and system integration during military vehicle development (Doran *et al.*, 2024). Similarly, strategically important technologies may require greater programme level control to preserve critical capabilities and reduce dependency on external sources (DOD, 2025)

Several analytical approaches have been developed to support make-or-buy decisions. Cost-oriented methods commonly apply total cost of ownership or lifecycle cost analysis, while capability-based approaches emphasise the retention of components associated with an organisation's core competencies. Strategic sourcing frameworks additionally consider supplier capability, market availability and long-term supply chain resilience (Govindan *et al.*, 2020; Liu *et al.*, 2021; Dubey *et al.*, 2022). However, many of these approaches require detailed cost estimates and supplier information which may be difficult to obtain during the early stages of defence research and development (Aspeteg *et al.*, 2025). Limited access to technical data and intellectual property can also create challenges for sustainment and future modification of defence systems (Draper-Amason & McGrath, 2025).

This limitation is relevant to the high mobility multipurpose vehicle (HMMV) programme, where preliminary sourcing decisions must be made while design information remains incomplete. The programme uses an existing base vehicle, hereafter referred to as the donor platform, and its components must be assessed to determine whether they should be retained, modified, procured or developed to meet military operational requirements. Therefore, a practical method is needed to support early stage sourcing decisions using engineering knowledge, observable vehicle characteristics and system level understanding despite the limited availability of detailed technical specifications. (Dullen, 2025).

This paper presents an inference-based framework for evaluating make-or-buy component selection strategies for the HMMV programme. The methodology combines functional system decomposition, analysis of observable donor-platform characteristics, qualitative component classification and a weighted decision matrix to assess in-house development, outsourced development, external procurement and modification options. Applied to the HMMV suspension system, the framework demonstrates how preliminary sourcing recommendations can be developed using non-proprietary information and structured engineering judgement. It is intended to support early design planning, identify areas requiring further investigation and highlight opportunities for targeted R&D.

2. MAKE-OR-BUY STRATEGY IN MILITARY VEHICLE DEVELOPMENT

Make-or-buy decisions influence development cost, system integration, operational performance and long-term sustainment in military vehicle programmes. Components may be developed in-house, procured externally or adapted from existing platforms depending on their technical complexity, strategic importance, availability and integration requirements. Although some sourcing principles are shared with commercial vehicle development, military programmes face additional constraints related to low production volumes, mission specific performance, extended service life, supply chain security and technological sovereignty.

2.1 Factors and Considerations in Military Vehicle Development

Commercial vehicle programmes typically operate at high production volumes, and benefit from economies of scale, standardised components and mature supplier networks. Therefore, their sourcing decisions can place substantial emphasis on cost efficiency, supplier capability and established production capacity (Lampón *et al.*, 2023; Yeung, 2024). In contrast, military vehicle programmes are usually characterised by lower production volumes, which can limit economies of scale and create

challenges in supplier development and cost competitiveness (Bernat, 2023), while their development must satisfy stringent operational requirements covering vehicle dynamics, protection, mobility and mission performance (Threepopnartkul *et al.*, 2024). Components must satisfy requirements related to protection, survivability, reliability, mobility, durability, as well as operation under complex environmental and mechanical conditions (Rybak *et al.*, 2024), while long service lives introduce additional sustainment concerns, including continued availability of spare parts, maintenance support, as well as the management of component obsolescence and future upgrade requirements (López-Almodóvar *et al.*, 2025).

Sourcing decisions are further influenced by the maturity and security of the supply chain. Dependence on foreign or single source suppliers may expose a programme to export controls, extended lead times, supply disruption and reduced control over critical technologies (Balakrishnan & Lazar, 2022). Standardised and non-critical components may be procured externally where capable suppliers are available, while mission critical or strategically sensitive components may require in-house development, closer design control or long-term supplier partnerships. Effective make-or-buy decisions must thus consider technical, economic, operational and strategic factors collectively. Poorly informed sourcing decisions can increase integration difficulty, development risk and lifecycle cost, while reducing maintainability and future adaptability (Dullen *et al.*, 2021; INCOSE, 2023; Wöhr *et al.*, 2023). A structured evaluation framework is consequently required to support early design decisions and balance internal capability development with the advantages of external sourcing.

2.2 Role of Vehicle Architecture and System Integration

Existing vehicle platforms are commonly used as the basis for military vehicle development because developing a complete vehicle from the ground up may be impractical in terms of cost, time and technical risk. Moreover, military systems are characterised by high complexity, substantial cost and long lifecycles, making architectural decisions important for managing cost, adaptability and uncertainty (Bordley *et al.*, 2011). In donor platform-based programmes, vehicle architecture is a major determinant of whether individual components can be retained, modified, externally procured or newly developed. Vehicle architectures may be broadly described as monolithic or modular. In a monolithic architecture, subsystems are tightly integrated and highly interdependent, with components often designed specifically for a particular platform. Such integration may improve structural or performance efficiency, but it reduces sourcing flexibility because replacing or modifying one component can affect several other subsystems. Therefore, monolithic architectures tend to require greater design control and more extensive integration and validation effort (Guo *et al.*, 2021; Hetherington, 2024).

A modular architecture divides the vehicle into relatively independent functional modules connected through defined mechanical, electrical and data interfaces. This arrangement allows modules to be developed, replaced or upgraded with limited impact on the remainder of the platform. Modularity supports parallel development, facilitates the use of supplier-provided or commercial off-the-shelf components, and enables technology insertion throughout the vehicle lifecycle (Hartmann *et al.*, 2021; Jackson, 2021; Sanchez & Shibata, 2021). These characteristics are particularly beneficial for military vehicles, which may require mission reconfiguration, capability upgrades, and obsolescence management over several decades of service (Morgan *et al.*, 2021; Dattathreya, 2024; Radoman *et al.*, 2025). However, modularity depends on clearly defined interfaces and careful architectural planning, as the relationships between components and interfaces influence the resulting product architecture and development complexity (Monetti & Maffei, 2024). Therefore, vehicle architecture must be considered during the preliminary design stage, as architectural decisions influence system integration and long-term adaptability, while modularity can also provide greater flexibility in component configuration and sourcing (Dattathreya, 2025).

3. METHODOLOGY

Conventional make-or-buy analyses commonly rely on detailed cost models, complete design specifications and comprehensive supplier assessments (Medina-Serrano *et al.*, 2020; Meyer *et al.*, 2021). However, during the early stages of defence research and development, such information may be incomplete, proprietary or restricted. The proposed methodology thus supports preliminary sourcing decisions using engineering expertise, observable design characteristics and system level understanding rather than confidential technical or commercial data.

3.1 HMMV Platform and Development Context

The HMMV project is a research and development initiative undertaken through a transfer of technology collaboration between the Science and Technology Research Institute for Defence (STRIDE) and EMAR Technology Sdn. Bhd. It aims to develop a multipurpose vehicle capable of supporting different operational roles, agencies and mission environments. The HMMV uses the Toyota Land Cruiser CBA-UZJ200W as its donor platform, selected based on its chassis capability and power requirements (Figure 1). Using an existing vehicle platform can reduce development time and cost by leveraging previously developed and tested systems, although subsequent modification and technology integration may introduce additional technical and testing challenges (Ware, 2004).

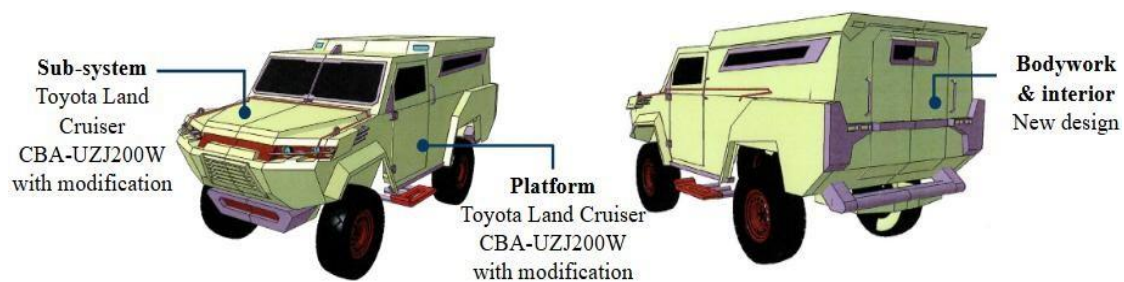


Figure 1: HMMV conceptual design and vehicle configuration.

Modularity is a central design consideration for the HMMV. The platform is divided into functional subsystems such as mobility, mission equipment, electronic systems and protection modules. Defined subsystem boundaries and interfaces enable communication equipment, surveillance sensors and other mission specific payloads to be integrated or replaced without extensive redesign of the base vehicle. From a sourcing perspective, this allows standardised or non-critical components to be procured externally while retaining closer control over strategically important or highly integrated subsystems. Customisation is also required because the vehicle must support roles such as patrol, surveillance, logistics support, as well as command and control operations. Therefore, existing components may need to be modified, while mission specific equipment, sensors and protection features must be integrated according to operational requirements. Components with strong platform dependencies or specialised interface requirements may consequently require internal design input or supplier-led customisation rather than direct procurement.

Adaptability ensures that the HMMV can accommodate evolving operational requirements and technological developments during its service life. New subsystems, upgraded components and additional mission equipment should be incorporated without major structural redesign. This reduces obsolescence risk, supports continued experimentation and enables several operational configurations to be developed from a common vehicle architecture. The combined application of modularity, customisation and adaptability thus provides the basis for HMMV make-or-buy decisions, enabling the programme to balance technical performance, integration requirements, strategic control, development costs and long-term supportability, while making effective use of the donor platform.

3.2 Study Approach

The study adopts an inference-based preliminary design methodology comprising four stages: functional system decomposition, analysis of observable design characteristics, component evaluation using classification criteria and decision matrix assessment. Together, these stages provide a structured and transparent approach for identifying plausible Make, Buy or Modify strategies under information-limited conditions (Cinelli *et al.*, 2020; Fernández *et al.*, 2021). Functional decomposition establishes the major vehicle systems, subsystems and components to be assessed, while observable design analysis identifies relevant structural features, interfaces and platform constraints from the donor vehicle. The classification stage evaluates each component against defined technical, economic and strategic criteria, and the decision matrix combines the resulting scores to determine a preliminary sourcing strategy. Table 1 summarises the four methodological stages and their functions within the evaluation process.

Table 1: Methodological steps for make-or-buy evaluation.

Methodological Step	Objectives	Significance
Functional system decomposition	To categorise the vehicle into major subsystems for structured analysis.	Allows identification of critical subsystems to be analysed and simplifies the evaluation of make-or-buy decisions at a system level.
Analysis based on observable design characteristics	To infer design characteristics and constraints from the donor platform.	Enables meaningful evaluation in the absence of full design specifications, leveraging observable data to support R&D decision-making.
Component evaluation based on classification criteria	To assess component criticality, complexity and integration requirements by engineering attributes.	Ensures that high risk or mission critical components are recognised early and prioritised for in-house development (if feasible) or careful sourcing.
Decision matrix assessment	To systematically identify plausible make, buy or modify sourcing strategies taking into consideration unique factors in military vehicle development programmes.	Provides a structured, transparent framework for early stage sourcing decisions, balancing technical, strategic, and operational considerations.

The methodology is intended to identify plausible sourcing options rather than verify the actual design and procurement decisions adopted in the HMMV programme. Its purpose is to provide defensible preliminary recommendations based on industry practice, vehicle design principles and structured engineering judgement.

3.3 System Decomposition and Observable Design Analysis

Functional system decomposition categorises the vehicle into major systems, subsystems and components to support structured analysis of technical complexity, system interdependencies and sourcing implications (Schmidt *et al.*, 2021; de Lima *et al.*, 2026). This process clarifies subsystem boundaries and enables the evaluation of how individual sourcing decisions may affect overall vehicle integration. Highly coupled components may require retention from the donor platform, substantial modification or close supplier involvement, whereas components with standardised interfaces may be more suitable for external procurement. Decomposition also supports the assessment of manufacturability, modularity, supplier availability and the engineering effort required for adaptation or redevelopment.

For the HMMV, the decomposition includes the chassis, powertrain, electrical and electronic systems, body systems, as well as mission systems. These are further divided into relevant subsystems and major components, as presented in Table 2. The resulting architectural structure provides the basis for identifying which components should be evaluated using the proposed classification criteria.

The donor platform, the Toyota Land Cruiser CBA-UZJ200W, is then examined to infer design characteristics and constraints relevant to HMMV development. As a mature commercial platform, it provides a practical basis for assessing structural configuration, subsystem layout and integration requirements without requiring access to proprietary design documentation (Ulrich *et al.*, 2020). The analysis considers visible mechanical interfaces, mounting points, structural joints, subsystem connections, available installation space and load bearing features. These characteristics indicate the level of integration between the chassis, suspension, powertrain, body and mission systems, as well as the likely effort required to retain, modify or replace individual components.

Table 2: Decomposition of the major systems and subsystems of the HMMV architecture.

Primary System	Subsystem	Major Components
Chassis system	Chassis platform	Frame, cross members, subframe, body mounts
	Suspension system	Front suspension (helical spring, bush, central clamp), rear suspension (leaf spring), shock absorbers, stabiliser bar, suspension mount insert, linkage system (lower arm, upper arm)
	Axle assembly	Axle shaft, axle casing, differential
	Wheel assembly	Wheel hub assembly, rims, tyres
	Brake system	Brake disc/drum, brake caliper, master cylinder, brake booster
	Driver control system	Steering system, gear shift system, accelerator system, parking brake system
Powertrain	Engine	Engine block, cooling system, air intake system, exhaust system
	Transmission system	Transmission gearbox, transfer case, clutch system (if applicable), differential
Electrical	Power and Control	ECU, wiring harness, battery system, alternator, fuse & relay box
	Communication & instrumentation	Instrument cluster, sensors, vehicle control modules
Body	Interior	Seats, dashboard, control panel, HVAC system
	Exterior	Doors, roof structure, bonnet/hood, fenders, bumpers, cargo body
Mission system	Communication & electronics	Radio system, antenna mounts, intercom system (interrelated with electrical systems)
	Mission equipment interface	Equipment mounting points, payload mounts, power distribution interface (interrelated with chassis systems)
	Protection system	Armour panels (if applicable), ballistic glass, underbody protection

Engineering judgement is used to interpret these observable characteristics and assess component complexity, platform dependency, integration criticality and sourcing feasibility under conditions of incomplete information (Palmås, 2024).

Components with standardised interfaces and limited dependency on the donor platform may be suitable for external procurement. In contrast, structurally integrated or highly platform-specific components may require modification or customised development. These findings provide the inputs for the component evaluation and decision-matrix assessment

3.4 Component Evaluation and Decision Matrix

Following system decomposition and donor-platform analysis, each component is evaluated against seven criteria: design complexity, integration criticality, manufacturing complexity, supply chain availability, economies of scale, lifecycle impact and strategic importance. These criteria reflect the multidimensional nature of sourcing decisions in complex defence projects, where technical complexity, supply chain conditions, cost considerations and lifecycle requirements must be considered together (Aspeteg *et al.*, 2025) while supply-chain resilience and dependency on single or foreign suppliers can further influence military vehicle sourcing (GAO, 2022).

Each criterion is assessed using a three level qualitative scale and converted into a numerical score from 1 to 3. Characteristics favouring external procurement receive higher scores, whereas those indicating a need for greater internal control or customised development receive lower scores. For example, a standard component with low integration dependency and abundant supplier availability would receive a higher score than a highly customised, tightly integrated or strategically sensitive component.

Weights are assigned according to the relative importance of each criterion in military vehicle development. Design complexity and integration criticality are each assigned a weight of 20%; manufacturing complexity and supply chain availability, 15% each; and economies of scale, lifecycle impact and strategic importance, 10% each. Table 3 presents the criteria, evaluation scope, scoring guidance and weights. The assigned weights are based on expert judgement and the priorities of preliminary military vehicle development, where technical integration and sourcing feasibility may be more influential than cost alone. This approach is consistent with subjective weighting methods in multi-criteria decision making (MCDM), particularly where objective data is limited (Sarkar *et al.*, 2026).

The weighted score for each component is calculated by combining the criterion scores with their respective weights. The aggregated scores are then mapped to actionable sourcing strategies using project specific decision thresholds, consistent with threshold-based classification in MCDM, where aggregated assessments are assigned to defined decision regions according to the requirements and objectives of the decision problem (Liang & Yang, 2025). Scores above 80 are classified as Buy, indicating suitability for external procurement; scores from 60 to 80 are classified as Modify, indicating that an existing component or commercial solution should be adapted; scores from 50 to below 60 are classified as Make (outsource), indicating that a customised component should be designed or specified by the programme and manufactured externally; while scores below 50 favour Make (in-house). These thresholds are proposed decision boundaries developed by the authors based on expert judgement, the relative importance of the evaluation criteria and the intended sourcing strategy.

The decision matrix integrates these scores to assign the recommended sourcing strategy. Components with standardised designs, low integration dependency and mature supplier availability generally favour Buy, while components requiring adaptation to the donor platform or military operational requirements tend to favour Modify. Highly customised or strategically important components with limited external availability may favour Make, either through outsourced manufacturing or internal development. These thresholds provide a consistent and transparent basis for preliminary comparison. Although engineering judgement remains necessary to ensure that the numerical results reflect relevant technical, operational and strategic considerations rather than functioning as an automatic decision rule, the resulting sourcing recommendation must also be considered within the broader defence procurement context. In Malaysia, procurement practices are subject to multiple considerations and procedural requirements that influence defence acquisition decisions (Muda *et al.*, 2023).

3.5 Limitations and Applicability

The methodology is intended for preliminary make-or-buy assessment and has several limitations. First, it relies on the Toyota Land Cruiser CBA-UZJ200W as the reference platform, meaning that the analysis is based on observable characteristics and publicly available information, and may not capture proprietary design features, detailed performance limits, or manufacturing constraints. Second, the study does not incorporate confidential specifications, engineering drawings, supplier quotations, manufacturing process data or lifecycle cost information. Therefore, the resulting recommendations should be interpreted as plausible sourcing strategies rather than final procurement decisions.

Third, the scoring and weighting process relies on qualitative assessment and expert judgement. Although predefined criteria improve consistency and transparency, the resulting scores may vary according to assessor experience and project priorities. The framework should thus complement, rather than replace, detailed engineering, cost, supplier and procurement analyses conducted during later development stages. Despite these limitations, the methodology provides a practical approach for early stage military vehicle development when detailed information is unavailable, enabling development teams to compare sourcing options systematically, identify components requiring further investigation, as well as establish preliminary priorities for procurement, modification or targeted research and development.

3. CASE STUDY: HMMV SUSPENSION SYSTEM

The proposed framework was applied to the HMMV suspension system to demonstrate its application in preliminary component sourcing assessment. Although the complete vehicle comprises several major systems, the suspension system was selected because of its direct influence on payload capacity, ride height, handling, off-road mobility and structural integration. The chassis platform itself was excluded from detailed evaluation because it forms the structural basis of the donor vehicle and is assumed to be retained, with modification where required to meet HMMV operational requirements. Table 4 presents the resulting decision matrix for the principal suspension components.

The front suspension, rear suspension, shock absorbers and linkage system each achieved a weighted score of 53.3 and were classified as Make (outsource). Although mature commercial technologies and capable suppliers are available for these components, direct procurement is unsuitable because the HMMV configuration introduces changes in payload, ride height, suspension travel and operational performance requirements. The front and rear suspension systems thus require project specific specifications to achieve the necessary load capacity, durability, mobility and vehicle stability. Similarly, the shock absorbers require customised damping, travel and load characteristics, while the linkage system must preserve appropriate suspension geometry, wheel alignment and structural performance. Outsourced manufacture or customisation enables these requirements to be met without establishing specialised in-house production facilities. In the case of the linkage system, engineering analysis indicates that the donor platform components may be retained where they satisfy the required performance.

The stabiliser bar achieved the highest weighted score of 90.0 and was classified as Buy. It has relatively low design complexity and integration criticality, is supported by a mature supply chain and benefits from established commercial production. Provided that dimensional compatibility and performance requirements are satisfied, direct procurement minimises development effort, cost and technical risk. By contrast, the suspension mount insert obtained a score of 66.7 and was classified as Modify. As part of the interface between the suspension system and chassis frame, it affects structural load transfer, suspension geometry and vehicle integrity. Therefore, retaining and adapting the donor platform design is more practical than developing an entirely new mounting arrangement, although modification is required to accommodate revised suspension loads, travel and ride height.

Table 3: Criteria and scoring guidelines for component classification.

Criteria	Purpose	Evaluation Scope	Score		Weightage	Scoring Guideline
Design Complexity	To distinguish between vehicle specific components and generic or standardised parts.	1. Level of modification 2. Design uniqueness 3. Platform dependency	Low	3	20	Standard/off-the-shelf design, minimal or no modification required, no platform specific dependency.
			Medium	2		Moderate design customisation required with some platform adaptation.
			High	1		Highly customised, proprietary or vehicle-specific design requiring extensive engineering and platform dependency.
Integration Criticality	To assess the degree of dependency and interface interaction with other subsystems.	1. Number of interfaces 2. Coupling with other systems 3. Impact on system if modified	Low	3	20	Standalone component with few interfaces, modification has negligible impact on other subsystems.
			Medium	2		Moderate interfaces with several subsystems, changes require limited system integration and validation.
			High	1		Highly integrated components with multiple subsystem interfaces, changes significantly affect performance or safety.
Manufacturing Complexity	To evaluate whether the component involves complex fabrication processes or straightforward assembly.	1. Specialised processes 2. Manufacturing and tooling 3. Assembly process 4. OEM capability	Low	3	15	Conventional manufacturing, simple assembly using standard tools and processes and high manufacturing capability, and short production lead time
			Medium	2		Requires moderate fabrication complexity, dedicated tooling or controlled manufacturing processes and medium manufacturing capability.
			High	1		Requires advanced manufacturing technologies, specialized equipment, precision tooling or highly skilled processes and low manufacturing capability.
Supply Chain Availability	To consider the maturity of the supply chain and availability of capable vendors, ranging from commodity items to niche technologies.	1. Local vendors' availability. 2. Foreign vendor accessibility. 3. Commodity/niche component.	Abundant	3	15	Multiple qualified local and international suppliers, commodity component with stable availability for off-the-shelf or customised components.
			Limited	2		Limited number of suppliers, partially dependent on foreign vendors or long lead times for off-the-shelf or customised components.
			Niche	1		Single source or niche supplier, import restrictions, proprietary technology or difficult procurement for off-the-shelf or customised components.
Economies of Scale	To examine the impact of cost in relation to expected production scale.	1. Unit cost impact. 2. Suitable for low/high volume production. 3. Affordability constraint.	High	3	10	High production volume resulting in low unit cost and strong economies of scale.
			Moderate	2		Moderate production volume with moderate unit cost benefits.
			Low	1		Low production volume resulting in high unit cost and limited economies of scale.
Lifecycle Impact	To include maintainability, upgrade potential and susceptibility to obsolescence over the vehicle's service life.	1. Maintainability. 2. Spare parts availability. 3. Obsolescence risk. 4. Upgrade potential.	Low	3	10	Easy to maintain, readily available spare parts, low obsolescence risk, high upgrade potential.
			Medium	2		Moderate maintenance effort with some spare part limitations and moderate obsolescence risk.
			High	1		Difficult maintenance, limited spare parts, high obsolescence risk and limited upgrade opportunities.
Strategic Importance	To differentiate mission critical or sensitive subsystems from noncritical components.	1. Mission-criticality. 2. Sensitivity of technology. 3. Need for internal control.	Low	3	10	Non-mission critical component with low technology sensitivity and no requirement for internal control.
			Medium	2		Moderately important component with some technology sensitivity and limited strategic value.
			High	1		Mission critical component involving sensitive technology, operational security or sovereign capability requiring internal control.

Table 4: Decision matrix for the HMMV suspension system.

			Component Classification Criteria / Score*							Score	Assessment	Sourcing Strategy (Make / Buy / Modify)
			Design Complexity	Integration Criticality	Manufacturing Complexity	Supply Chain Availability	Economies of Scale	Lifecycle Impact	Strategic Importance			
System Decomposition			Design Complexity	Integration Criticality	Manufacturing Complexity	Supply Chain Availability	Economies of Scale	Lifecycle Impact	Strategic Importance	Score	Assessment	Sourcing Strategy (Make / Buy / Modify)
Primary System	Sub-System	Major Components										
Chassis System	Suspension System	Front Suspension (helix spring system)	High	High	Medium	Abundant	Low	Medium	Low	53.3	Existing design requires adaptation for payload and ride height change.	Make (outsource)
		Rear Suspension (leaf spring system)	High	High	Medium	Abundant	Low	Medium	Low	53.3	Existing design requires adaptation for payload and ride height change.	Make (outsource)
		Shock Absorbers	High	High	Medium	Abundant	Low	Medium	Low	53.3	Existing design requires adaptation for payload and ride height change.	Make (outsource)
		Stabiliser Bar	Low	Low	Medium	Abundant	High	Low	Low	90.0	Standardised component that meets technical requirements.	Buy
		Linkage System (upper and lower arms)	High	High	Medium	Abundant	Low	Medium	Low	53.3	Analysis and simulation of the existing component meet technical requirements.	Make (outsource) - Retain
		Suspension Mount Insert	Medium	High	Medium	Abundant	Low	High	Low	66.7	Part of the chassis structure that provides the interface between the suspension and the frame; hence directly affects structural integration.	Modify

*Refer to Table 3 for criteria purpose, weightage and scoring guideline.

Overall, the suspension system predominantly favours outsourced customisation and selective modification, with only the stabiliser bar suitable for direct procurement and no component requiring complete in-house development. This outcome reflects the donor platform-based development strategy and the maturity of the commercial suspension industry. Although several components require application specific engineering, they do not involve strategically sensitive technologies that would justify establishing internal manufacturing capability. External suppliers can instead provide customised components using established manufacturing processes, testing expertise and supply networks.

The results also suggest that conventional suspension components are not a priority for comprehensive in-house research and development. This finding is further supported by the established use of reliability prediction and engineering analysis methods for evaluating the HMMWV suspension system and its components (Ghiocel *et al.*, 2011). Greater value may be obtained from targeted R&D in areas specific to HMMV integration, including suspension mounting structures, interface brackets, structural optimisation, load accommodation and suspension tuning. This approach enables the programme to use proven commercial technologies while concentrating internal engineering effort on the interfaces and modifications required to meet military operational requirements.

This case study demonstrates that the proposed framework can distinguish among direct procurement, outsourced customisation and modification even when detailed cost and proprietary engineering data are unavailable. For the HMMV suspension system, a combination of Buy, Make (outsource) and Modify strategies offers the most practical means of meeting performance requirements while controlling development cost, technical risk and compatibility with the donor platform.

4. CONCLUSION

This paper presents an inference-based methodology for preliminary make-or-buy component selection in HMMV development using functional system decomposition, observable donor platform characteristics, qualitative classification criteria and a weighted decision matrix. The application to the suspension system showed that most components favour Make (outsource) or Modify, while the stabiliser bar is suitable for Buy and no component requires Make (in-house). These findings support the use of mature commercial technologies and external manufacturing capabilities while concentrating internal engineering effort on application-specific integration, mounting structures and structural optimisation.

Although the framework relies on limited design information, qualitative scoring and expert judgement, it provides a practical and transparent basis for early sourcing decisions under information-limited conditions. Future work should validate the framework using detailed technical, supplier, cost and lifecycle data and extend its application to other HMMV subsystems.

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CFD-BASED OPTIMISATION OF A C-D ROCKET NOZZLE USING RESPONSE SURFACE METHODOLOGY FOR EXHAUST PLUME CHARACTERISTICS AND THRUST PERFORMANCE

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ABSTRACT

Rocket propulsion systems typically utilise convergent-divergent (C-D) nozzles to effectively generate the thrust necessary for lift-off and flight. Nonetheless, there remains limited research examining the combined relationship between nozzle configuration, exhaust plume characteristics and thrust performance. Recent research has concentrated only on discrete performance elements, such as flow separation management and flow performance analysis. This study presents a computational fluid dynamics (CFD) based design optimisation of a C-D rocket nozzle using the response surface methodology (RSM) approach to investigate the combined effects of nozzle geometry on thrust profile and exhaust plume characteristics. CFD analyses are performed using ANSYS Fluent to accurately evaluate exhaust plume characteristics, while rocket motor software is used to determine the thrust profile. The results indicate that throat diameter is the dominant parameter affecting thrust generation, while convergent and divergent angles primarily influence plume expansion behaviour and flow stability. Throat diameter of 16 mm, and the smallest convergent and divergent angles are the ideal rocket nozzle configuration for producing maximum thrust of 2.4 kN. This study demonstrates the effectiveness of combining CFD and RSM techniques for performance-oriented rocket nozzle optimisation.

Keywords: Rocket nozzle; exhaust plume; thrust; response surface methodology (RSM); computational fluid dynamics (CFD).

1. INTRODUCTION

A rocket is a vehicle that runs without the use of atmospheric oxygen by propelling itself forward by releasing high-speed exhaust gasses from its engine. Rockets are now widely employed for a variety of purposes, including development of military and exploration technologies, launch of satellites, transportation of personnel to space, as well as research missions (Alemayehu *et al.*, 2020; Mahjub *et al.*, 2020). A rocket propulsion system uses Newton's third law to lift and manoeuvre a spacecraft by combining an engine with feed systems that accelerate propellant and expel it rearward, creating thrust. Major engine types include electric propulsion (ion, Hall) for high-efficiency, low-thrust station-keeping and deep-space transfers (Remissa *et al.*, 2023). Besides, air-breathing engines such as turbojet, ramjet and scramjet are used for atmospheric acceleration (Pylypenko *et al.*, 2020). Chemical rockets, which include liquid, solid and hybrid propulsion systems, are usually used for high-thrust launches and orbital insertions (Wei *et al.*, 2024).

Using a convergent-divergent (C-D) nozzle typically designed for supersonic flow, rocket propulsion systems convert stored chemical or electrical energy into high-velocity exhaust through controlled combustion or ion acceleration. The resulting thrust is described by the fundamental rocket thrust equation. In mission design, parameters such as thrust, specific impulse, propellant mass and structural limitations must be carefully balanced, while successful lift-off requires a sufficient thrust-to-weight ratio to ensure that the net force exceeds both gravitational and aerodynamic drag forces (Kopacz *et al.*, 2022). Fundamental principles of fluid dynamics and thermodynamics govern thrust generation and propulsion performance. Within the combustion chamber, chemical energy stored in the propellant is converted into thermal energy, producing hot, high-pressure gases that subsequently expand through the C-D nozzle, where thermal energy is transformed into kinetic energy. The following equation describes the overall thrust generated (Wei *et al.*, 2024):

$$dF = \dot{m}V_e + (P_e - P_a)A_e \quad (1)$$

where $\dot{m}$ is the mass flow rate of exhaust gases, V_e is the exhaust velocity, P_e and P_a are the exhaust and ambient pressures respectively, and A_e is the nozzle exit area. The exhaust velocity itself can be derived from energy conservation as (Kopacz *et al.*, 2022):

$$V_e = \sqrt{\frac{2\gamma RT_c}{(\gamma-1)}} \left[1 - \left(\frac{P_e}{P_c} \right)^{\frac{\gamma-1}{\gamma}} \right] \quad (2)$$

where T_c and p_c are the combustion chamber temperature and pressure respectively, γ is the specific heat ratio, and R is the specific gas constant. The rocket's efficiency is often measured using specific impulse I_{sp} using the following equation (Kopacz *et al.*, 2022):

$$I_{sp} = \frac{F}{\dot{m}g_0} \quad (3)$$

which represents the thrust generated per propellant weight flow. Together, these linkages control how propulsion systems are designed and optimised to provide the rocket with the power and efficiency that it needs to lift off and accomplish its mission goals.

C-D nozzles, sometimes referred to as de Laval nozzles, consist of two sections, which are a convergent part and a divergent section with an intermediate piece known as the throat (Rohini *et al.*, 2022). C-D nozzles are predominantly utilised in jet engines and rockets to enhance exit velocity. Hot gases possess elevated temperatures and pressure within the combustion chamber, which, when entering the C-D nozzle, diminish at the cost of velocity. The exhaust gas flow at the C-D nozzle intake is subsonic and continues to be subsonic in the convergent portion (Rohini *et al.*, 2022; Dave *et al.*, 2024). The flow reaches sonic velocity in the throat of the C-D nozzle, meaning the Mach number equals 1 when the nozzle is choked (Dave *et al.*, 2024). In the divergent section, the Mach number rises concurrently with velocity, resulting in supersonic flow when the Mach number exceeds 1. The primary function of the C-D nozzle is to enhance the flow of combustion gases and generate thrust at the exit. Occasionally, shock waves may manifest in the flow through the nozzle, resulting in a reduction of the Mach number upon attaining supersonic conditions. Shock waves are often linked to supersonic flows, but under specific conditions, they may also manifest in subsonic regimes (Okninski *et al.*, 2021). As a result of shock, the output flow either turns subsonic or stays supersonic, although with a reduced Mach number. The flow devoid of shock can be regarded as isentropic if the flow is inviscid and adiabatic (Jones *et al.*, 2020; Marque *et al.*, 2022). The flow characteristics of exhaust gases within the nozzle are directly influenced by the design of the C-D nozzle (Zhu *et al.*, 2014).

Alili *et al.* (2024) claimed that optimising the design of the C-D nozzle and analysing the flow characteristics within it is an expensive experimental effort. In order to address this, some researchers have conducted several computational analyses using computational fluid dynamics (CFD). The researchers examined several facets of C-D nozzles, such as its flow characteristics, velocity, pressure behaviour contour and turbulence flow. For example, Zhu *et al.* (2014) investigated C-D nozzles' shock

wavelength. In a different investigation, Jeevaraj *et al.* (2024) investigated the separation of supersonic flow in C-D nozzles. The impact of mesh grid and turbulence model on the convective heat transfer of C-D nozzles was examined by Makhija *et al.* (2024). Additionally, Das *et al.* (2021) used CFD to examine flow behaviour inside the C-D nozzles. They examined the Mach number, velocity, pressure and density of flows inside C-D nozzles using the characteristics of compressible flow. Moreover, comparable research also examined flow characteristics at various Mach numbers (Hosseini *et al.*, 2026).

Even though individual parts of rocket nozzle design have been well studied, there is still a significant research gap in the combined optimisation of the interaction between exhaust plume features, thrust production and C-D nozzle geometry. The high-velocity stream of gases released from the nozzle is known as exhaust plume in rocket science, and the reactive force produced as these gases accelerate backward and move the rocket forward is known as thrust (Rad *et al.*, 2025). In order to guarantee optimal propulsion performance, reduced flow losses and stable operation across a range of altitude circumstances, exhaust plume behaviour and thrust production must be assessed throughout the C-D nozzle optimisation process. Without establishing a thorough link between the two parameters, most previous investigations concentrate either on optimising thrust efficiency or on examining plume growth independently (Silva *et al.*, 2025; Subramani *et al.*, 2025). The comprehension of how nozzle shape changes concurrently impact thrust performance and plume behaviour, particularly under various operating and altitude circumstances, is limited by this lack of integrated optimisation. Therefore, a CFD-based optimisation research that methodically examines and analyses this connection is necessary to provide a comprehensive framework for enhancing C-D nozzle design to achieve improved propulsion efficiency and stable exhaust flow characteristics.

The complexity of rocket nozzle design, with multiple interacting performance parameters, underscores the need for clearer and more systematic optimisation methods to enhance understanding of fundamental propulsion principles. Studies by Neelakandan *et al.* (2025) and Tian *et al.* (2025) demonstrate that approaches such as deep reinforcement learning and hybrid surrogate models not only optimise performance but also provide structured insights into design sensitivities and trade-offs, thereby improving comprehension of core rocket behaviour.

In this research, the approach to optimise rocket nozzle configurations using response surface methodology (RSM). Three design parameters, which are convergent angle, divergent angle and throat diameter, are simultaneously adjusted to examine their impact on the flow characteristics (maximum exit temperature, maximum exit pressure and exit velocity) of a rocket C-D nozzle. This work further proposes an ideal design condition for the C-D nozzle in high-speed rockets to enhance flow characteristics. The main objective of this research is to optimise the design of a C-D rocket nozzle by focusing on two key performance parameters, which are exhaust plume behaviour and thrust generation. The exhaust plume characteristics, including flow uniformity and expansion pattern, are analysed through CFD simulations using ANSYS Fluent, which provides detailed insights into the fluid flow and pressure distribution within the nozzle. Meanwhile, the thrust performance is evaluated using Open Motor software, an open-source simulation tool designed for predicting solid rocket motor performance based on propellant and geometry parameters. The optimisation process is then conducted using RSM in Minitab, where all simulation data from ANSYS Fluent and Open Motor are systematically used as input to develop mathematical models and response surfaces that identify the optimal nozzle configuration for achieving maximum thrust and stable exhaust plume expansion.

2. SETUP AND METHODOLOGY

2.1 Research Work Frame

This research focused on optimising a C-D nozzle design for rockets using the RSM design of experiment (DOE) method to optimise nozzle configurations on the exhaust plume and thrust profile. The initial stage was to conduct DOE by selecting and adjusting the nozzle's design parameters.

Subsequently, the nozzles were designed in CATIA based on the DOE sample matrix. Next, CFD simulations were conducted using ANSYS Fluent, and the maximum exit temperature, maximum exit pressure and exit velocity contour were determined for each sample. Then, the thrust profile was evaluated using Open Motor. The third phase involved analysing RSM's design based on the response variables of flow using Minitab software.

2.2 Geometrical Modelling

Prior to conducting the DOE, the fundamental design of the nozzle, the fixed design parameters and the spectrum of variable design parameters were determined based on the literature (Ande *et al.*, 2018; Bukhari *et al.*, 2025; Subramani *et al.*, 2025;). The variable design parameters were modified at three levels, as indicated in Table 1. Convergent angles in the range of 10 - 18° are commonly used because smaller angles reduce boundary layer separation and minimise viscous losses (Pylypenko *et al.*, 2020). Divergent angles of 30 - 38° were selected to balance thrust augmentation with expansion efficiency; angles below 30° may under-expand the exhaust, whereas angles above 38° increase the risk of flow separation in the divergent section (Silva *et al.*, 2025).

Table 1: Rocket nozzle design parameter variables.

Parameter	Value	Type / Description
Nozzle throat diameter (mm)	16, 18, 20, 22, 24	Variable
Convergent angle (°)	10, 12, 14, 16, 18	Variable
Divergent angle (°)	30, 32, 34, 36, 38	Variable
Throat length (mm)	1	Constant
Nozzle exit diameter (mm)	48	Constant
Convergent length (mm)	According to the angle	Variable
Divergent length (mm)	According to the angle	Variable

C-D nozzles were modelled using CATIA, which is a software for computer-aided design (CAD), engineering (CAE) and manufacturing (CAM) developed by Dassault Systems, utilised for the design of intricate mechanical, aeronautical and automotive systems (Joshi *et al.*, 2020). For the other nozzle specification parameters, only the nozzle throat diameter, convergent angle and divergent angle were manipulated, while the other parameters remained constant. The number of nozzle specifications designed was determined based on the RSM matrix, which will be discussed in Section 2.5.

2.3 Meshing and Boundary Conditions

The following step involved importing each 3D C-D nozzle's designed geometries one at a time into the workbench of ANSYS Fluent. The models were discretised into finite volumes to represent the C-D nozzle flow domain. The mesh was chosen with 1,234 elements and 456 nodes to precisely represent all geometric features of the C-D nozzle while maintaining numerical stability (Ferdaus *et al.*, 2019). The meshed model of the C-D nozzle is depicted in Figure 1.

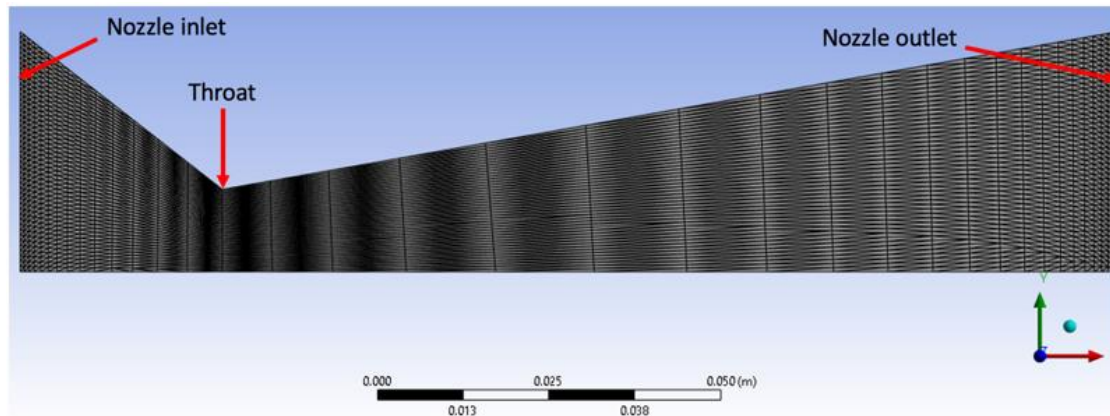


Figure 1: C-D rocket nozzle meshed model.

The mesh density was adjusted around the nozzle areas, such as the throat and exit sections, to guarantee that flow characteristics were captured with greater precision. In order to replicate the actual operating environment of the nozzle, boundary conditions were imposed once the meshing was completed. These conditions included specifying the intake pressure and temperature, exit pressure, as well as wall conditions. The boundary conditions in simulating the exhaust plume rocket nozzle were tabulated in Table 2.

Table 2: Boundary conditions in CFD solutions.

Parameter		Value / Type
Fluid type	Gas	
Inlet pressure (psi)	650	
Inlet temperature (K)	3200	
Boundary condition	Pressure inlet (input), Supersonic flow (outlet)	
Solver type	K-epsilon (2-eqn)	
Number of iterations	5000	

The results were examined using ANSYS CFX's CFD-post processor. Additionally, contours of various flow parameters were acquired on the plane. Exit velocity, maximum exit temperature and maximum exit pressure contours were constructed and recorded for all nozzle samples.

2.4 Rocket Motor Performance Simulation Using Open Motor

Open Motor is an open-source software for simulation and analysis utilised in the design and assessment of rocket motors. It enables users to simulate propellant grains, nozzle designs and combustion variables to forecast essential performance indicators such as thrust, chamber pressure, and burn duration (Gateru *et al.*, 2021; Fuller *et al.*, 2024; Kim *et al.*, 2025). The software offers an intuitive interface for entering geometric and material data, executing simulations, as well as visualising performance curves. The propellant specifications used for this thrust profile analysis were based on an ammonium perchlorate composite propellant (APCP) grain with a length of 585 mm. The propellant diameter was 55 mm with core diameter of 25 mm, and the hollow cylindrical configuration was used as a fixed propellant grain geometry. The type and dimension of the propellant for all the nozzle configurations remained constant.

2.5 Response Surface Methodology (RM)

The matrix table generated by the DOE in the RSM using Minitab contained a systematic arrangement of input parameters and their corresponding levels. RSM generated a total of 20 simulation runs, as presented in Table 3. The resulting data was imported into a post-processing workspace to construct a 3D contour visualisation. The maximum exit pressure, maximum exit temperature and exit velocity from the simulation output were combined with thrust data to create a comprehensive representation of

the nozzle's performance. These datasets were then interpolated and mapped onto a 3D model to highlight regions of optimal flow expansion and thrust efficiency. The resulting 3D contour plot illustrates the most optimised configuration among all tested parameters.

Table 3: Total runs generated by RSM.

Runs	Throat diameter (mm)	Divergent angle (°)	Convergent angle (°)
1	20	14	30
2	24	14	34
3	22	10	30
4	20	10	34
5	16	10	38
6	20	14	34
7	24	10	38
8	16	10	30
9	20	14	34
10	18	18	34
11	22	14	34
12	16	18	30
13	20	14	34
14	16	14	34
15	24	18	38
16	24	18	30
17	16	18	38
18	18	14	34
19	20	14	38
20	20	14	34

3. RESULTS AND DISCUSSIONS

3.1 Exhaust Plume Characteristics

With every simulation run, the exhaust air flow behaviour from the rocket C-D nozzle's exit varied. A total of 20 runs were simulated to determine the exhaust flow behaviour and thrust profile using ANSYS Fluent and Open Motor respectively. Figure 2 shows the velocity contour of the exhaust plume characteristics of five selected sample runs to characterise their behaviours. All five nozzles behave as a normal C-D rocket nozzle as the value of the exit velocity is between approximately 1,120 and 2,283 m/s. For nozzle configuration Run 1 in Figure 2(a), the flow continues to expand outside the nozzle in under-expanded conditions because its pressure is higher than the surrounding air pressure. This results in a larger exhaust plume form and a diverging plume with visible expansion fans, similar to findings made by Zhu *et al.* (2024).

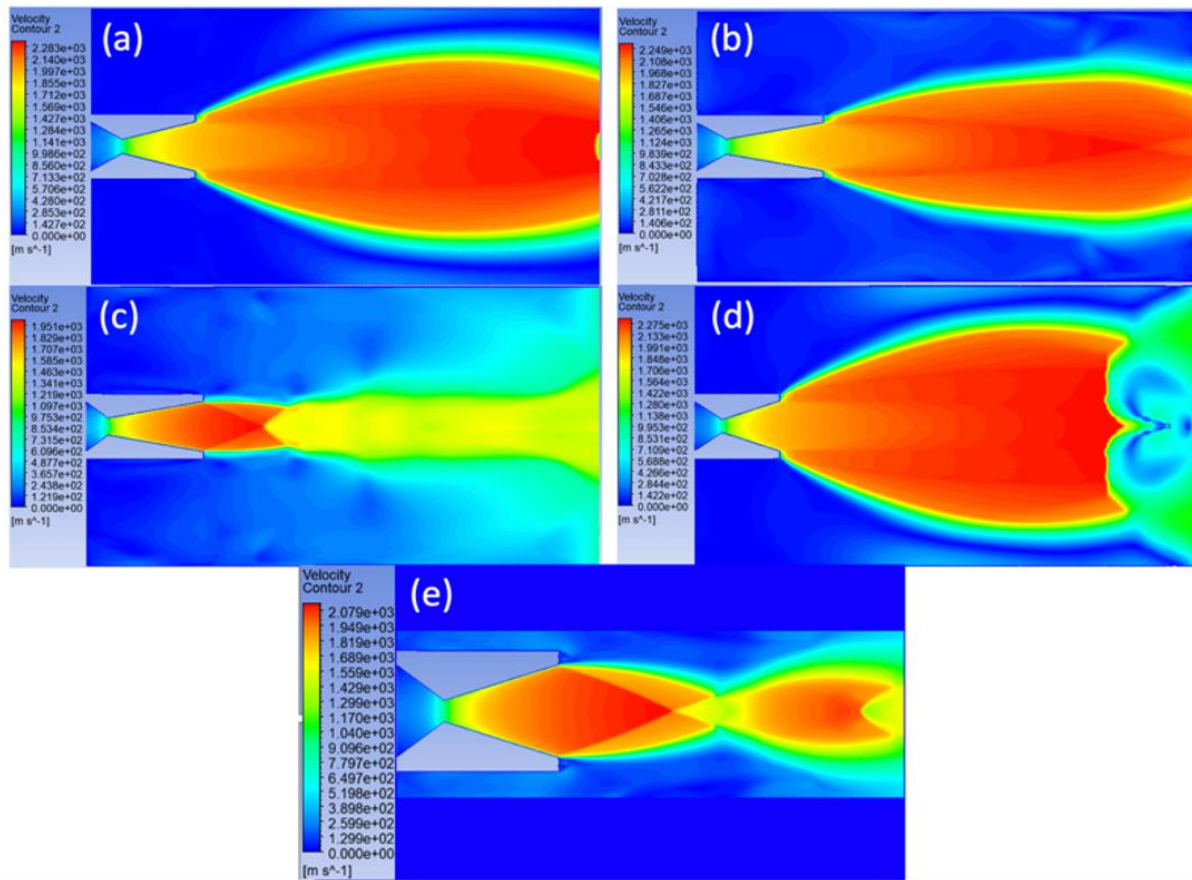


Figure 2: Velocity contours for nozzle configurations runs (a) 1, (b) 3, (c) 7, (d) 10 and (e) 17.

For nozzle configuration run 3 in Figure 2(b), a small under-expanded state results in limited outward expansion immediately before the nozzle exit because the exhaust pressure is just marginally greater than the ambient pressure. In comparison to a significantly under-expanded flow, the plume is nevertheless stable and modestly divergent, with fewer or smaller shock structures. For nozzle configuration run 7 in Figure 2(c), a smooth, straight plume free of overexpansion or apparent shock waves is produced when the exhaust pressure is equal to the ambient pressure, which is the ideal expansion condition. This happens when the nozzle's convergent and divergent angles are carefully planned to balance divergence and pressure expansion across the throat, guaranteeing optimal thrust efficiency. The exhaust gases for nozzle configuration run 10 in Figure 2(d) leave the under-expanded state with a brief plume at a pressure that is still greater than ambient, but the expansion stops fast because of the swift mixing with the surrounding air. Near the plume border, turbulent shear layers and localised shock interactions are created by the high-pressure exhaust. As the flow equalises with

ambient pressure, the pressure imbalance and strong velocity gradients lead the flow to lose coherence and create vortical structures, which result in the turbulence near the end of the plume. For nozzle configuration run 17 in Figure 2(e), the exhaust pressure nearly resembles the ambient pressure under ideal expansion conditions, resulting in a steady plume with visible Mach diamonds, which are diamond-like shock cells. As the exhaust flow adapts to slight residual pressure variations, cyclic recompression and expansion waves cause these sporadic brilliant and dark areas. When these shock interactions diminish and the exhaust gases re-expand and mix with ambient air, a new, less distinct plume boundary may emerge further downstream, resulting in a secondary plume shape.

The exit temperature behaviour can be illustrated in Figure 3, where the results show that the relationship follows the isentropic flow law, where the exit velocity is inversely related to the static pressure and temperature of the flow, consistent with the conservation of energy in adiabatic compressible flow (Joshi *et al.*, 2020).

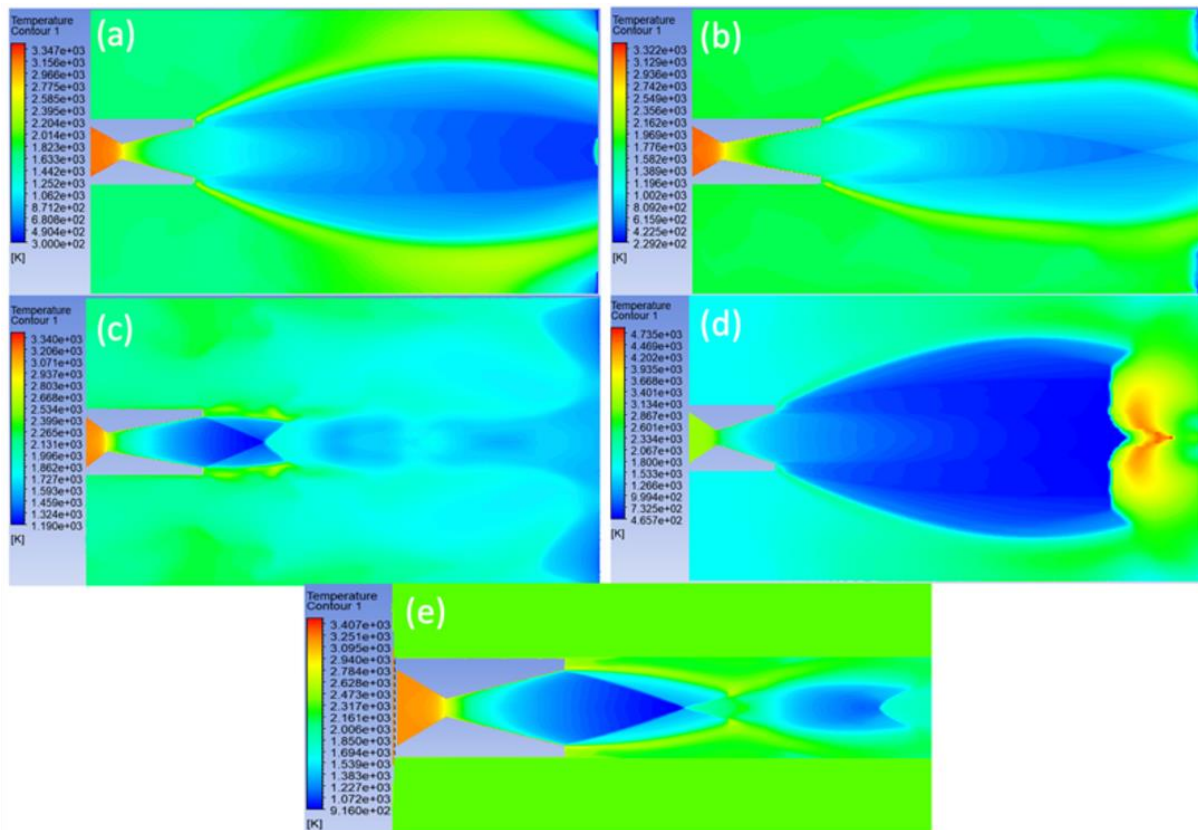


Figure 3: Temperature contours for nozzle configurations runs (a) 1, (b) 3, (c) 7, (d) 10 and (e) 17.

In the first under-expanded situation in Figure 3(a), the gases continue to expand beyond the nozzle because the exhaust leaves the nozzle at a pressure that is much greater than the surrounding air pressure. In this instance, the temperature contour displays a high temperature core close to the nozzle exit, which progressively cools and expands as it moves radially away. Regions of fast thermal and pressure change are indicated by the observable temperature gradients formed along the plume by strong expansion fans and shock structures. The plume displays a more constrained temperature contour with a shorter high temperature zone and softer temperature gradients for the nozzle condition in Figure 3(b), where the expansion is less pronounced. The overall plume stays comparatively constant with modest heat loss as the flow expands less forcefully, producing fewer and smaller shock cells. A uniform and symmetric temperature distribution along the plume axis is the consequence of the exhaust pressure precisely matching the ambient pressure under ideal expansion conditions, as referred to Figure 3(c). An effective conversion of thermal energy into thrust is demonstrated by the temperature contour's smooth transition and low shock generation. However, for nozzle in Figure 3(d), the temperature

contour exhibits a sharp temperature decrease close to the plume, the ideal expansion situation that creates a new plume shape following the first (Li *et al.*, 2025). The exhaust interacts with tiny changes in ambient pressure to create a new, weaker plume structure with alternating temperature areas, which results in these zones due to recompression and re-expansion actions. In Figure 3(e), the temperature contour first looks stable and well-aligned, but subsequently shows secondary heating and cooling zones downstream in expansion waves.

Figure 4 visualises the pressure contours of all five nozzle configurations. In the nozzle configuration Figure 4(a), the exhaust gases escape the nozzle at a pressure substantially greater than the ambient pressure, forcing the flow to expand rapidly beyond the nozzle exit. From the nozzle exit outward, the pressure contour displays a sharp pressure gradient, with alternating low and high pressure areas that represent compression and boundaries in the case of under-expanded flow with a short plume and turbulent waves at the end. This is because of too strong mixing and shear layer turbulence, which results in irregular and fluctuating thermal zones. In Figure 4(b), the pressure contour shows a milder pressure differential and smoother transitions between the high pressure core and surrounding low pressure portions. A more balanced relationship between internal nozzle expansion and exterior ambient pressure is suggested by the plume's continued moderate growth, but smaller and fewer shock cells. A straight, steady plume and a uniform pressure contour are produced when the pressure at the nozzle exit equals the ambient pressure, as referred to in Figure 4(c). The pressure contours show quick equalisation close to the nozzle exit for the nozzle in Figure 4(d). This is followed by irregular pressure changes at the plume border due to turbulent mixing and vortex generation. In Figure 4(e), the pressure contour first exhibits uniformity but thereafter discloses periodic compression and expansion zones downstream in the ideal expansion situation that creates a new diamond-like plume structure following the first. New diamond-shaped pressure areas that indicate the flow's dynamic adjustment beyond the initial plume are created by these secondary shock structures, which are caused by minute changes in the ambient pressure or reflected shock interactions.

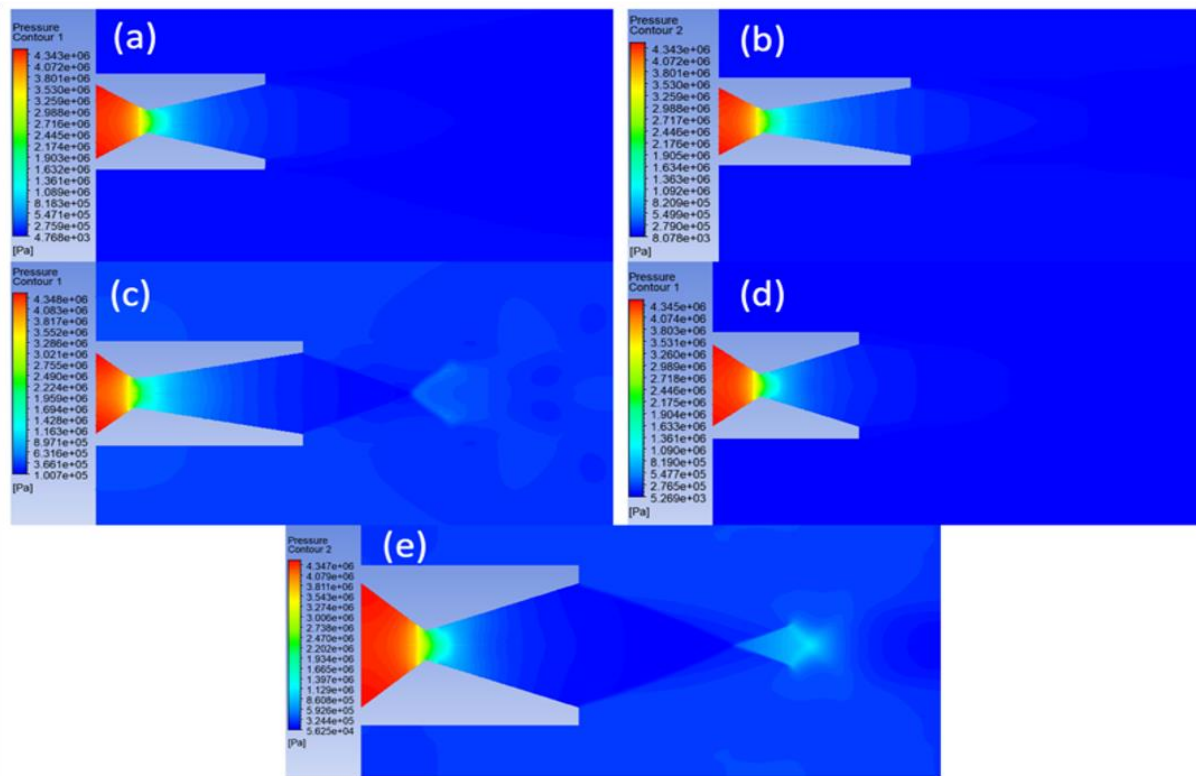


Figure 4: Pressure contours for nozzle configurations runs (a) 1, (b) 3, (c) 7, (d) 10 and (e) 17.

3.2 Thrust Performance Profile

The findings showed that among the examined configurations, lowering the nozzle throat diameter resulted in a discernible rise in the thrust profile and the highest thrust value. This behaviour is consistent with basic rocket propulsion theory, which states that a smaller throat area increases the chamber-to-throat pressure ratio, which raises the exhaust temperature and velocity at the nozzle exit. The thrust equation confirms that a larger thrust production is directly caused by the increased exit velocity, as in Equation 1. Similar results were reported by Wang *et al.* (2025), who found that a C-D nozzle with optimised throat diameter reduction can boost thrust efficiency by up to 12 - 15% because of better expansion characteristics and less shock wave formation close to the throat region. As shown in Figure 5, the thrust curve profiles of the five selected runs are presented to compare the behaviour of the curves across the range from maximum to minimum thrust values. All the thrust profiles observed the same thrust profile behaviour, which is progressive because all the configuration runs used a hollow cylindrical configuration solid propellant grain.

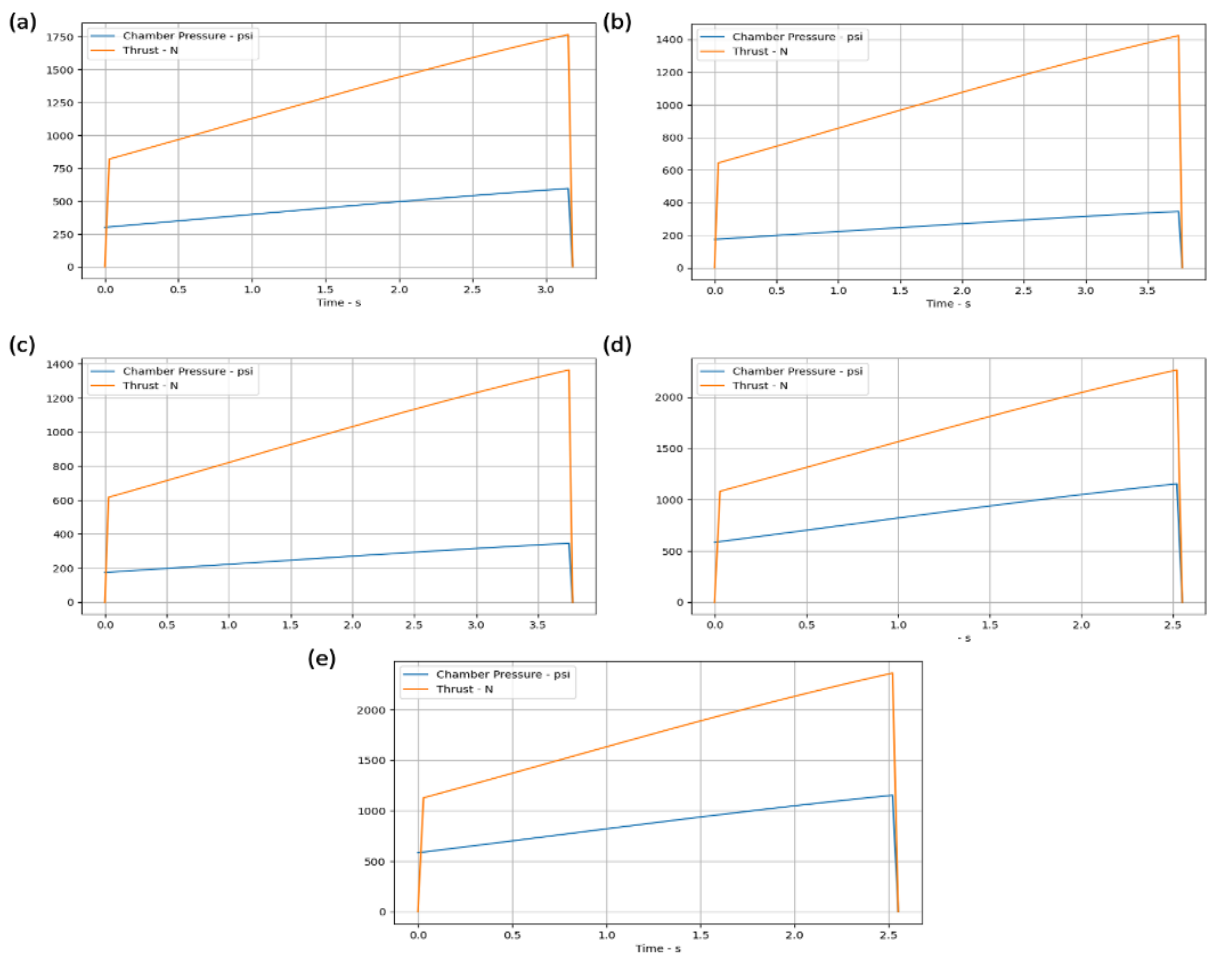


Figure 5: Thrust profile curves for sample runs of (a) 1, (b) 3, (c) 7, (d) 10 and (e) 17.

Based on Figure 5(e), nozzle configuration run 17 resulted in the highest thrust value of 2.493 kN due to its smallest throat diameter as compared to the others. In general, the larger throat diameter nozzles showed lower minimum and maximum thrust values due to weaker expansion ratios and decreased gas acceleration in the diverging portion. Incomplete energy conversion and flow expansion outside the nozzle is caused by exhaust gases leaving the nozzle at pressure greater than the ambient for under-expanded nozzle configurations, as in Figures 5(a) and 5(b). However, the thrust in Figure 5(b) is higher as compared to Figure 5(a) due to the throat diameter size. The nozzle configuration in Figure 5(c) has the lowest value of thrust due to the highest diameter of throat, which limits the exhaust pressure to match the ambient pressure, resulting in a low efficiency thrust output. Additionally, both nozzle

configurations in Figures 5(d) and 5(e) achieved thrust values of 2.201 and 2.394 kN respectively. Secondary shock diamonds are created downstream by localised recompression and re-expansion brought on by the reduced throat. These structures imply that tiny differences in thrust stability and flow uniformity at the exhaust outlet are caused by pressure oscillations and secondary expansion effects, even while thrust stays close to ideal.

3.3 RSM Optimisation

A smaller throat diameter raises chamber pressure and causes the exhaust gases to accelerate to sonic velocity at the throat, while the convergent angle controls how well the flow is compressed prior to this. As illustrated in Figure 6(a), increase in throat diameter lead to decrease in thrust values at all convergent angles. The convergent and divergent angles exhibited comparatively smaller influence on thrust generation than throat diameter, although they significantly affected plume expansion behaviour and flow stability.

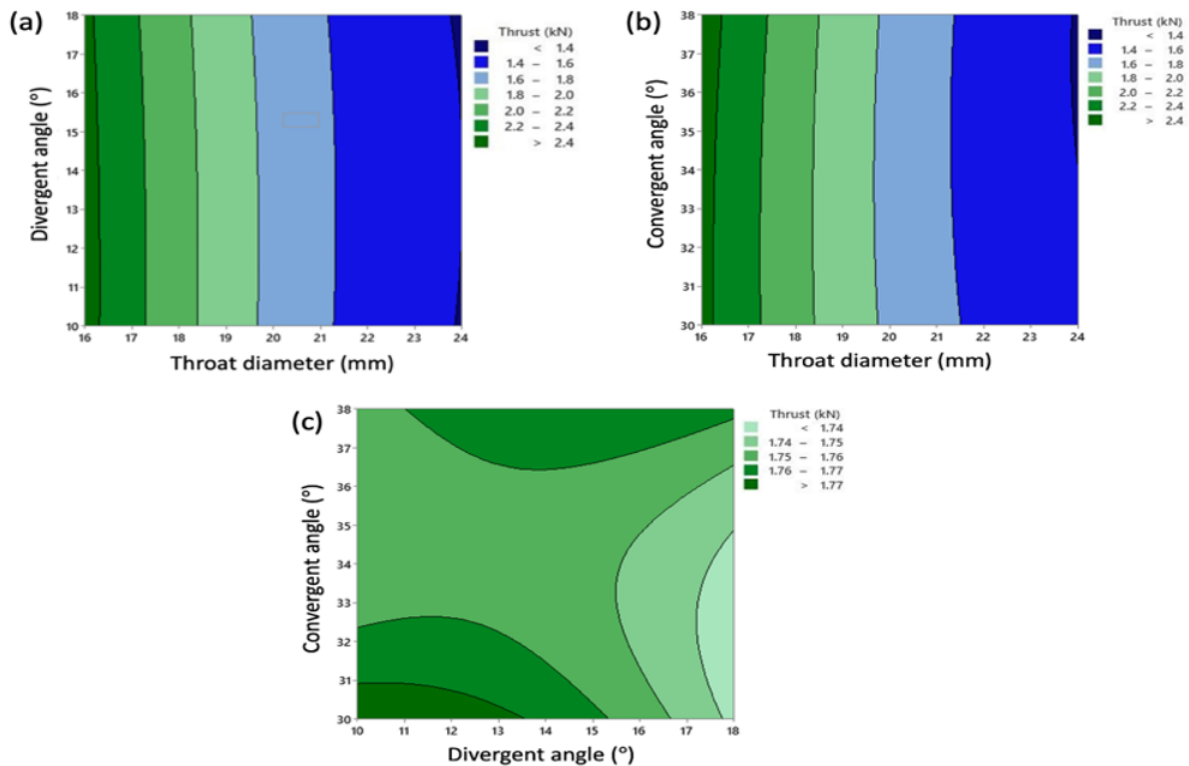


Figure 6: Contour plots of the resulting thrust values showing the relationships between: (a) Convergent angle and throat diameter. (b) Divergent angle and throat diameter. (c) Divergent and convergent angles.

In addition, it is also observed that thrust values decrease with increasing throat diameter at all divergent angles, as in Figure 8 (b). It is noticed that the divergent angle also does not significantly affect the thrust value as a throat diameter parameter. However, the relationship between divergent and convergent angles to thrust value production results in different ways. In Figure 6(c), it is observed that the maximum thrust value is produced at the convergent angle of 30° and divergent angle of 10°. Additionally, thrust values start to increase in the middle of the convergent angle and at the highest divergent angle. Moderate convergent angle reduces boundary layer effects and guarantees uniform flow at the throat, while higher convergent angle might cause flow separation and pressure losses. Furthermore, divergent angle regulates how the supersonic flow expands after the throat. A smaller divergent angle allows a gradual expansion, maximising kinetic energy conversion and minimising shock losses, while an excessively large angle may cause flow separation and under-expanded plume

behaviour, reducing thrust efficiency (Kim *et al.*, 2025). Thus, the optimum parameters in producing maximum thrust are the minimum convergent and divergent angles combined with the smallest throat diameter.

4. CONCLUSION

Throughout this optimisation investigation on the effects of C-D nozzle parameters on exhaust plume characteristics and thrust profile values, several conclusions can be drawn. The convergent and divergent angles of the nozzle configuration significantly influence plume characteristics and behaviour, where the convergent angle controls the boundary and separation layers, while the divergent angle regulates the expansion of the supersonic flow after the throat section. The nozzle exit pressure also plays an important role in thrust generation. When the exhaust plume is under-expanded, the nozzle exit pressure exceeds the ambient pressure, producing strong thrust but resulting in efficiency losses due to continued expansion outside the nozzle. In contrast, the optimally expanded condition occurs when the exhaust pressure matches the ambient pressure, producing maximum and most efficient thrust generation. Although the convergent and divergent angles do not significantly affect the thrust value of the rocket nozzle, the convergent section ensures uniform flow towards the throat, while the divergent section enables gradual gas expansion, maximising kinetic energy conversion and minimising shock losses at the nozzle exit. In addition, decrease in throat diameter increases chamber pressure and exhaust velocity, thereby enhancing thrust production due to the greater momentum of the exiting gases. Overall, the optimum rocket nozzle configuration for producing high thrust was achieved at the minimum convergent and divergent angles combined with the smallest throat diameter.

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EFFECT OF SOIL BARRIER SHAPE AND ARRANGEMENT ON BLAST WAVE MITIGATION

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ABSTRACT

Soil barriers are widely used as protective structures to reduce the effects of blast loading. This study investigates the effectiveness of rectangular, circular and hexagonal soil barrier configurations in mitigating blast waves using AUTODYN 3D. Pressure contour analysis was used to examine the interaction of the blast wave with the different barrier shapes and arrangements, while peak overpressure values were compared at locations behind the barriers. Among the five configurations investigated, Hex2 showed the best overall performance, followed by Hex1, Rect2, Circle1 and Rect1. The two hexagonal configurations also produced the largest blast overpressure attenuation at greater distances behind the barrier. The results indicate that the observed differences in attenuation are associated with blast wave diffraction and air vortex formation around the barriers. Overall, the findings demonstrate that appropriate selection of barrier shape and arrangement can improve blast wave mitigation.

Keywords: Soil barrier; surface burst; blast wave attenuation; blast overpressure; AUTODYN 3D.

1. INTRODUCTION

Soil is one of the oldest and most readily available construction materials worldwide. As it can often be sourced locally, its use may reduce transportation requirements.. In civil engineering, soil has been utilised in its natural state or with improvements as a primary component in the construction of highways, embankments and dams. Soil has also been used in military applications as a wall or barrier against blast overpressure, heat and fragment penetration (Keleş *et al.*, 2026).

In 1773, Charles-Augustin de Coulomb, an officer in the French Royal Corps of Engineers, pioneered the scientific analysis of soil stability and earth pressure to support the design of fortifications against artillery fire. Although protective earthworks had already been used for centuries, Coulomb's work provided a scientific basis for analysing their stability and the forces acting upon them. Owing to their simplicity and effectiveness, soil berms remain one of the oldest forms of protection for structures against military attack (Budhu, 2010). Despite these advantages, using soil to protect above ground structures requires a large base area and significant amount of soil due to its angle of repose. The large base area can disadvantage the protected structure, as a greater soil mass surrounding the target increases the likelihood of detonation within the soil. This, in turn, generates substantial ground shock pressures, approximately seven times greater than those produced by the same explosion in the air (Drake & Little, 1983).

Therefore, the design of soil barriers should aim to minimise the base size while remaining robust enough to withstand blast overpressure and fragment penetration, as well as being easy to construct. Some of above ground protective barriers include sandbags (Thawani *et al.*, 2021), geosynthetic-reinforced soil (Tseng *et al.*, 2022), reinforced earth (Ng *et al.*, 2000), sand grid revetments (Hyde, 1989) and Hesco bastions (Xu *et al.*, 2021). These barriers are made of soil that is reinforced or wrapped with synthetic materials, such as fabric, to enhance their performance. Notably, soil has limited tensile strength yet high compressive strength, whereas synthetic materials possess high tensile strength but limited compressive strength. By combining both materials, a strong composite structure is formed. Additionally, this technique allows the construction of near-vertical slopes, reducing the required ground space (Shukla, 2016).

However, most soil barriers are constructed in rectangular shapes, likely since they are easier to build as compared to other geometries (Scherbatiuk *et al.*, 2008). Furthermore, there is a lack of studies investigating the influence of different soil barrier shapes and arrangements on blast wave mitigation. Therefore, this study conducted numerical simulation using AUTODYN 3D (Isaac *et al.*, 2023) to evaluate how soil barrier shapes and arrangements affect blast overpressure attenuation, aiming to enhance their mitigation capabilities.

2. METHODOLOGY

2.1 Dimensions and Shapes of the Soil Barriers

Three basic shapes of soil barriers were used in this study: rectangular, circular and hexagonal. The barriers were designated as Hex1, Hex2, Circle1, Rect1 and Rect2, representing different barrier shapes and arrangements, and were subjected to blast loads from a hemispherical surface burst of 1 kg plastic explosive (PE4) (Figure 1). The rectangular barrier, Rect2, served as a reference for assessing the effectiveness of different shapes and arrangements in reducing blast pressure behind it. Moreover, all soil barriers were designed with the same overall volume and height to ensure comparability, as summarised in Table 1. For the numerical simulation, the barrier dimensions were scaled down to one-third of their actual size to facilitate field blast testing, as full scale testing would pose safety and cost challenges (Jelani *et al.*, 2016, 2023).

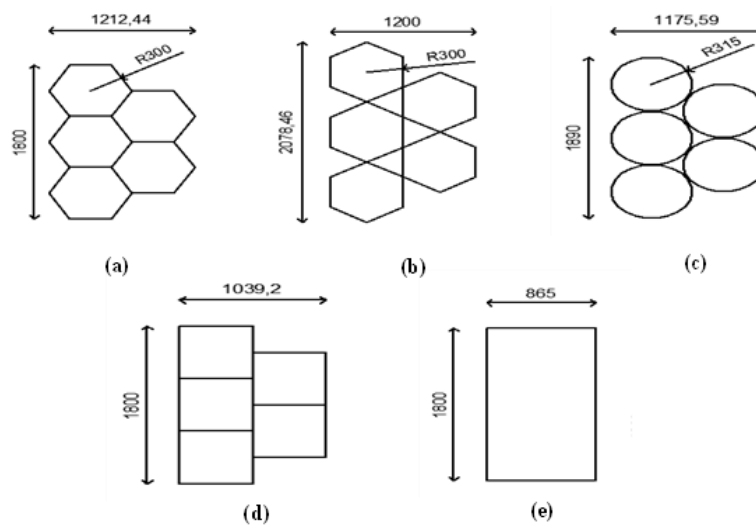


Figure 1: The proposed shapes and arrangements of soil barriers in plan view. All dimensions are in mm: (a) Hex1, (b) Hex2, (c) Circle 1, (d) Rect1 and (e) Rect2. All barriers have the same volume of 1.56 m³.

Table 1: Configurations of the proposed barriers in a one-third scale size that will be analysed using the numerical simulation methodology.

Shape	Case study	Height of barrier (m)	Total volume (m ³)	Type of explosive	Explosive weight (kg)	Eq TNT weight (kg)
Hexagon	Hex1	1	1.56	PE4	1	1.37
	Hex2					
Circle	Circle1					
Rectangular	Rect1					
	Rect2					

2.2 AUTODYN 3D Model

AUTODYN is an explicit dynamic hydrocode used to analyse nonlinear problems involving blast-wave propagation, impact dynamics and interactions between structures, liquids and gases (Choi *et al.*, 2014, Taha *et al.*, 2021). In this study, the AUTODYN 3D computational domain measured $3,400 \times 2,000 \times 2,000$ mm along the x , y and z axes respectively. A quadrilateral element size of 20 mm was used for both the Euler and Lagrange solvers, as suggested by previous studies (Jestin *et al.*, 2014, 2015). Air was modelled using the Euler solver, while the soil barrier was represented using the Lagrange solver.

In order to reduce computational time, a one dimensional detonation model was mapped onto a three dimensional Eulerian domain, and only half of the soil barrier was modelled using symmetry along the x - z plane. A trinitrotoluene (TNT) equivalence ratio of 1.37 was adopted for the PE4 charge, resulting in an equivalent spherical TNT charge radius of 58.54 mm (Rigby & Sielicki, 2014).

Pressure gauges were positioned to monitor blast pressure in front of and behind the soil barrier. Gauge 1 was located at the centre of the front face of the barrier, 1 m from the detonation point, to measure the reflected pressure. Gauges 2, 3 and 4 were positioned behind the barrier at distances of 2.6 m and 3.1 m from the centre of the explosive and at elevation of 200 mm above the ground to capture blast wave interactions downstream of the barrier. The locations of the four gauges are illustrated in Figure 2. Flow out boundary conditions were applied at all external boundaries to minimise artificial blast wave reflections within the computational domain.

2.3 Constitutive Model

Modelling blast wave interaction with structures and materials response towards blast loading involves complex, highly nonlinear engineering phenomena. The materials modelled in AUTODYN 3D were TNT, air and sand. Air was modelled using the ideal gas equation of state, as presented in Equation 1 (Grisaro & Edri, 2017), where P is the pressure, γ is the adiabatic constant (equal to 1.4), ρ is the air density (1.225 kg/m^3), E is the specific air internal energy ($2.068 \times 10^5 \text{ kJ/kg}$), C_v is specific heat at constant volume, and T is temperature. As air does not sustain shear strength, no strength or failure model was assigned.

$$P = (\gamma - 1) \rho E. \quad (1)$$

The explosive detonation and expansion were modelled using the Jones-Wilkins-Lee (JWL) equation of state (Schwer, 2016), which is presented in Equation 2 (Dobratz & Crawford, 1985). P is the hydrostatic pressure, while C_1 , C_2 , R_1 , R_2 , and ω are empirically derived constants that provide different constant values for different explosives. Meanwhile, V is the specific volume of detonation product over the specific volume of undetonated explosive, and E is the specific internal energy. The values of C_1 , C_2 , R_1 , R_2 and ω for TNT explosive are $3.738 \times 10^2 \text{ GPa}$, 3.747 GPa , 4.15 , 0.9 , and 0.35 respectively. The density of TNT is $1,630 \text{ kg/m}^3$. No strength or failure model was assigned to the explosive.

$$P = C_1 \left(1 - \frac{\omega}{R_1 V}\right) e^{-R_1 V} + C_2 \left(1 - \frac{\omega}{R_2 V}\right) e^{-R_2 V} + \frac{\omega E}{V}. \quad (2)$$

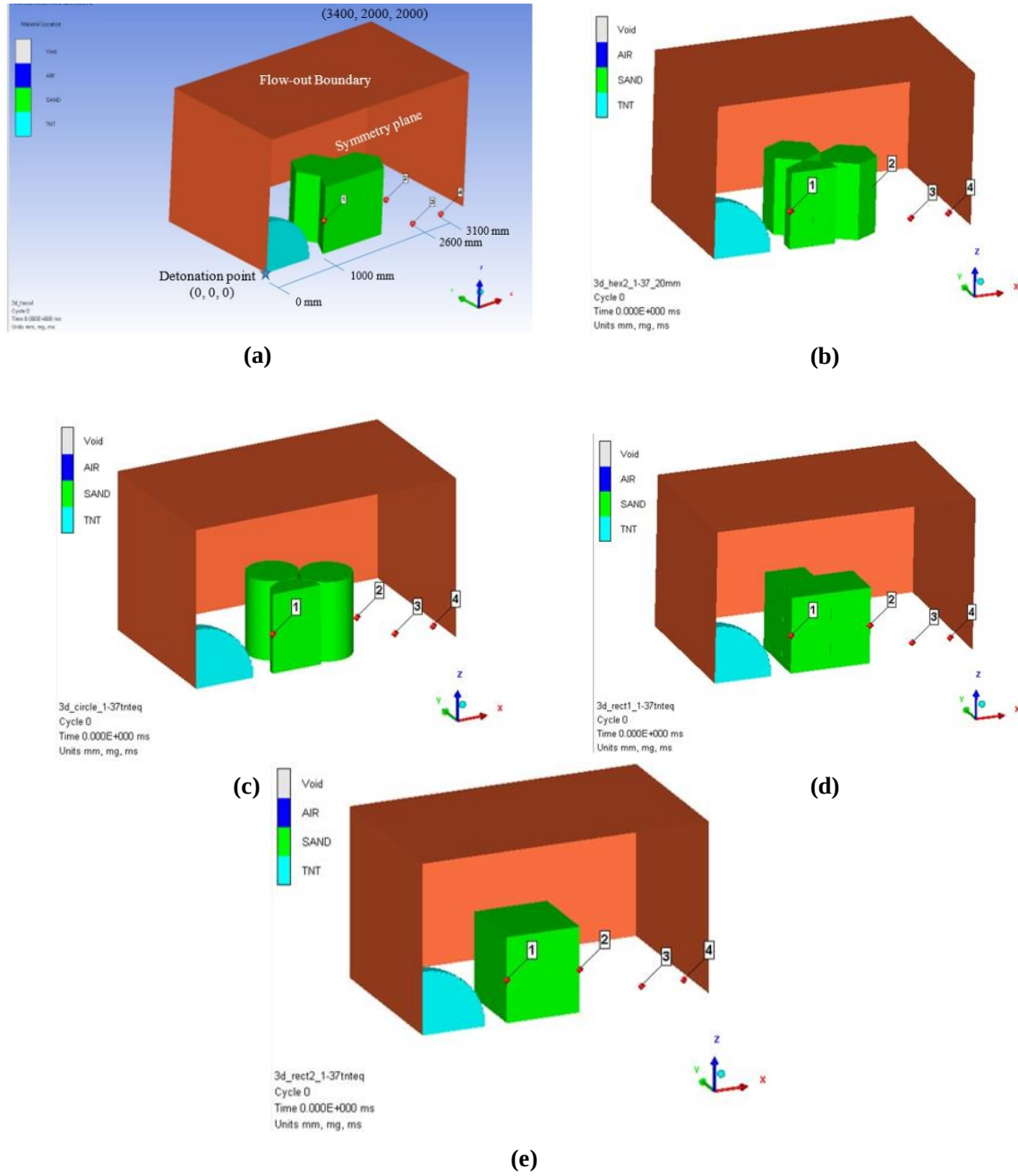


Figure 2: AUTODYN 3D model setup for the hexagonal soil barriers and the positions of pressure sensors: (a) Hex1 (b) Hex2 (c) Circle1 (d) Rect1 (e) Rect2.

The equation of state used to model sand in AUTODYN is compaction, which was developed by Laine & Sandvik (2001), as presented in Equation 3, where P is pressure, c is sound speed and ρ is density.

$$P = c(\rho)^2 \rho \quad (3)$$

The strength model used to model porous material such as sand is the granular strength model, as presented in Equation 4 (Laine & Sandvik, 2001). This model describes the non-linear behaviour of the material under deviatoric strain. The model also assumes that yield strength varies with both pressure and density, where Y is yield strength, ρ is density and P is pressure. The sand failure model used in AUTODYN is the hydro tensile failure model. Sand failure was defined by minimum pressure criterion of $P_{min} = -1 \times 10^{-3}$ Pa.

$$Y(\rho, P) = F_1(\rho) + F_2(P). \quad (4)$$

3. RESULTS AND DISCUSSION

3.1 Blast Wave Interaction with the Soil Barriers

Figure 3 shows the propagation of the blast wave and its interaction with the Hex1 barrier in AUTODYN 3D, with the blast wave travelling from left to right. The incident blast wave is first reflected from the front surface of Hex1, producing a reflected wave of higher intensity and velocity that propagates in the opposite direction. At the same time, a transmitted compression wave propagates through the soil in the same direction as the incident blast wave, compressing the barrier forward. The velocity of this wave is higher in the soil medium than in air.

At $t = 0.92$ ms, the blast wave reaches the top of Hex1 and an air vortex develops at the upper front corner of the barrier. The pressure in this region is lower than that of the incident shock front, as indicated by the pressure contours. At $t = 1.59$ ms, the reflected blast wave merges with the incident blast wave and is reflected away from Hex1. The blast wave begins to diffract from the upper rear corner at $t = 2.81$ ms. An air vortex subsequently develops between $t = 2.97$ and 4.18 ms, resulting in a lower pressure region behind the barrier. This vortex impedes the diffracted blast wave from directly impinging on the rear surface of Hex1, thereby reducing the pressure in this region.

At $t = 4.66$ ms, the rear surface of Hex1 is almost fully loaded by the blast wave and begins to reflect it. The resulting reflected wave propagates in the same direction as the incident blast wave and subsequently catches up with it between $t = 5.42$ and 5.97 ms. The two waves merge close to the ground, resulting in the formation of a Mach stem.

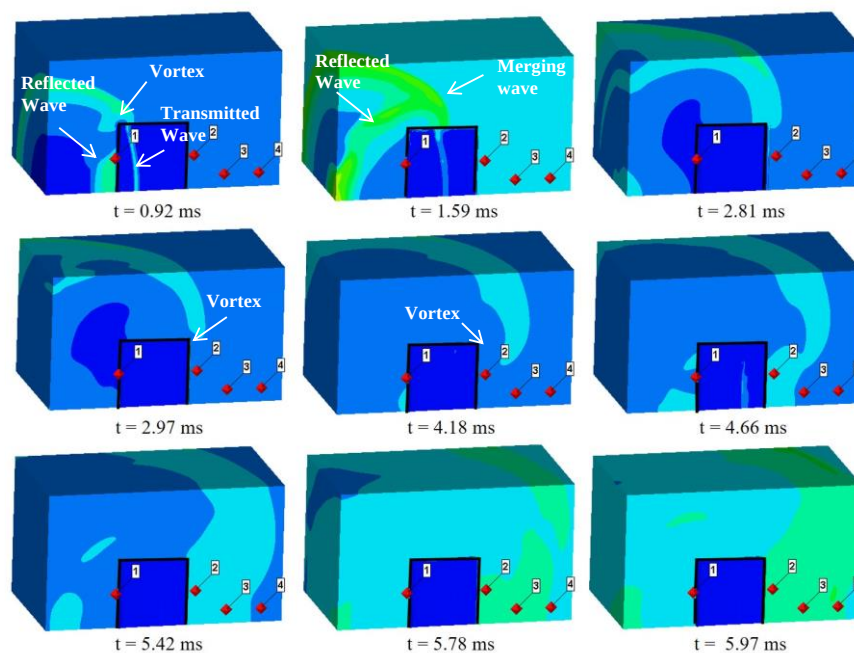


Figure 3: Blast wave propagation in interaction with soil barrier Hex1.

The initial blast wave interaction with Hex2 from $t = 0.28$ to 0.88 ms is similar to that observed for Hex1, as shown in Figure 4. The main difference occurs when the blast wave reaches the edge of the first barrier at $t = 1.87$ ms and diffracts downward into the void between the two barriers. Within this confined space, the blast wave undergoes repeated reflections between the internal walls, with the pressure contours from $t = 2.45$ to 3.96 ms indicating an intensity comparable to that of the incident blast wave.

At $t = 2.45$ ms, the blast wave begins to diffract for a second time at the second barrier. By $t = 3.22$ ms, an air vortex develops at the upper rear corner of the second barrier. This vortex impedes the blast wave from directly impinging on the rear surface of Hex2 and reduces the overpressure behind the barrier, thereby improving its mitigation performance.

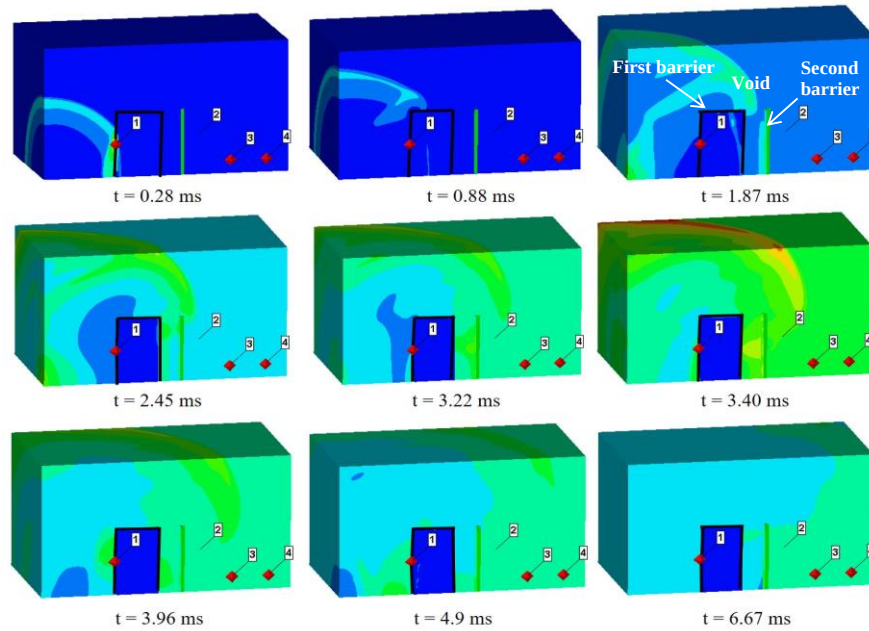


Figure 4: Blast wave propagation in interaction with soil barrier Hex2.

The blast wave interaction with Circle1, shown in Figure 5, is broadly similar to that observed for Hex2. The incident blast wave first diffracts through the void space at $t = 2.23$ ms, although the void in Circle1 is smaller than that in Hex2. A second diffraction occurs at $t = 3.00$ ms. Unlike Hex2, no air vortex develops following the second diffraction at $t = 4.13$ ms. The diffracted blast wave therefore impinges directly on the rear surface of Circle1 with relatively little attenuation before propagating towards the ground. Consequently, the pressure reduction behind Circle1 is lower.

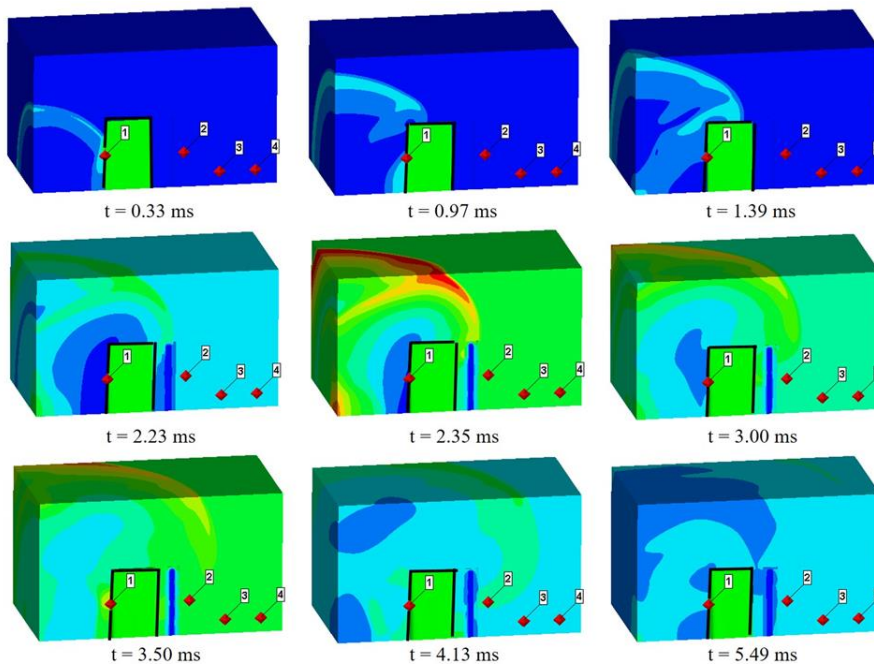


Figure 5: Blast wave propagation in interaction with soil barrier Circle1.

Figure 6 presents the blast wave interaction with Rect1. The initial reflection and transmission processes are similar to those observed for the preceding cases. However, Rect1 does not contain a void space, and the blast wave thus propagates across the top of the barrier without the intermediate diffraction observed in Hex2 and Circle1.

At $t = 3.26$ ms, the blast wave begins to diffract from the upper rear corner of Rect1 and moves towards the ground by $t = 3.87$ ms. No air vortex is observed, and the blast wave impinges directly on the rear surface with little attenuation. By $t = 4.76$ ms, the rear surface is fully loaded by the blast wave and subsequently reflects it, as observed at $t = 5.26$ ms. The reflected wave later catches up with the incident blast wave at approximately $t = 6.02$ ms, and the two waves merge close to the ground surface, increasing the blast-wave intensity.

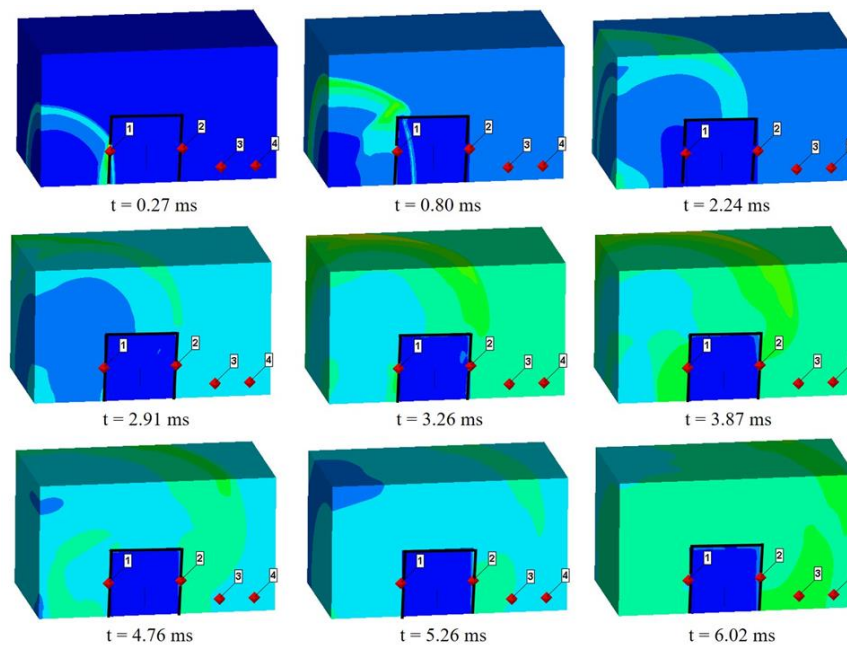


Figure 6: Blast wave propagation in interaction with soil barrier Rect1.

Figure 7 illustrates the blast wave interaction with Rect2, which serves as the reference configuration for comparison with the other cases. The overall propagation pattern is broadly similar to that observed for Rect1. The main difference occurs during diffraction at the upper rear corner, where an air vortex forms at $t = 2.95$ ms. Although this vortex is less intense than that observed in Hex2, it still reduces the blast wave intensity behind the barrier. Consequently, Rect2 provides slightly better blast wave mitigation than Rect1.

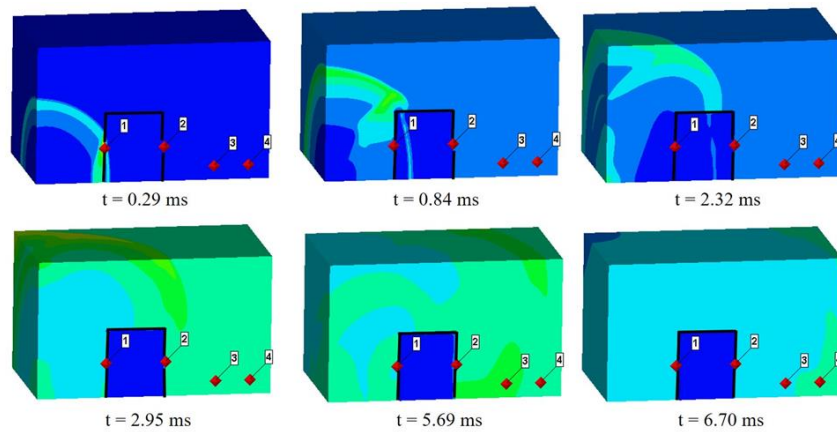


Figure 7: Blast wave propagation in interaction with soil barrier Rect2.

3.2 Comparison of Blast Overpressure Attenuation

Following the qualitative assessment of blast wave propagation in Figures 3 to 7, the attenuation performance of the five barrier configurations was compared using the peak overpressure values recorded at Gauges 2, 3 and 4. Figure 8 presents the percentage difference in peak overpressure relative to Rect2. Values above the horizontal axis indicate better attenuation than Rect2, while values below the axis indicate lower attenuation performance.

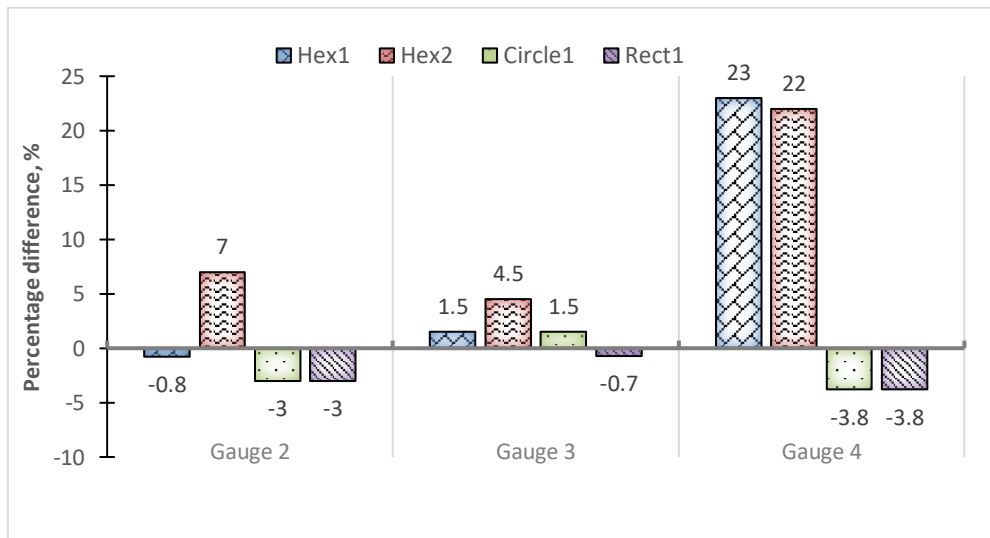


Figure 8: Percentage difference of peak overpressure values in comparison with Rect2 for gauges located behind the barrier (Gauges 2, 3 and 4).

At Gauge 2, located directly behind the barrier, Hex2 provides the greatest reduction in blast overpressure, with improvement of 7% compared with Rect2. The other configurations show lower effectiveness than Rect2, with percentage differences of approximately 0.8% to 3%. The performance of Hex2 is consistent with the diffraction and vortex behaviour described in Section 3.1. Hex1 shows a relatively small percentage difference of 0.8% despite having one of the lowest front surface pressures as compared with Rect2. This suggests that blast wave attenuation is independent of the pressure measured at the front of the barrier (Eslami *et al.*, 2023). A similar trend is observed for Hex2, which records the highest front pressure but one of the lowest pressures behind the barrier.

At Gauge 3, located 2.6 m behind the barrier, Hex2 again records the highest percentage difference, with a 4.5% improvement over Rect2. Hex1 and Circle1 show similar performance, with both recording approximately 1.5% greater attenuation than Rect2, while Rect1 provides the lowest attenuation. The improved performance of Hex1 and Circle1 at this location is attributed to oblique reflection behind the barriers, which redirects the diffracted blast wave away from Gauge 3.

At Gauge 4, located 3.1 m behind the barrier, the attenuation effect becomes more pronounced for the two hexagonal configurations. Hex1 and Hex2 record improvements of 23 and 22%, respectively, as compared with Rect2. In contrast, the attenuation performance of Rect1 and Circle1 decreases by approximately 3.8% as the distance behind the barrier increases.

Overall, the results indicate that the effectiveness of blast wave attenuation varies with barrier shape and arrangement. The circular and rectangular configurations show comparatively limited attenuation at greater distances behind the barrier, whereas the hexagonal configurations produce greater downstream pressure reduction. Since the present study focuses on numerical performance evaluation, a detailed assessment of constructability and life cycle cost is beyond the scope of this work.

4. CONCLUSION

The results demonstrate that blast wave attenuation is influenced by the shape and arrangement of the soil barrier. Among the five configurations investigated, Hex2 showed the best overall performance, followed by Hex1, Rect2, Circle1 and Rect1. The two hexagonal configurations also produced the largest blast overpressure attenuation at greater distances behind the barrier.

The pressure contour analysis indicates that these differences are associated with the diffraction of the blast wave at the upper and rear edges of the barriers and the formation of air vortices. In the hexagonal configurations, particularly Hex2, vortex formation reduced the direct impingement of the diffracted blast wave on the rear region of the barrier. In contrast, the circular and rectangular configurations generally exhibited lower attenuation where vortex formation was weak or absent. Overall, the findings show that appropriate selection of barrier shape and arrangement can improve blast wave mitigation, with the hexagonal configurations providing the greatest downstream pressure reduction among the cases examined.

ACKNOWLEDGMENT

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ANALYSIS OF PHYSICAL AND MECHANICAL PROPERTIES AFFECTING WATER PENETRATION IN COATED FABRICS

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ABSTRACT

This study investigates the effects of physical and mechanical properties on the water penetration resistance of coated fabrics, focusing on two materials: nylon coated with polyurethane (PU) (Material A) and polyester coated with polyvinyl chloride (PVC) (Material B). The research evaluates key properties such as breaking strength, tearing strength, mass per unit area, air permeability and water penetration resistance. Material B demonstrated superior mechanical properties, including higher breaking and tearing strength, as well as significantly greater water penetration resistance, averaging 1,001.15 cmH₂O as compared to Material A with moderate water penetration resistance of 43.02 cmH₂O. The findings highlight the importance of optimising fabric properties to achieve the desired performance characteristics, with Material B being ideal for heavy-duty applications requiring robust water penetration resistance, and Material A better suited for lightweight and breathable applications. The study underscores the interplay between physical and mechanical properties in determining the functional performance of coated fabrics in various industrial and consumer applications.

Keywords: Coated fabrics; water penetration resistance; tensile and tearing properties; polyurethane (PU) coating; polyvinyl chloride (PVC) coating.

1. INTRODUCTION

The coated fabrics industry has grown significantly in recent years, driven by increasing safety requirements in sectors such as aerospace, military, emergency rescue and industry by the need for materials capable of operating reliably in both extreme environments and everyday applications (Xu *et al.*, 2024). In military settings, fabrics used in equipment such as tents, protective clothing, packs and webbings must provide strong resistance to moisture while maintaining mechanical durability. Similarly, outdoor and technical apparel require materials that can protect against environmental conditions while still providing adequate breathability and comfort. As a result, coated fabrics have become important engineering materials in both industrial and consumer applications (Ghosh *et al.*, 2025).

Coated fabrics are composite materials consisting of a textile substrate, either woven or non-woven, combined with a polymer-based coating applied to the surface. The coating modifies the functional properties of the textile by enhancing characteristics such as water penetration resistance, durability and chemical stability (Essa, 2024), while the textile substrate provides structural strength and flexibility (Rastogi *et al.*, 2020). Consequently, the performance of coated fabrics depends on the combined behaviour of both the textile and coating layers. Coating chemistry is one of the factors that affects these overall efficiency (Alvi *et al.*, 2024), coating thickness (Durão *et al.*, 2026), application methods (Abdi *et al.*, 2024) and the intrinsic physical properties of the underlying textile material (Kim, 2021).

One of the most critical performance requirements of coated fabrics is water penetration resistance. The mechanisms governing water ingress into coated textile systems are complex and involve several interacting processes. Water can possibly penetrate through capillary pathways formed by voids within yarns or fibres, particularly if the coating layer is incomplete or discontinuous. In addition, defects such as micro-cracks, pores or coating delamination may develop under mechanical stress, creating pathways through which water can pass (Rungruangkitkrai *et al.*, 2024). While some studies have suggested that water penetration resistance is largely determined by the properties of the coating material (Siddique *et al.*, 2025), others have shown that the mechanical behaviour of the textile substrate, including bending and shear deformation, can also influence the integrity of the coating layer and consequently the resistance to water penetration (Padleckienė & Petrulis, 2010).

The performance of waterproof and breathable coated fabrics had been examined in previous studies, by analysing parameters such as water penetration resistance, tensile strength and water vapour permeability. Razzaque *et al.* (2019) reported that the application of water-repellent coatings can significantly enhance water penetration resistance and tensile strength without greatly reducing breathability. Cho *et al.* (2004) demonstrated that increasing the concentration of polyurethane coating solutions reduces water vapour permeability while influencing the mechanical behaviour of the coated fabric. In addition to serving as a barrier against moisture, coatings also give influence to mechanical properties such as tensile strength, elongation at break and elasticity (Asadi *et al.*, 2018). These findings highlight the importance of understanding the relationship between the physical and mechanical characteristics of coated fabrics and their water penetration resistance.

Water penetration resistance is commonly evaluated using hydrostatic pressure testing. In this method, water pressure is gradually increased on the fabric surface until penetration occurs, providing a measure of the water penetration resistance of the material. This test is particularly relevant for applications such as outdoor equipment and military protective systems, where fabrics are exposed to sustained moisture and mechanical stresses during use (Revaiah *et al.*, 2020). In such applications, coated fabrics must maintain both barrier performance and mechanical integrity under conditions of bending, stretching and repeated loading (Ghezal *et al.*, 2019).

Various polymeric materials are used as coatings to provide waterproofing and durability. Common coating materials include polyurethane (PU), polyvinyl chloride (PVC), silicone elastomers and fluorocarbon-modified polymers (Jahid *et al.*, 2018). Each coating system offers distinct advantages depending on the application requirements. PU coatings generally provide flexibility and breathability, making them suitable for lightweight applications. PU coatings on fabric such as nylon enhances moisture permeability and water penetration resistance properties to the base fabric. These fabrics are the best alternative for synthetic leather clothing used in extreme weather especially in the defence industry (Sikdar *et al.*, 2022). On the other hand, PVC coatings typically offer greater durability and higher resistance to water penetration. For example, polyester fabrics coated with PVC are widely employed in architectural design due to their favourable mechanical performance and weather resistance (Xu *et al.*, 2024). The mechanical performance of coated fabrics is also influenced by factors such as coating thickness and polymer concentration, which may affect properties including modulus, elongation and air permeability (Sikdar *et al.*, 2022).

Despite the considerable body of research on waterproof and breathable fabrics in apparel and technical textile applications, there remains a limited understanding of how specific physical and mechanical properties collectively influence water penetration resistance (Padleckienė *et al.*, 2009; Padleckienė & Petrulis, 2010), particularly for heavy-duty or defence-related coated fabrics. In particular, the relationship between mechanical deformation and water penetration resistance has not been extensively quantified. Parameters such as tensile strength, tearing resistance, mass per unit area and air permeability may significantly influence the ability of coated fabrics to resist water penetration under hydrostatic pressure.

Therefore, this study investigates the relationship between selected physical and mechanical properties of coated fabrics and their water penetration resistance. Two types of coated fabrics were examined: nylon coated with PU (Material A) and polyester coated with PVC (Material B). Mechanical tests, including breaking strength and tearing strength, were conducted together with measurements of mass per unit area, air permeability and water penetration resistance. The objectives of this study are to evaluate how differences in fabric structure and coating material influence the overall water penetration resistance of coated fabrics, as well as to provide insights into material selection for functional textile applications.

2. EXPERIMENTAL DETAILS

2.1 Methodology

2.1.1 Breaking Strength

Breaking strength was measured using a Tinius Olsen H25KS tensile test machine according to ISO (2016a). The specimen size was kept at 200 mm x 50 mm, while the testing speed was 100 mm/min. The breaking force was recorded as the maximum force required to extend the specimen until failure.

2.1.2 Tearing Strength

Tearing strength was measured at room temperature using the tensile test machine, following (ISO, 2016b). Tongue-shaped tear specimens measuring 100 mm × 50 mm were prepared and tested at speed of 100 mm/min. The maximum tearing force required to propagate the tear was recorded.

2.1.3 Mass per Unit Area

The weight of 10 cm × 10 cm specimens was measured using a digital weighing balance. The mass per unit area was calculated using the Equation (1).

$$\text{Mass per unit area, } \frac{g}{m^2} = \text{Specimen weight (average of 3)} \times 100 \quad (1)$$

2.1.4 Air Permeability

Air permeability is the rate at which air flows through a known area between two surfaces of a material perpendicularly at a specified air pressure. The air permeability of the samples was measured using a SDL ATLAS MO21A air permeability tester, which measures airflow rate under constant air pressure in accordance with ASTM (2023). Due to the layered structures of the fabric samples, the test area was 20 cm² and the air pressure differential between the two surfaces remained at 200 Pa. The average of three measurements were made for every sample.

2.1.5 Water Penetration Resistance

Water penetration was conducted using an SDL ATLAS hydrostatic head tester (Model MO18) in accordance with ISO (2018) at temperature of 27 ± 2 °C. The water pressure was increased at rate of 60 ± 3 cmH₂O/min, with the compressor operating at a maximum pressure of 80 PSI. The water pressure at which penetration occurred from the outer to inner layer was recorded.

3. RESULTS AND DISCUSSION

Table 1 shows the results of the tests for both materials, nylon coated with PU (Material A) and polyester coated with PVC (Material B). The table highlights significant differences in all the results, where Material B exhibits higher breaking strength, tearing strength, mass per unit area and water penetration resistance than Material A.

Table 1: Physical and mechanical properties of Materials A and B.

Material	Sample	Breaking Strength (N)		Tearing Strength (N)		Mass Area (g/m ²)	Air Permeability (cfm)	Water Penetration (cmH ₂ O)	
		Warp	Weft	Warp	Weft			As Received	After Flexing
(A) Nylon coated with PU	1	2,268	2,022	396	380	374	0.139	100.64	40.37
	2	2,441	2,010	415	344	372	0.147	113.05	40.34
	3	2,433	1,984	381	369	376	0.149	109.23	48.36
	Average	2,381	2,005	397	364	374	0.145	107.64	43.02
(B) Polyester coated with PVC	1	3,481	3,599	417	475	1200	0.005	1,000.94	1,000.86
	2	3,409	3,331	461	445	1214	0.001	1,000.58	1,002.2
	3	3,267	3,561	447	482	1194	0.003	1,001.04	1,000.4
	Average	3,385	3,497	442	467	1203	0.003	1,000.85	1,001.15

3.1 Breaking Strength

Based on Figure 1, Material B demonstrated significantly higher breaking strength as compared to Material A in both warp and weft directions across all three samples and their averages. Material B exhibited average breaking strength values of approximately 3,350 N in the warp direction and 3,500 N in the weft direction, while Material A shows average breaking strength values of approximately 2,350 N in the warp direction and 2,000 N in the weft direction. This aligns with established research indicating that polyester coated with PVC fabrics typically demonstrate superior tensile strength properties as compared to nylon coated with PU (Jörg *et al.*, 2015). Luo *et al.* (2008) found that biaxial warp knitted polyester fabrics coated with PVC exhibits very high tensile and tearing strengths under biaxial loads. In a further study of polyester-reinforced PVC-coated fabric membranes, Zerdzicki & Jacomini (2019) reported strip tensile strengths in the range of 3,100 N/5 cm to 5,800 N/5 cm for weights of 800–1,100 g/m². Furthermore, the difference in breaking strength between Materials A and B is substantial, with Material B exhibiting approximately 42% higher strength in the warp direction and 75% higher strength in the weft direction as compared to Material A. This significant performance gap suggests that Material B would be more suitable for applications requiring higher tensile strength and load-bearing capacity such as industrial tarpaulins, architectural membranes and heavy duty covers (Eun *et al.*, 2020).

3.2 Tearing Strength

Based on the tearing strength data presented in Figure 2, Material B exhibited higher tearing resistance as compared to Material A across both warp and weft directions. Specifically, the average tearing strength for B-Weft and B-Warp is approximately 470 N and 440 N, respectively, while A-Warp averages around 400 N and A-Weft shows the lowest value at approximately 360 N. This suggests that the combination of polyester fabric and PVC coating provides superior mechanical properties in terms of tear resistance, which may be explained by the interfacial connections between PVC and polyester as well as the higher tensile strength of polyester fibres (Dobilaitė *et al.*, 2022).

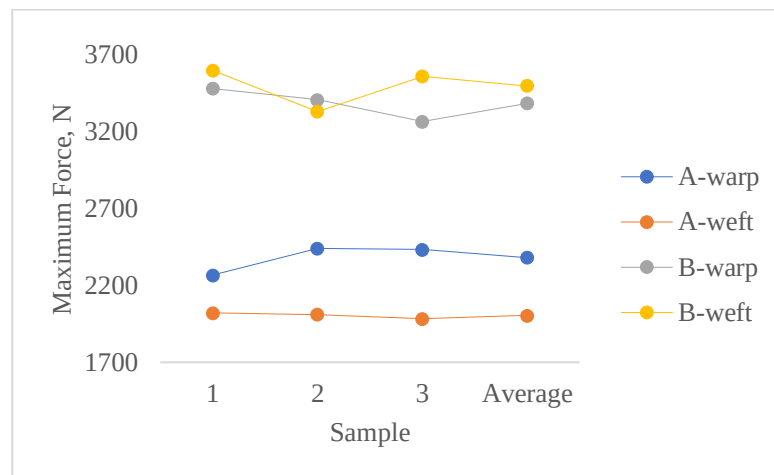


Figure 1: Breaking strength of Materials A and B.

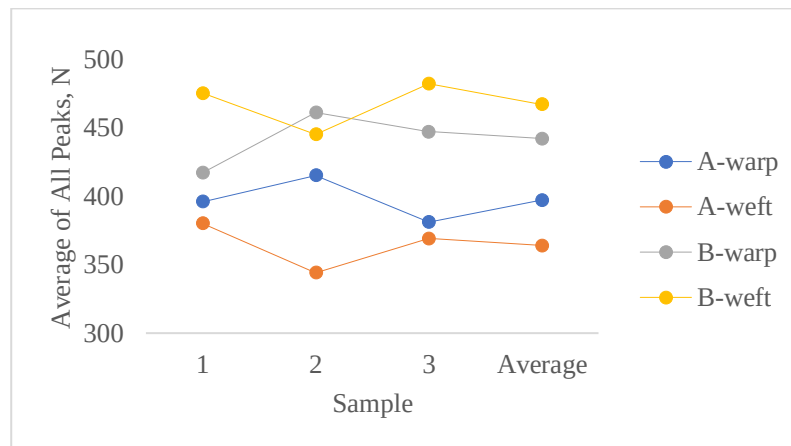


Figure 2: Tearing strength of Materials A and B.

Additionally, the data reveals directional anisotropy in tearing strength for both materials. Material A demonstrated higher tear resistance in the warp direction, whereas Material B showed superior performance in the weft direction. This variance highlights the influence of fabric structure and coating application techniques on the final mechanical properties (Nagamadhu *et al.*, 2023). The observed differences between warp and weft tearing strength suggest that the weaving pattern and coating process significantly impact the directional performance of these coated textiles, underscoring the importance of considering these factors in material selection for specific applications.

3.3 Mass per Unit Area

Based on the mass per unit area data shown in Figure 3, Material B exhibited substantially higher mass, averaging 1,203 g/m² as compared to Material A with average of 374 g/m². This indicates that Material B is approximately 3.2 times heavier per unit area. The significant mass difference between these materials suggests several functional disparities. Polyester coated with PVC combinations typically provide enhanced durability and weather resistance at the cost of increased weight, while

nylon coated polyurethane systems offer improved flexibility and lighter weight profiles (Uzumcu *et al.*, 2024). The lower mass of Material A makes it particularly suitable for applications where weight is a critical factor, such as lightweight protective clothing, backpacks and outdoor recreational equipment (Zhang *et al.*, 2019). The material's lighter weight also generally correlates with improved breathability and comfort characteristics for user-worn applications. Conversely, the substantially heavier Material B is suitable for applications where durability and weather resistance take precedence over weight considerations, such as heavy-duty tarpaulins, industrial covers and architectural membranes (Eun *et al.*, 2020). The additional mass typically contributes to better tear strength, puncture resistance (Xu *et al.*, 2021) and overall longevity in harsh environments (Dobilaitė *et al.*, 2022).

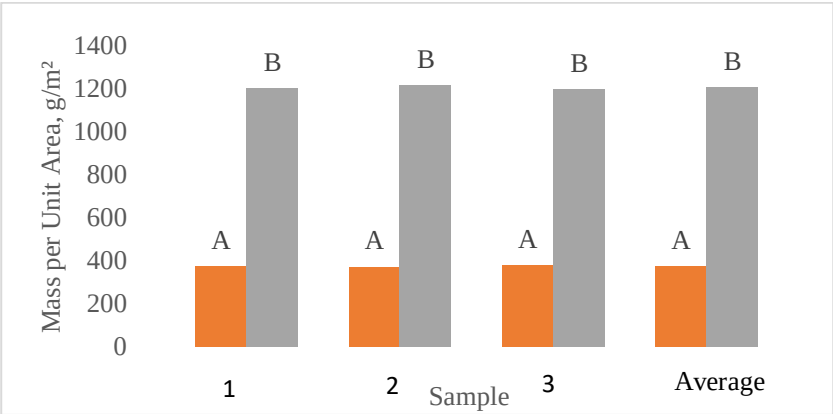


Figure 3: Mass per unit area of Materials A and B.

3.4 Air Permeability

The graph presented in Figure 4 compares the air permeability test results for Materials A and B. The test shows how easily air passes through a material, which is a critical parameter in evaluating the performance characteristics of coated fabrics for various applications. Material A exhibited significantly higher air permeability with values ranging from 0.139 cfm to 0.149 cfm, with an average of 0.145 cfm. On the other hand, Material B demonstrated substantially lower air permeability with values between 0.001 cfm and 0.005 cfm, averaging at just 0.003 cfm.

Material A with higher air permeability would allow better air circulation, making it more suitable for applications where user comfort is paramount, such as sports apparel and outdoor equipment (Lam *et al.*, 2020). Nylon fabrics are generally known for their good air permeability due to their lightweight and often porous nature. The PU coating may reduce this permeability slightly, but overall breathability is likely to remain relatively high. This makes Material A suitable for applications where comfort and ventilation are important, such as in activewear and lightweight outdoor gear.

On the other hand, polyester fabrics, especially when coated with PVC, tend to have lower air permeability due to the denser and more impermeable nature of the coating. This characteristic makes Material B more suitable for applications where airflow is less critical, such as in industrial covers or heavy-duty protective clothing. Reducing the air permeability can be beneficial in environments where protection from wind, dust or moisture is more important than breathability (Lee & Obendorf, 2007).

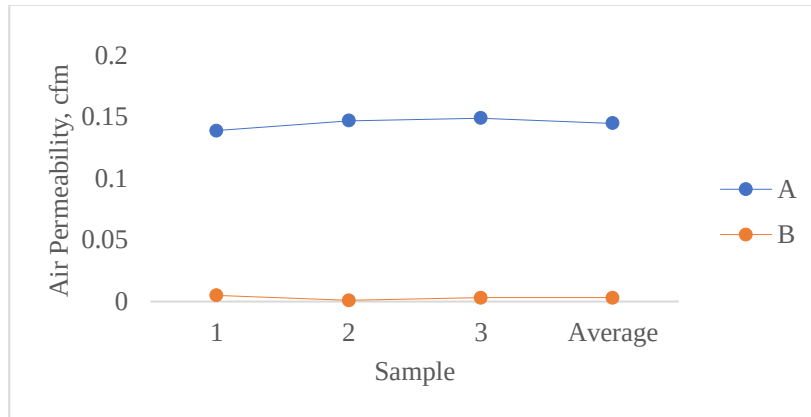


Figure 3: Air permeability of Materials A and B.

3.5 Water Penetration

As shown in Figure 5, Material B demonstrated significantly higher water penetration resistance, with values consistently close to 1,000 cmH₂O both before and after flexing. In comparison, Material A showed much lower water penetration resistance, with values averaging below 150 cmH₂O. After flexing, Material A showed a slight increase in water penetration. Flexing likely disrupts the integrity of the PU coating, creating micro-cracks or weakening its barrier properties. However, this increase is minimal, demonstrating that nylon coated with PU retains most of its water-resistant properties even after mechanical stress. Material B displays exceptionally high resistance to water penetration. The PVC coating provides a robust barrier against water ingress, outperforming Material A under identical conditions. This suggests that PVC coatings are inherently more impermeable to water as compared with PU coatings. Material B maintained its high resistance to water penetration even after flexing. Unlike Material A, flexing does not appear to compromise the coating's effectiveness significantly. This stability indicates that PVC coatings are more durable under mechanical stress and maintain their protective properties over time.

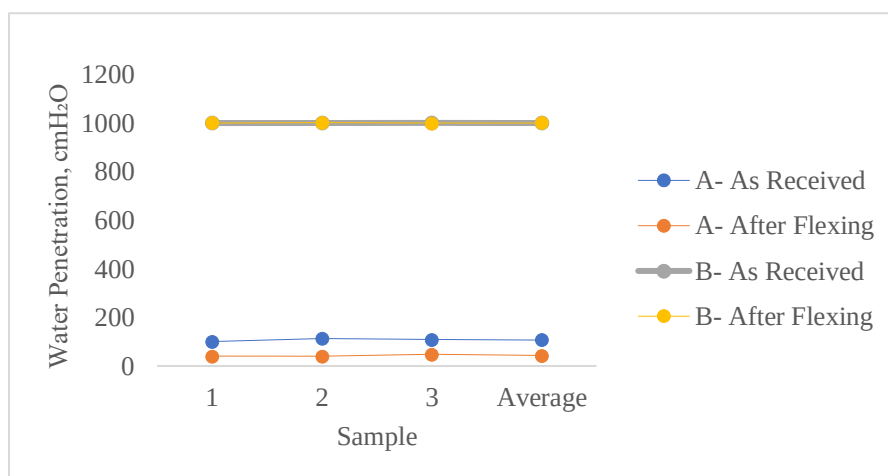


Figure 5: Water penetration of Materials A and B.

4. CONCLUSION

In this study, it was found that the physical and mechanical properties of the coated fabrics significantly influenced their water penetration resistance, as demonstrated by the test results. Nylon coated with PU (Material A) showed moderate water penetration resistance, with average of 43.02 cmH₂O. This performance is consistent with its lower breaking strength (2,381 N warp, 2,005 N weft), moderate tearing strength (397 N warp, 364 N weft), and lower mass per unit area (374 g/m²). Additionally, its higher air permeability of 0.145 cfm indicates that it has a more open fabric structure, which allows some water to penetrate under pressure. These properties make Material A suitable for applications requiring moderate resistance to water penetration, such as lightweight rainwear and outdoor gear, where breathability is also important.

In contrast, polyester coated with PVC (Material B) exhibited exceptional resistance to water penetration, with average of 1,001.15 cmH₂O. This superior performance is attributed to its high breaking strength (3,385 N warp, 3,497 N weft), excellent tearing strength (442 N warp, 467 N weft) and significantly higher mass per unit area (1,203 g/m²). The extremely low air permeability of 0.003 cfm further enhances its water penetration resistance by creating a dense, impermeable barrier. These properties make Material B ideal for heavy-duty applications, such as industrial covers and protective clothing, where maximum water penetration resistance is required under harsh conditions.

In conclusion, the results highlight the critical role of physical and mechanical properties in determining the water penetration resistance of coated fabrics. Material B's superior performance in breaking strength, tearing strength, mass per unit area and low air permeability makes it highly effective for applications requiring robust water penetration resistance. Material A, while less resistant to water penetration, offers a balance of moderate water penetration resistance and breathability, making it suitable for lighter applications. These findings underscore the importance of optimising fabric properties to achieve the desired level of resistance to water penetration for specific use cases.

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A REVIEW OF BIOSENSOR TECHNOLOGIES FOR AIRBORNE MICROORGANISM DETECTION

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ABSTRACT

Airborne microorganisms can spread rapidly and pose significant risks to public health, environmental safety and biodefence. Therefore, their timely detection is essential for disease surveillance and early response. This review examines developments in biosensor technologies for airborne microorganism detection, with particular emphasis on the integration of microfluidics and nanomaterials to improve detection efficiency, sensitivity and portability. Conventional methods, including culture-based assays, polymerase chain reaction (PCR) and enzyme-linked immunosorbent assays (ELISA), remain important but may require specialised equipment, extensive sample preparation or longer processing times. Biosensors offer the potential for rapid, portable and near real-time pathogen detection. However, challenges remain in bioaerosol capture, environmental interference, signal reliability, system integration and detection of pathogens at low concentrations. Future development should focus on miniaturised and integrated platforms that combine air sampling, sample preparation, sensing and data transmission to improve the sensitivity, speed and affordability of airborne microorganism monitoring.

Keywords: Airborne microorganisms; biosensors; detection technologies; environmental monitoring; microfluidics.

1. INTRODUCTION

Airborne microorganisms, commonly referred to as bioaerosols, include bacteria, viruses, fungal spores and other biological particles suspended in the atmosphere as shown in Figure 1. They originate from natural and human-related sources and may be transported over considerable distances through atmospheric movement, deposition and resuspension. In addition to their roles in environmental and atmospheric processes, some airborne microorganisms act as pathogens or allergens and may contribute to respiratory infections and other adverse health effects, particularly in densely populated urban areas and enclosed environments (Guo *et al.*, 2020; Wang *et al.*, 2021). According to Nabipur *et al.* (2025), bioaerosols can account for 5–34% of indoor particulate matter, originating from both outdoor infiltration and indoor sources such as building materials, furnishings, pets, plants, organic waste and human activities including walking, sneezing, and coughing. Over the past few years, there has been a growing interest in the detection of airborne microbial pathogens. This increased emphasis is largely ascribed to the existence of indoor bioaerosols, driven by growing awareness of their potential implications for indoor air quality and public health (Memon *et al.*, 2024).

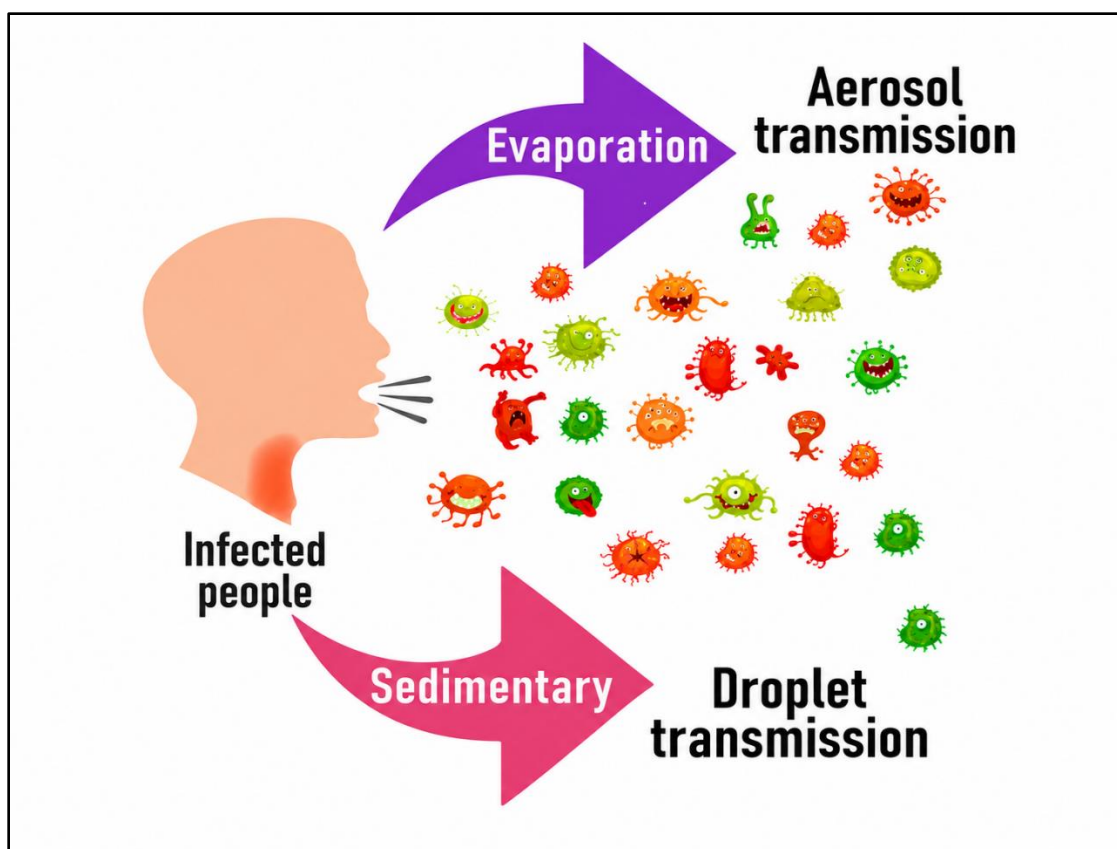


Figure 1: Airborne microorganisms capable of rapid dissemination via aerosol transmission.
(Source: Ma *et al.*, 2021).

Therefore, the timely detection of airborne microorganisms is important for public health surveillance, environmental monitoring, healthcare protection and biodefence. However, airborne pathogens are often present at low and variable concentrations, while their survival and detectability are influenced by environmental conditions, such as humidity, temperature, ultraviolet radiation and desiccation. Conventional culture, molecular and immunological methods remain important, but they may require lengthy processing, specialised laboratory equipment or extensive sample preparation, which limit their suitability for rapid or continuous field monitoring (Franchitti *et al.*, 2022; Rastmanesh *et al.*, 2024).

Biosensors provide a promising alternative by combining a biological recognition element with a transducer that converts a biological interaction into a measurable signal. Recent developments in electrochemical and optical sensing, nanomaterials, microfluidics and miniaturised platforms have improved the sensitivity, portability and potential response time of these systems. Their integration with air sampling and particle capture technologies may support more direct and near real-time detection of airborne pathogens, although challenges remain in sample collection, signal interference, selectivity, validation and standardisation (Ma *et al.*, 2021; Wang *et al.*, 2022b; Varughese *et al.*, 2023).

The objective of this review is to examine the development of biosensor technologies for the detection of airborne microorganisms. The review covers the characteristics and detection challenges of airborne microorganisms, conventional detection methods, air sampling and bioaerosol collection, biosensor recognition mechanisms, transduction and signal-amplification approaches, as well as the integration of microfluidics and nanomaterials into portable monitoring systems. Particular attention is given to the factors affecting sensitivity, efficiency and real-time operation, as well as the current limitations and future research requirements for practical airborne microorganism surveillance.

2. AIRBORNE MICROORGANISMS AND DETECTION METHODS

2.1 Airborne Microorganisms and Detection Challenges

Airborne microorganisms, or bioaerosols, encompass a range of biological particles suspended in the atmosphere, including bacteria, viruses, fungal spores and pollen grains. They originate from diverse sources, including soil, plants and animals, resulting in substantial variation in their types and abundance. They also differ in size, composition, metabolic capacity and resilience to environmental stresses, such as ultraviolet radiation, temperature fluctuations and desiccation (Song *et al.*, 2022). Airborne microorganisms contribute to ecological processes, including nutrient cycling, atmospheric chemistry and cloud formation through bioprecipitation (Šantl-Temkiv *et al.*, 2022). However, they may also pose significant health hazards, particularly when pathogenic microorganisms cause respiratory infections or allergic responses (Long *et al.*, 2024).

These effects can be especially serious among vulnerable groups, including older persons and individuals with comorbidities (Kumar *et al.*, 2021; Iizuka *et al.*, 2024). Studies of indoor airborne microbiomes further demonstrate the need to distinguish airborne microorganisms from other pollutants, as floor dust does not necessarily represent exposure to airborne bacteria (Shen *et al.*, 2024). Recent advances in detection technologies, as illustrated in Figure 2, are thus important for addressing the public health risks associated with airborne diseases in settings such as healthcare facilities (Varughese *et al.*, 2023). The detection of airborne microorganisms has become increasingly important in view of emerging infectious diseases. Accurate and timely detection is critical for managing outbreaks caused by diseases such as tuberculosis, influenza and COVID-19 (Chang *et al.*, 2023).

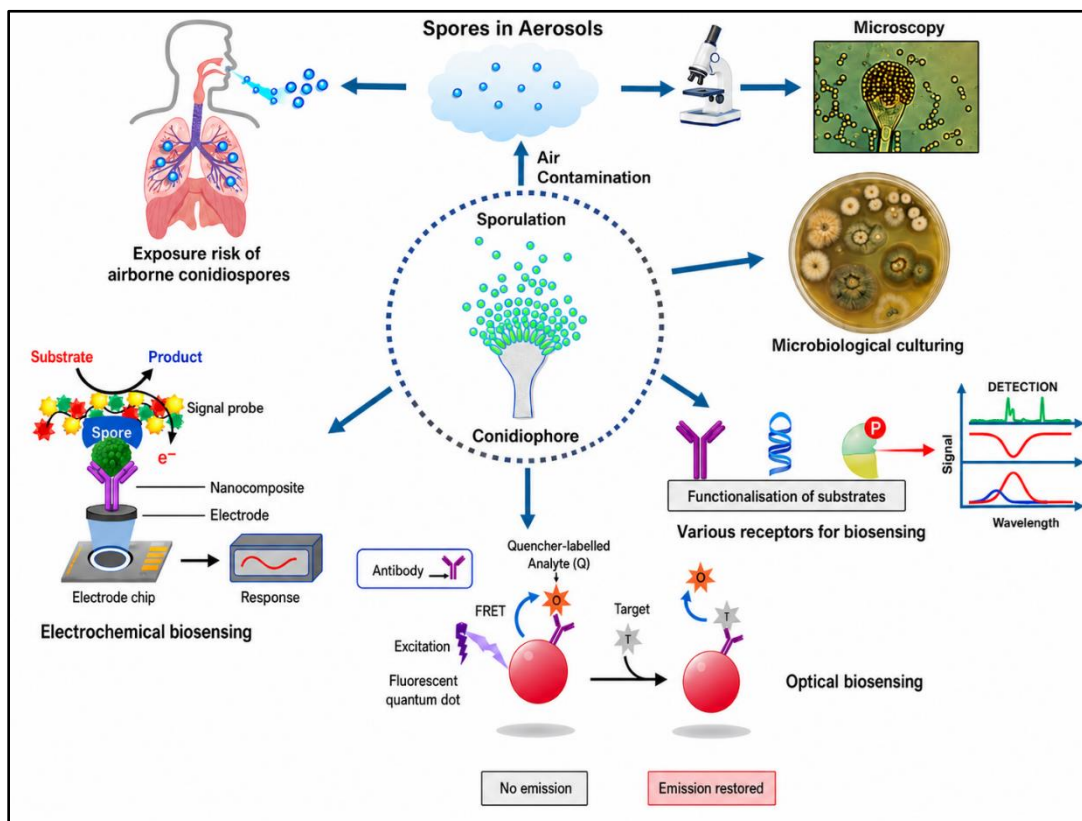


Figure 2: Recent advances in biosensor technology for the detection of airborne pathogenic spores.
(Source: Memon *et al.*, 2024)

Surveillance strategies incorporating rapid detection methods can improve response times and strengthen the effectiveness of public health measures during disease outbreaks (Franchitti *et al.*, 2022). However, conventional detection methods are affected by the characteristics of microbial communities and by environmental factors such as humidity and temperature, which can alter microbial viability and dispersal patterns (Rastmanesh *et al.*, 2024). Airborne pathogens may also occur at very low concentrations, while traditional approaches may lack the sensitivity required for reliable detection (Jayakumar *et al.*, 2024). Biosensor technologies employing approaches such as microfluidics may provide more efficient monitoring by supporting real-time analysis and portable operation (Wang *et al.*, 2022b; Varughese *et al.*, 2023). Nevertheless, substantial technical challenges remain, requiring continued research and interdisciplinary development.

2.2 Conventional Detection Methods

2.2.1 Cell Culture-Based Assay

Cell culture-based assays using agar plates to capture and incubate airborne microorganisms remain important for detecting viable microbial populations. However, the method has intrinsic limitations, particularly its inability to culture a wide range of microorganisms, which may lead to the underrepresentation of microbial diversity in environmental assessments. Conventional culture methods can substantially underestimate diversity, especially among rare microbial taxa, highlighting the value of combining culture-dependent and culture-independent techniques (Vitorino & Bessa, 2018; Li *et al.*, 2019).

Some microbial species also have specific growth requirements or dormant states that are not supported under standard laboratory conditions (Green *et al.*, 2020; Wu *et al.*, 2024). Prolonged incubation may yield additional colonies but requires more time and resources, while viable but non-culturable organisms may remain undetected (Ong *et al.*, 2019). High throughput sequencing and metagenomic profiling can complement culture-based methods by revealing microbial diversity that would otherwise be missed (Raymond *et al.*, 2019; Dang *et al.*, 2022). Therefore, culture-based assays provide valuable information on microbial viability and colony formation but are most effective when used alongside advanced molecular techniques (Flowers, 2022).

2.2.2 Polymerase Chain Reaction (PCR)

PCR is widely used for the rapid amplification of specific DNA sequences and enables airborne microorganisms to be detected without prior culture. During the COVID-19 pandemic, reverse transcription polymerase chain reaction (RT-PCR) was essential for tracing viral transmission and provided a faster turnaround than methods such as next-generation sequencing (Piana *et al.*, 2020). Its high sensitivity allows pathogens to be detected at low concentrations, supporting timely public health intervention (Lippi *et al.*, 2020). Nevertheless, strain variability may affect assay performance, while sample contamination can produce false positive results. Aggarwal *et al.* (2023) reported that increased handling during repeated PCR amplification can increase the risk of contamination. PCR also cannot generally distinguish between viable and non-viable microorganisms, complicating assessments of pathogen viability and associated health risks (Melvin *et al.*, 2024). These limitations may be reduced through rigorous laboratory procedures and complementary approaches such as viability PCR (vPCR) (Hongsibsam *et al.*, 2026). Continued improvement in sample preparation, contamination control and viability assessment will be important for enhancing the reliability of PCR-based airborne microorganism detection (Dinh Thanh *et al.*, 2025).

2.2.3 Enzyme-Linked Immunosorbent Assay (ELISA)

Enzyme-linked immunosorbent assay (ELISA) remains an important method for detecting microbial antigens. Its robustness and relatively rapid response make it useful in situations requiring timely diagnosis, including disease outbreaks. Recent advances have highlighted the importance of high quality antibodies and improved immobilisation methods in enhancing assay sensitivity and reliability. For example, covalent antibody immobilisation can improve antigen capture and increase ELISA sensitivity (García-Maceira *et al.*, 2021). Peptide-based assays may also reduce costs and biosafety concerns while maintaining suitable sensitivity (Zhao *et al.*, 2021). However, the sensitivity of commercial kits can vary according to the combination and quality of capture antibodies used (Enayati *et al.*, 2023). Therefore, the selection of appropriate antibodies and assay design has a direct influence on detection limits and overall performance (Liang *et al.*, 2021). Although ELISA remains a well-established method for microbial antigen detection, continued improvements are required to address the challenges presented by complex and heterogeneous sample matrices (Jeon *et al.*, 2025).

2.3 Air Sampling and Bioaerosol Collection

The detection of airborne microorganisms begins with the effective collection of bioaerosol particles from the surrounding air. Airborne pathogens are often present at low concentrations, while humidity, temperature and other environmental factors can influence their viability and dispersal. These conditions make sampling and concentration essential before the captured material can be analysed using conventional methods or biosensors (Jayakumar *et al.*, 2024; Rastmanesh *et al.*, 2024). A major challenge is achieving sufficient capture efficiency across different particle sizes, particularly for small, aerosolised pathogens such as viruses. Systems designed for larger particles, including bacterial spores, may be less effective for smaller particles. Sampling methods must thus preserve the biological or molecular characteristics of the target while providing a concentrated sample that is compatible with the subsequent detection process (De Penning *et al.*, 2025). For rapid and continuous monitoring, the collection stage should be integrated with sample preparation and biosensing in a single compact platform. Microfluidic particle capture systems provide a potential route for transferring collected bioaerosols directly to the sensing unit, reducing manual handling and delays between collection and analysis. Electrostatic capture combined with on-chip amplification has also demonstrated the potential for real-time airborne pathogen detection (Wang *et al.*, 2022b; Jayakumar *et al.*, 2024).

3. BIOSENSOR COMPONENTS, RECOGNITION AND DETECTION MECHANISMS

3.1 Biosensor Components and Recognition Mechanisms

The effectiveness of a biosensor depends on its ability to recognise specific biological targets that indicate microbial presence, as illustrated in Figure 3. A typical biosensor consists of a target analyte, a biorecognition element, a transducer and a signal processing system. Relevant targets and recognition elements may include whole microorganisms, antibodies, nucleic acids, enzymes, tissues and cellular receptors (Eltzov *et al.*, 2019). Whole cell detection can reduce the need for extensive sample preparation and may support the direct monitoring of airborne pathogens within a single device (Bohrn *et al.*, 2011). Whole cell biosensors can also provide information on cellular physiology, pharmacological responses and toxicological effects that may not be available from molecular biosensors (Gui *et al.*, 2017). Common approaches include impedance-based, optical and microfluidic whole cell biosensors (Chen *et al.*, 2023).

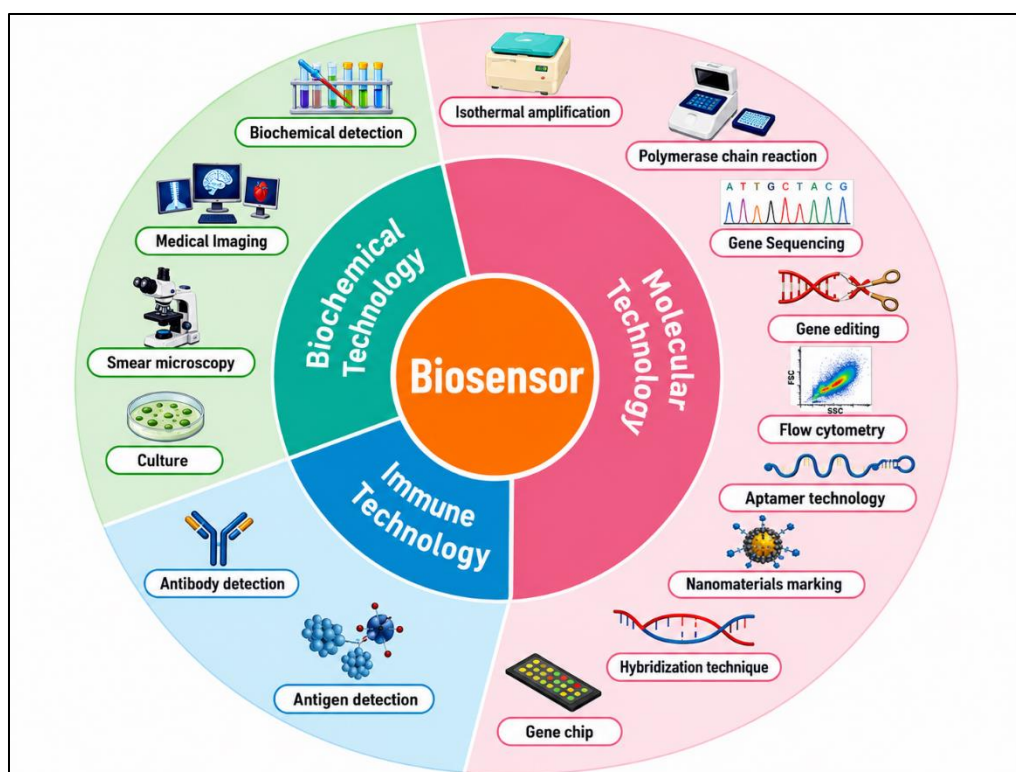


Figure 3: Biosensor detection methods for airborne microorganisms.
(Source: Ma *et al.*, 2021)

Protein-based detection targets microbial surface proteins or related biomolecules and is commonly used in biosensor development, including membrane protein-based systems (Misawa *et al.*, 2018). Lipopolysaccharides from Gram-negative bacteria are examples of endotoxins that can be detected using this approach (Goh *et al.*, 2002). Metabolite-based detection focuses on compounds produced through microbial activity, including transcription factor responsive metabolites and fermentation products (Zhou & Zhang, 2023). Pyocyanin produced by *Pseudomonas aeruginosa* is one example of a species-associated biomarker that has been detected using biosensors (Frigoli *et al.*, 2023). Nucleic acid detection targets microbial DNA or RNA to confirm the presence and activity of microorganisms. Paper-based biosensors and hybridisation methods, including clustered regularly interspaced short palindromic repeat associated protein (CRISPR-Cas) systems, have been applied to pathogen nucleic acid detection (Wang *et al.*, 2022a). Although these approaches differ in their recognition mechanisms, they share the objective of identifying specific biomarkers associated with microbial presence (Wang *et al.*, 2022a).

3.2 Signal Transduction Principles

Signal transduction in a biosensor is the process by which a biological interaction is converted into a measurable output. Depending on the biosensor design, the output may be electrical, optical, thermal or acoustic. When a microorganism or biomarker binds to the biorecognition element, the resulting physical or chemical change is detected by the transducer and converted into a signal (Ahmed *et al.*, 2014). The efficiency of this process strongly influences biosensor performance and sensitivity. Improvements in sensor construction, geometry and surface patterning can enhance signal conversion and overall performance (Sayad *et al.*, 2020). Electrode surface modification may also improve specificity and enable rapid, selective and highly sensitive detection (Saenchoopa *et al.*, 2021). An effective transduction mechanism is particularly important for detecting microbial activity at low concentrations (Iwanaga, 2021).

3.2.1 Electrochemical Biosensors

Electrochemical biosensors convert biological interactions into electrical signals, including changes in current, potential or resistance. They are suitable for the real-time detection of airborne pathogens because of their high sensitivity and potential for miniaturisation (Sivakumar & Lee, 2022). Electrochemical biosensors are commonly classified according to their signal conversion mechanism, including amperometric, voltammetric and impedimetric systems. Amperometric biosensors measure the current generated by oxidation or reduction reactions at an electrode surface while the applied potential is maintained at a constant value (Amine & Mohammadi, 2018). Electrodes may be manufactured from materials such as carbon, gold or platinum. For example, Rajarathinam *et al.* (2021) developed an amperometric biosensor for the rapid detection of bacterial infection that demonstrated good reproducibility and short-term stability.

Voltammetric biosensors measure changes in current as the applied potential is varied. They can detect microbial redox activity and associated biological reactions (Lopez-Tellez *et al.*, 2022). Once the required potential is reached, electron transfer produces a measurable current that can be used as an indicator of microbial presence (Marangoni *et al.*, 2023). Impedimetric biosensors, by contrast, measure changes in electrical impedance following a biological interaction. Their high sensitivity allows small changes arising from microbial presence or metabolic activity to be detected. They can also support applications such as antimicrobial susceptibility testing, with adaptable protocols and potential advantages in time and cost (Domingo-Roca *et al.*, 2023). Impedimetric devices commonly use carbon, gold or platinum electrodes. Electrochemical impedance spectroscopy can then be used to analyse the signal and estimate the concentration or characteristics of microbial contamination. For example, Ward *et al.* (2014) demonstrated the detection of *P. aeruginosa* and showed that impedance measurements can provide useful information on pathogen specific electrode interface characteristics.

3.2.2 Optical Biosensors

Optical biosensors detect microbial presence by measuring changes in light properties such as intensity, wavelength or refractive index. Their operation involves recognising and binding a target molecule, converting the resulting biological interaction into an optical signal and processing that signal to quantify the result (Lei & Guo, 2021). For example, bioluminescent biosensors can detect bacterial products such as siderophores, and may provide rapid, sensitive and specific screening for pathogenic bacteria (Visaggio *et al.*, 2021). Surface plasmon resonance (SPR) is another widely used optical approach that detects changes in refractive index when target molecules bind to a sensor surface. SPR has been used to investigate protein-protein interactions involved in bacterial cell-wall biosynthesis, providing insight into protein assemblies required for bacterial survival (Avila-Cobian *et al.*, 2022). It has also been applied to assess the binding affinity of proteins associated with pyocyanin gene expression in *P. aeruginosa* (Feng *et al.*, 2025).

3.2.3 Fluorescence-Based Biosensors

Fluorescence-based biosensors generate a fluorescent signal following a biological interaction. A fluorophore emits light after excitation, and changes associated with the binding of a biomolecule to the biorecognition element can be detected and quantified (Verma *et al.*, 2023). Fluorescence resonance energy transfer (FRET) is one approach used in pathogen detection. In a FRET system, energy transfer occurs between two fluorophores in close proximity, and changes in their separation or orientation following target binding alter the emitted signal. FRET-based biosensors have been developed to detect viral spike proteins and have demonstrated specific, stable and rapid performance (Montepietra *et al.*, 2025). FRET sensing has also been used for the rapid detection of pathogenic bacteria (Wang *et al.*, 2018).

3.3 Signal Amplification Methods

Signal amplification is important because it directly affects the sensitivity and reliability of a biosensor. The detection of airborne pathogens is particularly challenging because target concentrations may be low and signals may be affected by dust and other airborne particles (Fronczek & Yoon, 2015). Therefore, amplification methods are used to convert weak biological interactions into measurable outputs (Wang *et al.*, 2022c). Figure 4 summarises the principal signal amplification approaches used in biosensing systems.

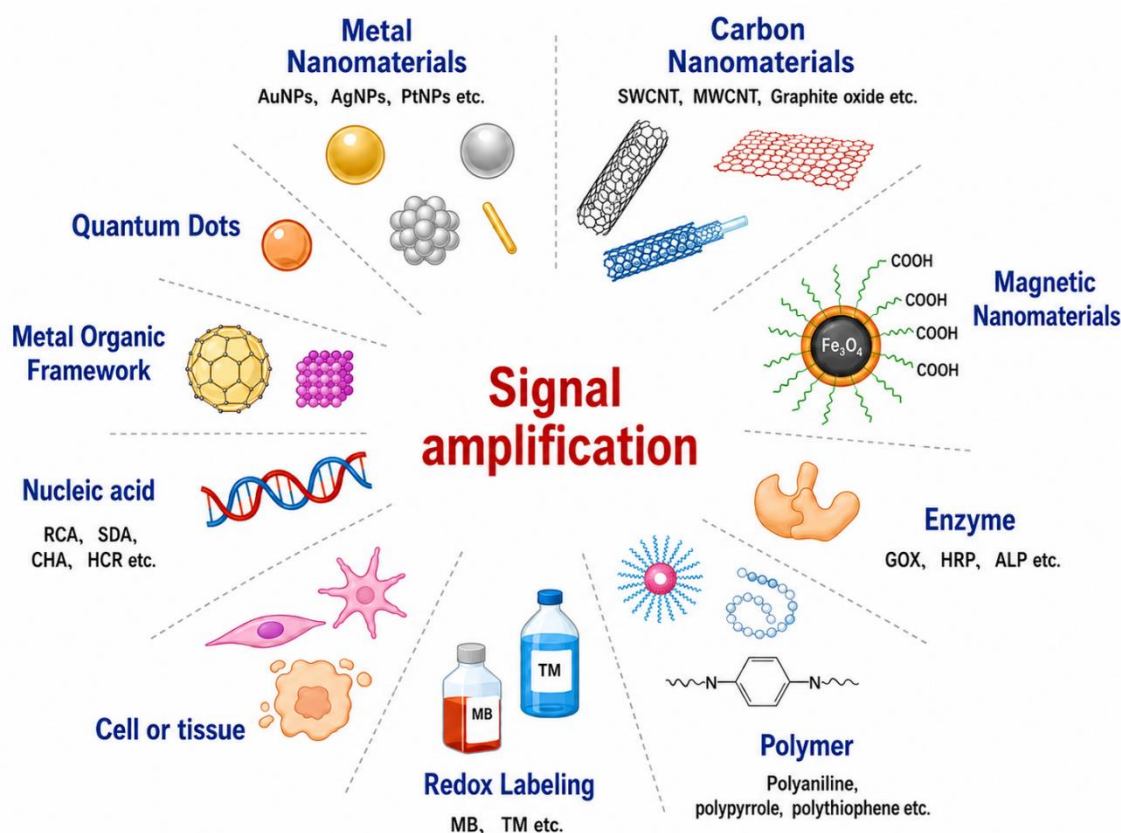


Figure 4: Major signal amplification methods used in biosensing systems.
(Source: Wang *et al.*, 2022c).

3.3.1 Nanomaterial-Based Signal Amplification

Nanomaterials have received considerable attention for biosensor signal amplification because of their high surface-to-volume ratio, small size, as well as favourable mechanical, electrical and thermal properties. Gold nanoparticles (AuNPs), carbon nanotubes (CNTs), graphene and quantum dots (QDs) are among the materials commonly used. Gold nanoparticles have been incorporated into modified electrodes to improve the detection of pyocyanin biomarkers associated with *P. aeruginosa* infection (Elkhawaga *et al.*, 2019). AuNP-based systems have also demonstrated improved detection of quorum sensing molecules (Capatina *et al.*, 2022). Carbon nanotube electrodes provide an accessible and potentially cost-effective sensing platform for virulence factors such as pyocyanin (McLean *et al.*, 2022). Quantum dots can enhance fluorescence-based detection through their strong optical performance and stability and have been applied to the detection of pathogenic bacteria (Tu *et al.*, 2022).

3.3.2 Enzyme-Based Signal Amplification

Enzyme-based amplification enhances biosensor signals through catalytic reactions. A single enzyme molecule can catalyse many substrate molecules, thereby converting a weak biorecognition event into a stable and measurable signal. In these systems, the biorecognition molecule is linked to an enzyme that reacts with its substrate to produce a colorimetric, electrochemical or fluorescent output (Feng *et al.*, 2023). Enzyme-mediated amplification can thus increase sensitivity when target analytes are present at very low concentrations. Recombinase polymerase amplification (RPA), although more appropriately classified as an isothermal nucleic-acid amplification method, can also be integrated with CRISPR-based biosensing to enable rapid and specific bacterial pathogen detection (Liu *et al.*, 2023).

3.3.3 Nucleic-Acid Amplification Technology

Nucleic-acid amplification is particularly useful for improving the sensitivity of nucleic acid biosensors. CRISPR-based molecular systems can support rapid, low-cost and highly specific on-site detection of target nucleic acids (Hu *et al.*, 2022). PCR, quantitative PCR (qPCR) and isothermal amplification methods can increase the number of target DNA or RNA sequences before biosensor detection, enabling pathogens at very low concentrations to be identified (Choi & Yoon, 2023). Isothermal methods are especially attractive for portable applications because they operate at a constant temperature and can reduce equipment requirements. For example, Dong *et al.* (2021) combined loop-mediated isothermal amplification with a nanoparticle-based lateral-flow biosensor for rapid *P. aeruginosa* detection. Therefore, the integration of target amplification with biosensing can improve both sensitivity and the ease of result interpretation.

4. INTEGRATED SYSTEMS, PERFORMANCE AND FUTURE DIRECTIONS

4.1 Microfluidic Technology

Conventional biosensors often rely on the direct application of liquid samples to the sensing surface, which can make sample handling difficult to control and leave measurements susceptible to external factors such as temperature, light and humidity (Wang *et al.*, 2025). Microfluidic technology addresses some of these limitations by integrating fluid handling, signal detection, conversion and data presentation within a compact chip-based system (Rackus *et al.*, 2015). Microfluidic devices combine advances in optics, electronics, biology and related disciplines to support miniaturised biosensors, automated sample handling and integrated analytical processes (Liu *et al.*, 2021). In a microfluidic biosensor, biological information is converted into measurable electrical, optical, magnetic or other signals through an integrated sensing mechanism (Naresh & Lee, 2021). The small dimensions of these devices can improve analytical sensitivity, reduce sample and reagent requirements and support the detection of weak biological signals (Wang *et al.*, 2025).

4.2 Enhancement Using Nanomaterials

Nanostructured materials have had a major impact on biosensor development, particularly for biothreat detection. Their integration can support sensor miniaturisation, reduce sample-volume requirements and lower overall costs. Nanomaterials may also improve signal-to-noise performance by increasing the available surface area for target binding and reducing non-specific adsorption (Bhalla *et al.*, 2016). For example, nanoporous anodised aluminium oxide (NAAO) can be produced through the electrochemical anodisation of aluminium using a rapid and relatively cost-effective process. Its well defined and uniform nanopores provide a large surface area for biomolecule immobilisation and can improve sensor sensitivity

(Santos *et al.*, 2013). Anisuzzaman *et al.* (2024) developed an NAAO-based electrochemical platform functionalised with an aptamer for detecting pyoverdine associated with *Pseudomonas* species. These examples demonstrate the potential of nanostructured surfaces to improve sensitivity, support miniaturisation and enable the development of portable tools for biothreat detection.

4.3 Detection Efficiency and Sensitivity

A major challenge is improving particle capture efficiency, particularly for small, aerosolised pathogens such as viruses. Microfluidic systems designed for larger particles, including bacterial spores, may be less effective for smaller particles. Future research should thus optimise capture mechanisms across a wider range of particle sizes while maintaining efficient, real-time processing and improving the detection of low concentration biothreats. Surface functionalisation methods can also influence sensitivity. For example, De Penning *et al.* (2025) found that heterobifunctional crosslinkers were more effective than homobifunctional crosslinkers for aptamer immobilisation, resulting in higher immobilisation densities and a more consistent sensing response. Such improvements could enhance the specificity and sensitivity of biosensors for airborne biothreat detection.

4.4 Continuous Monitoring and Portable Systems

Effective monitoring of airborne biothreats requires microfluidic particle capture and biosensing to be integrated within a single compact device. Many existing systems use separate components for sample collection and analysis, which reduces efficiency and delays real-time detection (De Penning *et al.*, 2025). Integrated platforms could improve sample handling, reduce manual intervention, as well as shorten the interval between collection and detection. Advances in microfluidic design, including the incorporation of aerosol capture mechanisms into compact and automated biosensing units, are thus important for improving detection sensitivity and speed. In the longer term, portable biosensors could be connected to broader environmental surveillance networks to provide more comprehensive coverage and support rapid responses to biological threats (De Penning *et al.*, 2025).

5. CONCLUSION

Biosensor technologies offer considerable potential for the rapid, sensitive and portable detection of airborne microorganisms, particularly where conventional culture-based, molecular and immunological methods are limited by lengthy processing, specialised equipment or extensive sample preparation. Electrochemical, optical and fluorescence-based biosensors provide different advantages in terms of sensitivity, miniaturisation and response time, while nanomaterials and signal amplification techniques can further improve detection at low pathogen concentrations. However, the practical performance of these technologies depends not only on the sensing element but also on effective bioaerosol collection, concentration and transfer to the detection platform. Therefore, air sampling remains a major technical bottleneck, especially for small particles, low concentration pathogens and complex environmental samples containing dust and other interfering substances.

The integration of air sampling, sample preparation, biological recognition, signal transduction, and data processing within microfluidic platforms represents an important direction for future development. Nevertheless, further research is required to improve selectivity, signal reliability, pathogen viability assessment, environmental robustness, and long-term operational stability. Standardised validation procedures and field trials under realistic conditions are also needed before these systems can be widely adopted. Ultimately, compact and automated biosensors connected to environmental or biodefence

surveillance networks could support continuous monitoring and earlier warning of airborne biological threats.

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