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TECHNOLOGY READINESS LEVEL: ADVANCING LOCALLY MADE UNMANNED VEHICLES

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ABSTRACT

Effective technology commercialization is critical for successful product delivery in the current environment of intense innovation competition. Although market acceptance is a crucial factor in the commercialization process, it is equally imperative to attain the suitable Technology Readiness Level (TRL). Given a lack of research on TRL of locally produced unmanned vehicles, this study aims to address the gap by proposing a comprehensive framework for the TRL of its locally developed products. To construct this framework, the research employed a qualitative approach via two rounds of Semi-Structured Interviews (SSI) and the Delphi Method. The interviews engaged expert inventors in evaluating the extent to which their products meet market needs, reflecting the Expertise Opinion Analysis (EOA). Furthermore, the respondents were involved in accordance with their level of active engagement and successful attainment of ultimate TRL stages in the development of the unmanned vehicles products. The information gathered was analysed with meticulous analysis to create a comprehensive TRL framework specifically designed for unmanned vehicles. The analysis considers variations in TRL and aims to promote the integration of local unmanned vehicles technology into the commercial market, thereby enhancing the effectiveness of technology commercialization in Malaysia, fostering innovation, and driving economic growth in this sector through the proposed framework.

Keywords: Technology Readiness Level (TRL), Unmanned Vehicles, Semi-Structured Interviews, Expertise Opinion Analysis

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1. Introduction

The unmanned vehicles industry has experienced rapid global development and adoption across diverse sectors. Its applications span from aerial photography, videography, and surveillance to agriculture, infrastructure inspection, and delivery services, among others. This growth is driven by both established technology companies and startups, continuously advancing drone design, capabilities, and autonomy. In parallel, the Asia-Pacific region, including ASEAN, has emerged as a significant market for unmanned vehicles, offering an ideal environment for research, development, and innovation in this field. The region's diverse geographical landscapes, infrastructure requirements, and flourishing economies, including China, Japan, South Korea, India, and ASEAN member states, contribute to the increasing demand for unmanned vehicles technologies. This trend reflects the industry's ability to provide solutions to complex technical challenges that traditional human intervention may struggle to address (Md Habibur Rahman, et al., 2024; Bharat Acharya, et al., 2021).

Similarly in Malaysia, the unmanned vehicles industry has experienced a surge in growth in recent years, fuelled by the increasing recognition of vast potential and their applicability across diverse sectors. The government has actively supported this industry by instituting regulations and launching initiatives to ensure the safe and responsible utilization of drones, thus encompasses a wide spectrum of activities, ranging from research and development, manufacturing, and service provision to training programs and engagement of recreational drone enthusiasts. Unmanned vehicles technology has found significant application in Malaysia, notably in aerial photography, videography, infrastructure inspection, precision agriculture, environmental monitoring, surveillance, security, and disaster management (Mohsan, et al., 2023). Collaboration between universities, research institutions, and industry players has played a vital role in elevating unmanned vehicles capabilities and driving exploration of new applications within the industry.

Consequently, the unmanned vehicles industry is currently facing a few challenges that will require collaboration among various stakeholders to solve, as it is expected that the industry will expand globally if challenges are overcome. The incorporation of cutting-edge technologies will increase the capabilities across all industries, involving the well-being of researchers, business institutions, and government agencies, all of whom will recognise the sector's potential to contribute to economic expansion and societal well-being (Mohsan, et al., 2023; Bharat Acharya, et al., 2021).

It is high time the advancement of technology in unmanned vehicles requires a systematic approach, progressing through essential stages from initial idea to actual implementation, to achieve successful results. Hence the objective of this study is to determine the measures involved in the development process while investigating the primary difficulties, including technical, regulatory, and market-related barriers, that affect it. In addition, the research aims to create a thorough Technology Readiness Level (TRL) framework specifically designed for the unmanned vehicles industry. The focus is on comprehending the potential advantages and limitations of this framework.

Certain limitations, particularly the selection of participants—mainly inventors and specialists in the unmanned vehicles sector, covering land, air, and water vehicles—contributed to a narrower focus in this exploration. This limited scope might have led to missing out on valuable insights from other key players like industry experts, researchers, and regulatory bodies. As a result, the findings may not fully capture the diverse challenges and processes involved in developing unmanned vehicle technologies. Additionally, the customized Technology Readiness Level (TRL) framework presented in this work may face hurdles in broader applicability and generalization across the unmanned vehicles industry. Tailored to specific regional conditions, the framework might overlook variations in technological advancement methods and regulations across different areas or countries. Consequently, further validation was necessary to ensure its effectiveness in guiding development and overcoming challenges in diverse settings, particularly within Malaysia's unmanned vehicles sector.

Although the framework is primarily designed to boost the efficiency and long-term viability of technology commercialization, its application in different contexts or industries might require further adjustments and validation. The framework’s impact on the overall growth and advancement of the unmanned vehicles industry may also depend on factors such as industry acceptance, regulatory support, and market dynamics. It’s crucial to keep these limitations in mind when evaluating the results and implementing the proposed framework for advancing unmanned vehicle technology beyond this study's specific focus. Ongoing research and validation are essential to overcoming these limitations and enhancing the framework’s effectiveness and utility.

Through this initiative, the focus on the progress of locally produced unmanned vehicles and the creation of a customized TRL framework, particularly aimed at boosting efficiency, sustainability, and innovation within the industry, is expected to drive economic growth and industry advancement tailored to the local context. The outcome aspires to increase the market relevance of unmanned vehicle products. By adapting the TRL framework to the needs of locally developed unmanned vehicles, it offers valuable insights into their readiness to meet market demands, ensuring a more accurate assessment of technology maturity and accelerating deployment.

This exploration underscores the significance of collaboration and expert analysis, employing methods like the Delphi Method and Expertise Opinion Analysis, to foster knowledge sharing among inventors, industry experts, and researchers (Skulmoski, et al., 2007). This comprehensive approach enhances the understanding of the challenges and opportunities in unmanned vehicle development, influencing policy decisions, research priorities, and industry practices. The proposed TRL framework is vital for improving the efficiency and sustainability of technology commercialization in Malaysia's unmanned vehicles industry. It offers a systematic approach to assess technology maturity, optimize resource allocation, minimize risks, and improve decision-making processes. This framework helps identify gaps, refine development strategies, and ensure smooth transitions from research to market deployment.

The significance of this exploration lies in addressing the research gap on Technology Readiness Levels (TRL) concerning locally produced unmanned vehicles. By enhancing the understanding of technology readiness and presenting a customized framework, this work aims to promote the growth, competitiveness, and successful commercialization of domestically developed unmanned vehicles, positioning Malaysia as a hub of innovation and technological advancement in the unmanned vehicles field.

2. Overview of the Framework

A thorough understanding of technological readiness is vital for advancing and commercializing domestically manufactured unmanned vehicles. Assessing the development level and readiness of this technology is essential for effectively introducing it to the market and addressing unique challenges. This literature review thoroughly examines research and literature on Technology Readiness Level (TRL) and its application in advancing domestically manufactured unmanned vehicles. It aims to analyse the existing knowledge base, identify information gaps, and contribute to creating a customized TRL framework for their advancement.

The Technology Readiness Level (TRL) framework was developed by NASA in the late 1970s to assess technology maturity for space missions. It provided a common language and methodology for evaluating readiness across disciplines. Originally a five-level system, it expanded to nine levels in 1989, offering a detailed assessment of technology maturity. The TRL framework bridges the gap between development and application of new technologies, guiding decision-making in their integration.

The TRL framework has been widely adopted beyond NASA, serving as a valuable tool in various sectors. It enables systematic development; tracks progress and informs investment decisions. The framework's legacy within NASA and its global adoption highlights its effectiveness in promoting collaboration, supporting informed decision-making, and advancing cutting-edge technologies.

2.1 Differences Between Unmanned Vehicles Used on Land, Air and Water

Unmanned Vehicles used on land, in the air, and on water have different characteristics and requirements due to the unique challenges of each environment. Land-based Unmanned Vehicles, for example, are designed for ground operations and have wheels, tracks, or legs to traverse various terrains. They excel at tasks such as surveillance, infrastructure inspection, and precision farming (Peng Li, et al., 2024; Kesia Joies, et al., 2023; Andrew Hay, et al., 2018). This is distinct from airborne unmanned aerial vehicles, or drones, which are designed for atmospheric flight (Timothy Munsie, et al., 2024; Zurriati Mohd Ali, et al., 2023; Jun Ni, et al., 2020) and include multi-rotor drones and fixed-wing aircraft used for delivery, aerial photography, videography, and other purposes. Unmanned surface vehicles (USVs) or unmanned underwater vehicles (UUVs), also known as water-based unmanned vehicles. They are designed specifically for operations on or beneath the water. They perform underwater exploration, oceanographic research, and maritime surveillance (Salimzhan Gafurov, et al., 2015).

Each type of unmanned vehicles must be designed with specific factors in mind to meet the requirements of its operating environment, for example, uneven surfaces are given less importance by land-based unmanned vehicles than stability, adaptability, and maneuverability, whereas those that operate in the air must adhere to aviation regulations and focus on developing lightweight (Zurriati Mohd Ali, et al., 2023; Salimzhan Gafurov, et al., 2015), aerodynamic designs, and water-based unmanned vehicles require buoyant, corrosion-resistant structures that are watertight, and despite the fact that these unmanned vehicles share similar technological components, their designs have been carefully selected to ensure the best performance in each field. Table 1 below shows the main difference between unmanned vehicles designed for land, air, and water.

Table 1. Difference between unmanned vehicles designs for land, air, and water.

Unmanned Vehicles Operating Environment	Land	These unmanned vehicles are primarily designed to operate on the ground or on land-based surfaces. They are suitable for various terrains, such as urban areas, rugged landscapes, or agricultural fields.
	Air	These unmanned vehicles are designed to operate in the atmosphere and fly. They are the most common type of unmanned vehicles and can be used in various sectors, including aerial photography, surveillance, delivery, and research.
	Water	These unmanned vehicles are designed to operate on or in bodies of water, such as lakes, rivers, or oceans. They can navigate over water surfaces or dive underwater for specific applications.
Unmanned Vehicles Design and Construction	Land	Land-based unmanned vehicles typically have wheels, tracks, or legs to facilitate movement on the ground. They may have robust chassis and suspension systems to handle uneven surfaces and obstacles.
	Air	Airborne unmanned vehicles have aerodynamic designs that enable them to achieve lift and maneuverability, feature wings, propellers or rotors, and flight control systems for stable flight and control.
	Water	Water-based unmanned vehicles may have hydrodynamic designs to enable smooth movement through water. They can be equipped with flotation devices, water-resistant components, and propulsion systems suitable for aquatic environments.
Unmanned Vehicles Propulsion Systems	Land	Land-based unmanned vehicles typically utilize electric motors or internal combustion engines to drive their wheels or tracks. Some may employ hybrid propulsion systems for increased efficiency and range.
	Air	Airborne unmanned vehicles use various propulsion systems, including electric motors, internal combustion engines, jet engines, or rotor systems (such as multirotor or fixed-wing propellers), to generate thrust and achieve flight.
	Water	Water-based unmanned vehicles may use electric motors, water jets, or propellers to navigate through the water. They may have specialized water propulsion systems for surface movement or thrusters for underwater propulsion.
Unmanned Vehicles Payload and Applications	Land	Land-based unmanned vehicles are used in applications such as land surveying, agriculture, infrastructure inspection, search and rescue, and security surveillance.
	Air	Airborne unmanned vehicles have a wide range of applications, including aerial photography and videography, mapping and surveying, disaster management, delivery services, surveillance and monitoring, and scientific research.
	Water	Water-based unmanned vehicles find applications in marine research, environmental monitoring, aquatic surveys, marine life observation, and maritime security.

2.2 History of the Development of Unmanned Vehicles

Throughout the history of unmanned vehicles, numerous public figures have contributed to their development, including engineers, scientists, military personnel, and innovators. Notable figures include Archibald Low, Reginald Denny, Abraham Karem (designer of the Predator drone), and various military leaders and government officials involved in the implementation and advancement of unmanned Vehicles technology worldwide (Dr. Palik, et al., 2019). Listed below is a brief timeline highlighting significant milestones and the involvement of key public figures:

1. 1849: Austrian army officer, Franz von Uchatius, conceptualizes and builds the first recorded UAV, a pilotless hot air balloon.
2. 1898: Tesla's "Teleautomaton" is demonstrated, showcasing the concept of remotely controlling a vessel through wireless transmission.
3. 1916: Aerial Target was developed by Archibald Low, a British engineer, as a radio-controlled aircraft used for anti-aircraft training during World War I.

4. 1935: Reginald Denny, an English actor, develops a radio-controlled model plane, known as the "Dennymite," which later serves as the foundation for future UAV designs.
5. 1944: The German military introduces the V-1 flying bomb, an early cruise missile, remotely controlled and used as a weapon during World War II.
6. 1959: The United States' US Navy and US Air Force collaborate on Project Bee, leading to the development of the Ryan Firebee series of unmanned vehicles, which are used for reconnaissance purposes.
7. 1964: The Dassault Étendard IV becomes the first jet-powered unmanned aircraft to be successfully launched and recovered from an aircraft carrier.
8. 1982: Israel's Aircraft Industries develops the IAI Scout, a small reconnaissance UAV for surveillance during the Israeli-Lebanese conflict.
9. 1990: The General Atomics MQ-1 Predator, a remotely piloted aircraft, is introduced by the United States Air Force, revolutionizing the concept of armed unmanned vehicles for surveillance and combat missions.
10. 2001: In the aftermath of the September 11 attacks, the United States deploys armed Predator drones in Afghanistan for targeted airstrikes against Taliban and Al-Qaeda forces.
11. 2007: The United States Army introduces the RQ-11 Raven, a small hand-launched UAV for reconnaissance and surveillance ground troops.
12. 2010: The General Atomics MQ-9 Reaper, an armed, multi-mission UAV, enters service with the United States Air Force, expanding capabilities for intelligence gathering and precision strikes.
13. 2016: The DJI Phantom 4, a commercially available consumer drone with advanced flight capabilities and automated features, gains popularity, marking a significant milestone in the civilian UAV market.

2.3 Interrelationships between Unmanned Vehicles for Use on Land, Water and Air

While unmanned vehicles designed for land, water, and air have distinct operating environments and design considerations (Zurriati Mohd Ali, et al., 2023; Mohsan, et al., 2023; Acharya, et al., 2021), there are also similarities and mutual items of development or study that apply to all three types. Table 2 below shows the interrelationships between unmanned vehicles developed for use on land, water and air.

Table 2. Interrelationships between unmanned vehicles for the use in land, water and air

Control Systems	Regardless of the operating environment, all unmanned vehicles require sophisticated control systems to manage flight operations, navigate through the environment, and maintain stability (Jun Ni, *et al*., 2020). This includes flight control algorithms, sensors (such as accelerometers and gyroscopes), and communication systems.
Autonomy and Automation	Unmanned vehicles across land, water, and air often incorporate autonomous or semi-autonomous capabilities. These features enable them to perform tasks or follow pre-programmed routes without constant human intervention. Autonomy can improve efficiency, safety, and operational capabilities in various applications (Mohsan, *et al.*, 2023).
Power and Energy Systems	Unmanned vehicles require reliable and efficient power sources to operate. This includes batteries for electric propulsion systems, fuel for internal combustion engines, or alternative power generation methods. Development and optimization of power and energy systems are crucial for enhancing its endurance, range, and payload capacity.
Payload Integration	Unmanned vehicles can be equipped with various payloads, such as cameras, sensors, communication devices, or cargo compartments, depending on their intended applications. Payload integration involves designing appropriate mounting systems, ensuring payload compatibility, and optimizing the unmanned vehicles performance while carrying the payload.
Communication and Data Transmission	All unmanned vehicles require reliable communication systems to transmit data between the vehicles and the ground station or other platforms. This includes wireless communication protocols, data encryption, signal strength

	optimization, and real-time data processing techniques (Timothy Munsie, *et al.*, 2024).
Safety and Regulatory Compliance	Unmanned vehicles development and operation involve adherence to safety regulations and standards set by relevant aviation authorities. This includes aspects like collision avoidance systems, fail-safe mechanisms, flight termination systems, and compliance with airspace regulations, regardless of the operating environment (Mohsan, *et al.*, 2023).
System Integration and Testing	Unmanned vehicles development involves integrating various subsystems, components, and software to create a functional and efficient system. Integration testing ensures proper communication and compatibility between different parts of the unmanned vehicles. It includes overall system testing, performance evaluation, and verification of functional requirements.
Research and Development	Unmanned vehicles technology advancements, materials, aerodynamics, control algorithms, and sensor technologies are areas of ongoing research and development across all types of unmanned vehicles. Innovations and studies in one domain can often inform and benefit advancements in others.

While specific design and operational aspects differ among land, water, and air-based unmanned vehicles, the overarching principles of unmanned vehicles development, control, autonomy, safety, and integration remain relevant and interconnected across all environments (Acharya, et al., 2021).

3. Methodology

In this study, a combination of the Delphi Method and qualitative approaches was used to develop a comprehensive Technology Readiness Level (TRL) concept framework for unmanned vehicles. The Delphi Method was employed to gather expert insights on technology readiness through a series of structured interactions with five (5) selected respondents, in the background of inventors and known for their expertise working with industries in unmanned vehicles.

The research process began with two (2) rounds of semi-structured interviews with these experts. During the first round, participants engaged in open-ended discussions about their experiences and perspectives on unmanned vehicle technology, focusing on aspects such as development challenges, commercialization strategies, and market readiness. These discussions allowed for a thorough exploration of their knowledge and facilitated a broad understanding of the current state of technology readiness.

In the second round, follow-up interviews were conducted to refine and validate the findings from the initial round. This iterative process helped to build a consensus among the experts, ensuring that their insights were accurately represented and integrated into the TRL framework. The follow-up interviews aimed to clarify any ambiguities, address emerging themes, and confirm the relevance of the information gathered.

In addition to the Delphi Method, Expert Opinion Analysis (EOA) was employed to further assess the experts' knowledge. This analysis focused solely on qualitative data derived from the interviews. Thematic analysis was used to identify and interpret key themes and patterns within the interview data. This involved examining the qualitative responses to uncover significant factors affecting technology readiness and commercialization.

The final TRL concept framework was developed based on the insights obtained from these qualitative analyses. It considers variations in TRL across different industry fields and incorporates considerations related to local Intellectual Property (IP) exploitation and commercialization policies. The framework aims to provide practical guidance for inventors, researchers, and industry professionals, enhancing the efficiency and sustainability of unmanned vehicle technology commercialization in Malaysia.

By employing these qualitative methods, the study contributes to a deeper understanding of unmanned vehicle technology readiness and supports the advancement of local technology through a well-informed, expert-driven framework.

Table 3. Procedure for selection of expert panel members (Colton, 2004)

Steps	Procedures	Results
Step 1	Review literature to compile a list of potential panel members.	Compile list of names.
Step 2	Assess and analyze published publications and literature review for technology commercialisation and business model practices from other international universities	Mark for evidence of the best practice process and related information.
Step 4	Check ISI Social Sciences Citation Index for number of citations and references	Mark number of citations.
Step 5	Develop construct and set of questionnaires for Interview materials	2 Set of Questionnaires to meet Delphi method
Step 6	Evaluate potential experts as to their contributions to the subject matter.	Rate potential experts on a suitability-to-the-study
Step 7	Potential respondent's expertise evidence is presented to the supervisors of this research for review.	Invitation of participation from potential respondents is revised by developing a final list.
Step 8	Purpose and scope of the study is explained to each potential respondent via telephone and email invitations.	Follow-up respondents who commit to the study with telephone calls and email.

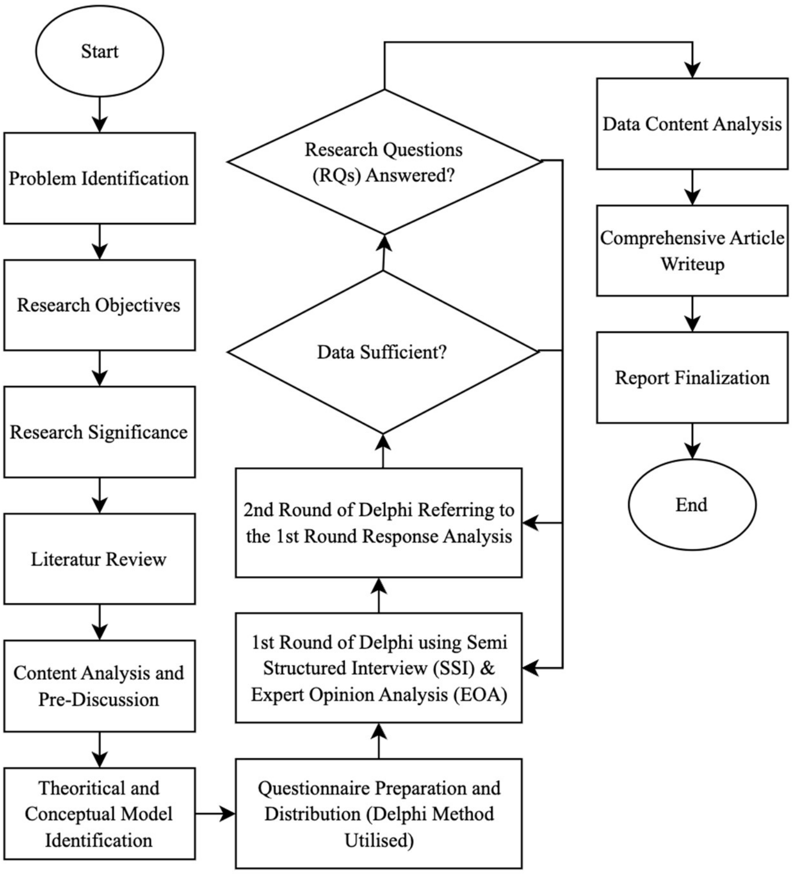

Figure 1. Flow process of the research

4. Results

In all cases, the TRLs of unmanned vehicles for land, air, and water applications progress through similar stages of development, including concept formulation, prototype testing, system integration, and operational testing, as concluded from interviews with experts, 40% of whom have more than 10 years of experience and 60% of whom have at least 5 years. However, the specific technical requirements and social needs vary depending on the intended application environment. To ensure the successful development and deployment of unmanned vehicles in each domain, it is crucial to address technical challenges specific to the environment and consider social factors such as safety, privacy, public perception, and regulatory compliance. Collaboration between technology developers, regulators, and stakeholders is essential to establish a comprehensive framework that ensures the safe and effective integration of unmanned vehicles for land, air, and water applications (Acharya, et al., 2021). Look at Figure 2 showing some area of expertise that are important for UV industry development.

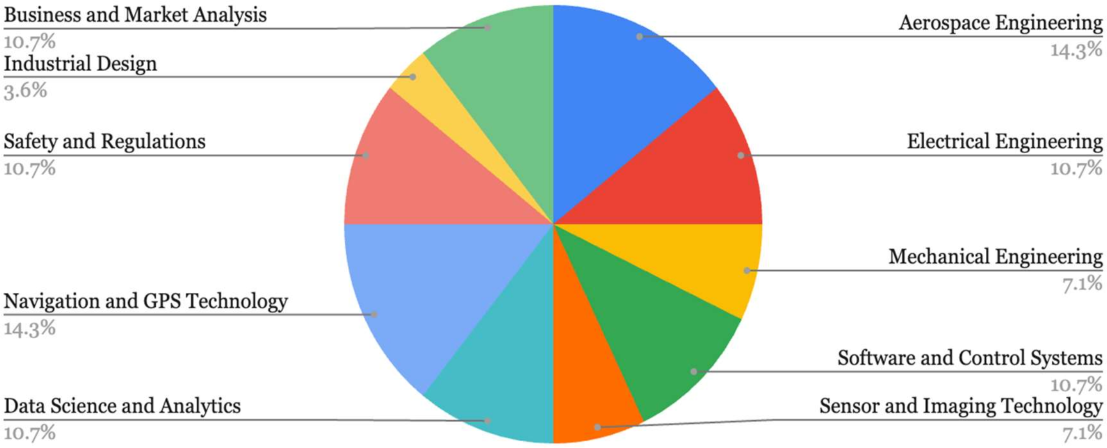

Figure 2. Area of expertise that are important for unmanned vehicles industry development.

The pie chart illustrates the distribution of various fields of expertise necessary for the development of a UAV, with each segment representing a specific area of knowledge. The largest portions of the chart, each comprising 14.3%, are dedicated to Aerospace Engineering and Navigation and GPS Technology, indicating their critical importance. Business and Market Analysis, Electrical Engineering, Safety and Regulations, Data Science and Analytics, and Software and Control Systems each account for 10.7% of the chart, highlighting their significant roles as well. Mechanical Engineering and Sensor and Imaging Technology are represented by smaller segments, each comprising 7.1%, while Industrial Design has the smallest share at 3.6%. This distribution suggests that a broad array of expertise is considered essential, with particular emphasis on aerospace, navigation, and a combination of technical and analytical disciplines.

Furthermore, by considering the important it was found that the importance of various aspects in the development process of a UAV shown in Figure 3. The chart illustrates the relative significance of different factors in the process of developing UAVs, with "Testing and Validation" being identified as the most crucial, as indicated by 80% of the participants. Additional notable domains, each indicated by 60%, encompass TRL Definitions, Technology Components, Data Collection and Analysis, Safety and Certification, and Market Demands and Applications. Intellectual Property and Compliance, as well as Funding and Resources, were given less importance, with only 20% considering them crucial. In contrast, Collaboration and Knowledge Sharing were valued by 40%. This indicates a significant emphasis on verifying the technical aspects and ensuring safety, with a moderate level of emphasis on working together and minimal consideration for intellectual property and funding.

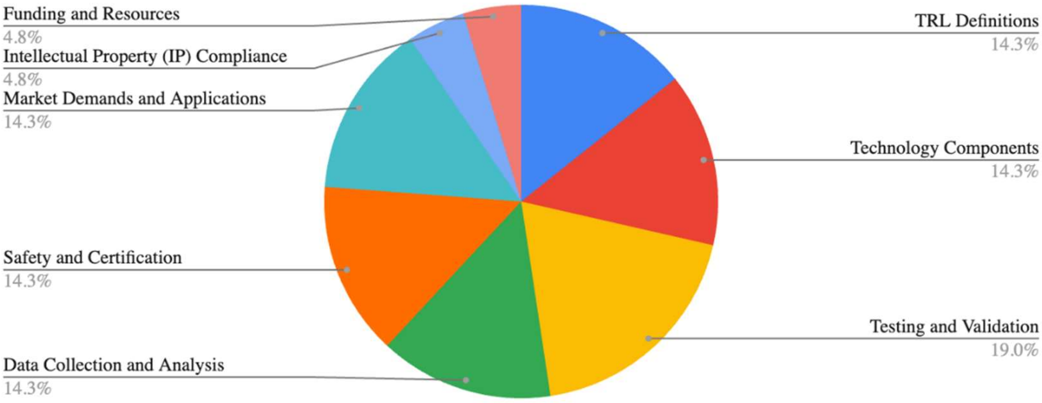

Figure 3. Importance aspects in the development process of unmanned vehicles

In addition to the technical challenges specific to the environment and the social factors mentioned earlier, there are several other technical challenges that need to be addressed in the use of unmanned vehicles for land, air, and water applications. By addressing these technical challenges, unmanned vehicles technology can be further advanced and optimized for their respective land, air, and water applications, enabling their full potential in various industries and domains. Outlined below are the technical challenges associated with achieving a favourable Technology Readiness Level (TRL) for unmanned vehicles-based products.

1. ***Power and Energy Efficiency:*** Unmanned vehicles require efficient power systems to ensure longer flight or operational durations. Enhancing battery capacity, optimizing power management, and exploring alternative energy sources are important considerations for extending unmanned vehicles' endurance.
2. ***Payload Integration and Capacity*****:** Unmanned vehicles must be able to carry and integrate various payloads such as cameras, sensors, communication equipment, or scientific instruments. Designing Unmanned vehicles with sufficient payload capacity, payload integration interfaces, and stability during payload operation are crucial technical challenges.
3. ***Sensor Integration and Data Processing*****:** Unmanned vehicles rely on sensors for navigation, environmental sensing, data collection, and payload operations. Integrating and calibrating sensors, developing real-time data processing algorithms, and ensuring accurate sensor data interpretation are technical challenges for unmanned vehicles development.
4. ***Communication and Connectivity:*** Unmanned vehicles require reliable communication systems to transmit data, receive commands, and maintain connectivity with ground control stations (Jun Ni, et al., 2020). Developing robust communication protocols, ensuring secure and efficient data transmission, and addressing communication limitations in remote or congested areas are important challenges.
5. ***Autonomous Operation and Collision Avoidance:*** Enabling Unmanned vehicles to operate autonomously and make intelligent decisions is a significant technical challenge. Developing sophisticated flight control algorithms, implementing

collision avoidance systems, and integrating advanced artificial intelligence and machine learning techniques are key focus areas.

6. ***Environmental Adaptability:*** Unmanned vehicles operating in different environments must be capable of withstanding various weather conditions and adapting to environmental challenges. Designing unmanned vehicles with weather-resistant materials, incorporating environmental sensors, and ensuring stable flight under adverse conditions are important technical considerations.
7. ***Maintenance and Reliability:*** Ensuring unmanned vehicles reliability, ease of maintenance, and minimizing downtime are crucial for operational efficiency. Developing robust maintenance procedures, addressing failure modes, and implementing self-diagnostic systems contribute to the overall reliability and availability of unmanned vehicles.
8. ***Regulatory Compliance:*** Unmanned vehicles operations are subject to regulations and restrictions imposed by aviation authorities, maritime organizations, and land-use policies. Addressing regulatory compliance challenges, understanding airspace restrictions, and obtaining necessary permits or licenses are essential for lawful and safe operations.

4. Discussions

This study explores the various aspects of Unmanned Vehicles technology, including technical challenges, research findings, and industry applications. The analysis of outcomes is contextualized within the research objectives and existing literature. The study emphasizes the importance of addressing both technical and social challenges specific to each sector to effectively integrate unmanned vehicles across industries. Collaboration between stakeholders, regulators, and technology developers is critical.

Unmanned vehicles development faces numerous technical challenges, including improving power systems for greater endurance, increasing payload capacity and stability, processing sensor data, ensuring reliable communication, enabling autonomous capabilities, weatherproofing, and improving reliability and maintenance protocols. Addressing these challenges is critical for advancing such technologies and realizing its full potential across industries.

The legal and secure operation of unmanned vehicles is dependent on strict adherence to regulations and a thorough understanding of airspace limitations. Collaboration with regulatory authorities is critical for ensuring compliance. Tailoring unmanned vehicles designs to specific environments is critical for maximizing performance under a variety of conditions.

The combination of Unmanned Aerial Vehicles (UAVs) and Unmanned Ground Vehicles (UGVs) improves capabilities in surveying, surveillance, infrastructure inspection, and environmental monitoring. Technological advancements in stability control, geophysical surveying, wildlife monitoring, and safety enhancement highlight the progress and potential applications of UAV and UGV technology.

Continued research and development broaden the range of potential applications, encouraging innovative solutions across multiple fields. To summarize, addressing technical challenges, adhering to regulatory standards, and considering environmental factors are critical for advancing Unmanned vehicles technology and fully utilizing its capabilities. Successful integration and implementation necessitate stakeholder collaboration, interdisciplinary research, and tailored solutions to specific application requirements.

5. Conclusion

The Technology Readiness Level (TRL) scale ranges from 1 to 9, indicating the maturity and readiness of a technology. These TRL provide a framework to assess the maturity and readiness of unmanned vehicles technology throughout its development and towards its commercialization. It allows for a systematic evaluation of the technological advancements and the progress made in transforming the unmanned vehicles concept into a deployable and commercially viable product. relevant items associated with each TRL level for the development and commercialization of an unmanned vehicles product are as follows:

Table 4. TRL Framework for Unmanned Vehicles Readiness for Commercialization

TRL 1: Basic Principles Observed
Theoretical studies and concept formulation
Proof-of-concept experiments
Technology feasibility assessments
TRL 2: Technology Concept Validated
Technology concept validation through analytical and laboratory studies
Identification of critical components and subsystems
Preliminary design and evaluation
TRL 3: Experimental Proof of Concept
Experimental proof of concept validation
Demonstration of technological feasibility in a laboratory or controlled environment
Initial assessment of performance characteristics
TRL 4: Technology Validated in a Lab Environment
Validation of the technology in a laboratory environment
Prototype development and laboratory testing
Detailed performance evaluation and analysis
TRL 5: Technology Validated in a Relevant Environment
Validation of the technology in a relevant operational environment
Prototype testing under realistic conditions
Evaluation of performance and functionality in simulated field settings
TRL 6: System Demonstration in a Relevant Environment
Demonstration of the fully integrated system in a relevant operational environment
Evaluation of system performance, reliability, and operational capability
Identification and resolution of technical issues and risks
TRL 7: System Prototype Demonstration in a Space-Like Environment
Demonstration of a system prototype in a space-like environment

Validation of performance and functionality in a realistic operational setting
Verification of system characteristics and capabilities
TRL 8: Actual System Completed and Qualified
Development of a complete, operational system
System qualification and verification testing
Validation of performance, reliability, and safety under operational conditions
TRL 9: System Proven Through Successful Operations
Technology fully matured and proven through successful operations
Deployment of the system in its intended operational environment
Verification of operational effectiveness, safety, and reliability

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Author Contribution

Azlin Abd Jamil contributed to the conceptualization, methodology, formal analysis, project administration, supervision, data curation, and writing—original draft preparation. Mohd. Adib Sarijari was involved in the methodology and writing—review and editing. Rozeha A. Rashid, Jaysuman Pusppanathan, and Kamarulafizam Ismail each contributed to the methodology. Mohd Shahir Shamsir provided input on the methodology, resources, and supervision.

Conflict of Interest

The authors have no conflicts of interest to declare.

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