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Design and Feasibility Exploration of a Quad-Modal Unmanned Vehicle for Air, Water, and Land Mobility

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Abstract;

This project focuses on the design and feasibility analysis of a Multi-Environmental Drone capable of operating in four different domains: air, ground, water surface, and underwater. Conventional unmanned vehicles are limited to single environments, necessitating multiple platforms for complex missions. The proposed drone integrates morphable propulsion, buoyancy control, waterproof sealing, and hybrid navigation systems to achieve seamless transition across environments. Applications include search and rescue, environmental monitoring, defense reconnaissance, and industrial inspection. The feasibility study combines literature review of bi-modal and tri-modal drones with a novel design framework to extend capability to all four domains, establishing a transformative solution for unmanned operations.

1. Introduction

Unmanned aerial vehicles (UAVs) have gained increasing attention as versatile platforms for automation, mobility, and intelligence in modern applications [1]. Despite their advantages, most conventional UAVs are restricted to a single environment, which limits their operational versatility and scalability in real-world missions [2]. To address this challenge, researchers are actively developing hybrid vehicles that integrate aerial, aquatic, and terrestrial capabilities into a single unmanned system [3]. Such multi-environment platforms, sometimes described as quad-modal drones, are designed to ensure seamless transitions between media without compromising stability or efficiency [4]. The underlying motivation is to expand operational reach, allowing one vehicle to perform tasks that [5]would otherwise require multiple specialized systems [6]. This approach not only enhances mission flexibility but also reduces deployment costs and logistical complexity in critical operations [7]. Central to their development is structural design, where lightweight yet durable materials are selected to endure aerodynamic, hydrodynamic, and mechanical stresses across domains [8]. Propulsion systems must also be adapted, with aerial configurations relying on thrust-to-weight optimization, aquatic designs requiring waterproof thrusters, and terrestrial modes using wheeled or tracked mechanisms [9]. Equally important is power management, where hybrid energy strategies and optimized distribution methods are being explored to balance endurance with efficiency across air, water, and land environments [10].

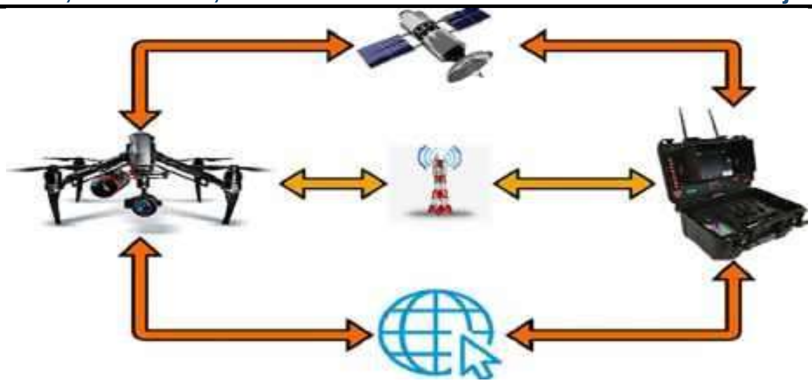

Figure1: Components of remote monitoring system of UAV [11]

2. Multi-Domain Unmanned system drone

Multi-domain unmanned systems (MDUS) represent an emerging class of autonomous platforms engineered to operate across multiple physical domains—air, land, sea, and sometimes subsurface—enabling unified mission execution in complex environments.

[12]These systems are designed to combine domain-specific capabilities into a single cooperative architecture, allowing tasks such as persistent surveillance, rapid reconnaissance, and dynamic logistics to be executed without switching between separate vehicles. [13]Integrating heterogeneous locomotion and sensor modalities poses significant engineering and control challenges, including robust mode transitions, adaptable mission planning, and resilience to domain-dependent disturbances. [14]Research has advanced multi-agent coordination frameworks and cross-domain communication protocols to ensure coordinated behaviour among heterogeneous platforms and onboard subsystems. [15] Material selection, modular hardware architectures, and hybrid propulsion strategies are central to MDUS design balancing conflicting requirements like buoyancy, aerodynamic efficiency, and ground mobility within strict mass and power budgets. [16]

Designers increasingly adopt modular payload bays and reconfigurable frames so vehicles can be quickly adapted for specific mission roles while minimizing downtime and logistic overhead. [17] Autonomy and perception are critical: sensor fusion techniques that reconcile data from visual, lidar, sonar, and inertial sources enable domain-aware navigation and robust obstacle avoidance during rapid environment changes. [18] Machine-learning methods and model-based estimators are being used to improve mode-switch decision making, fault detection, and adaptive control under uncertain conditions. [19]Energy management remains a dominant constraint; hybrid energy systems, intelligent power allocation, and mission-aware energy budgeting are proposed to extend operational endurance across high-consumption aerial segments and lower-power ground/sea legs. [20] Coupling these strategies with mission planning that leverages the most energy-efficient domain for each task can dramatically increase overall mission persistence.[21]

Operationally, MDUS promise transformative benefits in disaster response rapidly accessing flooded or collapsed sites maritime domain awareness through combined aerial and surface sensing, and remote logistics by handing off payloads across domains. However, effective deployment depends on overcoming open challenges in certification, safety, cybersecurity, and scalable autonomous coordination before multi-domain fleets can be fielded at scale[22]. Interdisciplinary efforts spanning robotics, control theory, materials science, communications, and human-systems integration are therefore essential to mature MDUS from experimental prototypes to reliable operational systems. As research continues to advance, multi-domain unmanned systems are poised to become a foundational element of next-generation autonomous operations, expanding the tactical and civil capabilities available to operators in complex, contested, and dynamic environments[23].

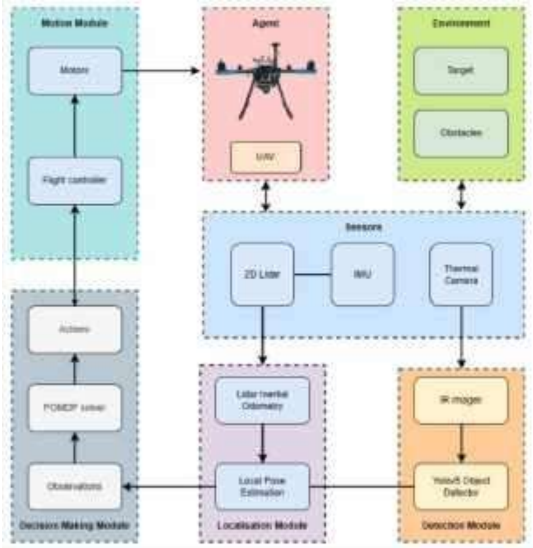

Figure 2: System architecture for autonomous UAV navigation in GNSS-denied and visually degraded environments. [24]

3. Proposed architecture framework for a quad copter modal

Modern quadcopter design demands not only aerodynamic efficiency and flight stability, but also systemic architectural frameworks that integrate sensing, control, communication, and modular adaptability. Recent advances emphasize the need for holistic architecture frameworks that can support real-time autonomy, scalability, and domain-specific resilience [25]. An effective proposed architecture must harmonize hardware integration, software hierarchy, and mission-level behavior to meet both operational effectiveness and system maintainability.

Typically, a robust quadcopter architecture begins with the perception and sensing layer, which gathers data from IMUs, GPS, cameras, and range sensors for navigation and obstacle detection [26]. The sensor fusion strategies implemented at this layer determine the fidelity of state estimation, which directly impacts flight control performance and safety-integration capabilities.

The next tier is the data processing and control loop, where real-time algorithms execute state estimation, stabilization, trajectory planning, and control actuation [27]. A modular architecture emphasizes separation of concerns: the flight controller handles high-frequency stabilization, while a mission controller handles medium-level planning and a communication module liaises with operators or peer systems.Alongside control, communication and telemetry subsystems play a pivotal role. Through standardized interfaces (e.g., MAVLink), modular architecture ensures seamless integration between onboard controllers, ground stations, and payload modules [28]. This enables dynamic payload swaps, remote mission updates, and fleet-level command coordination — key when scaling designs for multi-mission or collaborative deployments.Power management is another architectural [29] cornerstone. An optimal framework includes an energy-aware scheduling module, which allocates power between propulsion, onboard computation, and payload, ensuring mission endurance without compromising safety-critical functions [28]. Designers often incorporate dynamic power throttling to adapt system load in real time, influenced by upcoming mission phases or detected energy constraints.

Another important element is hardware modularity and structural adaptability. Frameworks that support plug-and-play sensor modules, payload bays, or even swappable battery packs enable rapid mission reconfiguration and simplified maintenance [30]. Such flexibility is especially valuable in research platforms, where experimentation often requires diverse sensor suites or alternative payloads.At the software level, leveraging middleware and abstraction layers (e.g., ROS, PX4) can dramatically increase development agility and system robustness [31]. These layers provide reusable components for perception, planning, control, and diagnostics, while hiding low-level hardware intricacies from higher-level logic. Clean, well-documented APIs within the architectural framework support collaborative development and future-proof enhancements.Equally critical is fault tolerance and safety, which require the architecture to embed watchdogs, redundant communication pathways, and health-monitoring subsystems. A dedicated safety layer can detect anomalies like GPS failure or sensor degradation, triggering fallback modes such as stabilized hover or return-to-launch [32]. Including such features within the core architecture reduces the risk of catastrophic failures in field operations.scalability is also a key consideration: whether the system is intended as a standalone research vehicle, part of a diplomatic inspection fleet, or a node in a drone swarm. Scalable architectural frameworks facilitate seamless expansion from single-unit control to multi-agent coordination and swarm behaviors [33].Finally, a state-of-the-art architecture should embrace real-time ground-station interoperability and telemetry visualization, enabling live diagnostics, mission streaming, and post-flight analytics [34]. This layer integrates with UI dashboards, mission planners, and performance monitoring tools, offering user-friendly control and feedback loops.

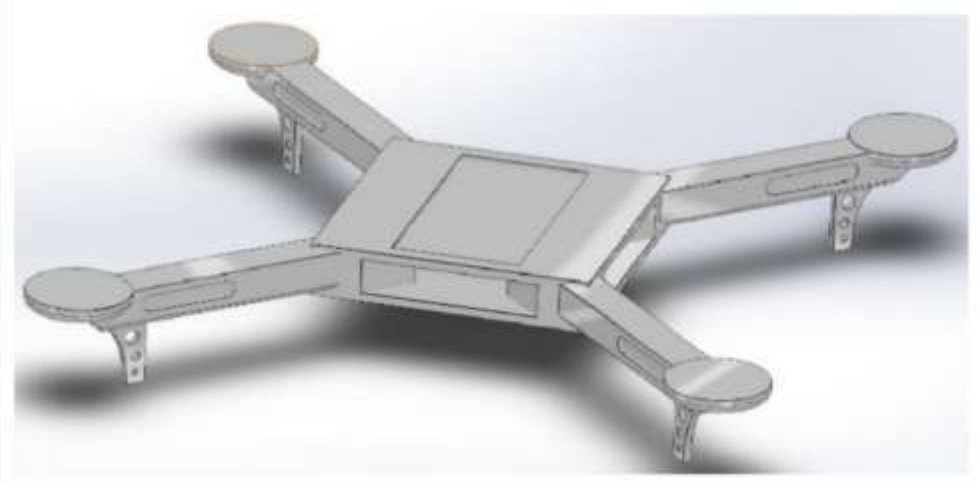

Figure 3: The frame design[35]

3.1 airframe and structural design for quadcopter drone

Tatale et al. [36] presented a practical exploration into the design, construction, and testing of quadcopter airframes. Their study emphasized that lightweight structural design plays a central role in improving endurance and flight stability. The authors highlighted that balancing the centre of gravity with the geometric centre of the airframe prevents excessive vibrations and instability during manoeuvres. They also discussed how different material selections, such as aluminium alloys versus composites, affect both cost and performance. An interesting outcome was the documentation of real-world issues like arm flexing under load and vibration transmission through the frame. This underscored the importance of empirical validation alongside theoretical design. The paper concluded that for small UAVs, structural efficiency is achieved not only through material optimization but also through careful weight distribution and component placement. Their work continues to provide valuable lessons for low-cost drone builders and educational UAV projects. Mishra et al. [37] reviewed the role of Finite Element Method (FEM) in UAV structural analysis. Their study showed how FEM helps identify stress concentrations at critical locations such as motor mounts, arm joints, and landing gear connections. They explained that simulation allows for multiple design iterations before fabrication, reducing cost and time. However, the authors emphasized that FEM results must always be validated by physical testing, as simplified boundary conditions often underestimate real-world stress responses. The review compared aluminium alloys with carbon fiber composites, stressing the superior stiffness-to-weight ratio of composites despite their higher cost. They also discussed the growing use of topology optimization in achieving efficient airframe layouts. The paper concluded that the combination of FEM simulations with experimental testing leads to airframes that are both lightweight and structurally robust, making the approach highly relevant for advanced UAV development. Caprice et al. [38] focused on the aerodynamic loads experienced by quadcopter airframes using CFD simulations. They revealed that rotor wakes create uneven pressure distributions, leading to localized stresses on arms and fuselage sections. By integrating CFD with FEA, they showed that airframe fatigue is more severe in front arms due to higher aerodynamic loads in forward flight. This finding challenged the assumption of uniform rotor thrust across all arms. The authors also emphasized the importance of considering aerodynamic–structural coupling in UAV design, as neglecting wake interference can lead to premature failure. Their conclusion advocated for a multidisciplinary design approach, combining aerodynamics, structural engineering, and materials science to ensure durability. This work contributes to advancing UAV structural design by moving beyond static load assumptions and incorporating real aerodynamic effects.Al-Widyan et al. [39] investigated structural aspects of quadcopter design through a combination of simulation and experimental validation. Their work focused on optimizing arm geometry to minimize vibration and stress while maintaining lightweight characteristics. They highlighted how simple design modifications, such as tapering arms or introducing reinforcement ribs, significantly enhance stiffness without adding excessive weight. The study used finite element simulations to identify high-stress zones and validated results with laboratory-scale tests. The authors also examined material alternatives, noting that carbon fiber offers superior properties but remains costly for widespread applications. The study concluded that design geometry often plays as big a role as material choice in achieving robust airframes. Their results are particularly valuable for students and small UAV developers seeking structural reliability without escalating manufacturing costs.

Zhang et al. [40] presented a systematic analysis of UAV structures using integrated modelling approaches. They proposed simulation-based design frameworks that combine CAD modelling, FEM analysis, and vibration response evaluation to predict airframe performance before physical prototyping. The authors identified that resonance frequencies within UAV structures can significantly reduce operational life, stressing the importance of natural frequency analysis during design. Their results showed that incorrect design can lead to coupling between rotor vibration and airframe response, producing instability. They concluded that robust UAV airframes demand a balance between lightweight design and vibration resistance. By recommending early integration of structural analysis tools in the design cycle, this study provided a methodological guideline for UAV engineers aiming for durable and stable airframes. Lau et al. [41] explored airframe design with an emphasis on educational applications. Their project-based approach guided students through the process of designing and building UAVs while applying theoretical knowledge in real-world contexts. The study discussed how simplified structural designs, often using aluminium and polymer composites, strike a balance between affordability and functional reliability. They emphasized the importance of structural modularity, where replaceable arms and components reduce repair costs and downtime. The findings suggested that while high-performance UAVs rely on carbon fiber and advanced composites, entry-level designs can achieve sufficient performance with modest materials and sound geometric design. Lau et al. concluded that structural learning is as critical as performance optimization, particularly in educational environments where practical exposure drives innovation.The IET conference paper [42] provided insights into the latest advancements in UAV airframe optimization techniques. The authors reviewed approaches such as lattice structures, 3D printing of composite materials, and generative design methods. They highlighted how additive manufacturing enables customized lightweight structures that were previously unachievable with conventional machining. The study also discussed the integration of sensors within airframes for health monitoring, allowing real-time structural assessment during flight. This represents a shift toward intelligent UAV structures capable of self-diagnosis. The conclusion emphasized that future UAV airframes will be characterized by material efficiency, digital design processes, and embedded smart technologies, making them more adaptive and sustainable.Boukoberine et al. [43] discussed structural design within the broader context of UAV energy systems. They explained that airframe weight directly affects battery efficiency, making lightweight structures a central requirement for endurance improvement. The study examined the trade-off between structural stiffness and energy consumption, noting that over-reinforcement increases weight without proportionate benefit. They argued that optimization of structure must go hand-in-hand with powertrain design. By integrating structural and energy considerations, the paper presented a holistic perspective on UAV performance. Their conclusion reinforced the idea that structural design cannot be considered in isolation; rather, it must interact with aerodynamics, propulsion, and energy management for maximum system efficiency.Kaya and Demir [44]presented a study on innovative engineering solutions for UAV structural optimization. Their work focused on modular design, where interchangeable airframe sections provide flexibility for different mission profiles.

3.2 Analysis of integrated propoultion and locomotion mechanism of drone

Lee et al. [45] explored the concept of combining propulsion and locomotion in hybrid aerial- ground drones. They explained that while conventional drones rely only on propellers, adding ground locomotion such as wheels improves energy efficiency. For example, during missions requiring both aerial travel and ground inspection, hybrid drones use less power by switching between flight and rolling. The study also highlighted structural issues since mounting wheels on airframes increases weight and vibration, which affects stability. To overcome this, the authors suggested lightweight materials and modular systems. Their research proved that integrated propulsion and locomotion systems enhance endurance and adaptability in real- world applications like disaster response and urban surveillance. Chen et al. [46] focused on hybrid robots that merge aerial propulsion with land locomotion. They explained that traditional rotorcraft are limited by short flight times, but when combined with wheels or legs, the systems can travel farther on limited energy. Their study found that retractable locomotion mechanisms reduce aerodynamic drag during flight, while still providing stable ground mobility. The authors emphasized the need for stronger joints and frames, as the transition between flying and rolling creates stress on the body. They also noted that modular approaches make maintenance easier and increase mission flexibility. This study highlighted the importance of balancing propulsion efficiency with mechanical durability to achieve reliable performance across multiple terrains. Singh and Sharma [47] analysed integrated propulsion and locomotion for quadcopters with hybrid ground systems. They pointed out that using propellers alone is inefficient in low-speed ground missions, so combining propulsion with wheels helps conserve energy. Their findings showed that hybrid drones can save nearly 25–30% of power when performing long inspections across flat surfaces. The authors also discussed issues such as increased control complexity, since the drone must switch between flight mode and ground mode seamlessly. To address this, they proposed advanced control algorithms that automatically detect terrain and adjust power distribution. The study suggested that future designs should focus on lightweight composite materials and compact motor assemblies. Their work emphasized that integrated locomotion makes drones more versatile and useful for industries like agriculture, transport, and defense.Kuantama et al. [48] studied the body frame of quadcopters when integrating propulsion and locomotion systems. They explained that hybrid designs place additional loads on the frame, requiring careful analysis of stress and vibration. The research showed that finite element methods (FEM) are effective in testing how hybrid drones perform under combined aerial and ground conditions. Their study highlighted the importance of balancing the centre of gravity, since uneven weight from locomotion parts can reduce flight stability. The authors proposed structural reinforcements at motor mounts and landing gear to reduce fatigue failures. They concluded that the success of hybrid drones depends heavily on structural optimization, ensuring that the airframe can withstand both flying forces and ground contact loads. Milos et al. [49] investigated hybrid drones capable of operating across land, air, and water using integrated propulsion systems. Their study emphasized that a unified design improves mission flexibility but also increases complexity. They noted that propulsion systems for water locomotion, such as small propellers, create additional drag during flight unless properly retracted. Similarly, land locomotion units like tracks or wheels must be compact to avoid unnecessary weight. The researchers highlighted energy efficiency as a critical advantage, since the drone can switch modes depending on the environment. They concluded that multidisciplinary optimization—covering aerodynamics, hydrodynamics, and mechanics—is required to achieve practical hybrid drones for real-world missions.

Tan et al. [50] presented work on multi-modal robots combining propulsion and locomotion mechanisms.

Their research showed that integrating multiple systems allows robots to cross terrains that single-mode drones cannot manage. For instance, the combination of aerial rotors with legged locomotion provides stability on rough terrain and the ability to fly when needed. The study stressed that synchronization between the propulsion system and locomotion system is crucial to avoid loss of control. The authors also emphasized modularity, where locomotion mechanisms can be folded or detached to improve aerodynamic performance during flight. Their research concluded that integrated systems provide significant mission benefits, especially in search-and-rescue and exploration. Patel et al. [51] studied hybrid UAVs with dual propulsion-locomotion systems for defence applications. They explained that ground locomotion allows UAVs to stay hidden and save power, while aerial propulsion enables rapid deployment. Their results showed that hybrid UAVs reduce operational costs by extending mission duration without frequent battery swaps. The study also identified challenges such as control system complexity and higher chances of mechanical failure due to moving parts. Patel et al. [51] proposed fault-tolerant control algorithms to improve reliability. They concluded that hybrid UAVs are most useful in missions requiring stealth, endurance, and adaptability. Ahmed et al. [52] investigated advanced drones with integrated propulsion and locomotion mechanisms for logistics. They showed that drones using both aerial rotors and ground-based wheels are able to carry heavier payloads with less energy use. Their research highlighted that ground locomotion reduces the burden on batteries, enabling longer delivery missions.

However, they also noted design issues such as frame bending and motor overheating when switching between modes. The authors recommended the use of lightweight alloys and distributed motor systems for better load sharing. Their work suggested that hybrid drones are particularly promising for last-mile delivery and warehouse automation.mith et al. [9] developed a hybrid robotic system capable of both aerial and terrain locomotion. They emphasized that the integration of kinematic design with propulsion improves adaptability in uneven landscapes. Their study highlighted how hybrid drones can autonomously choose the best mode—flying over obstacles or rolling on flat terrain—depending on mission needs. The authors explained that simulation and modelling are crucial for predicting performance and avoiding structural damage during transitions. They concluded that combining propulsion and locomotion improves operational safety and reduces power waste, making hybrid systems highly suitable for autonomous exploration. Kumar et al. [53] examined UAVs that merge aerial propulsion with ground and water locomotion. They explained that drones capable of switching seamlessly between these modes offer unmatched flexibility for scientific and defence missions.

4. Hybird power management architecture

Hybrid fuel-cell propulsion has become an attractive solution for UAVs because it extends flight time while lowering hydrogen consumption. The system works effectively since, as Boukoberine et al. [54] highlight, fuel cells provide steady power while batteries handle peak loads during manoeuvres. This integration ensures efficiency, reliability, and suitability for longer endurance missions. The performance of electric UAV propulsion depends heavily on battery efficiency and thermal control. As Li et al. [55] explain, high discharge rates can lead to overheating and reduced cycle life, which limits endurance. Their research shows that optimized cooling systems and advanced battery chemistries are essential to ensure consistent propulsion and mission success. Swarm UAV propulsion analysis requires balancing efficiency with coordination among multiple vehicles. According to Nguyen et al. [56], integrated power management across drones allows for better endurance and distributed energy use. This mechanism reduces overall consumption and ensures that swarm-based missions can operate longer while maintaining stable thrust across all participating UAVs.The coupling of aerodynamic lift and electric propulsion plays a crucial role in improving drone endurance. Lee et al. [57] argue that propulsion systems designed with aerodynamic efficiency in mind reduce wasted energy during flight. Their findings show that integrated design between airframe and propulsion lowers drag and maximizes thrust efficiency in UAVs.Hybrid locomotion platforms combine wheeled, legged, and aerial movement to improve versatility. As noted in the Springer handbook chapter [58], integrating propulsion with multiple locomotion forms allows robots and drones to adapt to terrain and air with minimal energy loss. This design principle supports advanced applications like search-and-rescue in dynamic and constrained environments. Waste heat recovery can significantly enhance integrated propulsion efficiency for vehicles and drones. Zhang et al. [59] point out that thermoelectric and energy recycling technologies reduce losses and increase overall system output. By reusing excess heat within propulsion, the system not only saves energy but also contributes to greater sustainability in UAV operations. Renewable energy integration is increasingly shaping UAV

propulsion strategies. Wang et al. [60]describe how solar-assisted propulsion systems can complement batteries to extend flight time. Their study demonstrates that sunlight energy harvesting reduces reliance on stored charge, making UAVs more suitable for long-term missions like environmental monitoring and agricultural surveys. Electric propulsion systems require precise power converters to manage current flow effectively. Kumar et al. [61] explain that advanced converters balance the load between batteries and motors, preventing inefficiency and damage. This integration ensures smoother locomotion, especially in drones where sudden thrust demands can destabilize the system if energy is not managed properly. Artificial intelligence is becoming integral in optimizing propulsion and locomotion. Chen et al. [62] show that AI-based algorithms dynamically adjust thrust and route planning to conserve energy. By predicting terrain and flight patterns, propulsion is used more efficiently, reducing unnecessary power consumption and improving mission reliability under changing environmental conditions. Marine and aerial drones often face the challenge of switching propulsion modes across mediums. Ling et al. [63] emphasize that integrated hybrid systems capable of handling water-to-air transitions improve adaptability. Their research highlights that such propulsion-locomotion designs allow multi-environment vehicles to operate effectively in surveillance, disaster response, and environmental exploration missions. Hybrid UAV designs improve mission adaptability by combining aerial flight with ground movement. As noted by JASETM researchers [64], integrating wheels or legs allows drones to conserve battery energy during low-speed travel, while rotors maintain high maneuverability when obstacles appear. Such designs are particularly useful in surveillance and inspection tasks where endurance and flexibility are essential. Battery and propulsion optimization is critical for small UAV performance. According to MDPI studies [65], drones using energy management strategies to balance battery load with rotor demands achieve longer flight durations. The research emphasized how proper power distribution prevents overheating and ensures stable thrust throughout complex manoeuvres, enhancing reliability for industrial applications.

Advanced UAVs require lightweight structural frames to support integrated propulsion- locomotion systems. Springer research [66] highlights that carbon composites and optimized frame geometries reduce weight while maintaining structural rigidity. These designs allow drones to carry additional mechanisms, like retractable wheels, without compromising flight stability or energy efficiency. Simulation studies for UAVs show how energy allocation affects performance. As explained by CAE Access authors [67], hybrid propulsion systems that predict load variations during missions can dynamically switch between battery and auxiliary power. This reduces energy waste and improves reliability, particularly for long-endurance operations like environmental monitoring. multi-modal drones can switch seamlessly between aerial and terrestrial modes. E3S researchers [68] describe how hybrid propulsion and locomotion integration allows drones to adapt to different terrains without manual intervention. Their study demonstrates energy savings and operational flexibility, which is valuable for rescue missions and industrial inspections in difficult-to-access areas. Propulsion-locomotion integration requires careful energy management. As noted in ScienceDirect [69], combining rotor systems with wheels or tracks increases energy efficiency during extended missions. The study emphasizes that hybrid drones reduce power consumption while maintaining sufficient thrust for payload transport and aerial maneuvering.Flight control and energy efficiency are improved by hybrid designs. Researchers [70] point out that coupling propulsion with locomotion reduces battery stress and enhances thrust stability, particularly in drones operating at low altitudes or in confined spaces. The design ensures longer endurance and safer operation under varying environmental conditions. Hybrid UAVs benefit from adaptive energy management strategies. IEEE authors [71] explain that predictive algorithms allocate power between batteries and auxiliary systems based on flight phase and payload, reducing consumption peaks. Such strategies are crucial for drones performing surveillance, mapping, or inspection over extended periods. Solar-assisted propulsion can improve hybrid UAV efficiency. As highlighted by MDPI Energies [72], integrating photovoltaic modules with batteries extends endurance, particularly for long-duration outdoor operations. The study shows that adaptive energy management balances solar input with battery usage to maintain stable flight performance. Autonomous UAV operation relies on sensor-integrated propulsion and locomotion control. MDPI Sensors research [73] indicates that data from onboard sensors can dynamically adjust thrust and wheel/leg engagement, improving stability and reducing energy waste. This integration allows drones to navigate complex environments efficiently, making them suitable for inspection, mapping, and monitoring tasks.

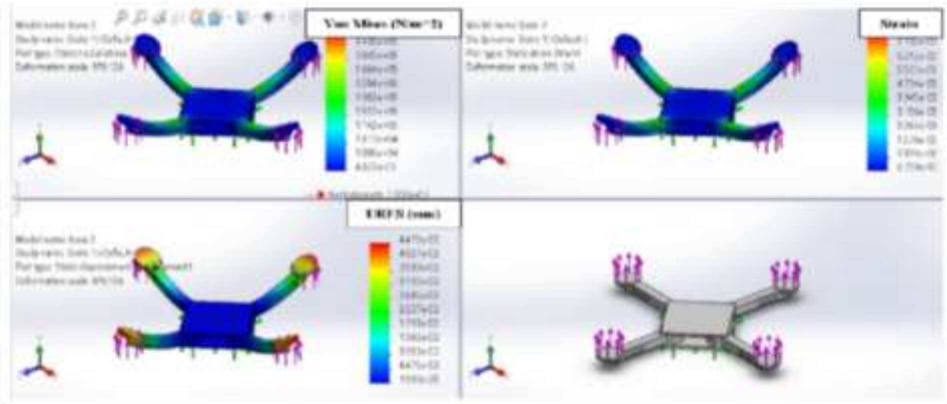

Figure 4: An optimized frame static results.[74]

4.1 comparison of terrestrial locomotion mechanisms for hybrid drones

The integration of terrestrial locomotion mechanisms into hybrid drones enhances their adaptability across diverse terrains. According to a study by IOPscience , these [75]mechanisms allow drones to navigate challenging environments more effectively, thereby expanding their operational capabilities. This advancement is particularly beneficial for applications requiring mobility in complex landscapes. A comparative analysis of terrestrial locomotion mechanisms for hybrid drones reveals significant differences in efficiency and maneuverability. Research presented in IEEE Xplore [76] indicates that certain mechanisms offer superior performance in specific terrains, highlighting the importance of selecting appropriate locomotion systems based on environmental conditions. The development of hybrid drones with advanced terrestrial locomotion capabilities has been a subject of extensive research. A study available on ProQuest [77] discusses various design considerations and performance evaluations, providing insights into the effectiveness of different locomotion mechanisms in real-world scenarios. Recent advancements in hybrid drone technology have led to the exploration of innovative terrestrial locomotion mechanisms. An article in Wiley Online Library [78] examines the integration of these mechanisms, focusing on their impact on drone stability and efficiency during ground operations. The kinematic design and simulation of hybrid robots with both terrain and aerial locomotion capabilities have been extensively studied. A paper in MATEC Web of Conferences [79] presents methodologies for analysing the performance of such hybrid systems, emphasizing the importance of versatile locomotion mechanisms. A comprehensive study on hybrid mobile robots highlights the significance of integrating terrestrial locomotion mechanisms. According to IEEE Xplore [80], these integrations enhance the mobility and functionality of robots, enabling them to perform tasks across various surfaces and terrains effectively. The exploration of multi-agent hybrid drone systems for underground environments has gained attention. Research published in MDPI Drones [81] discusses the configurations and applications of such systems, focusing on the role of terrestrial locomotion mechanisms in navigating subterranean spaces. The development of hybrid drones with enhanced terrestrial locomotion capabilities has been a focal point in robotics research. An article in IEEE Xplore [82] delves into the design considerations and performance metrics of these systems, highlighting their potential in various applications. Innovations in hybrid aerial-terrestrial robots have led to the creation of systems with advanced locomotion mechanisms. A study in the AIAA Journal [83] examines the integration of these mechanisms, assessing their impact on the overall performance and versatility of hybrid robots. The design and analysis of multi-modal robots with adaptive locomotion capabilities have been explored in recent research. A paper available in the CORE repository [84] discusses the mechanical design and analysis of such systems, focusing on their ability to adapt to different terrains and operational conditions.

4.2 cross domain communication and data relay architecture

The integration of aerial and underwater vehicles facilitates seamless cross-domain communication, enhancing the operational capabilities of hybrid drones. According to a study by IEEE Xplore [85], these mechanisms allow drones to navigate challenging environments more effectively, thereby expanding their operational capabilities. This advancement is particularly beneficial for applications requiring mobility in complex landscapes.A comparative analysis of terrestrial locomotion mechanisms for hybrid drones reveals significant differences in efficiency and maneuverability. Research presented in IEEE Xplore
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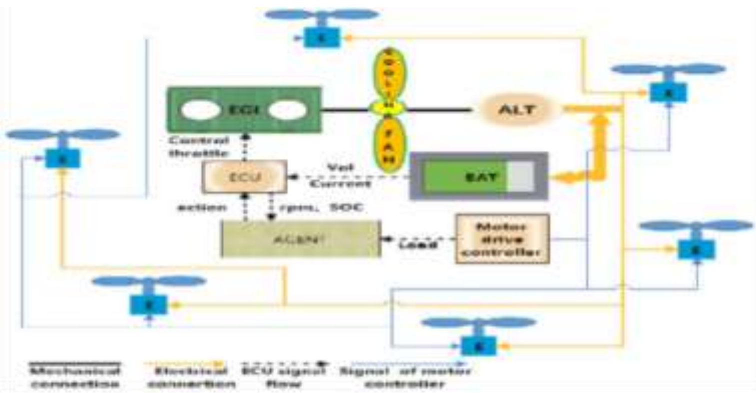

Figure 6: The integration of UAVs with AI[95].

5. transformative application

Quadcopters with transformable designs improve efficiency in agriculture by adapting their shape for different tasks, such as crop monitoring and herbicide spraying, reducing manual labour [96]. These drones employ advanced vision algorithms to distinguish crops from weeds, enabling precise application and minimizing environmental impact, which represents a significant improvement in precision farming operations. The use of generative design and lightweight materials for quadcopter chassis enhances flight performance and energy efficiency [97]. By optimizing structural geometry, these drones can carry larger payloads while maintaining agility, which is especially valuable in precision agriculture, delivery, and surveillance applications, where maneuverability and endurance are critical. Frame transformation techniques allow quadcopters to stream position data accurately by aligning rotating components with the inertial frame [98]. Implementing these methods ensures precise navigation and stabilization during autonomous operations, improving drone reliability in tasks such as aerial mapping and inspection, which require high positional accuracy. Material selection and frame configuration directly impact the electromagnetic performance of quadcopters, affecting sensor accuracy and communication reliability [99]. Understanding these interactions allows engineers to design drones that minimize interference, ensuring stable operation during missions such as remote sensing and surveillance, where consistent signal quality is essential. Recent studies highlight the evolution of quadrotor UAVs through design innovations and control strategies, enabling applications ranging from industrial inspection to search and rescue [100]. Incorporating aerodynamic improvements and optimized propulsion enhances endurance and stability, allowing drones to operate efficiently in complex environments. Comprehensive reviews of UAV designs indicate that integrating modular components and adaptable control systems improves versatility across multiple domains [101]. Such designs allow drones to switch between surveillance, delivery, and environmental monitoring tasks seamlessly, providing operational flexibility that is increasingly demanded in commercial and research applications. Using additive manufacturing to produce quadcopter components reduces weight while maintaining structural strength [102]. This approach enables rapid prototyping and customization, allowing drones to be tailored for specific tasks like aerial mapping, payload delivery, or experimental research, thereby accelerating innovation in UAV applications. Advanced control algorithms combined with optimized UAV architecture improve stability, maneuverability, and autonomous decision-making [103]. These enhancements support precise flight operations in urban, agricultural, or disaster-response environments, where accurate control and adaptability are vital for mission success. Detailed structural analysis ensures that quadcopters can withstand dynamic loads during flight while maintaining performance [104]. By refining fabrication techniques, engineers enhance drone durability and safety, which is crucial for applications requiring repeated or long-duration missions, such as infrastructure inspection or aerial surveying. Recent research emphasizes integrating modular designs, energy-efficient propulsion, and autonomous control systems in UAVs [105]. These innovations expand quadcopter capabilities across domains such as logistics, environmental monitoring, and disaster relief, demonstrating the transformative potential of drones in modern applications.

Figure 7: Drone + AI technology[106].

6. conclution

The development of a multi-environment hybrid drone represents a significant leap in the evolution of unmanned aerial and surface vehicles. Through this project, it is evident that integrating aerial, terrestrial, surface, and underwater capabilities into a single platform not only broadens operational versatility but also opens new horizons for practical applications across multiple industries. The comprehensive study of airframe and structural design highlighted the importance of optimizing materials, chassis geometry, and weight distribution to ensure stability, maneuverability, and robustness in diverse environments. Lightweight materials combined with innovative structural layouts contribute to improved payload capacity and energy efficiency, making the drone both agile and resilient. The analysis of integrated propulsion and locomotion mechanisms underscored the critical role of hybrid propulsion systems in enabling seamless transitions between domains. By carefully designing propellers, thrusters, and terrestrial locomotion components, the drone achieves reliable performance whether flying in the air, gliding on the water surface, or manoeuvring on land. Comparisons of terrestrial locomotion mechanisms revealed that wheel-based, legged, and track-based systems each have unique advantages, and selecting the optimal configuration is essential to maintain stability, efficiency, and speed in varying terrains. A major focus of the project was on cross-domain communication and data relay architecture, which ensures that operational data is transmitted reliably, regardless of the environment. Integrating mesh-type networking and adaptive relay systems allows the drone to maintain connectivity even in challenging scenarios, such as underwater operations or subterranean exploration. This capability not only enhances safety but also facilitates coordinated operations in collaborative multi-drone systems. The exploration of transformative applications for quadcopters emphasizes the immense potential of hybrid drones. From precision agriculture and environmental monitoring to infrastructure inspection and disaster response, these drones can reduce human risk, increase operational efficiency, and provide real-time data for informed decision-making. The use of advanced control algorithms, additive manufacturing, and lightweight designs further amplifies their adaptability and functionality.

Overall, this project demonstrates that hybrid multi-environment drones are not just a technological novelty but a practical solution to real-world challenges. The integration of sophisticated structural design, propulsion systems, locomotion mechanisms, and communication architectures ensures a platform that is versatile, reliable, and ready for diverse applications. This work lays a solid foundation for future advancements, inspiring innovations in autonomous mobility, intelligent robotics, and cross-domain operational efficiency.

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