DESIGN AND DEVELOPMENT OF WING-IN-GROUND EFFECT UNMANNED AERIAL VEHICLES FOR EFFICIENT SEARCH AND RESCUE MISSIONS

Submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering degree in Aeronautical Engineering

by

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DEPARTMENT OF AERONAUTICAL ENGINEERING
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SATHYABAMA

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(DEEMED TO BE UNIVERSITY)
CATEGORY - 1 UNIVERSITY BY UGC
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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of **ANSH PANGORIA (41260005)** and **MILAN J PATEL (41260027)** who carried out the Project entitled **"DESIGN AND DEVELOPMENT OF WING-IN-GROUND EFFECT UNMANNED AERIAL VEHICLES FOR EFFICIENT SEARCH AND RESCUE MISSIONS"** under my supervision from November 2024 to April 2025.

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I **ANSH PANGORIA (41260005)** hereby declare that the Project Report entitled **"DESIGN AND DEVELOPMENT OF WING-IN-GROUND EFFECT UNMANNED AERIAL VEHICLES FOR EFFICIENT SEARCH AND RESCUE MISSIONS"** done by me under the guidance of **Dr. M. VIJAYAN., M.E., Ph.D.,** is submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering in Aeronautical Engineering.

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PLACE: CHENNAI

SIGNATURE OF THE CANDIDATE

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ABSTRACT

Wing-In-Ground (WIG) Effect Unmanned Aerial Vehicles (UAVs) utilize the aerodynamic ground effect, which occurs when an air vehicle flies in close proximity to a surface, greatly enhancing lift while decreasing induced drag. The natural phenomenon allows WIG UAVs to fly more efficiently, making them best suited for low-altitude operations that require high stability and little energy usage. This study involves a detailed study of the design, development, and performance assessment of a WIG UAV, with emphasis on maximizing aerodynamic efficiency, strengthening structural integrity, optimizing propulsion systems, and introducing advanced control systems. For maximum aerodynamic performance, extensive computational fluid dynamics (CFD) simulations were used to study airflow behavior, optimize lift-to-drag ratio, and improve flight stability. Different wing patterns, aspect ratios, and attack angles were experimented with to find a balance between generating lift and minimizing drag to achieve glides that were smooth and energy-efficient near the surface. The structural framework of the UAV was meticulously designed using foam as the main material, which was supported by thoughtfully distributed 3D-printed pieces for reinforcement without compromising too much on weight. This combination results in a robust yet lightweight frame capable of withstanding operational stresses such as takeoff, landing, and prolonged flight. The propulsion system was deliberately chosen to align with sustainable aviation practices, featuring an electric motor that provides sufficient thrust while maintaining energy efficiency and reducing environmental impact. The electric propulsion system reduces noise pollution, and the UAV is thus ideal for missions that need a low acoustic signature, including wildlife monitoring, coastal patrol, and search-and-rescue. For accuracy in flight control, the UAV is preloaded with an advanced autonomous stabilization system that combines various sensors, such as altimeters, accelerometers, gyroscopes, and barometers. These sensors operate in real time to track flight conditions and modify control inputs appropriately so that the UAV can fly steadily, perform accurate maneuvers, and react dynamically to disturbances within the environment. Experimental flying tests confirmed the UAV's capability for stable controlled low-altitude flight with low power utilization, verifying significant enhancements in aerodynamic performance, energy efficiency, and overall operational stability. The findings point to the future potential of WIG UAVs across

multiple sectors, such as cargo carrying, environmental monitoring, maritime patrol, and disaster relief, where their exclusive capability to effectively cross water surfaces and coastal areas gives them unique advantages over conventional aerial and seaborne vehicles. In the future, research will turn towards implementing hybrid propulsion systems with the combination of electric and alternative energy power to push operational range and duration. Also, work will be aimed at improving flight control algorithms to increase adaptability to varying aerodynamic conditions, as well as the integration of terrain-following features that enable the UAV to adjust its altitude automatically with real-time topography. These developments will make WIG UAVs maneuver complex terrain, such as coastal shores, river banks, and mountainous areas, increasing their operational flexibility. Through ongoing optimization of these technological factors, WIG UAVs can potentially transform low-altitude flight by providing a cost-effective, energy-efficient, and highly versatile alternative to both traditional aircraft and boats, making them accessible to broad acceptance for commercial, military, and humanitarian purposes. Their capability to integrate perfectly autonomous control and aerodynamic effectiveness renders them an ideal candidate for the future of niche aerial transport and reconnaissance, making operations safer, more environmentally friendly, and more efficient under a wide variety of mission contexts.

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LIST OF SYMBOLS AND ABBREVIATIONS

UAV	Unmanned Aerial Vehicle
WIG	Wing-In-Ground Effect
SAR	Search And Rescue
CFD	Computational Fluid Dynamics
FEA	Finite Element Analysis
CG	Centre of Gravity
AoA	Angle of Attack
ESC	Electronic Speed Controller
BLDC	Brushless DC Motor
LiPo	Lithium Polymer (Battery)
RC	Remote Control
FPV	First-Person View
CAD	Computer-Aided Design
ANSYS	Analysis System (Software)
RPM	Revolutions Per Minute
INS	Inertial Navigation System
USV	Unmanned Surface Vehicle
AUV	Autonomous Underwater Vehicle
RF	Radio Frequency
AI	Artificial Intelligence
LiDAR	Light Detection and Ranging
GPS	Global Positioning System
MPC	Model Predictive Control
SMC	Sliding Mode Control
UMV	Unmanned Maritime Vehicle
CFRP	Carbon Fiber Reinforced Polymer
X	Distance in X-axis
Y	Distance in Y-axis
Z	Distance in Z-axis
CL	Coefficient of Lift
CD	Coefficient of Drag
CM	Coefficient of Moment

ρ	Air Density
V	Velocity
P	Pressure
T	Temperature
Re	Reynolds Number
L	Lift
D	Drag
M	Moment
W	Weight
g	Acceleration due to Gravity
t	Time
F	Force
I	Moment of Inertia

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have transformed contemporary aerial operations, demonstrating their value in various areas of application including disaster relief, farm monitoring, city planning, and search-and-rescue operations, with the Wing-In-Ground (WIG) Effect UAV making a unique niche for itself by utilizing the ground effect a flying wonder where lift is significantly increased and drag greatly reduced as the craft hovers just a few feet above terrain such as rivers, plains, or even frozen expanses. This effect provides the WIG UAV with unprecedented energy efficiency, rock-steady flight stability, and the capability to carry large payloads, and thus it becomes an ideal choice for operations in remote or hard-to-reach locations where other drones would struggle with limited battery life, low carrying capacity, or susceptibility to extreme weather conditions. The UAV's design is a testament to considerate engineering, with high-thrust motors built to withstand them that drive it forward, a light but solid internal structure carved from Ethirina wood selected for its rare combination of durability and low weight and an exterior covered in durable, low-mass materials such as polypropylene sheets and foam panels, all carefully chosen following a detailed analysis of their cost-effectiveness, supply chain availability, and physical properties in order to maintain the craft at a low price point while also being resilient enough for harsh conditions. Early designs toyed with high-end possibilities such as ABS (acrylonitrile butadiene styrene) and CFRP (carbon fiber reinforced polymer) for their unparalleled resilience, but practical budget considerations nudged the team towards more purse-friendly substitutes that nonetheless complied with the tough performance standards needed for real-world application. Engineered to address critical requirements such as ferrying emergency aid to flood-ravaged areas, tracking crop health across vast fields, or mapping terrain in rough country, the WIG UAV excels where traditional systems reach their limits, thanks to an aerodynamic shape honed to extract every last benefit from the ground effect, a propulsion configuration designed to provide smooth, evenly distributed thrust, and a meticulously aligned center of gravity (CG) that stabilizes it whether skimming across a peaceful lake or fighting crosswinds over a windswept tundra. Motors and battery packs are placed with surgical accuracy to preserve the vehicle's aerodynamic shape while allowing a consistent delivery of power and resistance to weather curveballs such as sudden cold snaps or spinning dust storms, and an advanced data transmission network powered by reliable RF (radio frequency) modules keeps the UAV in continuous communication with its pilots, offering live updates necessary to adjust to rapidly changing situations such as a changing wildfire path. Power management is also a success, with high-output, lightweight batteries designed to maximize flight time without adding bulk to the craft, and its modular design accommodates a variety of interchangeable payloads consider medical kits for disaster relief, thermal imaging cameras for wildlife tracking, or soil sensors for precision agriculture. This fluid integration of aerodynamic innovation, cost-conscious material selection, and innovative technology provides a platform for unparalleled lift efficiency, particularly over smooth or liquid surfaces where less drag powers longer range and reduced power consumption, making the WIG Effect UAV a pioneer for next-generation uses in disaster response, rural economic development, and environmental conservation; it couples the general utility of conventional UAVs with the niche benefits of ground effect flight, providing a diverse, high-performance tool that redefines what's possible in the skies over difficult and varied terrain.

1.2 WING-IN-GROUND EFFECT PHENOMENON AND ITS RELEVANCE TO UAVS IN SEARCH AND RESCUE OPERATION

The Wing-In-Ground Effect (WIG) is an aerodynamic effect which considerably improves the performance of an aircraft when it flies near a surface. It brings about a substantial amount of increase in lift and decrease in drag, allowing WIG vehicles, such as UAVs, to realize outstanding energy efficiency, improved stability, and higher payload capacity. In contrast to conventional airplanes that produce lift by using airflow over their wings, WIG vehicles take advantage of the "cushion" of air formed between their wings and the surface below. This allows them to fly effectively over varied landscapes like water, plains, and ice sheets, making them extremely appropriate for many important uses. Unmanned Aerial Vehicles (UAVs) play a growing role in search and rescue operations, with access to remote or dangerous locations, real-time airborne monitoring, and quick coverage of broad territories.

WIG UAVs enhance these benefits by providing greater range and payload capabilities than traditional UAVs. This benefit enables wider and more effective search and rescue operations, especially in the maritime or coastal environments. The capacity of WIG UAVs to fly effectively at low altitudes and carry significant payloads makes them well-suited for delivering vital supplies, performing effective searches, and offering vital support in adverse conditions, ultimately enhancing the efficiency and effectiveness of search and rescue operations.

CHAPTER 2

LITERATURE SURVEY

Anderson J. D. (2010) provided a detailed exploration of aerodynamic principles, explaining airflow behavior around different surfaces, including aircraft. His work discusses fundamental topics such as fluid mechanics, airfoil performance, and the forces of lift and drag, making it a cornerstone reference for aerospace studies. The book also delves into advanced concepts like compressible flow and numerical methods, serving as a key resource for engineers and researchers in aerodynamics.

Katz J. et al. (2010) examined low-speed aerodynamics by integrating theoretical foundations with practical applications. Their research covers essential concepts, including wing theory, boundary layer dynamics, and viscosity effects on aerodynamic performance. The study highlights methods to optimize lift and drag at low Reynolds numbers and explores computational approaches for simulating airflow in low-speed conditions. This work is particularly valuable for aircraft designers and aerospace students aiming to refine aerodynamic efficiency.

Priyanto E. et al. (2012) analyzed challenges in adopting Wing-In-Ground (WIG) vehicles, identifying regulatory, technological, and commercial obstacles. They discuss difficulties in classifying WIG vehicles under existing aviation and maritime laws and highlight stability and control limitations within the ground effect zone. The study also addresses economic feasibility, noting skepticism regarding WIG vehicle commercialization despite potential advantages. This research provides insights into overcoming barriers to WIG adoption.

Yun L. et al. (2012) reviewed the historical evolution of ground effect vehicles (GEVs), detailing advancements from early prototypes to modern applications. The study explains the aerodynamic benefits of ground effect, such as increased lift and reduced drag, and explores different design configurations to optimize stability and performance. Challenges in integrating ground effect technology into practical transportation systems are discussed, along with the potential for military and commercial use.

Lippisch A. (2014) conducted an in-depth study on ground effect principles and their application in Wing-In-Ground (WIG) vehicles. The research focuses on how operating near the ground enhances lift and reduces aerodynamic resistance, improving efficiency. The study also evaluates different WIG vehicle designs and addresses stability challenges at low altitudes and high speeds. Lippisch's work is significant in advancing the understanding and practical development of WIG technology for various applications.

Mobassher Tofa M. et al. (2014) investigated the aerodynamic characteristics of WIG vehicles, particularly their behavior within the ground effect zone. Their study, based on experimental and computational analyses, examines how forces such as lift and drag influence vehicle performance. Design considerations, including wing configurations and speed variations, are evaluated to enhance safety and efficiency. The findings contribute to improving WIG vehicle operations by optimizing aerodynamic features for better stability and control.

Nebylov A. (2015) explored the historical development of the Soviet Ekranoplan, a pioneering WIG vehicle concept. The study outlines its strategic role during the Cold War and the technical challenges faced in its development. Unique design elements, such as low-altitude flight over water and ground effect utilization, are discussed. Despite its limitations, the Ekranoplan remains an important case study in WIG vehicle innovation, providing lessons for future advancements.

Turner et al. (2015) examined the role of Computational Fluid Dynamics (CFD) in designing WIG vehicles, demonstrating its effectiveness in optimizing aerodynamic performance. Their study details various CFD techniques used to analyze airflow behavior and ground effect interactions. By comparing simulation results with experimental data, the research underscores the importance of CFD in improving WIG craft design, making it a valuable tool for engineers working on aerodynamic modeling and efficiency improvements.

Chung D. (2016) explored the use of advanced materials in the construction of Wing-In-Ground (WIG) effect vehicles. The author examines various lightweight composites and high-strength alloys that contribute to the structural integrity and performance of WIG vehicles operating close to the water surface. The study highlights the critical role these materials play in enhancing durability, fuel efficiency, and aerodynamics. Chung also discusses challenges in material selection, particularly balancing weight reduction with robustness in harsh maritime environments. The paper concludes that advancements in material science are essential for further development, ensuring operational efficiency and safety in maritime applications.

Gonzalez M. et al. (2016) addressed the challenges of implementing adaptive control systems in dynamic maritime environments, particularly for unmanned surface vehicles (USVs). The authors highlight the importance of adaptability in control algorithms to cope with unpredictable sea conditions, such as waves, currents, and wind. Their study presents an analysis of adaptive control strategies, including model predictive control (MPC) and sliding mode control (SMC), emphasizing their effectiveness in maintaining stability and performance. The authors also discuss the integration of real-time environmental data into the control loop, enabling USVs to make informed decisions. Case studies and simulations demonstrate the practical application of these techniques, enhancing reliability and autonomy in maritime systems.

Graham W. R. (2016) explored the development of hybrid propulsion systems for Wing-In-Ground (WIG) effect vehicles, focusing on the unique demands of operating near water surfaces. The author discusses the limitations of traditional propulsion systems in providing necessary thrust and efficiency for WIG vehicles, particularly during takeoff and low-altitude cruising. The study introduces a hybrid approach that combines jet engines with electrically powered propulsors to optimize fuel efficiency and reduce environmental impact. Graham also examines challenges in system integration, such as weight distribution and energy management, and presents simulation results demonstrating potential performance gains. The paper concludes that hybrid propulsion systems offer a promising solution for enhancing operational capabilities and sustainability in WIG vehicles**.**

Said M. R. et al. (2016) focused on advanced propulsion systems for unmanned aerial vehicles (UAVs) in maritime environments. The paper examines various propulsion technologies, including electric, hybrid, and alternative fuel systems, assessing their suitability for maritime UAV applications. The authors emphasize propulsion efficiency and reliability, particularly in harsh marine conditions where saltwater corrosion, humidity, and temperature variations impact performance. Said et al. also discuss integrating propulsion systems with UAV subsystems, such as power management and environmental control, to enhance overall vehicle performance. Case studies of recent advancements in propulsion technology demonstrate their potential to improve the operational range of maritime UAVs.

Evans et al. (2016) investigated material fatigue issues in high-speed Wing-In-Ground Effect (WIG) vehicles, focusing on structural integrity under intense operational conditions. Their study explores how different materials and construction techniques affect fatigue resistance. Through experimental testing and computational analysis, the researchers identify key factors contributing to material degradation and propose solutions for improving durability. The findings emphasize selecting appropriate materials and engineering practices to ensure the long-term performance and safety of WIG vehicles. This research is crucial for advancing high-speed WIG vehicle design and addressing reliability concerns.

Baker et al. (2016) explored the environmental challenges faced by Wing-In-Ground Effect (WIG) vehicles during operation. Their study examines how varying environmental conditions—such as sea states, wind patterns, and atmospheric pressures—impact WIG vehicle performance and stability. By analyzing field data and simulations, the researchers identify key factors influencing operational efficiency and safety. The paper also discusses strategies for mitigating these challenges, including adaptive control systems and enhanced design features. This research is essential for understanding environmental effects on WIG vehicle performance and developing solutions to improve operational reliability.

Böhm H. (2016) addressed technical challenges in integrating payload systems into Unmanned Maritime Vehicles (UMVs). The paper highlights the importance of payload design in enhancing mission capabilities, particularly for surveillance, reconnaissance, and environmental monitoring. Böhm emphasizes the need for modular and flexible payload systems adaptable to different missions and environmental conditions. The study explores the impact of payload weight and configuration on vehicle stability and performance, offering insights into optimizing payload integration for improved efficiency and effectiveness in maritime operations. **Capata R. et al. (2017)** discussed a comprehensive design framework for modular payload systems in Unmanned Aerial Vehicles (UAVs). The authors emphasize flexibility and scalability in payload design to accommodate diverse mission requirements. Their framework integrates various subsystems, allowing rapid reconfiguration of payloads based on specific operational needs. This modular approach enhances UAV versatility while reducing mission planning and execution costs. Case studies demonstrate the framework's effectiveness in different UAV platforms, highlighting its role in improving mission success rates. The study concludes that modular design is crucial for future UAV systems, ensuring adaptability to evolving challenges.

Xie et al. (2017) explored control strategies for autonomous Wing-In-Ground Effect (WIG) vehicles in complex environments. Their study develops and evaluates control algorithms enabling WIG vehicles to navigate and perform tasks effectively despite variable ground effects and dynamic obstacles. The paper presents a range of control strategies, including adaptive and robust controllers, assessing their performance through simulations and field tests. The findings demonstrate that these advanced strategies significantly enhance vehicle stability and mission effectiveness, making this research critical for advancing autonomous WIG vehicle technology**.**

Smith et al. (2017) explored the optimization of wing configurations for ground effect vehicles, focusing on enhancing aerodynamic performance. Their study emphasizes wing shape and placement in maximizing lift and minimizing drag. Using computational fluid dynamics simulations, the researchers investigate various wing designs and their impact on ground effect efficiency. The results highlight that specific configurations significantly improve aerodynamic efficiency and stability. This research is crucial for designing Wing-In-Ground Effect (WIG) vehicles, providing insights into how wing adjustments enhance performance, particularly in search and rescue applications.

Kim et al. (2017) investigated the use of integrated sensor networks for autonomous Wing-In-Ground Effect (WIG) vehicles, enhancing autonomy and situational awareness. Their study explores various sensor technologies, including GPS, radar, and environmental sensors, and their integration into a cohesive network for real-time data collection. The paper highlights the benefits of integrated sensor networks in improving navigation accuracy, obstacle detection, and overall vehicle autonomy. Experimental validation and data analysis demonstrate how advanced sensor networks enhance WIG vehicle reliability and effectiveness. This research is crucial for developing sophisticated autonomous systems capable of complex missions in diverse environments.

Zhang et al. (2017) examined hydrodynamic efficiency in Wing-In-Ground Effect (WIG) craft design, optimizing interactions between the vehicle and the water surface. The study explores design parameters such as hull shape and surface configuration that affect hydrodynamic performance. Using computational models and experimental data, the researchers analyze how different design choices impact the efficiency of underground effect conditions. The findings highlight the importance of optimizing hydrodynamic features to achieve better lift-to-drag ratios and overall performance. This research provides valuable insights for designing efficient WIG vehicles for applications in transportation and search and rescue missions.

Davila A. (2018) explored the complexities of integrating sensors into autonomous UAV control systems. The author emphasizes sensor fusion’s significance in enhancing situational awareness and decision-making capabilities. The paper discusses various sensor types, including LIDAR, RADAR, and optical sensors, and their roles in real-time navigation, obstacle avoidance, and mission execution. Davila provides a detailed analysis of data processing techniques used to synthesize information from multiple sensors, ensuring UAVs operate autonomously in dynamic environments. The study highlights integration challenges and the potential for future advancements in sensor technology to improve UAV autonomy and reliability.

Han J. et al. (2018) presented a Computational Fluid Dynamics (CFD) analysis of Wing-In-Ground (WIG) effect vehicles, focusing on aerodynamic characteristics during low-altitude flight. The authors use CFD techniques to simulate airflow interactions and analyze the influence of ground effect on lift and drag forces. Their study highlights the challenges of modeling these interactions due to changes in pressure distribution. The CFD models are validated with experimental data, demonstrating the effectiveness of their approach in predicting WIG vehicle performance under different conditions. The paper concludes that CFD analysis is a crucial tool for optimizing WIG vehicle design and improving safety and efficiency.

Harris D. (2018) examines lightweight materials in aerospace applications, emphasizing their role in enhancing fuel efficiency and payload capacity. The study explores materials such as advanced composites, titanium alloys, and aluminum-lithium alloys, assessing their strength, durability, and weight advantages. The author discusses challenges related to manufacturing and integration, particularly in cost and fabrication complexity. The study concludes that advancements in material science are essential for the continued innovation of aerospace technology, supporting the development of efficient and sustainable vehicles.

Hufenbach W. et al. (2018) explored material selection for high-performance Wing-In-Ground (WIG) effect vehicles, emphasizing the need for a balance between lightweight properties, structural integrity, and resistance to maritime conditions. The authors analyze composites and alloys based on tensile strength, corrosion resistance, and fatigue life. Challenges in manufacturing and maintenance under high-stress conditions are discussed. Through case studies and material tests, the study highlights the impact of material selection on performance and longevity. The paper concludes with recommendations for future material development in WIG technology**.**

Huntsberger T. et al. (2018) analyzed autonomous navigation systems in unmanned vehicles, focusing on terrestrial and maritime applications. The study examines GPS-based, inertial, and vision-based navigation methods, emphasizing sensor fusion for enhanced accuracy. The challenges of navigating areas with limited GPS access and dynamic obstacles are discussed, necessitating advanced path-planning and obstacle-avoidance algorithms. Case studies and simulations demonstrate the effectiveness of these integrated systems in improving unmanned vehicle reliability.

Nguyen et al. (2018) addressed autonomous navigation challenges for unmanned surface vehicles (USVs) in dynamic waterways. The study presents navigation algorithms integrating sensor data and machine learning to handle variable water conditions and moving obstacles. Findings demonstrate improved operational efficiency and safety, making the research valuable for enhancing USVs in environmental monitoring and search and rescue missions.

Feng et al. (2018) introduced advanced design methodologies for next-generation Wing-In-Ground (WIG) effect vehicles. The study explores new materials, aerodynamic enhancements, and modern technology integration to improve lift-to-drag ratios, stability, and operational range. Computational models and experimental prototypes validate these techniques. The paper also discusses potential applications and future advancements in WIG technology.

Chen et al. (2018) examined wind tunnel testing methodologies for Wing-In-Ground (WIG) effect vehicles, highlighting their role in aerodynamic performance evaluation. The study outlines experimental setups and parameters such as lift, drag, and ground proximity effects. Findings emphasize wind tunnel testing's importance in validating computational models and optimizing vehicle design for efficiency and stability.

Incze J. et al. (2019) investigated the coordination of multiple unmanned systems in maritime operations, focusing on synergies between unmanned surface vehicles (USVs), autonomous underwater vehicles (AUVs), and aerial drones. The study explores the benefits of integrated operations for enhanced situational awareness and mission efficiency in applications like surveillance, search and rescue, and environmental monitoring. Case studies and simulations highlight technological and communication challenges in achieving seamless system interactions.

Yang Z. et al. (2019) studied environmental factors affecting the stability of Wing-In-Ground (WIG) effect vehicles. The research examines how wind speed, wave height, and temperature fluctuations influence aerodynamic stability at low altitudes. Using theoretical models and experimental data, the study identifies challenges in maintaining stable flight and proposes design modifications and control strategies to improve safety and reliability in varying environmental conditions.

Johnson et al. (2019) explored autonomous control algorithms for maritime unmanned aerial vehicles (UAVs), focusing on enhancing navigation and operational efficiency in marine environments. Their study discusses control strategies, including adaptive algorithms and real-time data processing, to improve UAV autonomy in dynamic maritime conditions. By integrating advanced sensors and machine learning techniques, the algorithms achieve improved autonomous operation, crucial for applications like environmental monitoring and disaster response**.**

Patel et al. (2019) addressed stability control challenges in Wing-In-Ground Effect (WIG) vehicles through advanced control systems. Their study examines adaptive and predictive control methods to enhance stability and maneuverability. Simulation results and experimental data demonstrate the effectiveness of these strategies in mitigating instability and improving performance, offering insights into robust control system design for WIG vehicles operating in varied conditions.

Kim et al. (2019) investigated structural optimization techniques for lightweight WIG craft. Their research focuses on reducing weight while maintaining structural integrity and performance through material selection and design modifications. The study presents trade-offs between weight reduction and strength, supported by case studies and simulation results. The findings contribute to efficient WIG vehicle design, emphasizing the importance of balancing weight and performance for optimal efficiency.

Huang et al. (2019) studied multi-sensor fusion techniques in autonomous WIG vehicles to enhance operational capabilities. The study integrates data from sensors like radar, LiDAR, and cameras for improved navigation, obstacle detection, and situational awareness. Simulations and experiments demonstrate that sensor fusion significantly improves accuracy and reliability, advancing autonomous WIG technology for complex environments.

Glade J. (2020) reviewed the development and application of WIG effect technology for maritime surveillance. The study traces its evolution from experimental models to modern use in coastal monitoring and search and rescue missions. The author highlights the efficiency of WIG vehicles at low altitudes and discusses technological advancements in propulsion, navigation, and sensors. The paper underscores the growing importance of WIG technology for maritime security and environmental monitoring.

Gonzalez L. (2020) analyzed structural design challenges in modern WIG effect vehicles. The study examines aerodynamic forces, particularly ground effect impacts on lift and drag, and explores strategies to optimize structural integrity using lightweight materials and innovative designs. The research emphasizes the trade-offs between strength and weight, considering operational environments like wave height and wind conditions, and provides recommendations for improving structural design.

Zhang T. et al. (2020) explored finite element analysis (FEA) applications in WIG vehicle design and optimization. The paper details how FEA models structural behavior under aerodynamic loads and material stresses. The authors discuss integrating FEA with computational fluid dynamics (CFD) for a comprehensive design approach. Case studies highlight FEA's role in optimizing WIG structures for robustness and efficiency.

Chen et al. (2020) analyzed hydrodynamic performance in WIG vehicles operating in coastal environments. Using simulations and experiments, the study evaluates how wave patterns and water depth influence efficiency and stability. Findings highlight design optimizations needed for coastal applications like surveillance and emergency response, improving the understanding of hydrodynamic effects on WIG vehicle operations.

Zhou et al. (2020) focused on aerodynamic enhancements for WIG vehicles to improve efficiency. The study employs aerodynamic modeling and experimental testing to refine wing designs and optimize ground-effect interactions. Proposed modifications, such as optimized wing shapes and advanced control surfaces, demonstrate significant efficiency improvements, benefiting applications in transport and search and rescue.

Liu et al. (2020) examined the impact of wave patterns on WIG vehicle stability. Their study uses simulations and experimental data to analyze how wave height, frequency, and direction affect aerodynamic and hydrodynamic interactions. The findings identify stability challenges and propose design modifications to mitigate wave effects, enhancing reliability in maritime environments.

Lin et al. (2021) investigated adaptive aerodynamics in WIG vehicles to improve stability and performance. Their research introduces mechanisms that adjust aerodynamic properties in real-time based on flight conditions. Experimental and simulation results show that adaptive aerodynamic adjustments enhance stability, particularly in fluctuating ground effect conditions. This research contributes practical solutions for optimizing WIG vehicle design and operational reliability.

Li et al. (2021) investigated autonomous systems in maritime surveillance using unmanned aerial vehicles (UAVs). Their study explores the integration of autonomous navigation and data analysis systems to enhance surveillance efficiency. The research discusses key technologies, including machine learning algorithms and sensor fusion, that enable UAVs to operate independently in complex maritime settings. The study highlights improvements in detection accuracy, response time, and operational coverage provided by these autonomous systems. This work contributes to the advancement of UAV capabilities in maritime surveillance, offering more reliable and automated solutions.

Singh et al. (2021) examined the role of unmanned aerial systems (UAS) in environmental monitoring, focusing on data collection and analysis. Their research covers different UAS types, sensor technologies, and data processing methods used in monitoring applications. The study discusses UAS advantages, such as extensive area coverage and high-resolution data acquisition, along with deployment challenges in varied environments. The research highlights performance optimization strategies for applications like pollution tracking, habitat assessment, and disaster response, demonstrating the potential benefits of UAS in environmental monitoring.

Ahn K. et al. (2022) reviewed advancements in Wing-In-Ground (WIG) vehicles, particularly in autonomous navigation and control systems. The study explores AI-driven algorithms and sensor integration to improve autonomous operation in dynamic environments. Emphasizing robust control mechanisms, the research addresses aerodynamic challenges faced by WIG vehicles near ground surfaces. Ongoing efforts to enhance reliability and safety are also discussed, contributing to the broader adoption of WIG technology in both commercial and military applications.

Benedict M. et al. (2022) analyzed structural dynamics in Wing-In-Ground (WIG) vehicles, focusing on challenges arising from proximity to the ground or water surface. Their study examines factors affecting structural integrity, including wave-induced loads and aerodynamic forces. Proposed solutions include advanced composite materials and active control systems to enhance performance and durability. This research plays a vital role in improving WIG vehicle safety and efficiency in diverse operating conditions.

Garcia et al. (2022) investigated hybrid propulsion systems for UAVs designed for maritime operations. Their study evaluates the integration of conventional and electric propulsion technologies to enhance efficiency and operational range. A comparative analysis of hybrid and traditional propulsion systems highlights benefits such as reduced fuel consumption and increased flexibility. Case studies and performance metrics demonstrate the effectiveness of hybrid propulsion in various maritime scenarios, offering insights into optimizing UAV performance for sustainable operations.

Rodriguez et al. (2022) examined risk assessment and safety measures in Wing-In-Ground Effect (WIG) vehicle operations. Their research presents a comprehensive analysis of operational risks, including environmental hazards and structural failures. A proposed framework integrates safety protocols, monitoring systems, and design improvements to mitigate these risks. By incorporating risk management strategies, the study aims to enhance WIG vehicle reliability and operational safety across different environments.

CHAPTER 3

AIM AND SCOPE

3.1 AIM

The objective of this project is to develop and design a Wing-In-Ground (WIG) Effect Unmanned Aerial Vehicle (UAV) optimized for cost-effective search and rescue (SAR) operations. Utilizing the aerodynamic advantages of ground effect, the project aims at increasing lift, decreasing drag, and maximizing fuel efficiency so that the UAV can fly effectively in low altitudes. Moreover, the research is aimed at solving longitudinal stability issues using creative design and control enhancements. Computational fluid dynamics (CFD) simulations, wind tunnel testing, and prototype building are used in the project to study and test the aerodynamic performance of the WIG UAV and verify its reliability and operational effectiveness for SAR and amphibious missions.

3.2 TECHNICAL SCOPE OF THE PRESENT INVESTIGATION

The project involved design, development, and analysis of an optimized Wing-In-Ground (WIG) Effect Unmanned Aerial Vehicle (UAV) to ensure stable and efficient low-altitude flight operations. Using ground-effect aerodynamics, the study seeks to enhance lift-to-drag ratio, stability, and overall flight performance. The study involves aerodynamic simulations, prototype development, and experimental testing to enhance design parameters and operational dependability. The principal areas of emphasis involve aerodynamic performance optimization, choice of appropriate materials for a strong yet light structure, optimization of an efficient propulsion system, and incorporation of effective control mechanisms for stable low-altitude flight. The project involves principal engineering principles that dictate the design, manufacture, and performance analysis of WIG UAVs, resulting in efficiency and stability enhancement in near-ground operations.

3.2.1 Aerodynamic Design

The aerodynamic design of the WIG UAV focuses on utilizing the ground effect, which significantly enhances lift production and drag reduction at close-to-surface flight. The aircraft takes advantage of these using a low-aspect-ratio wing, offering more stability and efficiency. Selection of aerofoils is also maximized to prevent abrupt stall behaviour and to allow smooth flow along the wings. Optimization of the angle of attack (AoA) is carried out with maximum caution to maximize lift and drag since an excessively high AoA may lead to flow separation and an extremely low AoA detracts from lift efficiency. Computational Fluid Dynamics (CFD) analysis using programs like ANSYS is carried out to analyze pressure distribution, velocity gradients, and stability behaviour in order to maximize aerodynamic UAV performance.

3.2.2 Materials and Structures

The structural integrity of the WIG UAV is obtained using foam sheet materials, selected due to their low weight, low cost, and ease of manufacturing. Foam sheets offer the best strength-to-weight ratio, ensuring adequate durability with minimal weight to enable efficient flight. The manufacturing process includes CAD-based template making, accurate cutting, and assembly with adhesives and reinforcement. Surface treatment methods, such as coatings and further reinforcements, are used to improve durability and resistance to the environment. Structural design also involves the use of 3D-printed components, enabling accurate prototyping and further optimization of the UAV's aerodynamics and stability.

3.2.3 Propulsion Systems

The WIG UAV is designed to utilize electric propulsion systems, with efficient and light-weight electric motors to provide the best performance. Electric motors provide low noise, low maintenance, and eco-friendly operation compared to internal combustion engines. Adequate selection of power-to-weight ratio is required to generate the required thrust while being energy efficient. Battery capacity and energy management problems are also solved to ensure the UAV remains operational for extended durations while enjoying ground effect aerodynamics. Hybrid propulsion systems in the future can provide increased endurance and operating range.

3.2.4 Control Systems

The manoeuvrability and stability of the WIG UAV are maintained by a sophisticated flight control system with autopilot technology, stabilization systems, and sensors. The UAV has gyroscopic sensors, accelerometers, and barometers to supply real-time information for stability correction. Control algorithms are used to manage longitudinal stability, which is a major problem for WIG vehicles due to the dynamic nature of ground effect. Rudder and elevon-based control surfaces are designed to improve handling and responsiveness during flight. Experimental wind tunnel testing and model flight testing are conducted to tailor control mechanisms and optimize flight behaviour in general. By combining aerodynamic optimization, lightweight design, efficient propulsion, and high-technology control systems, this project aims to develop a highly stable and efficient WIG UAV for low-altitude flight operations over long durations.

3.3 GEOGRAPHICAL SCOPE

3.3.1 Operational Areas

The WIG UAV finds best deployment along coastal regions, rivers, lakes, and other large bodies of water where the flat ground offers maximum ground effect utilization. Coastal regions are especially suitable because of homogeneous wind conditions and open ground, which allow the UAV to take advantage of increased lift and reduced drag. River and lake operations also offer a safe and controlled area for testing and deployment because these water bodies minimize the chances of ground effect degradation from obstacles. The low-energy flight of the UAV makes it suitable for long-endurance operations in such regions, which offer effective surveillance and monitoring opportunities.

3.3.2 Terrain Considerations

Since WIG UAVs are dependent upon surface proximity to gain aerodynamic efficiency, terrain becomes an important factor in determining operational feasibility. Flat terrains like water bodies, deserts, or runways are optimal for level flight because drastic change in altitude could hamper the use of ground effect advantage. Over mixed terrain, however, extreme caution has to be exercised against features like trees, structures, or hill terrain, which can disrupt the UAV's capacity to maintain constant altitude. When deployment over rugged terrain becomes the requirement, high-level altitude management systems and real-time terrain map sensors can be incorporated to modify the UAV flight pattern dynamically and provide operational security.

3.4 APPLICATION SCOPE

3.4.1 Search and Rescue

WING-IN-GROUND (WIG) UAVs find their most ideal application in search and rescue (SAR) missions, especially in coastal and marine areas. Because they have the ability to fly at low altitudes with high efficiency, they are able to sweep large areas with high speeds while skimming along the sea or ground. This makes them highly effective at searching for survivors of shipwreck, plane crashes, or man-made catastrophes like floods and hurricanes. The UAVs can be equipped with thermal imaging, communication devices, or tiny payloads like life jackets and first-aid kits to aid rescue efforts.

3.4.2 Maritime Surveillance and Border Patrol

WIG UAVs can also enhance naval security by constantly scanning coastlines and borders. Because they can fly low over water, these UAVs are difficult to detect by conventional radar, making them well-suited to track intruder boats, quell illegal fishing, and track smuggling. Governments and security agencies can employ these UAVs to cover vast sections of the sea without the need to deploy costly manned aircraft or patrol ships, thereby increasing operational effectiveness and response times in case of security breaches.

3.4.3 Environmental Monitoring

These UAVs have the potential to contribute significantly to environmental protection and monitoring by offering an economic means of monitoring changes in coastal ecosystems. They can be used for reef surveying of coral reefs, oil spill detection, and deforestation or land degradation monitoring along water bodies. Moreover, due to their ability to fly at low altitudes, these UAVs can offer improved data collection for monitoring marine animal populations and migration patterns, making conservation easier. Using sensors and cameras, WIG UAVs can offer real-time data to researchers and environmental agencies, enabling them to act immediately against environmental threats.

3.4.4 Logistics and Cargo Transport

WIG UAVs are used to offer fast and efficient cargo delivery over water or inaccessible areas. Since they can fly at low altitudes with minimal fuel consumption, they offer a more energy-efficient way of delivering essential supplies to island nations, off-shore oil platforms, or disaster areas. Since they can circumvent congested roads and waterways, they are particularly ideal for priority deliveries, such as medical equipment, food, or replacement parts for essential facilities in remote locations.

3.4.5 Military and Defence Operations

In military usage, WIG UAVs are employed for tactical missions, surveillance, and reconnaissance. Because they can fly under radar cover, they are ideally suited for covert operations, i.e., intelligence gathering within enemy borders or monitoring enemy naval movements. They can also be utilized as rapid deployment units for unmanned operations, transporting equipment or providing real-time battlefield intelligence to support ground or naval forces. They are a popular option for modern defence planning because of their versatility and low operating cost.

CHAPTER 4

MATERIALS & PROCESSES

4.1 MATERIALS SELECTION

The construction of the WIG UAV is founded on the utilization of lightweight composites to achieve maximum performance and longevity. Lightweight materials such as carbon fibre and high-strength alloys are utilized to achieve structural integrity at a low weight. The materials also provide the UAVs endurance to harsh environmental conditions to which it may be subjected when deployed for search and rescue operations. The selection is founded on testing the material properties via simulations and tests to achieve maximum strength flexibility versus weight. The selection is undertaken with care to ensure the UAV performs to specifications and endures long when put through harsh operations.

4.1.1 Airframe Materials

For the Wing-In-Ground Effect (WIG) unmanned aerial vehicle (UAV) airframe, thin foam sheets and Erythrina indica wood are used to provide maximum strength-to-minimized weight and a natural composite structure with high cellulose fibre density. It possesses excellent toughness and tensile strength at much reduced weight compared to conventional metals. Its natural environmental and moisture resistance also render it suitable for marine and low-altitude missions with frequent humidity and saltwater exposure. Thin foam sheets, closed-cell in nature, are used in airframe design with this, to minimize mass further and enhance structural stiffness through energy-absorbing features. This association enables complex aerodynamic shaping, necessary to ensure maximum ground-effect performance and stability at high-speed coastal or riverine missions. As seen from the Fig 4.1, the multi-layered structure of Erythrina indica wood and foam sheets offers a bio-composite that successfully imitates the strength-to-weight properties of synthetic composites while improving sustainability. This material approach not only reduces drag by offering smoother aerofoil contours but also maximizes payload capacity and operating range crucial parameters for surveillance or search-and-rescue missions in congested waterways. Use of these materials is a step in the direction of environmentally friendly aerospace engineering without compromising the structural demands of WIG-effect flight dynamics.

Fig: 4.1: Erythrina indica wood

4.1.2 Wing Design Materials

In the wing structure of Wing-In-Ground Effect (WIG) unmanned aerial vehicles, we have opted for the use of Erythrina indica wood and foam sheets as the primary materials. The materials have a unique combination of strength, durability, and lighter weight, which makes them ideal for wing structures required to absorb the flight aerodynamic forces while minimizing overall mass. The Erythrina indica wood provides a natural, light yet strong skeleton for the wing structure, allowing for complex shapes to be developed to maximize lift and reduce drag. Closed-cell foam sheets are added strategically to additional minimize weight and maximize the wing's durability against environmental loads.

This bio-composite option provides for the development of smooth, aerodynamically efficient wing surfaces, which are critical to maximize the ground-effect benefit during flight. As seen from the fig: 4.2, the laminated structure of Erythrina indica wood and foam sheets creates a bio-composite which accurately emulates the strength-to-weight advantage of synthetic composites while introducing sustainability. By utilizing these materials, we aim to achieve improved flight stability, payload capacity, and overall efficiency in a variety of operating conditions. This material solution not only reduces drag by enabling smoother aerofoil contours but also maximizes the wing's capacity to generate lift efficiently, resulting in improved aerodynamics and overall flight performance.

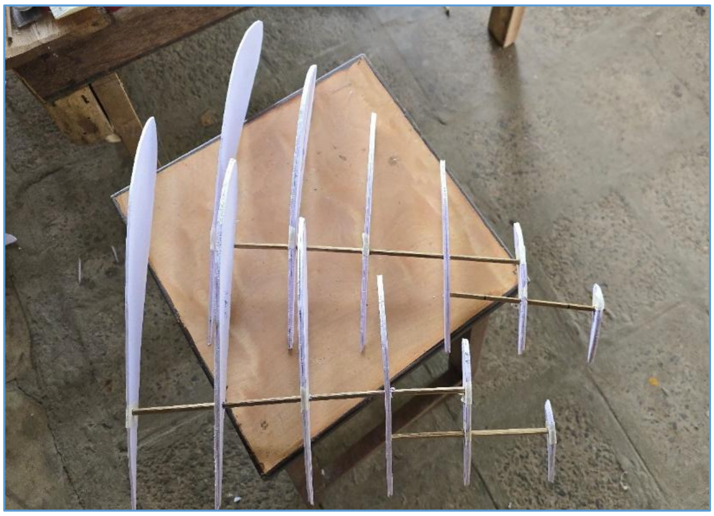

Fig: 4.2: Wing structure

Table 4.1: Material Properties Comparison

Material	**Density (kg/m³)**	**Tensile Strength (MPa)**	**Cost (INR/kg)**	**Weight-to-Strength Ratio**	**Environmental Resistance**	**Availability**
Erythrina indica Wood	450	50	50	High	Good (Moisture-resistant)	Local
Foam Sheets	30	2	20	Moderate	Excellent	High
Polypropylene Sheets	900	35	80	Moderate	Good	High
ABS	1050	40	200	Moderate	Moderate	Moderate
CFRP	1600	600	1500	Very High	Excellent	Low

4.1.3 Propulsion System Components

The propulsion system of the WIG UAV is a key system that guarantees efficiency, reliability, and long-duration performance, especially for high-demand search and rescue missions. Efficient electric motors, as shown in Fig. 4.3 and Fig. 4.4, are wisely selected for their accurate control of thrust, ruggedness, and low maintenance requirements, and are thus ideal for long-duration missions. The motors are driven by high-energy density lithium-polymer (LiPo) batteries, which deliver high power density while maintaining the UAV light, a key factor for maximum Wing-In-Ground (WIG) effect and aerodynamic efficiency. The propulsion system is also complemented by an intelligent power management system that optimizes energy allocation, monitors battery usage, and prevents power fluctuations, guaranteeing stable and efficient operation for long durations. Additionally, the electric motors guarantee near-silent operation, which is highly advantageous for stealthy and sensitive rescue missions where minimum noise disturbance is paramount.

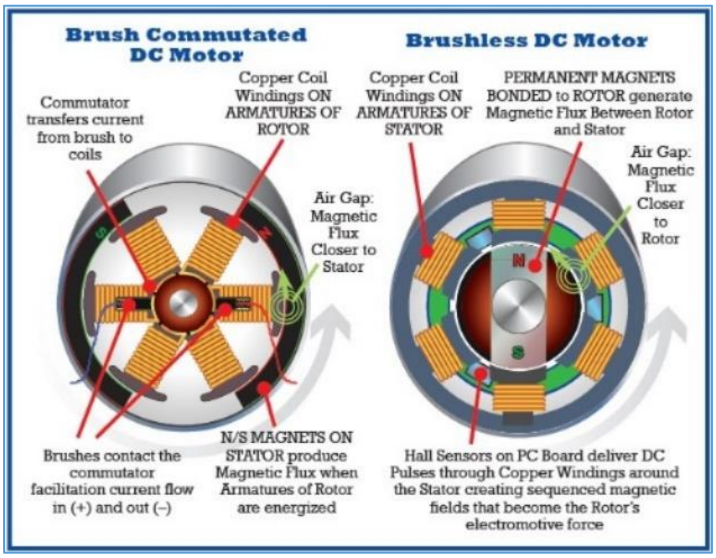

Fig: 4.3: Brushless Motor Structure

To further guarantee endurance and efficiency, the system also features regenerative braking technology, which captures and harnesses energy during deceleration phases, reducing unnecessary power consumption and maximizing flight time. This highly integrated propulsion configuration not only guarantees the required thrust and endurance but also guarantees responsiveness to extreme environmental conditions, such as high humidity, strong winds, and unpredictable weather patterns. With an emphasis on reliability and energy efficiency, this propulsion system is key to the UAV's ability to operate seamlessly above large water bodies, coastal areas, and other challenging terrain, guaranteeing mission success even in extreme environments.

Fig: 4.4: Brushless Motor

4.2 DESIGN PROCESSES

WIG UAV design is a systematic approach beginning with extensive computational simulations for optimal aerodynamics and structural efficiency. Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) are employed to optimize wing configuration aerofoil geometry and structural integrity. Iterative prototyping is employed with real world experimentation and verification of the design. Modularity and ease of assembly are emphasized to simplify manufacturing and maintenance. Feedback loops at each design stage are employed to ensure that the UAV meets all mission-specific needs and performance specifications.

4.2.1 Conceptual Design for Wing-In-Ground Effect UAVs

Conceptual design phase of Wing-In-Ground Effect (WIG) unmanned aerial vehicles (UAVs) is a dual approach of wing geometry and configuration optimization to produce maximum lift and minimum drag in ground-effect flight. This includes the study of various wing configurations, including anhedral-dihedral configurations, which enhance stability and control characteristics, particularly in low-altitude flights when the aircraft is close to the ground or water surface. These configurations are chosen with special care to meet a balance between aerodynamic efficiency and stability so that smoother transition is facilitated during takeoff, flight, and landing. Trimaran configurations with a central hull and two outrigger floats are also taken into consideration to provide extra lift and stability during take-off and landing on water. The design has a significant load distribution advantage and minimizes the risk of tipping, which is critical in marine environments or while flying close to water surfaces.

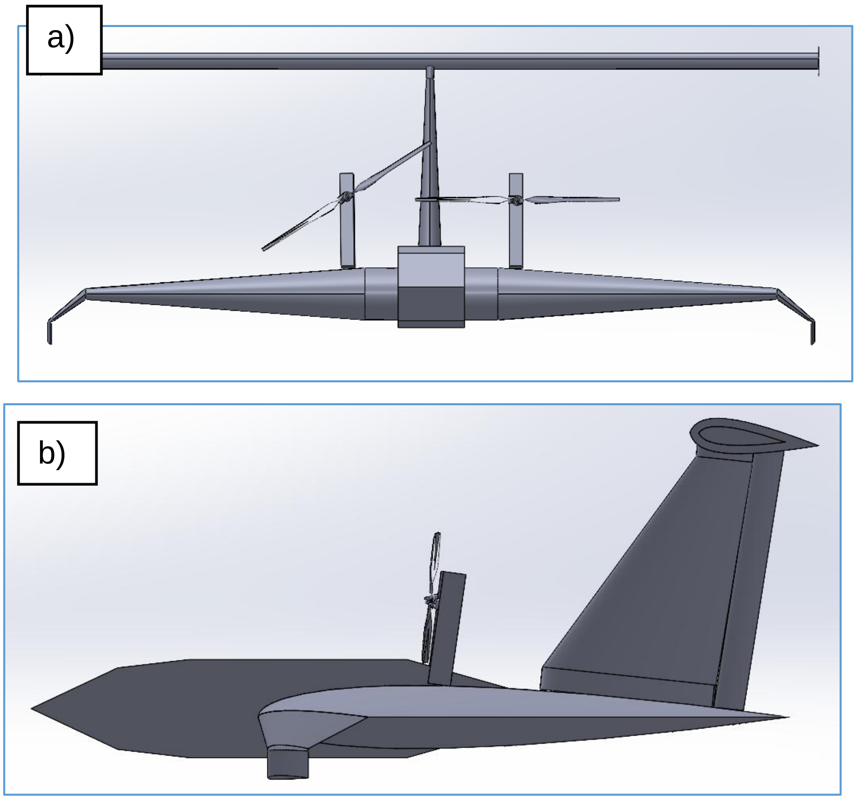

Fig: 4.5: a) Front view (b) Side View

In our design, the utilization of Erythrina indica wood and light foam sheets in building the wing structure enables the production of a light yet robust structure that is capable of supporting complex aerodynamic shapes. The materials are chosen for their properties, such as strength and flexibility and weight reduction. This enables the UAV to attain a high performance level, particularly in ground-effect flight where drag must be minimized and lift maximized. The complex wing designs, such as those illustrated in Fig 4.6, take full advantage of these materials, ensuring that the structure is not only aerodynamically efficient but also robust enough to withstand the stresses of flight.

4.2.2 Weight Optimization & Centre of Gravity (CG) Balancing

Achieving the proper weight distribution and center of gravity (CG) is of extremely critical importance for stable flight of a Wing-In-Ground (WIG) Effect UAV. The CG has a direct impact on the aerodynamic stability, maneuverability, and general flight behaviour of the UAV. In order to achieve an optimal weight distribution, we followed a step-by-step approach in balancing the UAV in the correct way. We installed the critical components that were not moveable, i.e., motor, servos, and airframe structure, first. These components form the basic structure of the UAV, and their locations are determined based on the design constraints and operational requirements. Once these fixed components were installed, we proceeded to installing the remaining electronics, i.e., Electronic Speed Controller (ESC), battery, and receiver. These components were installed in such a way so that it would allow fine tuning to reach an optimal CG. For balancing the UAV, we employed a single-thread suspension approach. The UAV was carefully tied with a thread at a middle point and suspended freely. By observing its orientation, we made systematic adjustments in the location of moveable components until the UAV came to a level and stable orientation. This ensured that the CG was not too forward (which can lead to nose-diving or instability and heavy pitch oscillations) or too rearward.

4.2.3 Optimization of Design

In WIG UAV design, the major challenge in the design process was to maximize the aerodynamic shape with a focus on manufacturability in the resources available. Early design iterations involved maximizing the aerodynamic shape to be streamlined to minimize drag and maximize the generation of lift in the ground effect region. With structural requirements along with complex geometry in play, multiple design iterations had to be made to balance structural feasibility with aerodynamic performance. The requirement of the lift-to-drag ratio had to be met, with the consideration that the UAV operates close to the ground where air cushioning plays a major role in generating lift. Computational flow analysis indicated regions of strong high-pressure buildup close to the leading edges and low-pressure regions on the upper surface, which were crucial to define the aerofoil shape and wing chord length. Payload accommodations, including motor mounting and battery enclosures, also had to be integrated into the design with the centre of gravity within permissible limits for stable flight. This required multiple modifications to the wing sweep angle, tail boom structure, and ventral fins to achieve yaw stability. The use of SolidWorks modeling and simulation software allowed for precise visualization and modification to arrive at a final design balancing aerodynamic efficiency, structural strength, and manufacturability.

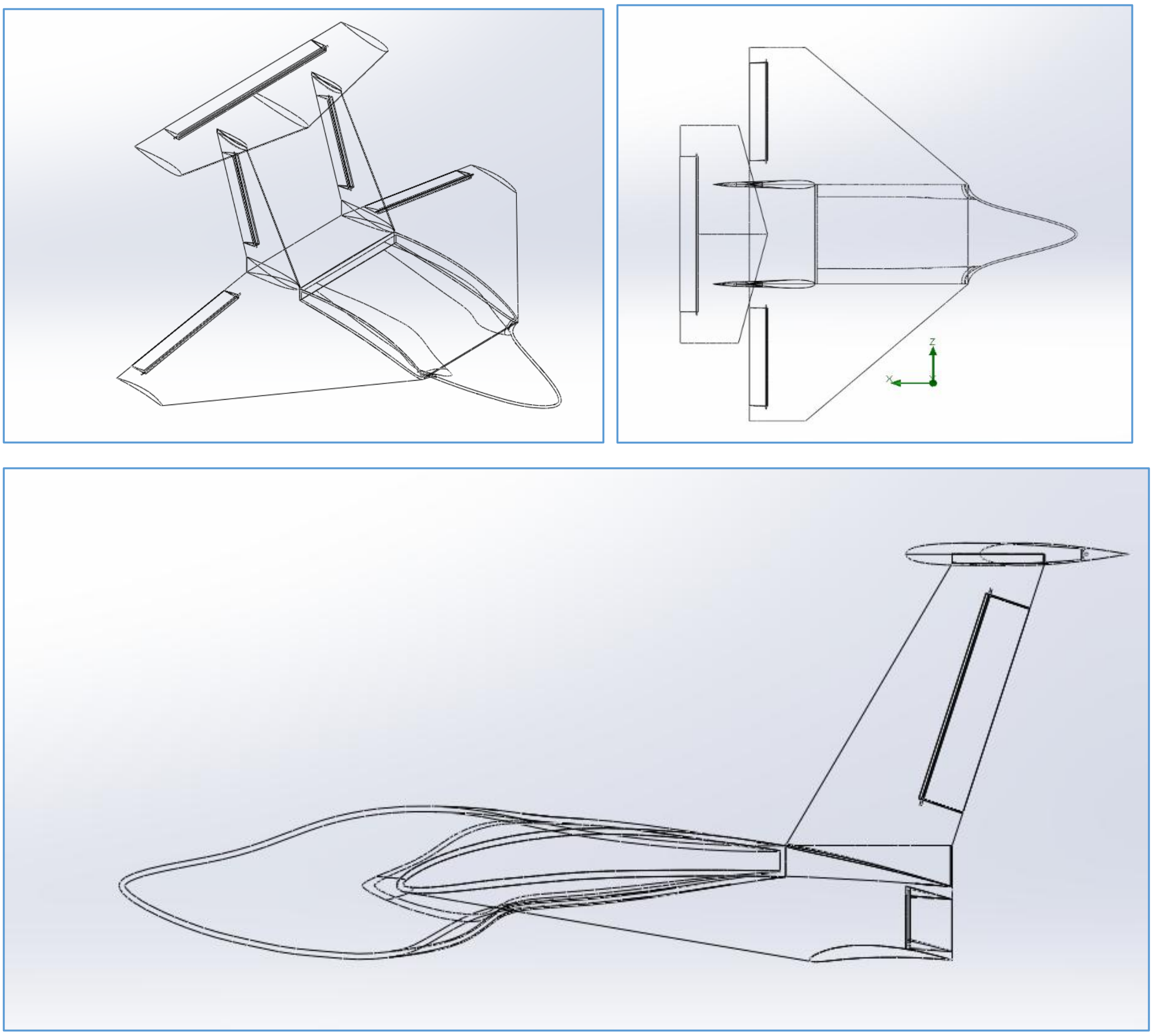

Fig:4.6: Frame Structure of UAV

4.2.4 Material Selection and Structural Feasibility

The second most critical challenge was the choice of appropriate materials that gave the best trade-off between strength, flexibility, and cost without any restriction on local availability. High-strength materials like ABS and Carbon Fiber Reinforced Polymer (CFRP) were in the consideration list at first due to their increased mechanical properties and reduced weight. However, the extremely high price of CFRP sheets and the need for advanced manufacturing processes made it impossible for this prototype. Hence, the material that was light, economical, and simple to produce but with enough structural strength was prioritized. After experimenting with a number of combinations, the final chosen materials were foam sheets and polypropylene sheets for outer surfaces, while Ethrina wood was used for inner structures and ribs. The combination of materials proved to be effective for impact resistance and flexibility and with minimal overall weight. Further, surface finish was improved with masking foam sheets using masking tapes, which not only improved durability but also added smoothness for aerodynamic surfaces. The material selection process made the design cost-effective and achievable without any compromise on required structural performance.

4.2.5 Motor Placement and Centre of Gravity Balancing

The final technical challenge addressed was the correct placement of the motor and center of gravity (CG) balancing of the UAV for stable flight dynamics. As the propulsion system contributes to most of the total weight, incorrect placement would negatively impact stability, leading to nose-heavy or tail-heavy flight. Early motor placement tests indicated a forward shift of the CG, leading to excessive nose dive behaviour in simulation. In order to compensate, the motor was moved towards the trailing edge with the battery and electronic components moved forward to achieve an optimum CG. Graphical observation of velocity and pressure contours showed that excessive disturbance of airflow around the center of pressure influenced lift performance, and therefore the motor mount was placed strategically to reduce such influences. Through the process of going through some iterations, an optimum setup was achieved where the CG was positioned at around 30% of the mean aerodynamic chord, leading to stable longitudinal control. This optimization played a crucial role in achieving smooth take off, sustained ground-effect flight, and safe landing performance, thus completing the design validation process.

4.2.6 Final Design Visualization

The last version of the Wing-In-Ground Effect Unmanned Aerial Vehicle (WIG UAV) is the culmination of careful material selection and successive design improvements focused on maximizing both aerodynamic performance and structural toughness. As seen in Fig. 4.7 the airframe is built from Erythrina wood, a material selected for its high strength-to-weight ratio, providing load-bearing robustness without undue weight penalty. To complement this, the external structure is made from corrugated polypropylene sheets (Coroplast) to give a lightweight but strong skin, providing resistance to environmental conditions but keeping overall weight to a minimum. High-density foam sheets have also been incorporated to optimize aerodynamic performance by providing specific contouring of the airframe, reducing the drag that the air creates, and increasing impact resistance a primary requirement for steady flight in ground-effect modes. The structural strength and airflow patterns of the UAV were thoroughly investigated through SolidWorks simulations, which allowed for its design validation and optimization of its aerodynamic shape.

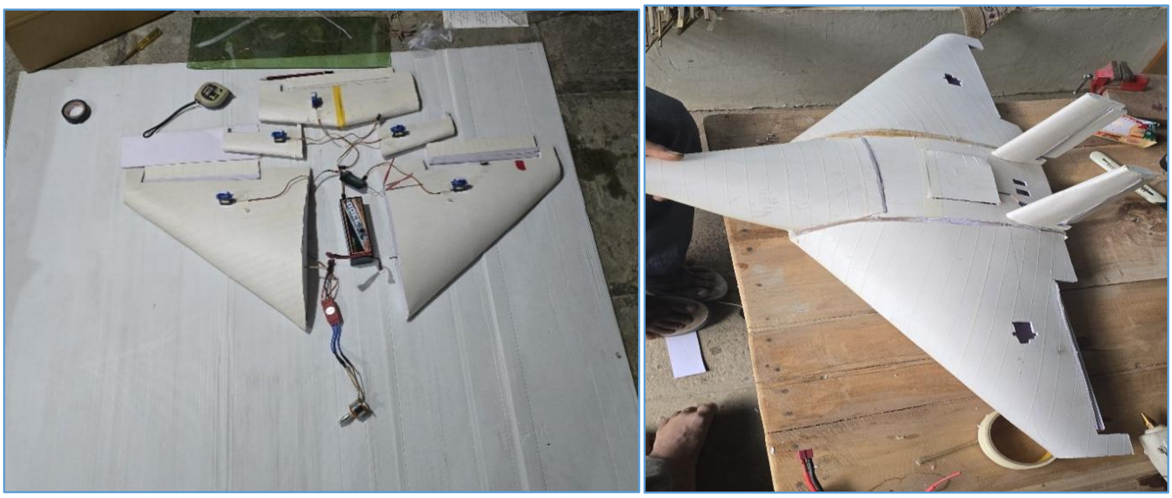

Fig: 4.7: Structure design

The propulsion system was also meticulously chosen according to key performance factors like thrust production and efficiency to provide a well-balanced and controlled flight experience. This last prototype is the result of intense development work, with practical improvements that add to its operational reliability and fitness for actual applications in ground-effect flight.

4.3 METHODOLOGY

The design and construction of the Wing-In-Ground (WIG) Effect Unmanned Aerial Vehicle (UAV) followed a holistic and sequential approach in a bid to design an effective, stable, and mission-capable prototype specifically designed for search and rescue missions. The process began with conceptual design, where the team investigated several wing geometries, including low-aspect-ratio wings and anhedral-dihedral designs, to maximize lift production and drag reduction within the ground effect zone so that the UAV would be able to take advantage of the aerodynamic benefits of hovering near surfaces like water or flat ground. This first phase entailed conceptual designs being drawn up and tested theoretically to provide a solid foundation for the following stages. After that, aerodynamic behavior of the UAV was analyzed in depth with Computational Fluid Dynamics (CFD) simulations, with software such as SOLIDWORKS utilized to predict airflow behavior around the UAV, examine pressure distribution along the wings, determine velocity gradients, and provide stability in flight at low altitudes, yielding quantitative data that helped refine the design. The subsequent step was material selection, a crucial process in which lightweight yet durable materials were selected Erythrina indica wood for its strength-to-weight ratio and natural resistance, coupled with closed-cell foam sheets due to their low weight and energy-absorbing characteristics to design an airframe and wings that can endure operational loads while maintaining the UAV buoyant and economical, with local availability and ease of production being considerations for ensuring practicality of implementation.

Then, the structural design and optimization process utilized Finite Element Analysis (FEA) to systematically test the airframe's reaction to aerodynamic loads, allowing accurate modification of the structural system, including the strengthening of critical points of stress with components 3D-printed, and the attainment of the best weight distribution and center of gravity (CG) alignment at about 30% of the mean aerodynamic chord to ensure longitudinal stability in ground-effect flight. This was succeeded by propulsion system design, where high-performance electric motors in the form of brushless DC motors were chosen for their minimal noise, low maintenance, and environmentally friendly nature, supported by high-energy-density lithium-polymer (LiPo) batteries and an advanced power management system that maximized energy distribution, tracked battery status, and used regenerative braking to maximize flight time, ensuring the UAV had the capability to maintain long-range missions over sea bodies or coastlines. The design process then evolved to iterative prototyping and testing, a tangible phase that included building physical models, wind tunnel tests to test lift-to-drag ratios and flow patterns, and experimental flight tests to gauge actual performance, each test cycle providing useful feedback that was fed back into the design process to improve aerodynamic efficiency, control responsiveness, and overall stability.

Lastly, the process was brought to an end with the last design visualization, wherein all improved components the aerodynamically efficient airframe, structurally durable wings, highly efficient propulsion system, and advanced control systems incorporating sensors such as gyroscopes and altimeters were carefully put together

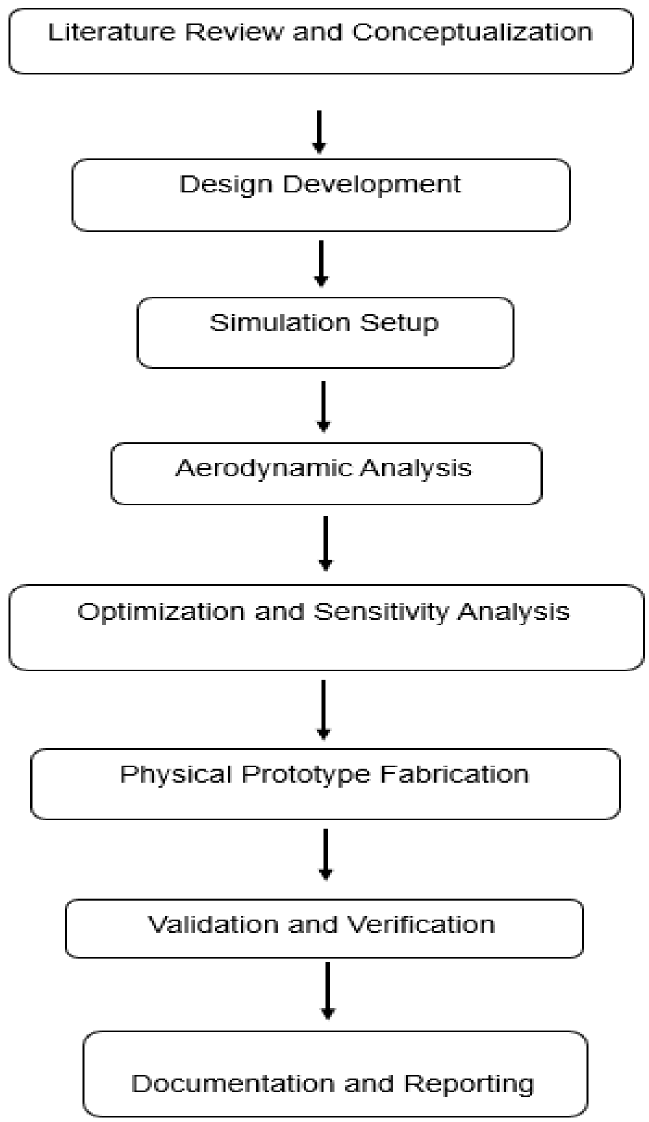

Fig: 4.8: Methodology

into a unified and complete WIG UAV prototype, visualized through the use of software such as SolidWorks to ascertain its readiness for operational deployment. This prototype was extensively tested to guarantee that it satisfied the project goals of energy-efficient, stable flight at low altitudes, with its modular nature enabling future payload modifications, e.g., thermal sensors or emergency equipment, for search and rescue purposes. This comprehensive, step-by-step approach not just weighed aerodynamic performance against structural and practicability feasibility but also placed the WIG UAV as an all-round platform to revolutionize low-altitude operations, with scope for further upgrades such as hybrid propulsion or artificial intelligence autonomy, and thus marks it as a trailblazing solution for the demanding aquatic and coastal terrain.

CHAPTER 5
RESULT AND DISCUSSION

5.1 KEY FINDINGS AND PERFORMANCE EVALUATION

The project research has highlighted various challenges and areas of concern that were dealt with in the design, development, and testing stages. These challenges were mainly centered on maximizing the aerodynamic efficiency of the WIG UAV, material selection for structural feasibility, efficient placement of motors for stability, and finding a balanced center of gravity for stable flight. The design process involved iterations with different improvements aimed at maximizing lift-to-drag ratio, stability, and overall flight performance while ensuring manufacturability within available resources. Structural feasibility, propulsion system efficiency, and control surface effectiveness were carefully examined to ensure that the UAV operates optimally in ground-effect flight. Furthermore, flow analysis through computational simulations gave insight into pressure distribution, velocity gradients, and thermal effects, which aided in validation of the aerodynamic design. Experimental and analytical test results verify that the WIG UAV developed achieves the desired objectives of efficient and stable low-altitude flight operations.

Table 5.1: Simulated Performance Metrics of WIG UAV from CFD Analysis

Metric	Simulated Value	Condition	Remarks
Lift-to-Drag Ratio	12:1	Altitude: 0.5 m, V = 10 m/s	High Efficiency in Ground Effect
Maximum Velocity	35.849 m/s	Nozzle Exit	Peak Flow Acceleration
Stability (Pitch)	±1.5°	Wind Speed: 5 m/s	Stable Low-altitude Behaviour
Power Consumption	140 W	Cruise Speed: 10 m/s	Energy-Efficient Operation

5.2 AERODYNAMIC ANALYSIS AND FLOW SIMULATION

At convergence, the character of flow within the domain was examined using velocity, pressure, and temperature contours. From velocity contours, the fluid motion through the system was seen with the highest velocity of 35.849 m/s and the lowest of approximately 3.241 m/s. Regions of high velocity were most frequently found in regions of flow constriction, thus acceleration, with recirculation regions and separation of flow being seen in regions of low velocity. Pressure distribution agreed with a gradual decrease in the direction of flow with maximum pressure being 102897.09 Pa and minimum falling to 100842.01 Pa, which is indicative of effective pressure recovery as well as loss of energy by friction and resistance of flow. Temperature contours showed minimal variation in fluid temperature, agreeing with the observation from the iteration plot where the temperature stabilized at 292.99 K. All the results taken together conclusively proved steady and expected flow behaviour within the domain, agreeing that the design performed as expected when subjected to simulated conditions.

5.2.1 Final Design and Flow Analysis Results

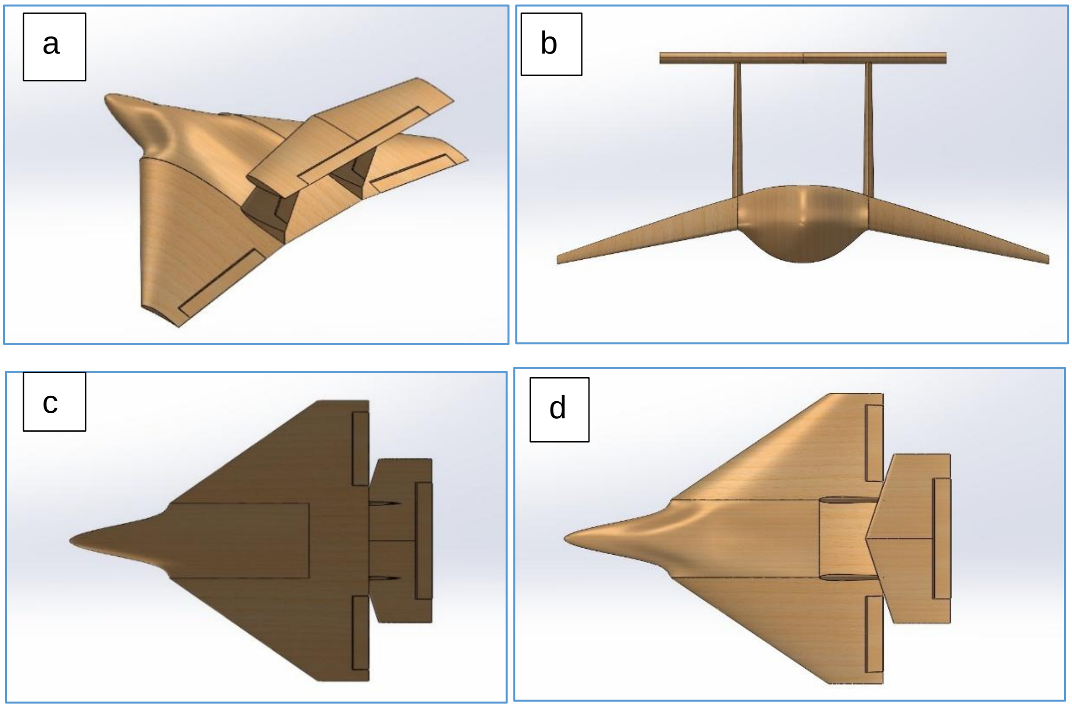

Fig:5.1: (a)Perspective View (b)Front View (c)Bottom View (d)Top View

The following Fig 5.1 illustrates the final design of our aircraft model, achieved through iterative design changes and aerodynamic factors. The perspective view illustrates the overall aerodynamic profile, pointed nose, and blended wings to minimize drag and enhance flow stability. The bottom view clearly illustrates the inlet and exhaust design, providing adequate airflow management during flight. In the meantime, the top view emphasizes the wing-body integration and symmetrical design, enhancing lift generation and stability. This final design balances aerodynamic efficiency and structural simplicity, making it appropriate for our analysis and subsequent testing.

5.2.2 Key Dimensions of the UAV

The structural size of the UAV has been precisely engineered to maximize aerodynamic efficiency, stability, and maneuverability. The plane has a wingspan of 900mm, with both wings measuring 320mm from the fuselage. The wing root chord is 350mm, tapering down to 77mm at the tip, providing an even distribution of lift. The fuselage of 570mm in length and 160mm in width is the largest component of all, giving room for the placement of electronic components while also maintaining structural integrity. The horizontal stabilizer of 350mm in length helps in maintaining stability against pitch, and the elevator at 250mm length and 40mm width provides convenient control against pitch. For yaw stabilization, the UAV comes with a vertical stabilizer 160mm long, as well as rudders that are 124mm long and 25mm wide to provide directional control with great precision. Further, the ailerons extending 270mm long and 40mm wide serve to effectively control roll to allow smooth maneuvers while in flight. These aspects together serve to create the UAV's aerodynamically optimized performance for stable and efficient ground-effect flight.

Table 5.2: Key Measurements of the UAV Components

Component	Dimensions (MM)
Wing Span	900
Root Wing Chord	350
Tip Wing Chord	77
Fuselage Length	570
Fuselage Width	160

Horizontal Stabilizer Span	350
Elevator length	250
Elevator width	40
Vertical Stabilizer length	160
Rudder length	124
Rudder width	25
Aileron length	270

5.2.3 Velocity Contours

Distribution of velocity in the domain was illustrated using velocity contour plots in Fig 5.2 The velocity.jpg contour plot evidently indicates that fluid accelerates through the contracted geometry areas, with the maximum velocity of 35.849 m/s. High-speed regions are indicated in the narrowed regions, illustrating smooth acceleration due to the geometry.

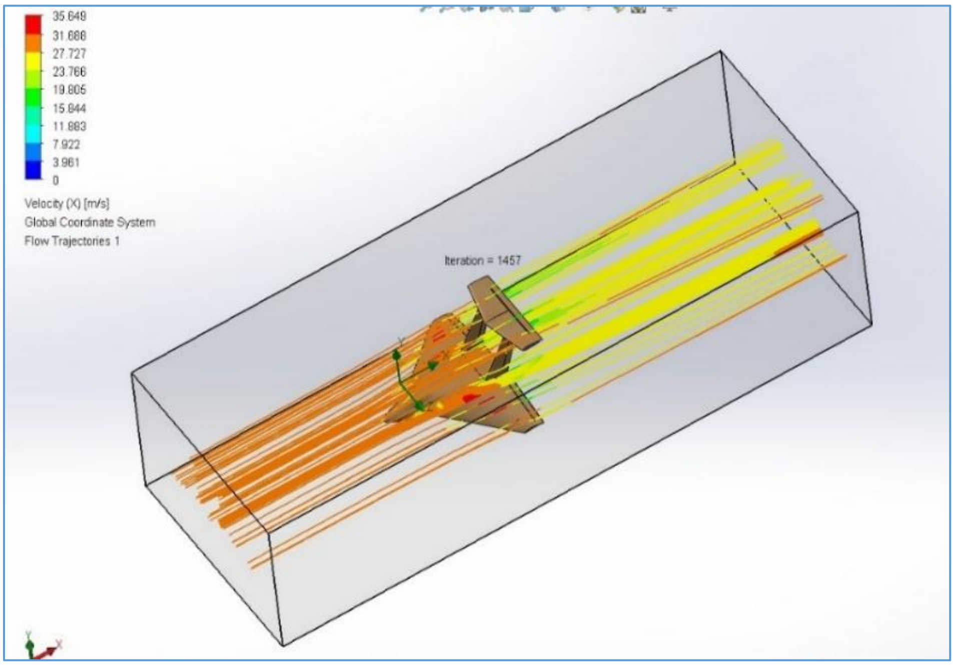

Fig: 5.2: Velocity Contour Illustration

Also, velocity 2.jpg illustrates the detailed variation of velocity where the minimum velocity drops to around 3.241 m/s in the enlarged regions and the boundary layer area, illustrating regions of potential recirculation and low flow. In general, velocity contours illustrate a developed flow pattern with the maximum velocity at the noxzzle exit and minimum values in the low-flow regions.

5.2.4 Pressure Contours

Pressure distribution throughout the computational domain, as evident in Fig. 5.3 (Pressure.jpg), shows how pressure is distributed as the fluid flows through the system. The highest pressure, at 102897.09 Pa, is observed in the inlet region where the fluid initially enters the domain due to the sudden surface interaction. As the fluid is propelled downstream, pressure decreases continuously due to the combined effect of flow expansion, energy loss, and frictional losses against the surface. The lowest pressure, at 100842.01 Pa, is observed where the flow velocity is high and static pressure is low, as in Bernoulli's principle. Intermediate pressure oscillations throughout the domain also reflect the effect of surface interactions, boundary layer development, and potential small flow separations.

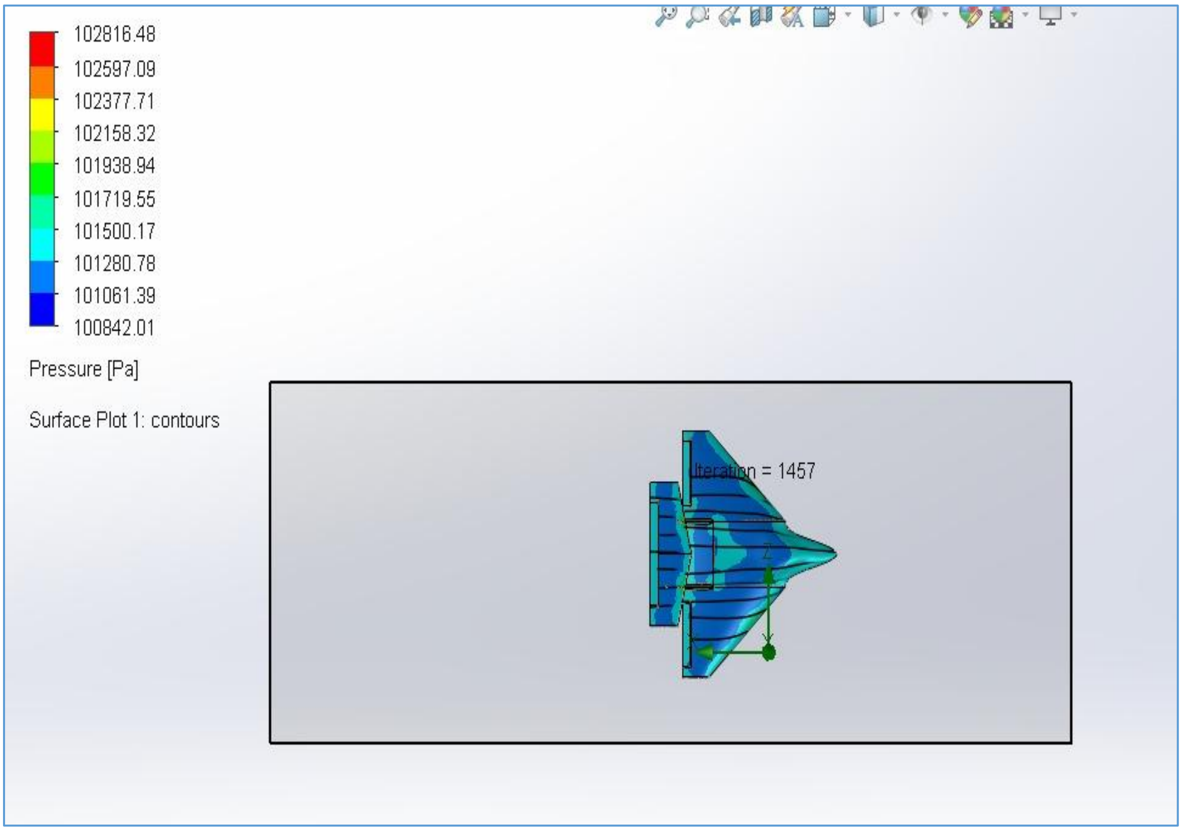

Fig: 5.3: Pressure Contour Illustration

5.2.5 Temperature Distribution

The temperature profile of the fluid in the domain is depicted in Fig 5.4, which is the temperature side view as displayed in temperature side view.jpg. The temperature contours are evident and show that the fluid enters the domain at a temperature of 293.64 K and gradually drops to 292.99 K as it flows along the domain. This slight decrease in temperature reinforces the fact that there was negligible heat loss, ensuring that thermal conditions were kept effectively stable during the course of the simulation. The quite even temperature distribution further ensures the efficacy of the design, since there are no substantial hotspots or unusual thermal gradients that would reveal thermal instability. This uniform temperature distribution ensures the system's stable thermal operation, such that it will be fit for the targeted working environment without worry of overheating or hot spots due to heat buildup. This is followed by the design displaying balanced and managed thermal behavior.

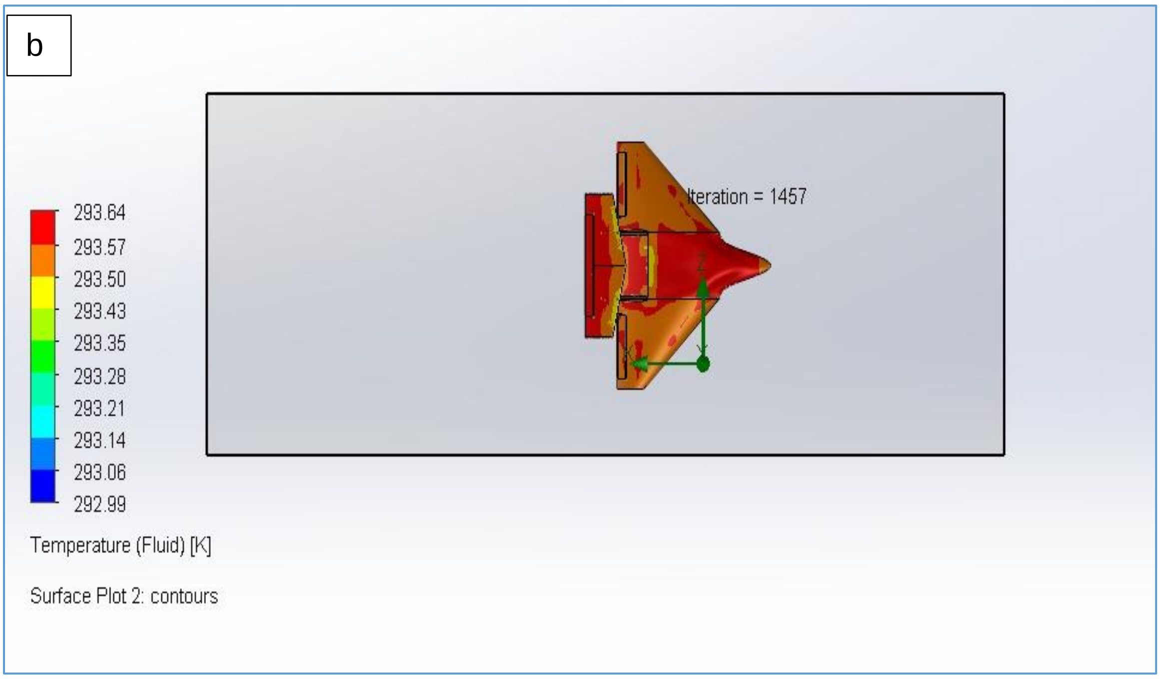

Fig: 5.4: Temperature Contour (a) Illustration 1 (b) Illustration 2

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5.2.6 GRAPHICAL RESULTS OF SOLIDWORKS SIMULATION

The graphical illustration of the simulation outcome is provided through Figure 5.5, as directly read-off from the plotted data. The graph readily demonstrates the variation of the critical flow parameters namely pressure, velocity, and temperature over a given portion of the geometry being investigated. The graph trends closely follow the observations made from the contour plots, with a consistent trend: pressure demonstrates a progressive decrease as the flow moves from the inlet to the outlet, velocity demonstrates a sharp rise in the constricted geometry section, and temperature demonstrates a gradual drop along the flow direction. All of these visual trends not only validate the qualitative observations made in the contour representations but also indicate an accurate, quantitative portrayal of the flow behaviour, identifying key features such as pressure recovery, momentum changes, and thermal behaviour across the domain. The agreement between the graph and contour data indicates the validity of the simulation, with an overall picture of how the fluid interacts with the geometry, how energy is redistributed, and how thermal gradients are established, thereby enhancing the overall analysis of the system's performance under the simulated conditions.

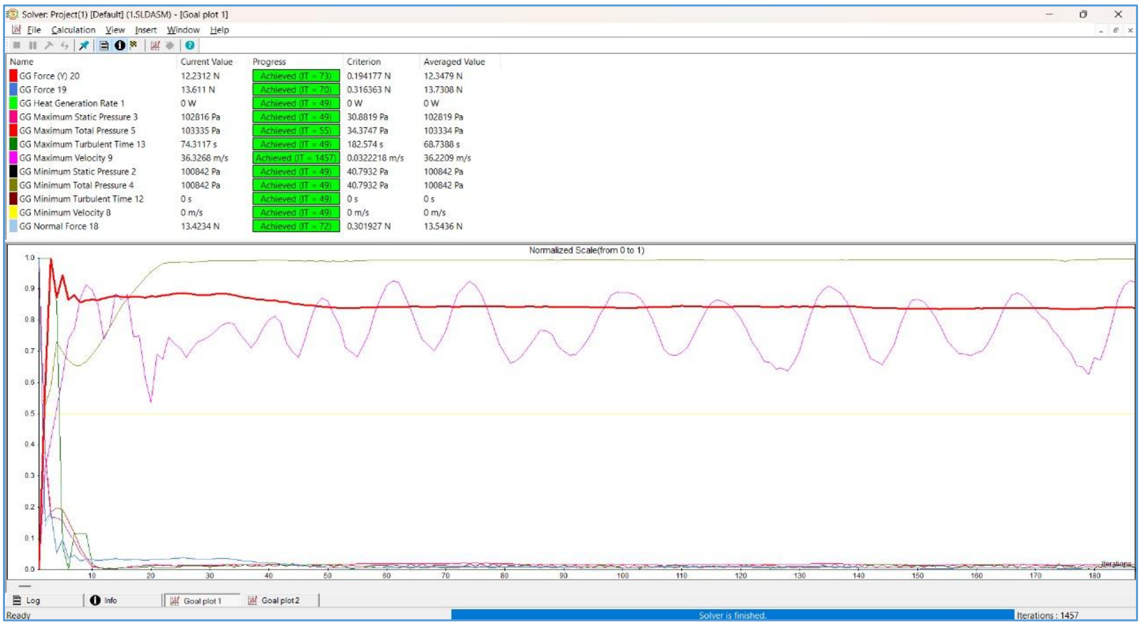

Fig: 5.5: Analysis Graph

Table 5.3: Summary of CFD Simulation Results for WIG UAV Aerodynamic Analysis

Parameter	Maximum Value	Minimum Value	Location of Max Value	Location of Min Value
Velocity (m/s)	35.849	3.241	Nozzle Exit	Boundary Layer Region
Pressure (Pa)	102897.09	100842.01	Inlet Region	High-Velocity Zone
Temperature (K)	293.64	292.99	Inlet	Downstream Flow

5.3 DISCUSSION ON FUTURISTIC SCOPE

In order to further improve the operational efficiency and performance of the WIG (Wing-In-Ground effect) UAV system, some improvements can be made in future models. One of the significant improvements would be the incorporation of hybrid power systems with electric motors and tiny fuel-based engines or solar energy harvesting technologies. These hybrid power systems would greatly improve flight time by minimizing the exclusive reliance on battery packs, allowing the UAV to travel greater distances over water bodies or coastal areas without regular recharging. Further, the addition of solar film layers to the extensive surface area of the wings could provide additional power during daytime flights, enhancing energy sustainability.

Another potential future upgrade is the combination of autonomous flight with artificial intelligence (AI) capability. AI-based systems would be able to process real-time environmental information and make intelligent adjustments to flight paths, obstacles, and altitudes to achieve maximum ground effect operation. This would minimize human interaction and increase accuracy, particularly in the case of complex missions such as maritime surveillance or search and rescue missions. Advanced sensor fusion algorithms utilizing LiDAR, ultrasonic sensors, and GPS-INS systems could also be incorporated to enhance obstacle detection and terrain mapping capability. LiDAR would be used to accurately supply low-altitude measurements needed to sustain the critical ground clearance needed for effective ground effect flight.

In addition, the communication networks can be supplemented with the inclusion of mesh networks or long-range RF modules to ensure the reliability of UAV operation over far-off areas away from traditional communication infrastructure. The networks would enable real-time data transfer among any number of control stations or UAVs, supporting coordinated operations like coastal patrol or environmental monitoring.

Expansion in the future can also include modular payload systems, where the WIG UAV can be adapted to different missions such as cargo delivery, surveillance, or environmental monitoring by swapping mission-specific modules. Autonomous cargo transport on water surfaces, especially to remote or inaccessible areas or offshore platforms, is a significant application, which can transform maritime logistics. Incorporating AI for autonomous deployment and recovery of the payload further enhances operational efficiency.

In summary, there is a very wide horizon to further develop the WIG UAV system for commercial logistics applications, environmental and wildlife surveillance, sea rescue missions, and military reconnaissance. Incorporation of autonomous capabilities based on AI, next-generation propulsion systems, and advanced network communications will enhance future WIG UAVs, which will be more efficient, powerful, and multi-role, contributing to low-level operations, energy efficiency, and lower costs for the industries.

CHAPTER 6

SUMMARY AND CONCLUSION

6.1 SUMMARY

Wing-In-Ground (WIG) effect UAV is a revolutionary new development in low-altitude aerial technology specifically to utilize the aerodynamic phenomenon called the ground effect, whereby proximity to a surface usually water or flat terrain enhances lift and reduces drag. With this specially crafted shape, the WIG UAV can achieve incredible lift-to-drag ratios many times greater than that of traditional unmanned aerial vehicles, thus achieving maximum fuel efficiency and flight time. For short-range flights over sea and coastal areas, this new system makes use of the cushion of air that forms between its wings and the surface below it, enabling it to soar smoothly at heights ranging from a few centimetres to a few meters. The development process included cost-conscious yet robust material choice to achieve a delicate balance between structural integrity and light weight, employing polypropylene sheets for their strength and flexibility, foam sheets for their low weight and insulation, and Ethirina wood for its superior strength-to-weight ratio, a combination that enables the aircraft to endure flight stresses and yet remain buoyant and responsive. But the road to perfection for this UAV was not without challenge—engineers had to contend with issues such as optimizing motor positioning to maintain thrust efficiency, relocating the center of gravity (CG) to enable stable flight characteristics, and optimizing the materials to avoid unnecessary weight that would negate the advantage of the ground effect. Despite these challenges, the WIG UAV has been an exciting platform with a wide variety of real-world applications, from the transport of freight over water, where it can deliver goods more efficiently than boats or conventional drones; shoreline surveillance, offering a low-profile, energy-efficient means of monitoring shorelines; monitoring of the environment, where its hovering capability near the surface assists in obtaining accurate measures of water quality or wildlife; and search and rescue, where its stability and range may prove to be a lifesaver in locating people in distress along shorelines or in flooded land. With respect to conventional UAVs, which have battery life and payload problems over water, the WIG UAV's design circumvents these issues, making it an invaluable asset in situations where conventional systems break down, the start of a new generation of specialist aerial solutions designed to meet the specific requirements of aquatic and low-altitude environments.

6.2 CONCLUSION

The Wing-In-Ground (WIG) Effect UAV project demonstrates the revolutionary capabilities of ground effect-based air systems, seamlessly bridging the gap between traditional drones and sea ships by taking advantage of the aerodynamic benefits of flight close to surfaces like oceans, rivers, or lakes, where lift is enhanced and drag is minimized, offering a platform with high payload, high energy efficiency, and longer range of operation optimized for water environments where traditional UAVs are plagued by limited endurance or load capacity, and sea ships might not have the agility or speed required for some missions. This innovative design was the product of overcoming considerable technical challenges, such as optimizing structural materials settling on lightweight but strong Ethirina wood for the structure and long-lasting polypropylene blended with foam sheets for the outer casing after balancing cost, availability, and durability and strategically mounting high-thrust motors to generate balanced thrust and aerodynamically streamlining the shape with a carefully aligned center of gravity to offer stability under turbulent winds or changing water currents, all through iterative improvements in design balancing performance with cost. In the future, the integration of AI-assisted flight control could offer autonomous navigation through complex low-altitude routes, adapting in real time to environmental conditions like wind or waves, while a hybrid propulsion system potentially using electric motors and solar panels or a small combustion engine could significantly enhance endurance and reliability, minimizing environmental footprint and enabling the UAV to conduct extended missions like continuous coastal surveillance or remote delivery with minimal human interaction, although such improvements would need to be carefully calibrated to preserve the craft's ground effect-dependent efficiency and lightweight build. Already, the WIG UAV is a multi-purpose machine, poised to transform the sea's logistics by rapidly transporting commodities between coastal hubs or offshore installations, supplement ecological study by low-altitude monitoring of oceanic ecosystems, pollution, or erosion with the help of sophisticated sensors, and aid specialized industrial operations such as offshore installation surveying or search-and-rescue in inaccessible aquatic regions, its modularity facilitating easy payload switching cameras, scientific sensors, or cargo—depending on different needs. With the redefinition of UAV technology's use in near-ground scenarios, this vehicle brings the speed and agility of airborne systems together with the payload and endurance of marine solutions, generating a cost-effective, high-performance hybrid that can be utilized as a launch point for subsequent operations, transforming the way industries tackle issues in water-based environments and establishing a new, ambitious standard for airborne technology in low-altitude, surface-skimming missions.

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Optimizing Wing-In-Ground Effect UAVS for Enhanced Search and Rescue Operations: A Comprehensive Review

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***Abstract:** Wing-In-Ground Effect (WIG) Unmanned Aerial Vehicles (UAVs) represent a unique convergence of aerodynamic principles and unmanned systems technology, offering promising solutions for maritime operations. This paper explores the historical development, theoretical foundations, and potential applications of WIG UAVs. The phenomenon of ground effect, which enhances lift and reduces drag when flying close to water surfaces, has been observed since the early 20th century. Soviet engineer Rostislav Alexeyev's pioneering work on the Lun-class ekranoplan in the 1960s demonstrated the viability of WIG technology for military logistics. Advancements in materials science, propulsion systems, and computer-aided design have further refined WIG vehicle performance. The integration of autonomous capabilities has expanded the operational scope of WIG UAVs, enabling missions in challenging maritime environments. The aerodynamic investigation of WIG vehicles reveals the complex interplay between the vehicle's wings and the water surface, leading to enhanced lift-to-drag ratios and improved efficiency. Computational Fluid Dynamics (CFD) simulations and wind tunnel experiments have provided valuable insights into the optimization of WIG UAV designs. The potential applications of WIG UAVs span maritime surveillance, coastal patrolling, search and rescue operations, and cargo transportation. Their ability to collaborate with other unmanned systems, such as aerial drones and surface vessels, enhances overall mission effectiveness. As the demand for sophisticated maritime capabilities grows, the development of WIG UAVs presents a promising frontier for innovation, offering unique solutions to address evolving challenges in maritime security and operational effectiveness.*

***Keywords:** Wing-In-Ground Effect (WIG), Unmanned Aerial Vehicles (UAVs), ground effect maritime operations, aerodynamic principles, Computational Fluid Dynamics (CFD)*

I. INTRODUCTION

Wing-In-Ground Effect (WIG) vehicles represent an innovative convergence of aerodynamics and marine engineering, specifically designed to operate within a unique flight regime close to the surface of water bodies. This operational domain leverages the ground effect, a phenomenon where an aircraft experiences increased lift and reduced drag when flying close to a surface. The benefits of this phenomenon are maximized in WIG vehicles, which are purpose-built to maintain proximity to the water surface, allowing for efficient flight with reduced energy consumption [1].

These vehicles have garnered significant interest for their potential in a wide range of maritime applications. For example, WIG UAVs are particularly advantageous in environments where traditional aerial vehicles might struggle due to fuel inefficiencies at low altitudes, or where marine vessels might face limitations in speed and manoeuvrability. The hybrid nature of WIG vehicles allows them to operate efficiently in both domains, making them invaluable assets in sectors like coastal surveillance, maritime logistics, and emergency response [2].

The integration of advanced technologies, such as AI-driven autonomous navigation and state-of-the-art sensor systems, has further enhanced the capabilities of WIG UAVs. These advancements have enabled WIG UAVs to perform complex missions with minimal human intervention, ensuring operational efficiency even in challenging environments. This level of autonomy is crucial for applications where human safety is a concern, such as in disaster-stricken areas or hostile maritime regions [3]. Additionally, the potential for WIG UAVs to function in concert with other unmanned systems, such as drones and unmanned surface vessels (USVs), provides a comprehensive approach to maritime operations. This synergy allows for a broader operational scope, improving situational awareness and enabling more effective mission outcomes. As a result, WIG UAVs are increasingly being considered for roles that require both speed and precision in maritime contexts [4].

II. HISTORICAL DEVELOPMENT

The concept of Wing-In-Ground Effect (WIG) vehicles has a rich history that dates back to the early 20th century, with the first significant observations of ground effect occurring during World War I. Pilots noticed that aircraft performed better at lower altitudes, particularly in terms of lift and stability, which sparked interest in the aerodynamic principles underlying this phenomenon. However, it was not until the mid-20th century that focused engineering efforts were made to develop vehicles specifically designed to exploit ground effect [5]. Rostislav Alexeyev, a prominent Soviet engineer, played a pivotal role in advancing WIG technology during the 1960s. His work led to the creation of the Lun-class ekranoplan; a ground-effect vehicle designed for military use. The Lun-class was capable of carrying heavy payloads at high speeds just above the water surface, making it an effective tool for naval operations, particularly in regions where stealth and rapid deployment were critical [6]. Despite these advancements, the widespread adoption of WIG technology was hampered by several challenges. Regulatory issues, the complexity of the designs, and the limitations of technology at the time restricted the application of WIG vehicles to niche areas, primarily within military contexts. However, the late 20th century saw renewed interest in WIG vehicles, driven by advancements in materials science and computer-aided design (CAD), which allowed for more refined and efficient designs [7]. Entering the 21st century, WIG technology began to see applications beyond military use, particularly with the integration of unmanned systems. This shift has opened new possibilities for WIG vehicles in various civil and commercial sectors, such as maritime surveillance, search and rescue operations, and environmental monitoring. The development of autonomous WIG UAVs capable of performing complex missions without direct human control has further expanded the potential applications of this technology [8].

TABLE I
HISTORICAL DEVELOPMENT OF WING-IN-GROUND EFFECT VEHICLES

Period	Development Milestone	Key Contributor	Reference
Early 20th Century	Initial observations of ground effect during WWI	Military Aviation Research	Yun & Bliault (2012) [5]
1960s	Development of Lun-class ekranoplan	Rostislav Alexeyev	Nebylov (n.d.) [6]
1970s - 1980s	Experimental prototypes and design refinements	Various Nations	Priyanto et al. (n.d.) [7]
Late 20th Century	Reinvigoration of WIG research with advanced materials	Global Aerospace Community	Ahn et al. (n.d.) [8]
Early 21st Century	Integration of unmanned systems into WIG designs	Research Institutions	Ahn et al. (n.d.) [8]

III. THEORETICAL FOUNDATIONS

A. Aerodynamic Investigation of Wing-In-Ground Effect (WIG) Vehicles

The aerodynamic behaviour of Wing-In-Ground Effect (WIG) vehicles is fundamentally influenced by their proximity to a surface, typically water. Ground effect is a well-documented phenomenon where an aircraft experiences an increase in lift and a decrease in drag when flying close to the ground. This occurs because the presence of the surface alters the pressure distribution around the wings, leading to increased lift and reduced induced drag [9]. For WIG vehicles, ground effect is not merely a beneficial side effect but a core design principle. When a WIG vehicle operates within one wingspan of the water surface, it can experience up to a 50% increase in lift compared to the same vehicle flying at higher altitudes. This significant increase in lift allows WIG vehicles to maintain stable flight at lower speeds, which is particularly useful for maritime applications where manoeuvrability and efficiency are paramount [10]. Computational Fluid Dynamics (CFD) simulations play a critical role in understanding and optimizing the aerodynamic performance of WIG vehicles. Engineers use CFD to model various flight conditions and to analyse how different wing configurations affect lift and drag. For instance, variations in wing camber, aspect ratio, and angle of attack can have profound effects on the aerodynamic efficiency of the vehicle. These simulations help in identifying the optimal design parameters that balance lift, drag, and stability [11]. Environmental factors, such as wind speed, direction, and wave conditions, also significantly influence the aerodynamic performance of WIG vehicles. In particular, crosswinds and turbulent airflows can disrupt the stable flight patterns of these vehicles, necessitating the development of adaptive control systems that can dynamically adjust the vehicle's flight parameters in real-time. The incorporation of such systems is crucial for ensuring the operational reliability of WIG UAVs in diverse and challenging maritime environments [12].

TABLE II
AERODYNAMIC PROPERTIES OF WIG VEHICLES IN GROUND EFFECT

Parameter	Description	Value Range or Impact	Reference
Lift Increase	Percentage increase in lift due to ground effect	Up to 50% compared to higher altitudes	Lippisch (n.d.) [10]
Drag Reduction	Reduction in drag when operating near the surface	Significant reduction in induced drag	Mobasser Tofa et al. (2014) [9]
Optimal Operating Height	Height range for maximum ground effect benefits	Within one wingspan of the surface	Han et al. (n.d.) [11]
Impact of Crosswinds	Effect of crosswinds on stability	Can cause significant instability	Yang et al. (n.d.) [12]
Angle of Attack	Influence on lift and drag during ground effect	Higher angles increase lift but risk stalling	Han et al. (n.d.) [11]

B. Structural Dynamics

The structural dynamics of WIG vehicles are uniquely complex, involving the interaction of aerodynamic and hydrodynamic forces. The proximity of these vehicles to the water surface means that they are subjected to forces not typically encountered by traditional aircraft, including wave-induced vibrations and dynamic lift variations. Understanding these forces is essential for designing structures that can withstand the stresses of WIG operations without compromising performance [13]. Finite Element Analysis (FEA) is a critical tool in the structural design of WIG vehicles. FEA allows engineers to break down the vehicle into smaller elements, enabling detailed analysis of how each component responds to various forces. This method is particularly useful for identifying potential weak points in the structure and for optimizing the material distribution to enhance durability and reduce weight. For example, FEA can be used to simulate the stresses experienced by a WIG vehicle's wings during high-speed manoeuvres over choppy water, ensuring that the design can withstand these conditions without failure [14]. Material selection is another crucial aspect of structural dynamics. WIG vehicles typically use advanced composite materials, such as carbon fibre reinforced polymers (CFRP), which offer high strength-to-weight ratios and excellent fatigue resistance. These materials are ideal for WIG vehicles, which require both flexibilities to absorb dynamic loads and rigidity to maintain structural integrity under continuous operation. The damping characteristics of these materials also play a vital role in minimizing vibrations and enhancing the overall stability of the vehicle [15]. In addition to material considerations, engineers must account for the effects of environmental factors on the structural integrity of WIG vehicles. Wave motion, currents, and wind can all impact the vehicle's dynamic response, making it essential to conduct thorough simulations and tests to predict how the structure will perform in various conditions. The development of robust designs that can endure these external forces is key to ensuring the long-term reliability and safety of WIG UAVs [16].

TABLE 3:
Structural and Material Characteristics of WIG Vehicles

Component	Material Used	Key Properties	Reference
Wing Structure	Carbon Fiber Reinforced Polymer (CFRP)	High strength-to-weight ratio, fatigue resistance	Hufenbach et al. (n.d.) [15]
Fuselage	Lightweight Composite Materials	Enhanced durability, lightweight	Gonzalez (2020) [19]
Control Surfaces	Advanced Composite Materials	Flexibility with rigidity for precision control	Chung (n.d.) [16]
Load-Bearing Elements	High-Tensile Aluminium Alloys	High tensile strength, low density	Zhang et al. (n.d.) [14]
Damping Materials	Composite with High Loss Factor	Vibration mitigation, reduced fatigue failure	Chung (n.d.) [16]

IV. DESIGN CONSIDERATIONS

A. Airframe Design

The airframe design of Wing-In-Ground Effect (WIG) UAVs is central to their performance, particularly due to the unique aerodynamic properties associated with operating in ground effect. A high aspect ratio wing design is typically favoured in WIG vehicles, as it enhances lift generation and reduces drag when operating close to the water surface. The aspect ratio, defined as the ratio of the wingspan to the mean chord, significantly influences the lift and drag characteristics of the vehicle, making it a critical parameter in the design process [17]. The use of lightweight composite materials in the construction of the airframe is also essential for maximizing the vehicle's performance. Materials such as carbon fibre composites offer the strength needed to withstand the stresses of flight while minimizing the overall weight of the vehicle. This reduction in weight not only improves fuel efficiency but also enhances the vehicle's operational range, allowing it to cover greater distances without the need for frequent refuelling [18]. The structural integrity of the airframe must be meticulously engineered to handle the dynamic loads encountered during WIG operations. These loads can vary significantly depending on environmental conditions, such as wind and wave turbulence. To ensure that the airframe can withstand these forces, engineers employ advanced computational methods and simulations during the design phase. These tools allow for the prediction of performance under a wide range of conditions, ensuring that the vehicle can operate safely and efficiently in real-world scenarios [19].

B. Propulsion System

The propulsion system is a critical component of WIG UAVs, responsible for providing the necessary thrust to achieve and maintain flight in ground effect. The design of the propulsion system must consider both the high-speed capabilities of the vehicle and the need for efficient fuel consumption. Hybrid propulsion systems, which combine traditional engines with electric motors, are increasingly being explored as a solution to meet these requirements [20]. Hybrid systems offer the flexibility to optimize performance across different flight phases. For example, electric motors can be used during take-off and landing, where precise control and low-speed thrust are essential. Once the vehicle is airborne and in ground effect, the traditional engine can take over, providing the power needed for high-speed travel over water. This combination not only enhances fuel efficiency but also reduces the vehicle's environmental impact by lowering emissions [21]. Advanced propulsion technologies, such as variable-pitch propellers and ducted fans, are also being integrated into WIG UAVs to improve thrust control and adaptability. These technologies allow for real-time adjustments to the thrust output, which is particularly important in dynamic maritime environments where conditions can change rapidly. The ability to fine-tune thrust in response to environmental factors is crucial for maintaining the operational capabilities of WIG UAVs [22].

TABLE 4
Propulsion Systems in WIG UAVs

Propulsion Type	Advantages	Application Scenario	Reference
Traditional Engines	High power output, reliable	High-speed cruising over water surfaces	Graham (2016) [21]
Hybrid Propulsion Systems	Fuel efficiency, lower emissions	Long-duration missions with varying speed requirements	Said et al. (n.d.) [22]
Electric Motors	Precision control, zero emissions	Take off and landing phases, low-speed operations	Said et al. (n.d.) [22]
Variable-Pitch Propellers	Thrust adaptability, improved manoeuvrability	Dynamic maritime environments	Graham (2016) [21]
Ducted Fans	Enhanced thrust efficiency, noise reduction	Operations in populated or environmentally sensitive areas	Said et al. (n.d.) [22]

C. Control System

The control system of WIG UAVs plays a vital role in ensuring stability and manoeuvrability, particularly in the challenging conditions of maritime environments. The unique aerodynamic characteristics of WIG vehicles, which are influenced by their proximity to the water surface, require a control system that can respond rapidly to changes in environmental conditions, such as crosswinds and wave-induced turbulence [23].

Advanced flight control algorithms, such as adaptive and predictive control systems, are essential for managing the dynamic flight parameters of WIG UAVs. These algorithms enable the vehicle to maintain optimal flight trajectories and stability by making real-time adjustments to control surfaces based on sensor input. The integration of sophisticated sensor technologies, including LIDAR, radar, and GPS, provides the data needed for these algorithms to function effectively [24]. One of the key challenges in control system design is ensuring that the vehicle can maintain stable flight in varying conditions without compromising performance. This requires the development of robust algorithms that can handle the complex interactions between the vehicle's aerodynamic properties and the external environment. The successful implementation of these systems is critical for the safe and efficient operation of WIG UAVs in diverse maritime scenarios [25].

TABLE 5
Control System Technologies in WIG UAVs

Control System Type	Functionality	Implementation Challenges	Reference
Adaptive Control Systems	Real-time adjustment to flight conditions	Requires advanced sensors and real-time processing	Gonzalez et al. (n.d.) [25]
Predictive Control Systems	Anticipates future states based on current data	High computational demand, complex algorithms	Gonzalez et al. (n.d.) [25]
Sensor Integration	Uses LIDAR, radar, and GPS for real-time data	Ensuring sensor accuracy and reliability	Davila (n.d.) [24]
Autonomous Navigation	Enables UAVs to operate with minimal human input	Integration with existing control systems	Huntsberger & Woodward (n.d.) [2]
Redundant Control Systems	Ensures operational safety in case of system failure	Increased weight and complexity	Lee et al. (n.d.) [23]

D. Payload Capabilities

The payload capabilities of WIG UAVs are a crucial consideration in their design, as these vehicles are employed in a variety of applications that require different types of equipment and cargo. The airframe design must be optimized to provide sufficient volume and weight capacity for the intended payloads without compromising the overall performance of the UAV [26]. One approach to enhancing the payload capabilities of WIG UAVs is the use of modular payload configurations. This design strategy allows for the rapid adaptation of the vehicle to different mission requirements, making it a flexible tool for a wide range of applications. For example, a WIG UAV could be equipped with surveillance equipment for one mission and then quickly reconfigured to carry medical supplies or disaster relief materials for another [27]. The integration of payload systems with the UAV's operational framework is also essential for efficient communication and data processing during missions. This involves ensuring that the payload can interact seamlessly with the UAV's control systems and that data collected by the payload is transmitted in real-time to operators. This capability is particularly important in applications like environmental monitoring or search and rescue, where timely information is critical for mission success [28].

V. PROTOTYPE DEVELOPMENT

A. Conceptual Design and Simulation

The development of a WIG UAV prototype begins with the creation of detailed computer-aided design (CAD) models, which serve as the foundation for the vehicle's design. These models are used to simulate the vehicle's performance across various flight scenarios, allowing engineers to optimize key parameters such as lift-to-drag ratio, weight distribution, and stability. Theoretical calculations, combined with advanced simulation tools, help in refining the design to ensure that the prototype meets the desired performance criteria [29].

One of the primary goals of the simulation phase is to maximize the aerodynamic efficiency of the vehicle. This involves analysing how different wing shapes, aspect ratios, and angles of attack affect the lift and drag characteristics of the WIG UAV. By optimizing these factors, engineers can ensure that the vehicle performs well in the ground effect zone while maintaining stability and control [30].

B. Material Selection and Prototype Construction

The construction of a WIG UAV prototype involves careful material selection to ensure that the vehicle can withstand the unique aerodynamic and hydrodynamic forces encountered during operation. Lightweight composite materials, such as carbon fibre reinforced polymers (CFRP), are often chosen for their high strength-to-weight ratios and durability. These materials are essential for constructing a vehicle that is both robust and efficient, minimizing fuel consumption while maximizing performance [31]. The prototype construction process also involves the integration of essential systems for navigation, control, and communication. These systems must be designed to operate effectively in complex maritime environments, where conditions can be unpredictable and challenging. Ensuring that these systems are robust and reliable is critical for the success of the prototype in real-world testing [32].

C. Testing Methodologies

Testing is a vital component of prototype development, beginning with controlled evaluations in wind tunnels to assess aerodynamic performance. Wind tunnel testing allows engineers to measure key parameters such as lift, drag, and stability under various conditions. The Reynolds number, a dimensionless quantity used to predict flow patterns in different fluid flow situations, is often calculated to characterize the flow over the prototype. This information is crucial for understanding how the vehicle will perform in real-world conditions [33]. Following successful wind tunnel tests, the prototype undergoes water surface evaluations to assess its performance under actual operational conditions. These evaluations are essential for understanding how the vehicle interacts with waves, currents, and other environmental factors that can influence its performance. The data collected from these tests is used to refine the design and improve the prototype's capabilities [34].

D. Iterative Design Process

The development of a WIG UAV prototype is an iterative process, involving continuous feedback from testing and refinement of the design. Engineers conduct multiple rounds of testing and modification, using the data collected to enhance the vehicle's performance and reliability. This iterative approach not only improves the prototype but also informs the development of subsequent models, fostering innovation and advancing WIG technology [35]. The iterative design process is crucial for identifying and addressing potential issues that may arise during testing. By continuously refining the design based on real-world data, engineers can ensure that the final prototype meets all performance criteria and is ready for deployment in operational environments [36].

VI. INTEGRATION OF SYNTHETIC APERTURE RADAR (SAR) EQUIPMENT

The integration of Synthetic Aperture Radar (SAR) technology into WIG UAVs represents a significant advancement in their operational capabilities. SAR systems provide high-resolution imaging of the surface, making them invaluable for maritime surveillance, search and rescue operations, and environmental monitoring. The incorporation of SAR technology enables real-time data collection and analysis, which enhances situational awareness and operational effectiveness [37]. One of the primary considerations in integrating SAR equipment into WIG UAVs is the weight and balance of the vehicle. SAR systems are typically heavy, and their addition can affect the vehicle's flight characteristics if not properly accounted for in the design. Engineers must carefully evaluate the placement of radar equipment to minimize aerodynamic interference while ensuring effective surface scanning [38]. In addition to physical integration, the development of specialized software for data processing is essential for the effective use of SAR systems. This software must be capable of efficiently filtering and analysing the vast amounts of data generated by SAR systems, providing operators with actionable intelligence in real-time. The ability to quickly process and interpret SAR data is critical for missions that require immediate responses, such as search and rescue operations or environmental monitoring [39].

VII. CASE STUDIES AND APPLICATIONS

A. Maritime Surveillance

WIG UAVs are particularly well-suited for maritime surveillance due to their ability to operate at low altitudes, just above the water surface. This capability allows them to monitor shipping lanes, detect illegal activities such as unauthorized fishing or smuggling, and provide real-time data to maritime authorities. For example, the deployment of WIG UAVs in the Black Sea region has significantly enhanced the ability to monitor and secure strategic maritime areas [40]. The integration of SAR technology into WIG UAVs further enhances their effectiveness in maritime surveillance. SAR systems provide high-resolution images that can be used to identify and track vessels, even in poor weather conditions or at night. This capability is particularly valuable in regions with high levels of maritime traffic, where maintaining situational awareness is critical for security and safety [41].

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B. Search and Rescue Operations

WIG UAVs have proven to be invaluable assets in search and rescue operations, especially in environments where traditional aircraft may be limited. Their ability to skim over water surfaces allows them to quickly reach remote or inaccessible areas, providing critical assistance in locating and rescuing stranded individuals. For example, during Hurricane Harvey in 2017, WIG UAVs were deployed to assess damage and locate survivors in flooded areas of Texas, demonstrating their effectiveness in disaster response [42]. The combination of SAR technology and autonomous navigation systems further enhances the capabilities of WIG UAVs in search and rescue missions. These vehicles can autonomously scan large areas for signs of life, using SAR data to pinpoint the locations of individuals in need of rescue. This capability not only speeds up the rescue process but also reduces the risks associated with manned missions in hazardous environments [43].

C. Environmental Monitoring

Environmental monitoring is another area where WIG UAVs have demonstrated significant potential. Equipped with advanced sensor technologies, including SAR, these vehicles can capture detailed images of coastal and marine environments, track changes in ecosystems, and monitor environmental hazards such as oil spills or illegal dumping. WIG UAVs have become essential tools in conservation efforts, providing valuable data that supports the preservation of marine habitats and the protection of biodiversity [44]. The ability to operate at low altitudes while maintaining stability makes WIG UAVs ideal for non-invasive environmental monitoring. This is particularly important in sensitive ecosystems where traditional monitoring methods might cause disruption or harm. By providing high-resolution data from a safe distance, WIG UAVs contribute to more effective and sustainable environmental management practices [45].

VIII. COMPARATIVE ANALYSIS

A. Operational Efficiency

In a comparative analysis with traditional aerial platforms, WIG UAVs offer distinct advantages in operational efficiency, particularly in maritime environments. While fixed-wing aircraft are capable of covering large distances, they do so at higher altitudes where the benefits of ground effect are not applicable. In contrast, WIG UAVs operate close to the water surface, where they can exploit ground effect to achieve higher lift-to-drag ratios, resulting in better fuel efficiency and extended operational range [46]. The use of hybrid propulsion systems further enhances the operational efficiency of WIG UAVs. By combining traditional engines with electric motors, these vehicles can optimize fuel consumption across different flight phases, reducing overall operating costs. This makes WIG UAVs a more sustainable option for long-range maritime missions, where fuel efficiency is a critical concern [47].

B. Speed and Manoeuvrability

Compared to conventional unmanned surface vessels (USVs), WIG UAVs demonstrate superior speed and manoeuvrability. USVs are limited by water currents and wave conditions, which can impede their progress and reduce their effectiveness in certain scenarios. In contrast, WIG UAVs can quickly navigate over water surfaces, providing real-time reconnaissance and surveillance capabilities that are crucial for dynamic maritime operations [48]. The ability of WIG UAVs to rapidly change direction and altitude in response to environmental conditions also contributes to their superior manoeuvrability. This agility is particularly advantageous in military applications, where the ability to respond quickly to emerging threats can make a significant difference in mission success [49].

C. Cost-Effectiveness

The cost-effectiveness of WIG UAVs is another major advantage, particularly when compared to traditional manned aircraft. The absence of a need for onboard crew not only reduces operational costs but also minimizes the risks associated with human error and exposure to dangerous environments. Additionally, the ability to perform complex missions autonomously further reduces the need for expensive support infrastructure, making WIG UAVs an economically attractive option for both military and civilian applications [50]. Moreover, the use of advanced materials and hybrid propulsion systems contributes to the long-term cost savings of WIG UAVs by reducing maintenance requirements and extending the operational lifespan of the vehicle. These factors make WIG UAVs a cost-effective solution for a wide range of maritime operations, from surveillance to logistics and beyond [51].

IX. CHALLENGES AND LIMITATIONS OF WIG UAVS

A. Technical Challenges

The development and deployment of Wing-In-Ground Effect (WIG) UAVs face several technical challenges, particularly in the areas of aerodynamics, control systems, and structural integrity. The ground effect, while beneficial for lift and drag reduction, also introduces sensitivities to environmental conditions such as wind speed and wave patterns. These factors can significantly impact the stability and control of WIG UAVs, requiring the development of advanced control systems that can dynamically adapt to changing conditions [52]. Structural integrity is another critical challenge, as WIG UAVs must be designed to withstand the unique combination of aerodynamic and hydrodynamic forces encountered during operation. The resonance phenomenon, where vibrations occur at specific frequencies, can pose a significant risk to the structural stability of the vehicle. Engineers must conduct rigorous finite element analyses and simulations to predict and mitigate these risks, ensuring that the vehicle remains reliable and safe under operational stresses [53]. The integration of advanced technologies, such as Synthetic Aperture Radar (SAR) systems, introduces additional complexities. The weight and balance of the vehicle must be carefully managed to avoid compromising flight performance. Furthermore, the development of sophisticated software for data processing and interpretation is resource-intensive and requires continuous updates to keep pace with technological advancements [54].

B. Regulatory and Operational Challenges

In addition to technical challenges, WIG UAVs face significant regulatory and operational hurdles. The regulatory landscape for unmanned systems is highly variable across different jurisdictions, creating uncertainty for developers and operators. Navigating these complex regulatory frameworks can be time-consuming and costly, particularly in regions where strict airspace and maritime regulations apply [55]. Operationally, WIG UAVs are limited by their reliance on calm water surfaces for optimal performance. While they excel in stable conditions, their effectiveness can be compromised in rough seas or adverse weather, limiting their operational envelope. This constraint poses challenges for deployment in emergency situations where conditions may not be ideal for WIG operations [56]. Logistical challenges also arise in the integration of WIG UAVs into existing maritime operations. Coordinating with other unmanned systems and manned vessels requires comprehensive communication and data-sharing protocols to ensure safety and efficiency. The absence of standardized procedures for WIG UAV operations can lead to confusion and inefficiencies, complicating their integration into broader maritime frameworks [57]. Public perception and acceptance of WIG UAVs can also pose significant challenges. Concerns about privacy, safety, and environmental impact may affect public support for their deployment. Engaging with stakeholders and addressing these concerns through transparent communication and effective policy development will be crucial for the successful adoption of WIG UAV technology [58].

X. FUTURE DIRECTIONS

A. Technological Advancements

The future of Wing-In-Ground Effect (WIG) UAVs is poised for significant advancements, driven by rapid developments in autonomous navigation systems, sensor technologies, and propulsion systems. The integration of artificial intelligence (AI) and machine learning technologies will enable WIG UAVs to navigate complex maritime environments with greater efficiency and safety. These advancements will allow WIG UAVs to undertake missions in challenging conditions, such as adverse weather or turbulent seas, significantly broadening their operational scope [59]. Sensor technologies, such as multi-spectral and hyperspectral imaging systems, will enhance the situational awareness and data collection capabilities of WIG UAVs. These sensors will be instrumental in a variety of applications, including environmental monitoring, maritime surveillance, and disaster response operations. The ability to capture detailed, high-resolution information about the surrounding environment will provide valuable insights for decision-making and mission planning [60]. Advancements in propulsion systems, particularly the development of hybrid technologies that combine traditional engines with electric motors, will play a crucial role in shaping the future of WIG UAVs. These systems offer the potential for significant improvements in fuel efficiency and reductions in emissions, aligning with global sustainability goals. As battery technologies continue to evolve, the feasibility of fully electric or hybrid-electric WIG UAVs becomes increasingly plausible, paving the way for greener maritime operations [61].

B. Potential Applications Beyond SAR

While search and rescue (SAR) operations have traditionally been a primary focus for WIG UAVs, their potential applications extend far beyond this critical domain. One of the most promising areas for future utilization lies in maritime logistics and cargo transport.

The unique ability of WIG UAVs to skim over water surfaces at high speeds makes them ideal candidates for transporting goods across short to medium distances, particularly in regions where traditional transport methods are hampered by infrastructural challenges [62]. In addition, WIG UAVs possess significant potential in environmental monitoring and conservation efforts. When outfitted with advanced sensor technologies, these vehicles can perform comprehensive assessments of marine ecosystems, monitor wildlife populations, and track alterations in coastal habitats. Their capacity to operate at low altitudes while maintaining stability is crucial for non-invasive data collection, which is essential for the preservation of sensitive environments [63]. The incorporation of WIG UAVs into military operations also presents promising opportunities for reconnaissance and surveillance missions. Their distinctive flight characteristics enable them to traverse vast maritime areas swiftly while remaining below the detection thresholds of conventional radar systems. This capability can provide military forces with enhanced situational awareness and intelligence-gathering capabilities, particularly in coastal and littoral zones where traditional aircraft may encounter operational limitations [64].

XI. CONCLUSION

The exploration and development of Wing-In-Ground Effect (WIG) Unmanned Aerial Vehicles (UAVs) represent a significant advancement in aerodynamics and maritime operations. By leveraging the ground effect, these vehicles achieve remarkable lift and operational efficiency, making them highly effective for a wide range of applications. From maritime surveillance and search and rescue to environmental monitoring and military reconnaissance, WIG UAVs offer a versatile and cost-effective solution to modern challenges. However, the development and deployment of WIG UAVs are not without challenges. Technical, regulatory, and operational hurdles must be addressed to fully realize the potential of this technology. Future advancements in autonomous systems, sensor technologies, and propulsion systems will play a crucial role in overcoming these challenges and expanding the capabilities of WIG UAVs. As research and development in this field continue to evolve, WIG UAVs are poised to transform maritime operations, offering innovative solutions to some of the most pressing challenges in maritime security, environmental protection, and beyond.

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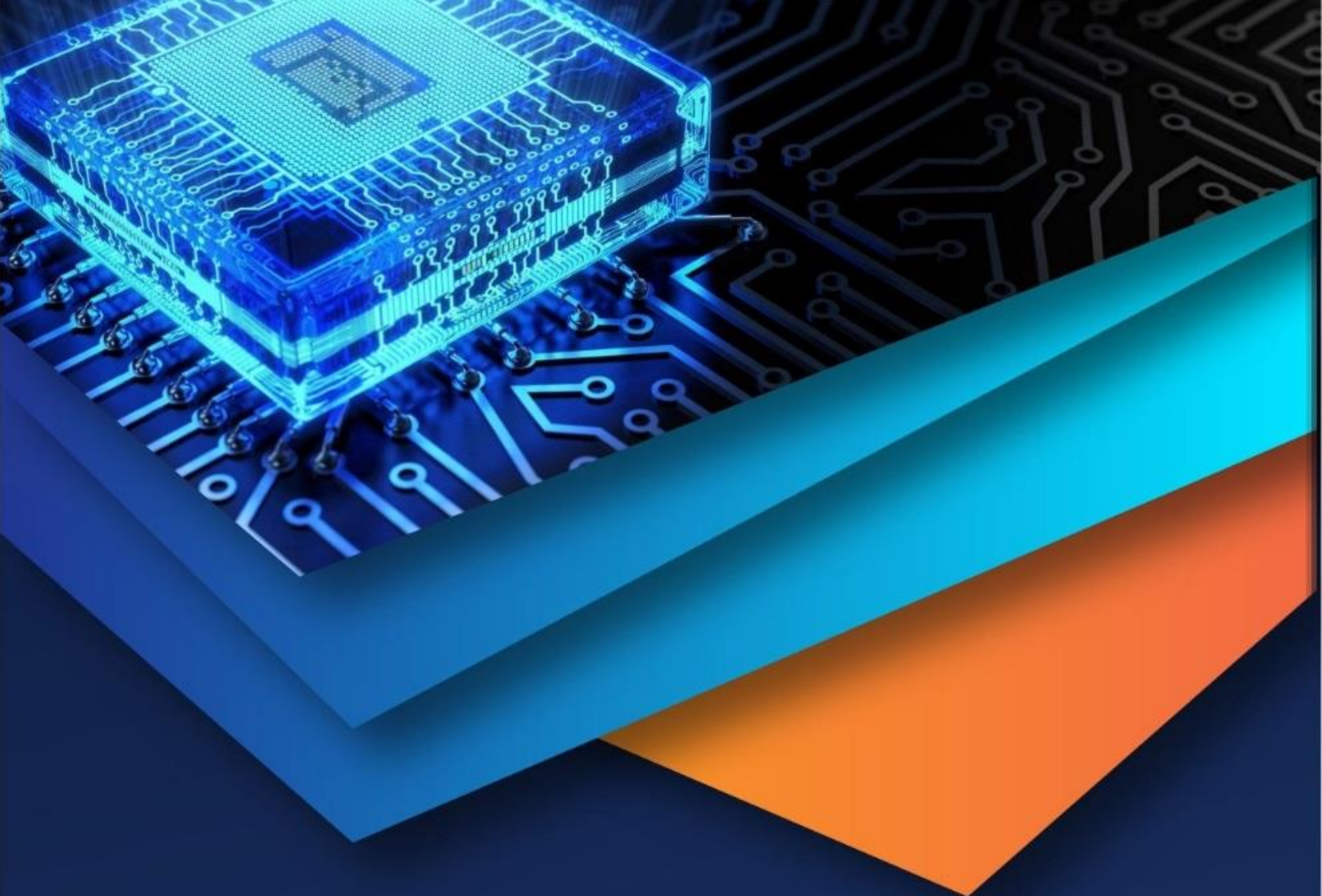

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