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ENHANCING AUTONOMOUS UNDERWATER VEHICLES (AUV) THROUGH LATTICE AND TOPOLOGY OPTIMIZATION TECHNIQUES

Muhtar HAFEZ

Master's Thesis

Supervisor

Asst. Prof. Dr. Yaser ALAIWI

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The thesis titled ENHANCING AUTONOMOUS UNDERWATER VEHICLES (AUV) THROUGH LATTICE AND TOPOLOGY OPTIMIZATION TECHNIQUES prepared by MUHTAR HAFEZ and submitted on 21/01/2025 has been **accepted unanimously** for the degree of Master in Science and Mechanical Engineering.

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I hereby declare that this thesis meets all format and submission requirements of a Master's thesis.

I hereby declare that all information/data presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

Muhtar HAFEZ

Signature

DEDICATION

This thesis is dedicated to various people whose continuous support and encouragement have helped me throughout my academic career.

To Dr. Öğr. Üyesi Yaser ALAIWI, whose advice, knowledge, and mentorship have influenced my understanding and spurred my interest for the topic. Your devotion to education and drive to greatness have motivated me to push the limits of knowledge and achieve academic success.

To my dear family, lovely wife & Father who I take as a role model, to my kind and patient mother, whose love, encouragement, and sacrifices have been the foundation for my success. Your continuous encouragement and conviction in my talents have been a constant source of inspiration and motivation, guiding me through the difficulties and victories of my academic endeavours.

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I am deeply grateful to everyone who has supported and believed in me. Your efforts, big or small, have had a tremendous impact on my academic journey and helped me attain this milestone. This thesis is a monument to our collaborative efforts and accomplishments.

With deepest appreciation,

Muhtar Hafez

ABSTRACT

ENHANCING AUTONOMOUS UNDERWATER VEHICLES (AUV) THROUGH LATTICE AND TOPOLOGY OPTIMIZATION TECHNIQUES

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This study investigates various advanced computational techniques in Lattice Optimization, aiming to maximize the hydrodynamic efficiency and structural design of the Autonomous Underwater Vehicles (AUV), to meet higher manoeuvrability performance, durability, and payload capacity.

Our goal is focused on reaching a very compact AUV design with high manoeuvrability as a base model.

ANSYS engineering simulation and N-Topology software were used to run rigorous Computational Fluid Dynamics (CFD) simulations, to assess the lattice configuration hydrodynamic performance. Lattice Optimization allows for incorporating more functions into AUV components by accommodating extra sensors and wiring while minimizing space usage.

Five different AUV streamlined design shapes, inspired by the Crab Shell, Mantay Ray, Reduced size, Cockroach Shape, and Tube Shape were selected for the study. The five different iterations of fluid flow patterns were examined through different thrusters and flange design configurations, scoring the advantages, recording the flaws of each design, and presenting the results.

The most effective lattice design was identified through the examination of the fluid flow patterns and drag coefficients, succeeding in reducing the hydrodynamic drag and improving overall AUV efficiency in underwater environment.

AUV design benefited from the employed optimization methods, and the detailed work is presented with appropriate actual Figures and Charts.

Keywords: AUV, Autonomous Underwater Vehicles, Topology Optimization, Lattice Optimization, Computational Fluid Dynamics.

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ABBREVIATIONS

ABS	:	Acrylonitrile Butadiene Styrene'
AUV	:	Autonomous Underwater Vehicle
CAD	:	Computer-Aided Design
NTOP	:	N-Topology
PLA	:	Polylactic Acid

LIST OF SYMBOLS

A_i	:	Cross-sectional Area of Element *i*
$C(\rho)$	:	Represents the Compliance of the Structure
F	:	Applied Load
k	:	Stiffness of the Structure
K_e	:	Stiffness Matrix of Element *e*
N	:	Total Number of Elements
u_e	:	Displacement Vector for Element *e*
V_0	:	Total Allowable Material Volume
V_e	:	Volume of Each Element
V_i	:	Volume of Element *i*
ρ_i:	:	Material Density of Element *i*

1. INTRODUCTION

The development of Autonomous Underwater Vehicles (AUVs) has received substantial attention in recent years due to its critical significance in a variety of underwater operations ranging from scientific research to industrial applications and defence. These autonomous vehicles can now carry out complicated operations in underwater environments, where human involvement is frequently impractical or impossible, with greater efficiency and accuracy thanks to developments in sensor technologies and computer capabilities.

AUVs, which stands for autonomous underwater vehicles is a very useful tool that could conduct a wide range of underwater tasks, Usually, in harsh environments that are too hard for humans to work indirectly, The first ROV that was manufactured, the "poodle," was manufactured in the 1950s by a French scientist and engineer name Dimitri, and by the 1980s there were more than 500 RV's all over the world which were used in a wide variety of industries such as scientific military and environmental [1] therefore it is a relatively new field that could see a drastic growth within the next few years.

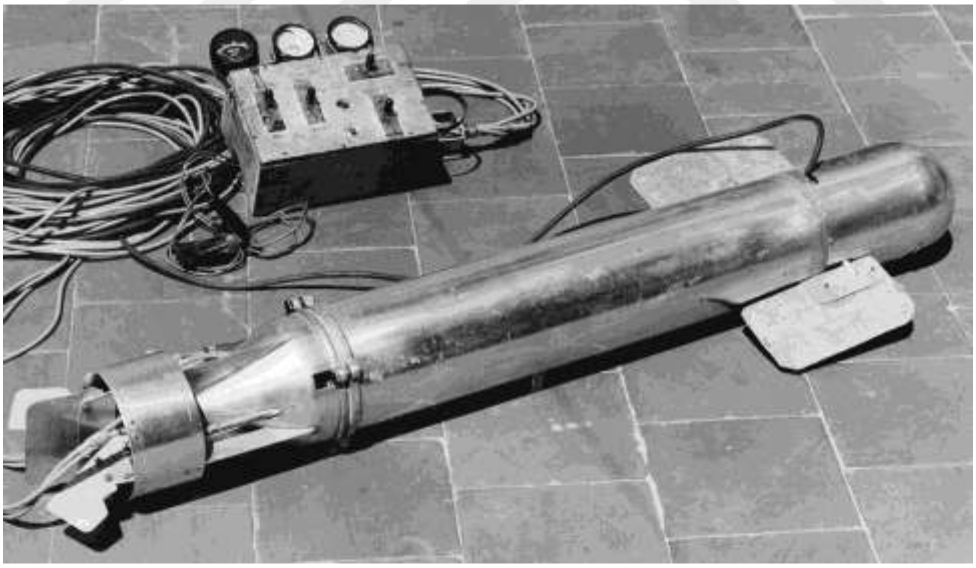

Figure 1.1: The World's First ROV, the Poodle.

Even with the amazing advancements in AUV technology, there are still obstacles to overcome in order to maximize their performance, especially with regard to hydrodynamic efficiency and structural design. Given the variety of challenging operating requirements that autonomous underwater vehicles (AUVs) must meet, including manoeuvrability, durability, and payload capacity, conventional design approaches might not fully realize the promise for improving AUV capabilities.

1.1 RATIONALE FOR OPTIMIZING AUV DESIGN THROUGH ADVANCED COMPUTATIONAL TECHNIQUES

The reason, for improving Autonomous Underwater Vehicles (AUVs) using methods is to boost their effectiveness in challenging underwater conditions where efficiency and durability are crucial. Progress in modelling and material science has enabled the use of optimization techniques like lattice and topology optimization, which have shown promise in industries such as aerospace and automotive engineering. These approaches can have an impact on AUV design in enhancing their structural strength and hydrodynamic performance.

Lattice optimization focuses on placing materials within a structure to achieve strength while keeping weight to a minimum. This method is particularly beneficial for applications where buoyancy and resilience to environments are vital. By utilizing lattice structures created with tools it becomes possible to distribute materials in patterns that are not only strong but also efficient leading to improvements, in payload capacity and energy consumption [2].

Topology optimization builds upon this idea by determining the material layout within a defined design space using mathematical calculations based on given load and boundary conditions. It aids in creating AUV components that are optimized for bearing loads and interacting with the environment thereby enhancing the vehicles performance during real world operations.

The use of topology optimization, in designing AUVs can result in creating vehicle shapes and structures that decrease resistance enhance handling and ensure stability across water flow scenarios [3].

In the realm of marine robotics, autonomous underwater vehicles, or AUVs, are a major technological achievement. They provide adaptable platforms for a range of underwater operations without the need for direct human involvement. The first advancements of AUVs were mainly motivated by military uses, including as mine countermeasures, surveillance, and submarine tracking, and may be traced back to the mid-1900s. AUVs can now be used for a wide range of scientific and civilian tasks, including underwater exploration, environmental monitoring, offshore industry support, and oceanographic study.

The incorporation of these design methods, in AUV development does not support the objectives of cutting operational expenses and expanding mission capabilities but also contributes to the broader goal of enhancing marine science and technology. By utilizing lattice and topology optimization AUVs can be tailored to function in extreme depths and conditions pushing the boundaries of ocean exploration and surveillance. This leads to data collection abilities with environmental impact [4].

This segment paves the way for an examination of how lattice and topology optimization can be employed in AUV design with the aim of overcoming existing constraints while leveraging the latest advancements, in computational design techniques.

1.2 HISTORICAL AND CURRENT APPLICATIONS OF AUVS

Autonomous Underwater Vehicles (AUVs) have significantly evolved since their inception, primarily used for simple, repetitive tasks, to becoming sophisticated platforms capable of performing complex, strategic missions that range from scientific research to military applications. The historical development of AUVs marks a trajectory filled with technological milestones that have expanded their utility in exploring one of Earth's final frontiers: the ocean depths.

The first uses of AUVs can be traced back to military applications during the Cold War, where they were employed for reconnaissance and data collection in hostile or inaccessible marine environments (Newman & Sayer, 2004). These early models were relatively primitive, limited by the technology of the era, particularly in terms of navigation and data processing capabilities. However, they laid the groundwork for the diverse applications we see today.

In the realm of scientific research, AUVs have become indispensable tools for oceanographers and environmental scientists. These vehicles are deployed to gather data from the ocean floor, map underwater geographies, and monitor environmental parameters that are critical in understanding climate change, such as temperature and salinity levels at various depths (Yuh, 2000). Advanced AUVs equipped with high-resolution cameras, sensors, and samplers have allowed scientists to reach previously inaccessible areas, such as the depths beneath ice sheets in the Arctic and Antarctic.

Commercially, AUVs are used in the oil and gas industry to inspect pipelines and infrastructure located on the seabed, ensuring their integrity and monitoring for potential environmental hazards. This application is crucial for maintaining the safety standards and operational efficiency required in such high-risk environments. Additionally, AUVs contribute to the installation of underwater structures, where precise placement and detailed surveys are necessary for successful project completion.

Recent advancements have seen AUVs equipped with more complex sensor suites and greater autonomy. These enhancements allow for more detailed and prolonged exploration missions, such as archaeological surveys to locate and study shipwrecks and submerged ruins, providing invaluable insights into human history (Harries et al., 2010). Moreover, the integration of artificial intelligence has enabled AUVs to make real-time decisions during missions, significantly expanding their capabilities and the scope of their applications.

As AUV technology continues to advance, their potential applications expand, pushing the boundaries of what is possible in underwater exploration and operation. The ongoing research and development in optimizing AUV design through lattice and topology optimization are set to further enhance these capabilities, promising a new era of efficiency and effectiveness in autonomous underwater missions.

The significance of optimizing the structure and hydrodynamics in designing Autonomous Underwater Vehicles (AUVs) cannot be overstated.

1.3 STRUCTURAL OPTIMIZATION; ENHANCING DURABILITY AND EFFICIENCY

Optimizing the structure of AUVs is essential to ensure their ability to withstand the conditions of deep-sea environments. By employing lattice optimization methods, it becomes possible to enhance the strength of AUVs while keeping their weight minimal. This does not boost their durability. Also enhances energy efficiency by reducing the strain, on propulsion systems thereby increasing operational capacity and payload capabilities[5].

1.3.1 Hydrodynamic Optimization; Improving Propulsion Efficiency & Maneuverability

Hydrodynamic optimization focuses on refining the shape and external features of AUVs to minimize resistance and improve maneuvering capabilities in water. Through design supported by computational fluid dynamics simulations drag can be significantly reduced, leading to lower energy consumption, and extended operational ranges for AUVs. These optimizations are crucial for tasks requiring agility and speed such, as navigating through obstacles or intricate natural structures [6].

1.3.2 Combining Structural and Hydrodynamic Optimization

Integrating both structural and hydrodynamic optimization ensures that AUVs are not just sturdy and long lasting but also sleek and effective. This comprehensive approach, to designing vehicles allows the creation of AUVs that are tailored for missions, in demanding conditions, were adaptability and efficiencies crucial. By combining optimization techniques from both fields AUVs can handle a variety of tasks efficiently while minimizing their environmental impact [7].

1.4 LATTICE OPTIMIZATION: PRINCIPLES AND APPLICATIONS IN AUV DESIGN

1.4.1 Principles of Lattice Optimization in AUVs

To begin with reducing the amount of material used leads to a vehicle, which can greatly improve power efficiency and extend the AUVs operational range. For example, propeller blades optimized with lattice structures can decrease drag. Enhance thrust efficiency ultimately expanding the AUVs mission capabilities.

Additionally, lattice structures can be engineered to absorb vibrations and impacts compared to materials. This feature is especially valuable for enhancing the durability of AUVs that operate in challenging conditions where encounters with debris or rough surfaces are common. The flexibility inherent, in lattice designs allows for stress distribution thereby bolstering the vehicles resilience and lifespan.

Furthermore, optimizing lattices allows for incorporating functions into AUV components. For instance, these structures can be designed to accommodate sensors and wiring within their geometry safeguarding these parts from pressures and impacts while minimizing space usage.

This method does not simplify the design process but also provides a layer of safeguard, for the crucial electronic systems used in navigation and data gathering [8].

1.4.2 Challenges and Future Directions

Despite its benefits incorporating lattice optimization into AUV design comes with its set of challenges. The intricate nature of creating lattice structures demands an understanding of materials and sophisticated design tools posing obstacles for teams lacking access to such resources. Moreover, the production of lattice structures with the precision required for AUV applications often necessitates cutting edge manufacturing techniques like laser melting (SLM) or electron beam melting (EBM) which are costly and not widely accessible [9].

Nevertheless, the outlook for lattice optimization in AUV design appears promising as advancements in manufacturing technologies drive progress. With the increasing accessibility

and versatility of 3D printing across materials there is a growing potential for integration of optimized lattice structures in AUVs, Research moving forward is expected to concentrate on developing materials tailored for lattice designs to improve both the manufacturability and performance capabilities of AUVs.

Additionally, ongoing advancements in intelligence and machine learning opportunities, for enhancing the design process.

By using these tools such as (NTOP or ANSYS) designers can Enhance the optimization of lattice structures resulting in more effective and creative solutions, for addressing design challenges, in AUVs [10].

1.5 THESIS OBJECTIVE AND STRUCTURE OVERVIEW

1.5.1 Main Goal of the Thesis

The aim of this thesis is to investigate and showcase how lattice and topology optimization methods can enhance the design and performance of Autonomous Underwater Vehicles (AUVs). This study seeks to tackle challenges, in AUV design, such as ensuring durability, hydrodynamic efficiency and advanced features all while maintaining sustainability and cost effectiveness in AUV operations. By utilizing models and optimization techniques this thesis aims to propose innovative solutions that significantly enhance the operational capabilities of AUVs in intricate underwater settings.

1.5.2 Thesis Structure Overview

The layout of the thesis is thoughtfully crafted to lead readers through an exploration of the underpinnings, practical applications, and potential advancements in AUV design optimization.

The thesis is divided into chapters each serving a unique role within the broader research narrative.

Chapter 1; Introduction. This chapter establishes the context for the thesis by highlighting the significance of AUVs, the benefits of optimization methods and the specific objectives aimed at by this research.

Chapter 2; Literature Review. And in-depth analysis of existing studies concerning AUV technology, with a mathematical modeling and background for lattice optimization strategies and topology optimization techniques.

In Chapter 3; Methodology an initial design iteration and a breakdown of the tool’s techniques used for simulations and setups employed in carrying out the study. It delves into how lattice and topology optimization were applied in crafting AUVs.

Moving on to Chapter 4; Results it showcases the outcomes of the optimization experiments and simulations. This chapter scrutinizes how AUV designs have benefited from the optimization methods employed.

Chapter 5; Discussion and Conclusion interprets these results within the context of the research goals and theoretical framework. It explores what these findings mean for AUV design. also gives suggestions for endeavors and practical applications of these discoveries, in real world AUV operations.

2. LITERATURE REVIEW

2.1 EVOLUTION OF AUV TECHNOLOGIES

The progress of Autonomous Underwater Vehicles (AUVs) reflects the growth, in technology and robotics in recent decades. Initially designed as tools for underwater exploration AUVs have evolved into advanced platforms capable of independently carrying out complex tasks in various underwater settings. This section explores the progression, technological innovations, and the expanding roles of AUVs in applications.

2.1.1 Early Development and Historical Milestones

The roots of AUV technology can be traced back to the middle of the century driven by military and research requirements. Early AUV models such as the "Self-Propelled Underwater Research Vehicle" (SPURV) developed by the University of Washingtons Applied Physics Laboratory in the 1950s were basic in design and function. SPURV, among the pioneering AUVs known was crafted for collecting data. Could operate at depths reaching 3,000 meters marking a significant breakthrough in underwater robotics [11].

During the 1970s and 1980s AUV technology progressed further with systems, like the "Autonomous Benthic Explorer" (ABE) developed by Woods Hole Oceanographic Institution.

In the 1980s ABE was created for exploring the sea and included advanced navigation systems and sensors that could gather detailed geological and chemical data from the ocean floor [12].

2.1.2 Expanding Roles and Applications

The development of AUVs has been greatly shaped by progress in technological fields; Navigation Systems; Modern AUVs come with sophisticated navigation systems like Inertial Navigation Systems (INS) Doppler Velocity Logs (DVL) and GPS based surface navigation. These technologies enable AUVs to navigate challenging terrains with precision enhancing their capacity for surveys and data collection missions [13].

Energy Storage and Propulsion; The use of energy storage solutions such as lithium-ion batteries have expanded the operational capabilities and endurance of AUVs. Furthermore, advancements in propulsion systems including thrusters and bio inspired propulsion mechanisms have enhanced the agility and speed of AUVs allowing them to engage in dynamic missions [14].

Sensor Technologies: By integrating high resolution sonar, optical cameras, and a variety of sensors the functionalities of AUVs have been broadened.

These sensors allow underwater autonomous vehicles (AUVs) to create maps monitor the environment and detect objects serving as tools, for scientific studies, resource exploration and environmental conservation [15].

Data Processing and Communication; Improvements in onboard data processing capabilities and underwater communication technologies have boosted the time data collection and transmission abilities of AUVs. Modern AUVs can analyze large datasets onboard. Share their discoveries with surface vessels or shore stations enabling analysis and decision making [16].

The applications of AUVs have significantly expanded alongside their capabilities. In research AUVs are utilized for mapping the ocean floor researching marine ecosystems and monitoring conditions. Their capacity to operate independently for durations allows researchers to collect data from harsh environments aiding our comprehension of the ocean's impact on climate regulation and biodiversity [17].

In the business realm AUVs play a role in the oil and gas sector by conducting pipeline inspections seabed surveys and infrastructure upkeep. Their accuracy and effectiveness make them perfect, for tasks that involve examination and monitoring reducing the need for risky human involvement [18].

AUVs are also increasingly used in defense settings for activities like countering mines, surveillance, and reconnaissance. Their ability to operate discreetly and gather information in challenging environments enhances the awareness of situations and operational capacities of forces [19].

2.1.3 Future Trends and Innovations

Looking ahead the progress of AUVs is expected to continue fueled by advancements in artificial intelligence, machine learning and sensor technologies. By integrating AI and machine learning algorithms AUVs will be able to make decisions to adjust to changing environments and optimize their missions in real time. Furthermore, advancements in materials and manufacturing methods like manufacturing will result in stronger and more adaptable AUV designs [20].

2.2 WEIGHT AND TOPOLOGY OPTIMIZATION

In engineering and design fields, like aerospace and automotive industries and structural engineering sectors weight optimization and topology optimization are frequently employed to enhance the effectiveness and functionality of structures or systems when performance and material efficiency are factors to consider.

2.2.1 Key Concepts in Weight Optimization

Reduced weight optimization involves minimizing the weight of a structure or product without sacrificing its performance or safety standards while enhancing efficiency and functionality in engineering and manufacturing fields for cost savings and better performance outcomes like fuel efficiency, in vehicles.

Creating designs that're both lightweight and structurally efficient involves a comprehensive strategy that incorporates various advanced approaches. To achieve efficiency entails placing materials precisely where required to support the loads and stresses of the component. Choosing materials that're strong yet lightweight. Like composites and specialized alloys. Is essential, for maintaining structural strength while minimizing weight. An integral part of this process is topology optimization which utilizes simulation software to determine the material distribution in a design by eliminating excess material while upholding structural integrity. Moreover, modern manufacturing methods, additive manufacturing (also known as 3D printing) make it possible to create intricate designs that reduce the amount of material used which aligns perfectly with the goal of creating lightweight designs. Finally mathematical optimization methods are used to create a model that minimizes weight while meeting constraints, such as strength and durability standards to guarantee that the design is sturdy and suitable, for its intended purpose.

Achieving the desired weight reduction, in designs without compromising their integrity or performance involves employing various methods, which are commonly utilized in the industry.

2.2.1.1 Material selection and substitution

When aiming for more efficient designs in products or structures development process; the choice of suitable materials plays a crucial role. Opting for materials like aluminium and titanium as well as various composites has become increasingly common to replace heavier alternatives and achieve significant weight reduction without sacrificing performance. Composite materials such as carbon fibre are particularly popular due to their strength, to weight ratios that offer strong structural integrity while effectively reducing overall mass. Moreover¸ sophisticated alloys are utilized for their blend of robustness and lightness¸ rendering them suitable, for uses that call for both endurance and limited weight.

2.2.1.2 Topology optimization

When designing structures to be efficient and lightweight it's essential to optimize the shape by tweaking the geometry to eliminate material while keeping the ability to bear loads in mind. Stress analysis is important well; it helps evaluate how stress is spread out over the structure and highlight areas where material can be trimmed down without sacrificing performance. On top of that generative design uses software algorithms to create designs that're light, in weight and meet performance goals without compromising structural strength.

2.2.1.3 Manufacturing techniques

Cutting edge production methods play a role in crafting designs that are light yet sturdy. Using manufacturing (like 3D printing) intricate and optimized shapes can be crafted with minimal material wastage, perfect for lightweight uses. Thin wall casting permits the creation of parts with walls to lessen material consumption without compromising strength. Moreover, advanced machining techniques, like CNC and precise processes help remove surplus material with precision further aiding in efficient material use and reducing overall weight.

2.2.1.4 Structural optimization

To create structures that're both light and durable various methods are used to optimize their design. One approach is to convert frames or support structures into trusses, which decreases weight without compromising strength. Of using solid materials employ internal lattice structures to make components strong yet lightweight by optimizing the internal arrangement. Furthermore, strengthen areas by adding ribs or flanges strategically to improve rigidity using minimal materials ensuring the structure remains intact while staying lightweight, in design.

2.2.1.5 Use of fasteners and joints

Cutting down on weight frequently means reducing the reliance on conventional fastening techniques like screws and bolts to lessen the overall load by eliminating unnecessary hardware components. Furthermore, opting for welded and bonded joints over fasteners not only decreases material consumption but also results in a lighter design without the necessity for additional reinforcement, around fastener sites. These bonding methods enhance both material utilization efficiency and weight reduction thereby improving the structural effectiveness.

2.2.1.6 Multi-objective optimization algorithms

Optimizing structures involves using sophisticated computational methods to find the right balance between weight and strength as well as other key factors involved in the design process. Genetic algorithms mimic natural selection principles by evolving design alternatives that aim to enhance both weight and strength at the time. Simulated annealing takes an approach to examining different design possibilities systematically in order to refine choices and pinpoint solutions that are lightest, in weight. Moreover, finite element analysis (FE A) is utilized to simulate how a component reacts to forces, vibrations, heat and other factors. This process helps identify where material can be reduced in weight without impacting performance.

2.2.1.7 Shape and size optimization

When it comes to creating structures efficiently and effectively reducing material usage without compromising stability and strength involves tweaking the shapes of beams and support structures in profile optimization processes. In sizing optimization tasks it's all about tuning the dimensions and thicknesses of components while keeping load capacity in check by minimizing excess material. These methods play a role in developing designs that are both light in weight and high, in performance while meeting safety standards effectively.

2.2.1.8 Load path optimization

Structural optimization involves redesigning structures to create efficient load paths for transferring loads effectively and reducing materials in low stress areas without sacrificing strength. Furthermore, placing reinforcements in optimized bracing patterns helps decrease weight and enhance the structures rigidity. These methods work together to ensure the design is both lightweight and robust, by maximizing material efficiency.

2.2.1.9 Redesign for assembly

When it comes to part consolidation in design processes manufacturers often merge components into a single part to lessen the need, for extra connectors and assembly parts. This helps simplify the overall design and minimizes material use. On the contrary modular design focuses on using components that enable only essential parts to be put together during assembly ultimately reducing the overall weight in the manufacturing process. Each of these methods comes with its benefits and is frequently used together to strike the right balance, between weight and cost while delivering high performance to meet both functional and budgetary needs effectively.

2.2.2 Key Concepts in Topology Optimization

Topology optimization represents an approach that takes things to the next level by utilizing computational algorithms to create the best material arrangement in a specified area. It entails identifying the effective form and framework for a component which frequently leads to unconventional designs that excel in terms of both weight and durability.

Analysing the ways forces move through a structure and how stress is spread out within it helps in designing the shape for a part that uses materials efficiently while being strong and rigid, at the same time.

This method frequently leads to creating natural looking designs because the algorithm eliminates material from areas with less stress and strengthens sections that experience higher stress levels. In contrast to design methods that often use standard shapes like geometric forms topology optimization could produce extremely innovative and efficient structures, which are especially beneficial in industries such, as aerospace, automotive engineering, and biomedical engineering where minimizing weight is crucial.

Furthermore, the use of topology optimization frequently pairs well with manufacturing (such as 3D printing) enabling the creation of intricate shapes that would be difficult or unfeasible using traditional manufacturing approaches. Through the integration of topology optimization with fabrication methods engineers can create designs that are lightweight yet structurally sound resulting in enhanced performance lower expenses and increased sustainability, in product development.

The fundamental principles outlined here form the basis for grasping the functioning of topology optimization and its practical use in developing lightweight structures in diverse sectors. These integrated elements position topology optimization as a versatile method, for crafting effective and high performing designs within a range of engineering disciplines.

2.2.2.1 Objective function definition

The goal of topology optimization is determined by the function which can involve minimizing weight or maximizing stiffness. This function guides the algorithm to allocate material efficiently to meet the required performance goals.

2.2.2.2 Finite Element Analysis (FEA)

Topology optimization heavily depends on element analysis (FEA) a simulation method that forecasts how structures will react to different forces. FEA is crucial, for detecting stress distribution in the design and directing the placement of materials to strengthen high stress zones while reducing material usage in low stress regions.

2.2.2.3 Material distribution

When examining the outcomes of element analysis (FEA) topology optimization determines the most effective way to distribute materials by creating intricate structures that resemble organic lattice designs to increase strength and decrease weight efficiently. This optimized arrangement of materials improves performance while conservatively utilizing resources.

2.2.2.4 Iterative design process

Topology optimization involves a process where the design is continuously improved through multiple iterations of adjustments to the shape and structure according to stress distribution and performance criteria to reach an optimal solution step, by step.

2.2.2.5 Constraints and boundary conditions

Constraints are in place to make sure that the design fulfils the needs in actual scenarios like maximum acceptable displacement or stress limits. These boundary conditions such, as fixed supports and load placements determine how the part engages with its surroundings and influence the enhancement process to attain a dependable design.

2.2.2.6 Algorithm choice

In the field of topology optimization different algorithms can be utilized like gradient based methods algorithms and level set methods The selection of the algorithm is influenced by the intricacy of the design where each algorithm has its own advantages such, as speed adaptability or ability to manage intricate non-linear connections.

2.2.2.7 Multi-objective optimization

At times designs need to consider goals such as reducing weight while increasing stiffness. Methods for optimizing objectives enable engineers to factor in these conflicting considerations creating designs that fulfil all necessary requirements, in a harmonious way.

2.2.2.8 Additive manufacturing compatibility

Topological optimization often creates shapes that are well suited for additive manufacturing, like 3D printing enabling the production of complex geometries not easily attainable through conventional techniques. Ensuring designs can be feasibly manufactured from the beginning is key, to bringing optimized concepts to life realistically.

2.2.2.9 Post-processing and validation

After making improvements and carrying out adjustments, like fine tuning and reviewing the setup ensure that the design is feasible and can be manufactured effectively. Additional analysis using virtual simulation software or testing can be carried out to confirm that the design functions as planned and meets all necessary structural and operational criteria.

2.2.2.10 Sustainability considerations

Topology optimization enables design by utilizing essential materials to lower expenses and minimize waste while encouraging environmental consciousness; an aspect gaining significance in industries that value eco-friendly initiatives.

2.2.3 Applications

Both Weight Optimization and Topology Optimization aim to develop efficient and cost-effective solutions, in various industries by minimizing material usage and enhancing performance to improve overall system efficiency significantly when they are integrated together in the design process.

Weight Optimization and Topology Optimization are commonly employed in industries to boost effectiveness and cut down expenses while enhancing overall performance levels. Here is a detailed look, at how they're applied:

2.2.3.1 Weight optimization

Optimization of weight plays a role in different sectors as it greatly boosts effectiveness and cost efficiency levels. In the field of aerospace engineering materials are indispensable, for better fuel economy cutting down operational expenses and upholding the quality, safety and dependability of aircraft structures and parts. In the sector as well as in sports equipment design lightweight materials like aluminium and carbon fibre are employed to enhance fuel efficiency and performance while reducing emissions and ensuring durability and strength in components such, as body panels chassis powertrains bicycles skis and golf clubs contributing to improved agility comfort proficiency of the products

When it comes to consumer electronics like devices and laptops as well as wearables making them lighter helps make them easier to carry around without compromising their durability and features. In construction optimizing weight is used to create structures that lessen the load, on foundations boost energy efficiency and cut down on transportation expenses supporting eco-friendly building methods. In shipbuilding and the marine sector optimizing weight using composites and aluminium alloys boosts fuel efficiency. Enhances vessel performance ultimately reducing operational costs.

Machines in industries like robotics and cranes see benefits from using components that help save energy and enhance their overall performance and manoeuvrability. Weight optimization is crucial in the field for prosthetics and portable diagnostic tools to ensure they are both comfortable and effective. Moreover, in renewable energy technologies like wind turbines and solar panels weight optimization plays a role, in boosting energy efficiency while cutting down material expenses to support sustainable energy efforts even more effectively. Weight optimization is crucial for enhancing the functionality and cost effectiveness of product design and performance, in industries through a range of applications.

2.2.3.2 Topology optimization

Topology optimization is a design tool used in many industries to create lightweight and high performing components without sacrificing structural integrity and efficiency. In the aerospace and aviation sectors specifically topology optimization is utilized to design parts, like aircraft wings, fuselages, and engine components. By allowing for geometries, it helps optimize material usage while ensuring the strength and safety of essential structures are maintained. This ultimately enhances performance and fuel efficiency across the board. Topology optimization is applied in the sector to lighten crucial parts such as suspension systems and engine components to create cars that are both fuel efficient and budget friendly without compromising on safety or performance standards typical, in car design.

Topology optimization is commonly utilized in engineering to design robust support structures like beams and frames with the goal of maximizing material efficiency without compromising strength and stability levels. Particularly beneficial for extensive construction projects such as buildings and bridges in the realm of civil engineering works. Likewise, in manufacturing and product development sectors, topology optimization plays a role in ensuring that components strike an optimal balance, between performance effectiveness while keeping costs and weight considerations in check. This approach is often used for creating enclosures and supports well as structural components in everyday gadgets, like consumer electronics and machinery to address both practical and cost factors that are crucial.

In the field of engineering as well as in defence and military sectors topology optimization plays a crucial role in creating tailored prosthetics and medical devices that are lightweight and functional for patients needs as well as designing military vehicles and weapon components that are strong yet light, for efficient systems. In the field of marine and ship construction this method aids in enhancing parts like hull structures and propulsion systems. It plays a role, in achieving fuel efficiency lower emissions output and overall performance enhancement of marine vessels.

In the realm of sports gear design topology optimization plays a role. It helps create high performing equipment like tennis racquets and racing cars boosting strength and agility for athletes. Topology optimization is also used in the energy and power sector to enhance components, for energy systems like wind turbine blades and solar panel frames. This strategy improves efficiency cuts down on material expenses and boosts the durability of these systems. Topology optimization plays a role in the field of robotics by aiding in the creation of durable yet lightweight robot arms and frames as well, as enhancing mobility and energy efficiency in joints.

Lastly in the field of construction engineering topology optimization is utilized to develop more robust materials for constructing buildings which helps in lessening material consumption and expenses while enhancing structural strength and longevity This results in more eco-friendly building practices by reducing wastage and maximizing resource utilization Topology optimization has demonstrated its versatility and effectiveness across different industries, for creating components that are lightweight yet sturdy thereby enhancing functionality cost efficiency and environmental sustainability

2.3 MATHEMATICAL FORMULATIONS FOR WEIGHT AND TOPOLOGY OPTIMIZATION

2.3.1 Weight Optimization

Reducing weight is about making a structure lighter without compromising its ability to meet performance and safety standards, like strength and stability.

2.3.1.1 Mathematical formulation

Consider a structure made up of discrete elements indexed by i. The mass of each element is defined by:

$$m_i = \rho_i * V_i$$

Where:

- ρ_i: Material density of element i

- V_i: Volume of element i

The total mass M of the structure is the sum of the individual masses:

$$M = \Sigma_i (\rho_i * V_i) \tag{2.1}$$

2.3.1.2 Objective function

The objective is to minimize the total mass of the structure:

$$\text{Minimize} \qquad M = \Sigma_i (\rho_i * V_i) \tag{2.2}$$

2.3.1.3 Constraints

Stress constraint

The stress σ_i in each element should not exceed the material's yield stress σ_{yield}:

$$\sigma_i = \frac{F_i}{A_i} \leq \sigma_{yield} \tag{2.3}$$

Where:

- F_i is the force on element i

- A_i is the cross-sectional area of element i

Deflection constraint

The deflection δ of the structure under the applied load F should not exceed the maximum allowable deflection δ_{max}:

$$\delta = \frac{F}{k} \leq \delta_{max} \tag{2.4}$$

Where:

- F is the applied load

- k is the stiffness of the structure

Material constraints

The material density ρ_i of each element should lie within a valid range:

$$\rho_{min} \leq \rho_i \leq \rho_{max} \tag{2.5}$$

Thus, the optimization problem becomes:

$$\text{Minimize} \quad \Sigma_i (\rho_i * V_i) \tag{2.6}$$

$$\text{Subject to} \quad \sigma_i \leq \sigma_{yield} \quad \delta \leq \delta_{max} \quad \rho_{min} \leq \rho_i \leq \rho_{max} \tag{2.7}$$

2.3.2 Topology Optimization

Topology optimization is a method employed to discover the way to distribute materials in a specific design area while considering factors like external forces and performance goals such as enhancing stiffness by reducing flexibility, focusing on material properties rather than separate components, for a seamless outcome.

2.3.2.1 Mathematical formulation

Let the design domain be represented by Ω, and the material distribution is described by a function $\rho(x)$, where $\rho(x)$ represents the material density at each point x within the domain. The function $\rho(x)$ is constrained such that $0 \leq \rho(x) \leq 1$, where $\rho(x)=1$ represents full material and $\rho(x)=0$ represents void.

The objective in topology optimization is often to minimize compliance C, which is the inverse of stiffness. Compliance is defined as::

$$C = \int_{\Omega} u^T(x)\, K(\rho(x))\, u(x).\, d\Omega \tag{2.8}$$

Where:

- $u(x)$: Displacement field at position x

- $K(\rho(x))$: Stiffness matrix at position x, depending on material distribution $\rho(x)$

- Ω: Design domain

2.3.2.2 Objective function

The objective function is to minimize compliance subject to constraints such as stress and displacement limits:

$$\text{Minimize } C = \int_{\Omega} u^T(x)\, K(\rho(x))\, u(x)\, \mathrm{d}\Omega \tag{2.9}$$

2.3.2.3 Constraints

Volume constraint

The total volume of material used in the design should not exceed a specific fraction V_{max} of the design domain:

$$\int_{\Omega} \rho(x)\, \mathrm{d}\Omega \leq V_{max} \tag{2.10}$$

Where:

- V_{max} is the maximum allowed volume fraction.

Stress Constraints

The stress at any point in the design should not exceed the material's yield stress σ_{max}:

$$\sigma(x) \leq \sigma max \tag{2.11}$$

Displacement Constraints

The displacement at any point in the design should not exceed the maximum allowable displacement δ_{max}:

$$\delta(x) \leq \delta_{max} \tag{2.12}$$

2.3.3 SIMP Approach for Material Distribution

The Solid Isotropic Material with Penalization (SIMP) approach is employed to achieve a smooth material distribution and encourage a clear solid-void structure in topology optimization. This is accomplished by penalizing the material stiffness through the density function, $\rho(x)$, such that the penalized stiffness promotes the intended structural differentiation. The penalized stiffness is given by:

$$K(\rho(x)) = \rho(x)^p * K_0 \tag{2.13}$$

Where:

- K_0 is the stiffness matrix of the base material

- p is a penalization factor (typically $p \geq 3$) to promote a clear distinction between solid and void material.

Thus, the optimization problem becomes:

$$\text{Minimize} \quad \int_{\Omega} u^{T}(x)\,(\rho(x)^p * K_0)\,u(x)\,d\Omega \tag{2.14}$$

$$\text{Subject to} \quad \int_{\Omega} \rho(x)\,d\Omega \leq V_{max} \qquad \sigma(x) \leq \sigma_{max} \qquad \delta(x) \leq \delta_{max} \tag{2.15}$$

2.3.3.1 Mathematical formulation of the SIMP Method

The SIMP approaches rigorous mathematical framework and its capacity to generate designs have established it as a crucial component, in contemporary structural optimization practices that cater to various needs for robust yet lightweight and resource efficient solutions.

In the SIMP methodology the design area is divided into sections called finite elements each, with the ability to possess different densities (or "pseudo densities") to indicate the existence or non-existence of material. The density of each element ρ_e can take values between 0 and 1, where:

- ρ_e =1 represents solid material.
- ρ_e =0 represents void.

However, allowing intermediate values of ρ_e in the range 0< ρ_e <1 enables continuous optimization by loosening the strict binary criterion; this allows for materials to exist in varying quantities rather than just being either present or absent.

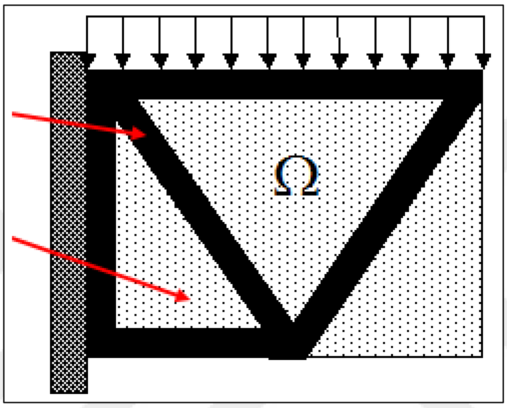

Figure 2.1: The Solid Elements With Densities ρ(e) =1 are Black, Whereas The Void Elements With ρ(e) = 0 Are Removed [4].

The SIMP method implements a nearly binary solution, by penalizing intermediate densities. Based on the density of each element, the stiffness is calculated using a penalization factor p, and the effective Young's modulus $E(\rho_e)$ of each element is stated as:

$$E(\rho_e)= \rho_e{}^{p}\ E_0 \tag{2.16}$$

where:

a. E_0 is the Young's modulus of the base (solid) material,

b. p is the penalization factor, greater than or equal to 3. Higher values of p apply a more solid-void structure by pushing the optimization towards binary density values (close to 0 or 1).

2.3.3.2 Optimization problem formulation

The SIMP-based topology optimization aims to minimize the total compliance of the structure by maximizing its stiffness, subject to constraints on the material volume. The optimization problem is formulated as follows:

Minimize: $C(\rho) = \sum_{e=1}^{N} \rho_e^{\,p}\, u_e^{T} K_e\, u_e$ (2.17)

subject to:

Volume Constraint: $\sum_{e=1}^{N} \rho_e V_e \leq V_0$ (2.18)

Density Constraints: $0 \leq \rho_e \leq 1 \quad \forall_e$ (2.19)

where:

a. $C(\rho)$ represents the compliance of the structure,

b. u_e is the displacement vector for element *e*,

c. K_e is the stiffness matrix of element *e*,

d. N is the total number of elements,

e. V_e is the volume of each element, and

f. V_0 is the total allowable material volume.

The compliance $C(\rho)$ is a measure of the structure's stiffness, and by minimizing it the design gets stiffer. The volume constraint enables the structure to remain within the desired material budget.

2.3.3.3 Iterative approach and convergence

In the SIMP method, the objective function and constraints are calculated by an iterative algorithm to update the density value of each element, until the desired convergence is attained. The compliance gradients and constraints of each element's density are calculated to reach the optimal material layout. As the iterations are calculated each time, the penalization factor p implements a transition towards 0 and 1 densities, leading into a sharper structure with solid and void sections.

2.4 TOPOLOGY OPTIMIZATION: PRINCIPLES AND APPLICATIONS IN AUV DESIGN

2.4.1 Fundamentals and Applications of Topology Optimization

Topology optimization is a method that alters how materials are arranged within a design area to achieve optimal performance based on specific loads and constraints. It plays a role, in enhancing the design of Autonomous Underwater Vehicles (AUVs) in improving structural strength and hydrodynamic effectiveness. By setting a function typically aimed at minimizing compliance to maximize stiffness topology optimization adjusts distribution through iterations resulting in designs that can endure operational pressures while being lighter and more resource efficient.

Figure 2.2: Topology Optimized Bracket [5].

In AUV applications the objective function for topology optimization often focuses on minimizing compliance to ensure the vehicles structure is rigid enough without use of materials.

Through simulations the process of topology optimization updates material distribution to enhance both structural efficiency and operational performance of AUVs.

The practical uses of topology optimization in AUV design are extensive. It significantly impacts the shape of the hull and layout of components enabling features like improved buoyancy, enhanced energy efficiency and increased stability in dynamic underwater environments. This optimization does not enhance attributes but also optimizes positioning and safeguarding critical internal systems such as sensors and batteries for their effective operation, within the optimized framework.

2.4.2 Fundamentals and Applications of lattice Optimization

Lattice optimization is a technique, in engineering that focuses on strategically arranging material within a given design area. The main aim is to create structures that maintain or improve performance by using repeating unit cells or lattice structures of different sizes, shapes and densities. These unit cells form a network that enhances the materials load bearing capacity and strength while reducing its weight significantly [21]

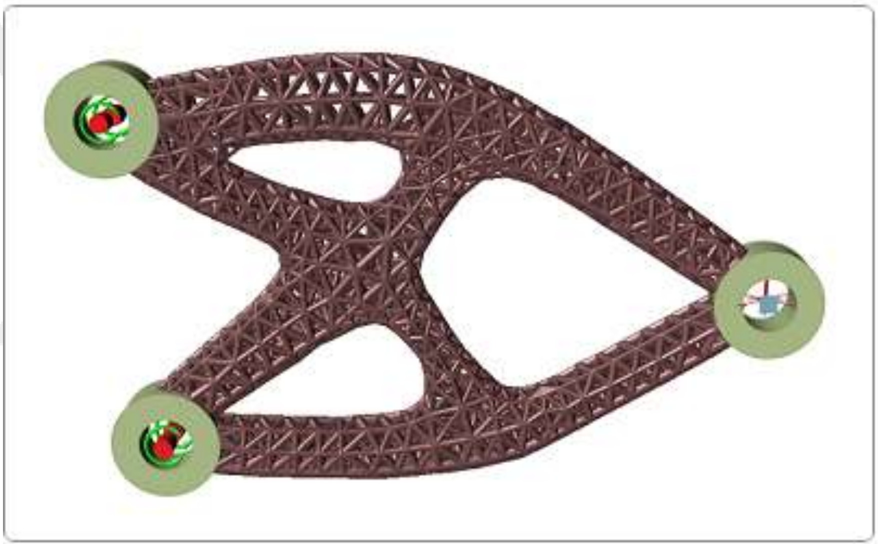

Figure 2.3: Topology & Lattice Optimized Bracket [5].

The mathematical basis of lattice optimization involves utilizing algorithms and computational techniques like the element method (FEM) to simulate and assess how different lattice configurations perform under varying load conditions. The goal function typically seeks to minimize material usage while maximizing performance.

2.4.3 Implicit Surfaces vs. Distance Fields

Implicit surfaces and distance fields are two approaches, to describing shapes in geometry and modeling systems, Implicit surfaces are for example if f(x,y,z)=0 When f is set to zero in this approach it creates representations of shapes and enables mathematical manipulations like combining shapes or finding their intersections or differences simpler to perform. The calculations related to surfaces can become intricate when dealing with tasks such, as determining where rays intersect and changing the surface structure entails adjusting the function that defines it which might not be very intuitive.

On the hand Distance fields or signed distance functions (known as SDF) express shapes by measuring the distance from every space point to the point, on the surface. The function f(x,y,z) calculates the distance. Determines if a point is inside or, outside the surface based on the sign it provides. Distance fields are handy for tasks that involve measuring distances and changing shapes like simulations and collision detection. They work well with both smooth surfaces; however, the accuracy of the representation depends greatly on the resolution of the field itself. Adjustments to the shape can be made by changing the distance function, which can be simpler, for uses compared to modifying surface functions.

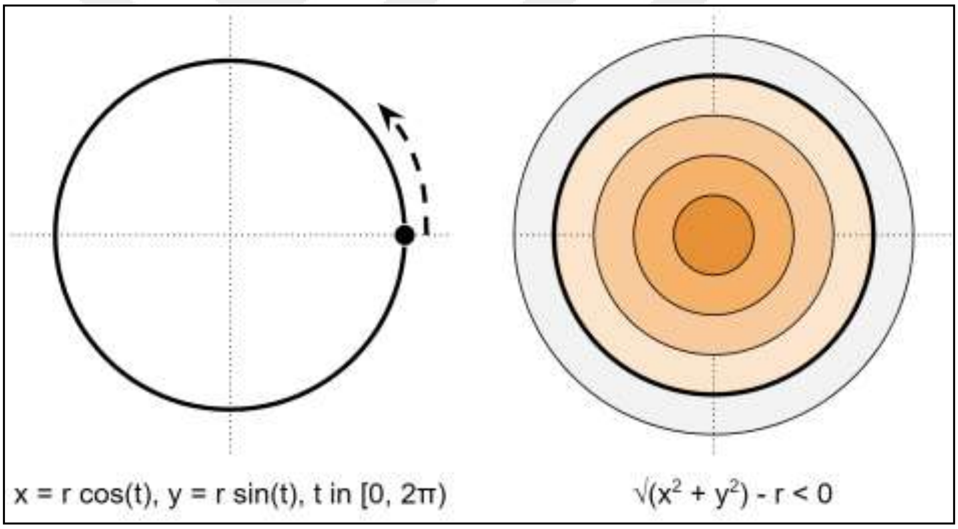

Figure 2.4: A Circle Represented in a B-rep (left) and a Distance Field (right) [6].

When we want to depict a circle as a line, in mathematics or graphics design work for instance, we must outline that boundary using a curve approach where a single variable defines the circles perimeter within a specific range while ensuring the starting and ending points align seamlessly as they form the circles shape. In cases like this one mentioned here with one point to monitor and follow along with the curve creation process is quite simple to understand and implement. However, when dealing with more intricate two-dimensional shapes such, as polygons or irregular forms. it becomes crucial that each starting point of one curve coincides perfectly with the endpoint of the one in order to accurately represent the shape without any gaps or overlaps.

To find the circles distance from a point, outside it; subtract the radius, from the centers distance to get a signed function that serves as a distance field.

The key practical distinction, between these functions lies in the fact that the boundary version solely accounts for data on the circle itself while information regarding all points in space necessitates computation steps. In contrast with the scenario where each point in space's aware of its precise distance, from the nominal surface and thereby offers a more comprehensive perspective of the shape [21].

Table 2.1. Eulerian vs Lagrangian Comparison Table.

	Eulerian	**Lagrangian**
Coordinate System	Global/fixed	Local/moving
Modeling Paradigm	Implicit	Parametric
Transforms	Passive	Active

2.4.3.1 Eulerian (implicit)

The first of these methods, or the Eulerian representation, seeks to describe shapes in terms of the space they embedded in. When combining two mesh spheres using operations a fresh set of vertices, edges and faces emerges. This interconnected structure comprises elements, from both spheres along with components to bridge the gap, between them.

Merging two mesh shapes is straightforward; however, when dealing with lattice structures the process often encounters challenges along the way leading to failure, at times. However, in modeling these obstacles are approached differently.

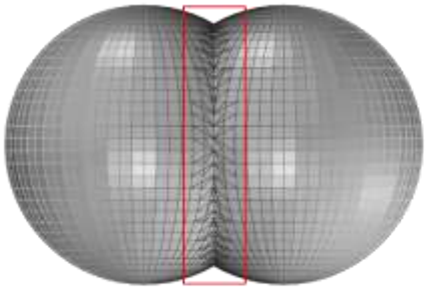

Figure 2.5: Mesh Boolean Union Potential Problem Area.

Seldom lead to failures. Perform an operation of combining two geometries involves extracting the minimum values from overlapping distance fields. Flipping this condition to extract the values, between the fields results in an intersection as illustrated below, where on the left he Boolean union of two fields in nTop, which extracts the minimum values between two fields. And on the right The Boolean intersect of two fields in nTop, which extracts the maximum values between two fields [6].

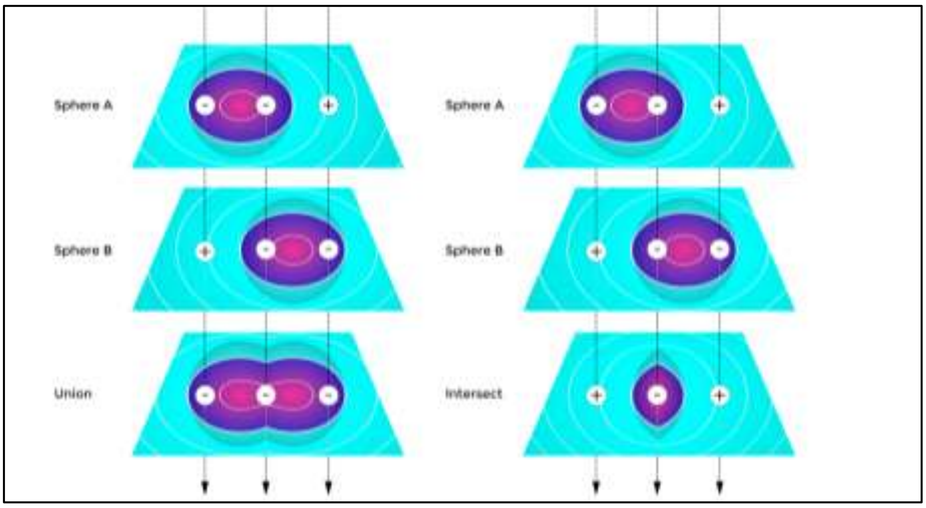

Figure 2.6: N-top Combining Two Geometries Logic

2.4.4 Challenges and Future Directions

Incorporating topology optimization into AUV design comes with its set of obstacles. The intricate shapes that result often demand manufacturing methods, like 3D printing to bring them to life physically. These techniques enable the construction of geometries that traditional manufacturing methods struggle to achieve aligning well with the detailed designs proposed by topology optimization. As additive manufacturing technologies progress they reduce the barriers to implementing optimized designs making them more practical and cost effective for AUV advancement.

Looking towards the future the evolution of topology optimization in AUV design holds the promise of integration of multidisciplinary goals, including considerations for acoustic characteristics, electromagnetic interference, and thermal regulation. Such thorough optimization strategies could transform AUV capabilities enhancing their adaptability to missions and their ability to function in conditions. Researchers are also investigating the potential of machine learning algorithms to boost the efficiency and effectiveness of the topology optimization process further potentially automating parts of the design process and allowing for real time adjustments, during missions.

3. METHODOLOGY

In this chapter, the design process of the AUV will be discussed in detail; the workflow of designing each iteration will be discussed; all the designs and schematics were made by Solid work 2021© or Fusion 360© for designing the propellers PropCad2021© was used.

3.1 DESIGNING WORKFLOW

The design workflow started by Designing by conceptual AUV model and then assigning the requirements and Restrictions of the design and then proceeding with the second iteration that takes those concerns into consideration [9].

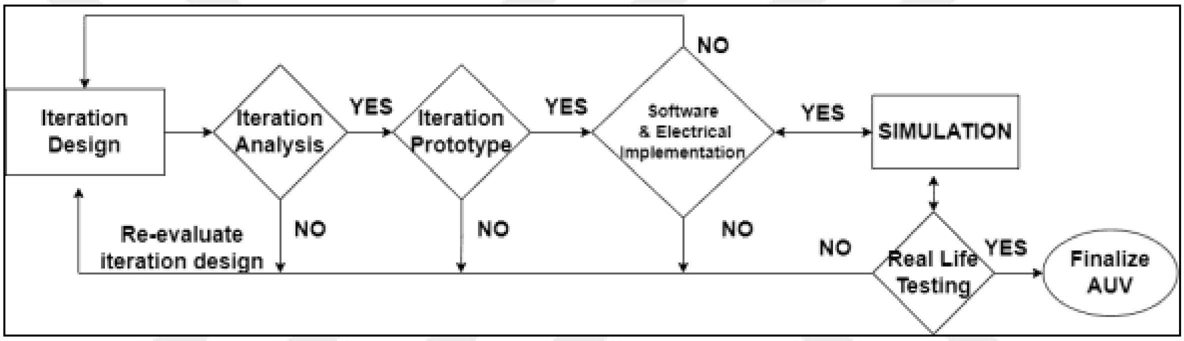

Figure 3.1: Design Workflow Process.

3.2 DESIGN USE CASE.

The main aim of the test designing process was to make a very compact AUV with high manoeuvrability as a base model that can be later on modified to add extra gadgets on top of it.

Using lattice optimization to improve Autonomous Underwater Vehicles (AUVs) structural design and performance is crucial. This optimization approach will maximize AUV potential using N-Topology, Fusion 360, and ANSYS. By utilizing N-Topology's skills in generative design, intricate lattice structures will be created to optimize structural efficiency and minimize material consumption. The lattice layouts will be extensively analyzed using Fusion 360 to verify their structural integrity and performance attributes. By repeatedly refining the lattice structures, we will ensure that they match strict design criteria, guaranteeing the durability and dependability of the final AUV form.

Through rigorous computational fluid dynamics (CFD) simulations, ANSYS will assess lattice configuration hydrodynamic performance. Through the examination of fluid flow patterns and drag coefficients, we will identify the most effective lattice designs to reduce hydrodynamic drag and improve the overall efficiency of autonomous underwater vehicles (AUVs) in underwater environments. During the optimization process, a wide variety of lattice structures and configurations will be investigated, such as regular cubic, hexagonal, Voronoi, and Gyroid structures. Every design will be thoroughly assessed according to its capacity to improve the ratio of strength to weight and minimize hydrodynamic resistance, guaranteeing that AUVs achieve unparalleled levels of performance, durability, and versatility in various underwater missions.

Lattice optimization employing N-Topology, optimizes AUV capabilities. Through the adoption of advanced optimization techniques and the investigation of various lattice configurations, autonomous underwater vehicles (AUVs) would possess improved structural efficiency, hydrodynamic performance, and overall functionality. This development represents a noteworthy achievement in the advancement of underwater robotics.

3.3 DESIGN CONSIDERATIONS.

When designing the AUV, multiple factors that had a higher priority needed to be taken into consideration, such as

3.4 THRUSTERS FRAME CONFIGURATION.

The configuration of thrusters in an Autonomous Underwater Vehicle (AUV) is essential in defining its mobility, propulsive force, and overall performance. Designers can customize the capabilities of the AUV by carefully adjusting the thrusters, considering characteristics such as mobility, stability, and efficiency to fit specific mission needs. Nevertheless, it is crucial to acknowledge that modifying the arrangement of the thrusters inevitably entails making compromises, as specific configurations may forfeit the ability to move in certain directions in exchange for greater thrust power, or vice versa.

A common six prevalent layouts for thruster frames, each possessing distinct advantages and limits gets used. Through the analysis of these configurations, designers can acquire valuable insights into the influence of thruster arrangement on the manoeuvring capabilities and overall performance of the AUV.

The selection of thruster frame configuration is contingent upon several criteria, such as the intended application, surrounding circumstances, mission objectives, and available resources. For instance, configurations that give priority to manoeuvrability may be favoured for activities that necessitate accurate navigation and nimble motion in limited locations or intricate underwater settings. Conversely, systems that are optimized for thrust power may be better suited for missions that require high-speed propulsion for currents.

Designers must meticulously assess the compromises linked to each thruster frame arrangement and choose the one that most closely matches the precise demands of the AUV's intended mission.

Therefore, the arrangement of thrusters in an Autonomous Underwater Vehicle (AUV) is a crucial design factor that greatly impacts its ability to move, stay balanced, and generate propulsive force. Through a comprehensive analysis of the consequences of various thruster configurations and a meticulous evaluation of the associated compromises, designers can create Autonomous Underwater Vehicles (AUVs) that are specifically optimized to outperform in their designated tasks, thereby enhancing the potential of underwater robotics for diverse scientific, industrial, and defensive objectives.

3.5 DESIGN ITERATIONS.

While designing the AUV, multiple iterations were made until the final form was last reached in each iteration that advantages and disadvantages of the design alongside renders will be provided.

Figure 3.2: Design Iteration Process.

3.5.1 Design iterations I

During the first iteration, the main design restrictions were not configured yet; therefore, a simple crab shell-inspired design was modeled to house the motors and electronic components.

Figure 3.3: Bottom Side View Render Of Iteration I.

The first design iteration weighs under 14 kg, emphasizing practicality and simplicity while yet allowing for the inclusion of necessary parts for basic operation. The AUV has four grippers and two cameras in addition to its propulsion system, which improves its sense and manipulation abilities for activities like gathering samples and monitoring the environment.

Even though it's straightforward, this design, which takes inspiration from crab shells, acts as a fundamental prototype for additional optimization and refinement in later generations. Optimizing the AUV's structural efficiency, hydrodynamic performance, cargo capacity, and overall autonomy will involve making tweaks and enhancements as the design process moves along and performance needs are determined.

This initial design iteration will be subjected to extensive testing and assessment in the future to determine how well it performs under various operational settings and environmental constraints.

Figure 3.4: Front Side View Render Of Iteration I.

3.5.1.1 Design iterations I advantages.

Iterative Design I has numerous benefits, starting with its cost-efficiency. This design achieves a substantial reduction in both initial capital expenditure and continuing operational costs by utilizing only three motors. This cost-effective strategy enhances the accessibility of the AUV for research institutes, university laboratories, and organizations with limited budgets, facilitating wider acceptance and application in underwater exploration and scientific efforts.

Furthermore, the AUV's operability is improved by the streamlined movement facilitated by the utilization of three motors. Equipped with an optimized propulsion system, operators may effectively control the vehicle's movements in the water column, encompassing ascent, descent, forward propulsion, and lateral manoeuvres. This simplicity not only improves user experience but also decreases the learning curve for operating the AUV, thereby making it accessible to a broader variety of users with different levels of proficiency in marine robotics and underwater technologies.

Moreover, the decreased intricacy of the design results in streamlined maintenance protocols. By reducing the number of components that need to be monitored and maintained, operators and technicians may perform maintenance duties more easily and efficiently, saving time. Moreover, the reduced probability of motor failures or malfunctions streamlines the process of identifying and solving technical problems, enabling faster resolution of difficulties, and limiting mission downtime. This optimized maintenance strategy improves the dependability and accessibility of the AUV, guaranteeing consistent efficiency and effectiveness in underwater operations.

Furthermore, the reduced complexity of the design contributes to its inherent reliability. By having a reduced number of moving parts and components, the potential sites of failure are also reduced, hence decreasing the probability of encountering technical issues or system breakdowns during missions. The enhanced dependability of this technology is especially beneficial in difficult underwater conditions where there may be limited or impracticable opportunities for maintenance or repairs. By placing a high importance on reliability during the design process, the AUV can successfully achieve its mission goals with minimal interruptions, resulting in improved operating efficiency and higher success rates in underwater exploration and research projects.

3.5.1.2 Design iterations I flaws.

Design Iteration I displayed certain advantages, but also demonstrated significant problems that require attention and thought for improvement. An important drawback was the intricacy of the electrical box design. The complex arrangement of components raised the manufacturing complexity of this design, which could result in production difficulties, higher expenses, and extended lead times. Furthermore, the intricate nature of the system could potentially create weaknesses in terms of wiring, component integration, and waterproofing, which could jeopardize the overall dependability and effectiveness of the AUV. Streamlining the design of the electrical box in succeeding versions would optimize manufacturing processes, decrease production costs, and improve overall durability.

Another recognized drawback was the incorporation of many grippers that were considered superfluous for the intended use of the design. The use of supplementary grippers introduces superfluous mass and intricacy to the AUV, potentially compromising its agility, energy efficiency, and payload capability. Additionally, unutilized grippers might take up important space inside the AUV, which can hinder the integration of other crucial components or decrease overall efficiency. By reassessing the need for several grippers and adjusting the payload arrangement accordingly, the AUV can attain a more efficient equilibrium between functionality, performance, and resource utilization.

To enhance the effectiveness, efficiency, and dependability of the AUV, it is crucial to rectify these shortcomings in future design iterations. Designers can improve manufacturing feasibility, expedite operation and maintenance, and maximize the overall performance capabilities of the AUV by simplifying electronic box design, eliminating extraneous components, and optimizing payload arrangement. By continuously improving and optimizing the design, the defects in Design Iteration I can be successfully reduced, allowing for the creation of more durable, economical, and efficient autonomous underwater vehicles that are specifically designed to meet specific mission needs and operational conditions.

3.5.1.3 Design iterations I thruster's configuration.

This configuration has the most straightforward thruster's configuration, even though this iteration includes four servo motors to control the mechanical grippers. The green Thruster in the picture indicates counter-clockwise propellers while the blue thrusters indicate clockwise propellers; even though this configuration removes a lot of the complexity of the AUV, it limits its movement [13].

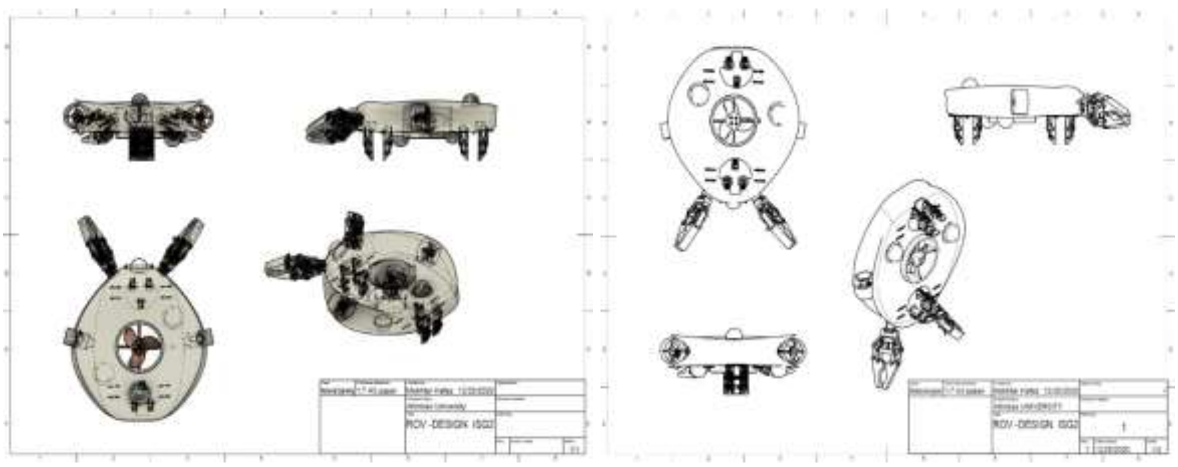

Figure 3.5: Design Schematics Of Iteration I.

3.5.2 Design iterations II

In the stage of designing revisions a sleek electronic casing was created taking cues from the shape of a manta ray. This design was selected to improve the sealing process and make manufacturing easier. The organic and fluid form of a ray strikes a balance, between beauty and practicality providing a structure to accommodate electronics with smooth curves ideal for underwater uses such, as AUVs.

3.5.2.1 Design iterations II advantage

The benefits of this design are plentiful. To start with its shape reduces water resistance, which helps the AUV move smoothly underwater. The rounded structure also simplifies the sealing process making it less likely for water to leak and enhancing the AUV durability under pressure. Moreover, the sleek and natural shape reduce the detection of the shape under water and can help the AUV blend in with environment. Furthermore, internally the design allows for use of space enabling arrangement due to the Cylindrical electronic box design that spread the components, enhancing heat dissipation.

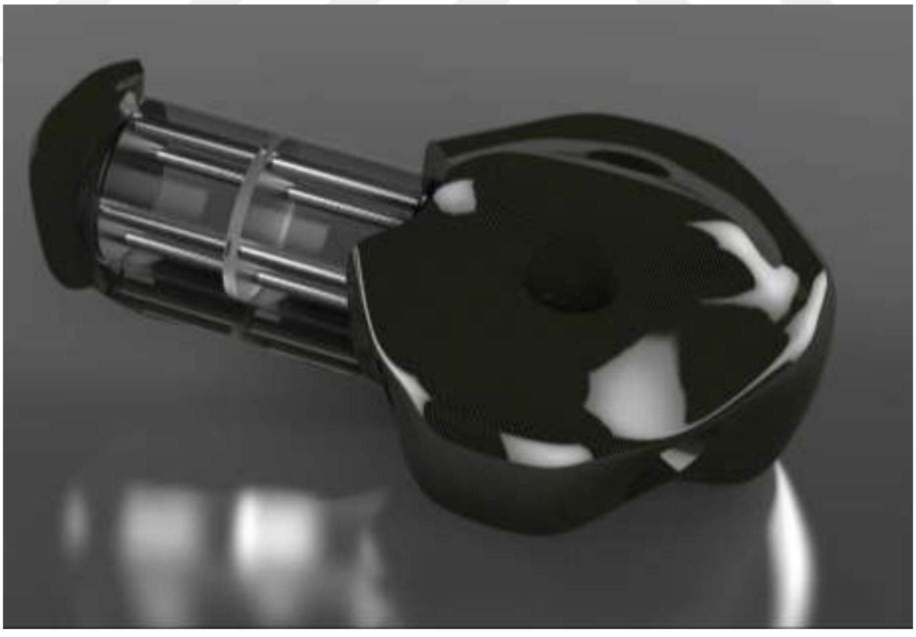

Figure 3.6: An Isometric View Render of Iteration II.

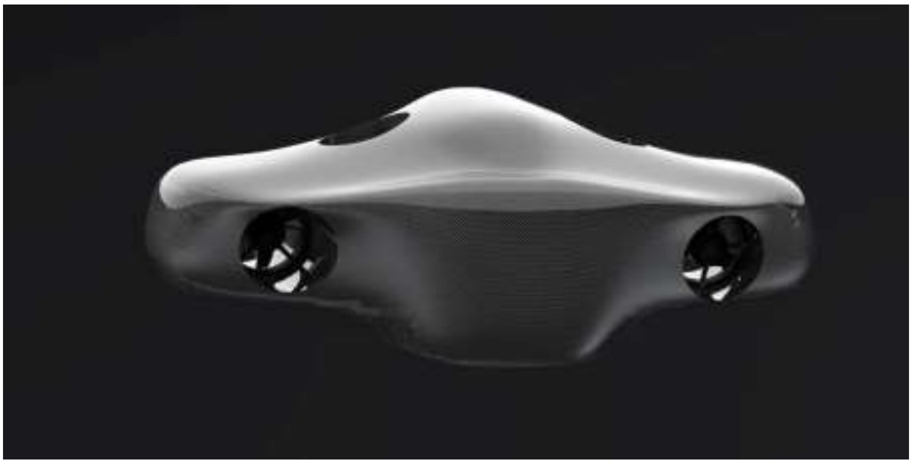

Figure 3.7: Front Side View Renders Of Iteration II.

3.5.2.2 Design iterations II disadvantages

Nevertheless, there are drawbacks, to the design inspired by rays. Despite the shape contributing to hydrodynamics, it might hinder the inclusion of sharp corners or edges necessary for specific mounting and integration needs. Furthermore, the distinctive form could present difficulties for manufacturers to biomimicry-based designs resulting in the need for production methods that may increase costs, in certain scenarios. This design was relatively big with a wingspan around 70 centimetres and a big frontal surface area which could produce much drag and vortexes; furthermore, there was no proper placement for the camera yet.

3.5.2.3 Design iterations II minor modifications.

In the design update, for the AUV (underwater vehicle) a small change was implemented to the front part of the vehicle to improve its movement in water by making it more streamlined and reducing drag as it navigates through aquatic environments This adjustment was crucial for enhancing the efficiency of the AUV and enabling it to glide through water with less resistance while also lowering its drag coefficient, which is a vital measure of resistance, by around 11%. The decrease, in resistance makes it easier for the AUV to save energy and travel distances on the power supply while also enabling it to conduct extended missions, with reduced energy usage.

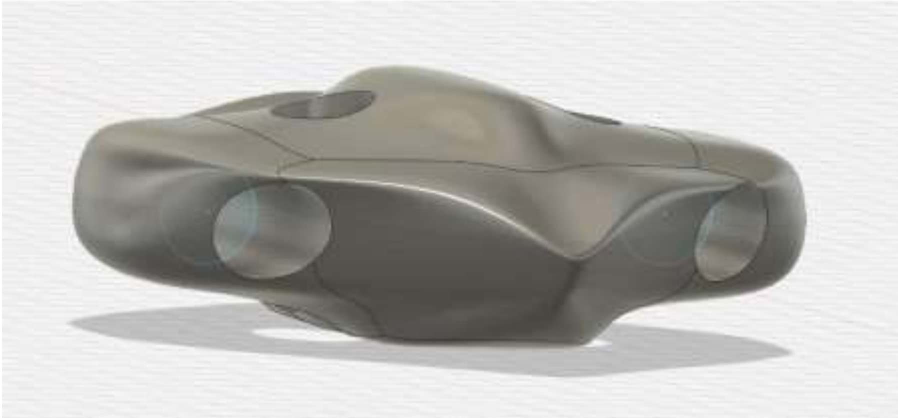

Figure 3.8: In Minor Frontal Modification On Iteration II.

3.5.2.4 Design iterations II thrusters' configuration

In this setup design, for the AUV (Autonomous Underwater Vehicle) the thrusters have been strategically positioned to enhance its manoeuvrability while keeping the system straightforward and effective. The inclusion of a thruster enables the AUV to handle weight without sacrificing its capability to execute intricate manoeuvres like rolling. This feature proves advantageous, for tasks demanding increased agility and accuracy. The thrusters are color coded for identification; green signifies counter propellers while blue indicates clockwise rotation. They are placed strategically to maintain balance and stability during operation. This propeller arrangement, in both directions helps the AUV maintain precise movements when carrying heavier loads. Perfect for missions that need enhanced performance without adding complexity to the design or control systems [14].

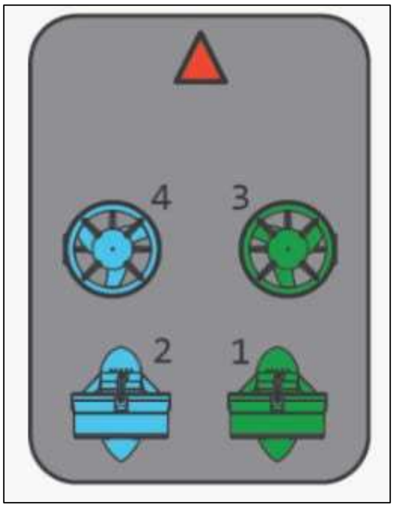

Figure 3.9: Iteration II Thrusters Configuration.

3.5.3 Design iterations III

During the round of design improvements, for the AUV (Autonomous Underwater Vehicle) adjustments were made to enhance efficiency and user friendliness by reducing its size and refining its features further. One notable improvement was the incorporation of a box to facilitate convenient storage and easier access during maintenance or part replacements. A significant upgrade included adding a dome over the camera to ensure performance of the image processing systems. This protective cover did not shield the camera. Also minimized distortion and interruptions, during underwater tasks. The smaller version of the design kept the features while focusing on enhancing how easily the AUV can move and adjust in different underwater settings.

3.5.3.1 Design iterations III advantages

This design has benefits noting; the retractable electronic compartment simplifies maintenance and lowers the chances of damage, in tight spaces during transportation or operation; moreover, the dome guarantees a clear and uninterrupted view for the camera to process images efficiently. A critical feature for tasks such as navigation or object recognition; lastly, by downsizing the design it enhances maneuverability and energy efficiency of the AUV leading to longer mission time and decreased operational expenses. The smaller size of the AUV also allows it to be used effectively in spaces, like caves or when exploring wreckage sites, with limited room available.

Figure 3.10: An Isometric Realistic Render Iteration III.

3.5.3.2 Design iterations III flaws

Making the design very compact meant there would be some compromises on the AUV performance since the tunnels of vertical thrusters are necked down in the middle to provide clearance for the design. The design could be furthermore streamlined to reduce the drag; this design had no proper cable management for the thrusters cables.

3.5.3.3 Design iterations III schematic

That circle and the schematic show us the retractable electronic Tube that has a

diameter of 110 millimetres and 2 separate flanges to seal it.

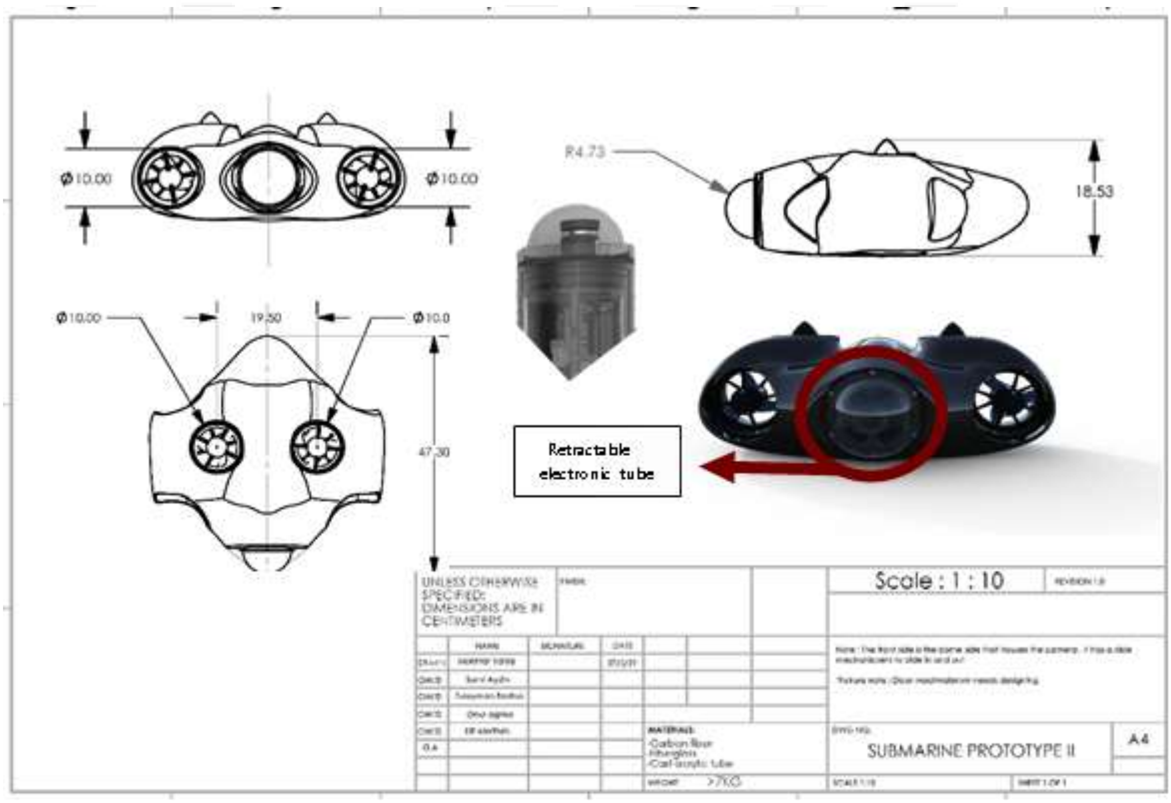

Figure 3.11: Design Schematic Of Iteration III.

3.5.3.4 Design iterations III thrusters configuration

In this version of the design plan, for the AUV (Autonomous Underwater Vehicle) it keeps the thruster setup consistent with what was used in the iteration (Iteration II). This setup involves arranging thrusters to improve the AUVs movement capabilities effectively. By adding a thruster to the mix now allows the AUV to carry weight without losing its ability to move swiftly and flexibly like before. The additional thruster enables movement for the AUV and gives it improved control over its rotation movements, especially handy when it needs to make precise turns or adjustments, in navigation and positioning scenarios.

This setup guarantees that with the load, on board the AUV can stay steady and execute intricate movements like rolling smoothly – a crucial ability, for underwater tasks demanding adaptability and precision control.

Figure 3.12: An Isometric Render Of Iteration III.

3.5.4 Design iterations IV

During this iteration, a new approach was taken, a hybrid open/closed shell design was made that includes 6 thrusters to increase the ease of manoeuvrability. The cockroach is an insect that has evolved to thrive in habitats, with its body shape that enables quick movement and manoeuvrability in confined spaces. Its segmented body with a profile reduces drag. Facilitates easy navigation, through narrow openings. Furthermore, the cockroaches sturdy yet lightweight exoskeleton offers protection without adding weight. Integrating these characteristics into the design of an AUV could offer advantages.

The divided body structure would reduce resistance. Enhance the AUVs manoeuvrability, in water. The sleek design would enable the AUV to navigate passages and reach spots, to larger vehicles. The exoskeleton like shell would offer protection while keeping weight to a minimum enhancing the AUVs effectiveness and prolonging its duration.

Figure 3.13: Cockroach – AUV Biomimicry.

Moreover, the cockroach has hairs on its body that aid, in its navigation which could serve as a model for where to place sensors on the AUV. The cockroach also exhibits a level of redundancy in its body structure enabling it to continue functioning even if one part fails. This characteristic could be integrated into the design of the AUV offering a mechanism for components, like propulsion and navigation systems.

Henceforth incorporating biomimicry into design leads to creating designs that're both efficient and effective, in natures image. The structure of a cockroach serves as an illustration of a versatile design that can be translated into the creation of an Autonomous Underwater Vehicle (AUV).

Introducing elements like a body shape with a profile and drawing inspiration from the exoskeleton for its shell design along, with incorporating redundancy and strategic sensor placement would yield substantial advantages in enhancing the AUVs performance and operational capabilities.

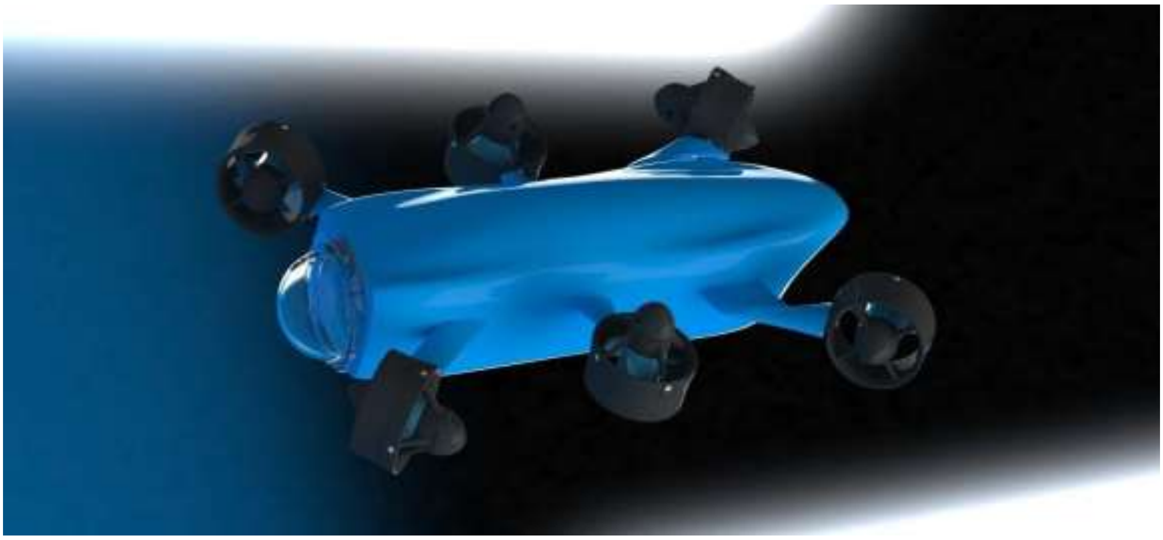

Figure 3.14: Design Iterations IV Render With a PLA Body, Without The Frontal Cover.

3.5.4.1 Design iterations minor modification IV

In this minor modification, a frontal plexi-glass cover that could be manufactured using a mold was designed to reduce the drag of the shell while still not obscuring the camera.

3.5.4.2 Design IV flaws

The main flaw of such a design is this their size look at compared to the previous design. It has a bigger footprint. Furthermore, the addition of the extra two thrusters adds around an extra kilogram to the total weight of the AUV and increases the complexity and count of the components.

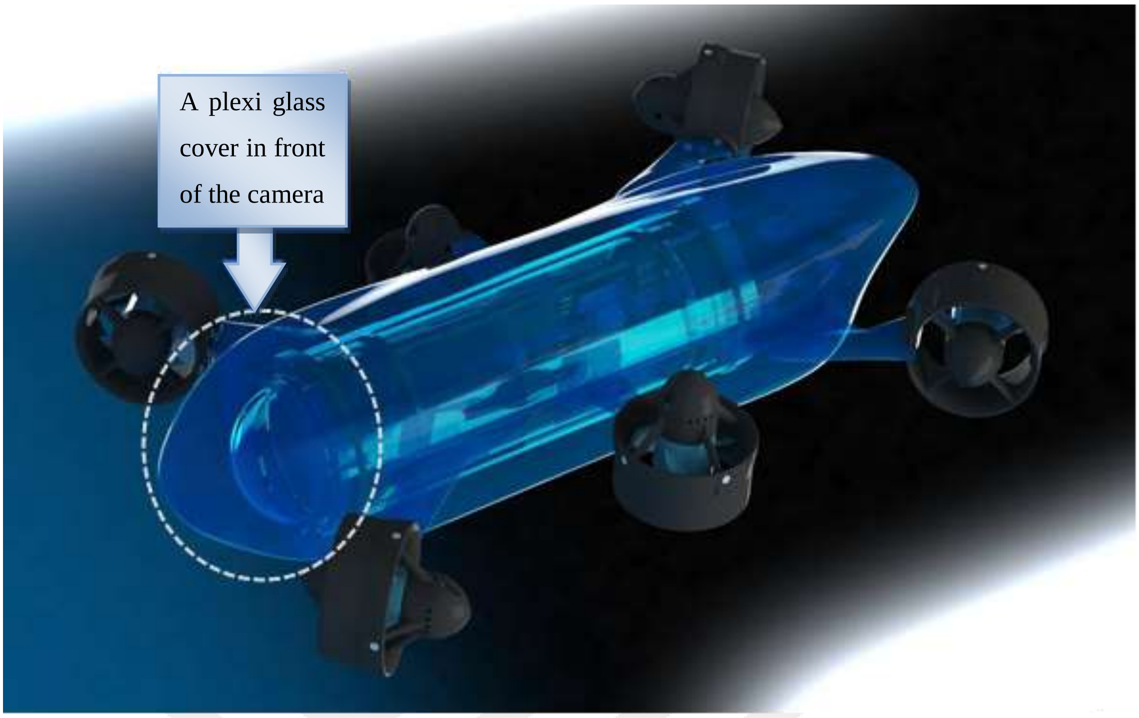

Figure 3.15: Design Iterations IV Render With a Transparent PLA Body And Clear Cover.

3.5.4.3 Design IV Schematic

In this setup the AUV comes with six vectored thrusters, for manoeuvrability and a strong thrust to weight ratio without achieving six degrees of freedom (known as 6 DOF) as it lacks the ability to pitch specifically; however, it can move precisely in any horizontal direction thanks to these thrusters help. The extra thrusters provide control allowing the vehicle to rotate more accurately compared to a typical configuration, with only four thrusters. In situations where quick and precise movement are essential, like navigating through spaces, this arrangement is found advantageous because it enables smoother side to side and rotational motions even though there are restrictions, on upward or downward tilting.

The High thrust, to weight ratio of this setup guarantees that the AUV stays nimble and adaptable when carrying loads and making sudden turns effortlessly possible. A valuable trait for tasks such, as underwater surveys or research expeditions that demand swift manoeuvrability amidst challenging conditions and obstacles alike.

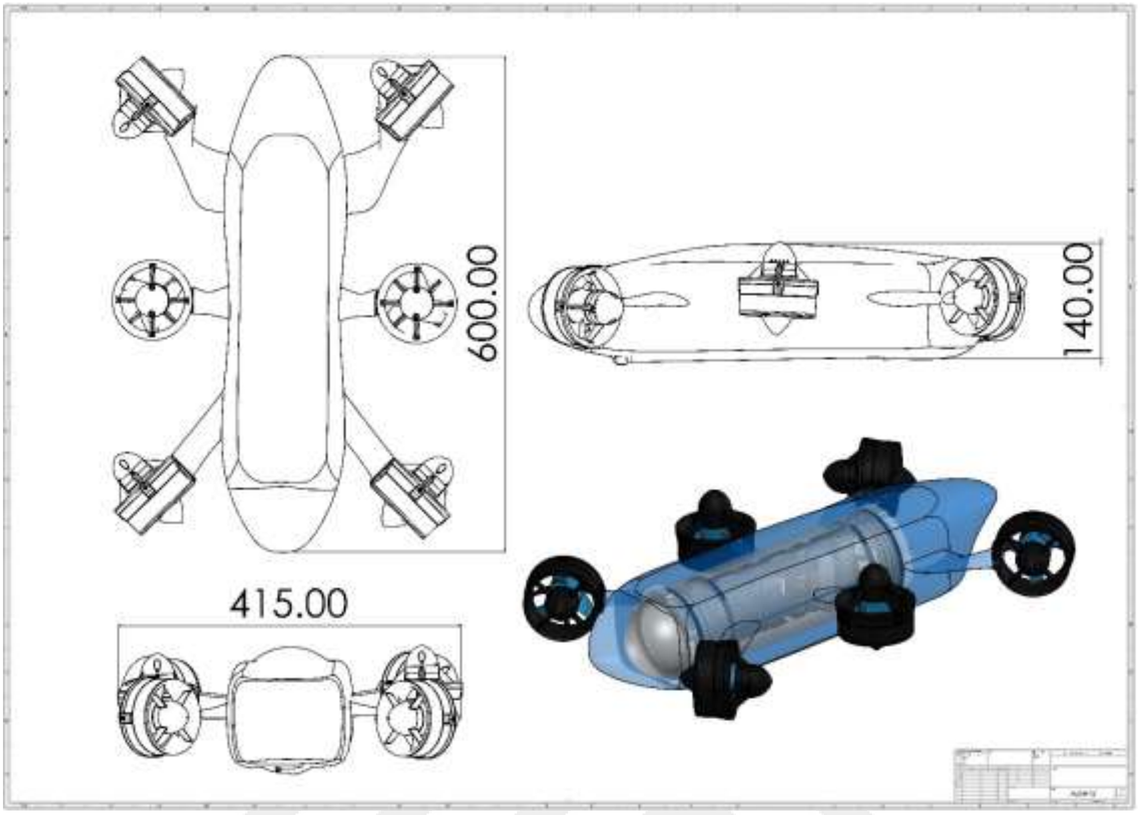

Figure 3.16: Design Iteration IV Schematic.

Yet the AUV faces constraints in its mobility due to its inability to pitch effectively; this hinders its capacity to tilt forwards or easily and may impede thorough exploration of intricate underwater landscapes or vertical navigation in tight spaces.

Nevertheless, the systems thrust, and rotational velocity render it exceptionally efficient, for horizontal and rotational operations, presenting a substantial enhancement compared to more basic setups.

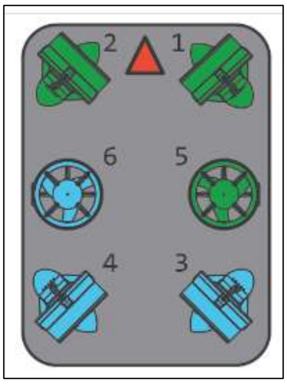

Figure 3.17: Iteration IV Thrusters Configuration.

3.5.5 Design iterations V

During this final iteration, many of their concerns were solved, such as having separate tunnels designed for cable management, while maintain the electronic tube shown in figure 3:19, and by adding tunnels for the thrusters, the water flow for the thruster the efficiency & manoeuvrability of the design is increased.

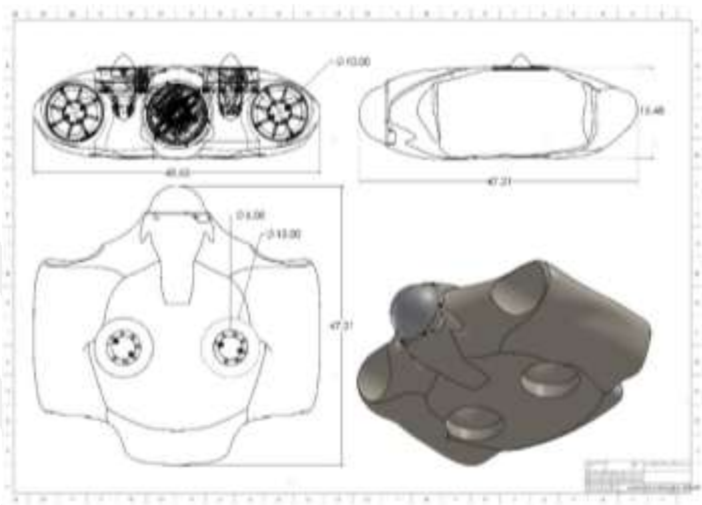

Figure 3.18: Iteration “V” Schematic.

Figure 3.19: Design Iteration V.

3.5.5.1 Design iterations V advantages.

This shell remains relatively simple; therefore, it can be manufactured easily either by Directly 3D printing it or creating a mold and using it today carbon fiber. It also shells out all the components and has cable management tunnels. It also features a removable magnetic back cover that has also been added to the design that makes the design easier to maintain.

3.5.5.2 Design iterations V flaws.

Making the design compact meant that some compromises were made on the performance of the vertical Thruster since the tunnels were necked down to provide clearance for the design.

3.5.5.3 Design iterations V electronic tube

The cylindrical Tube becomes a very logical shape to use for an underwater electronic box since it does not have many edges and with a simple, easy ceiling m it has double O-ring flanges from each end caps the holes made on CNC aluminium flange for cable connector.

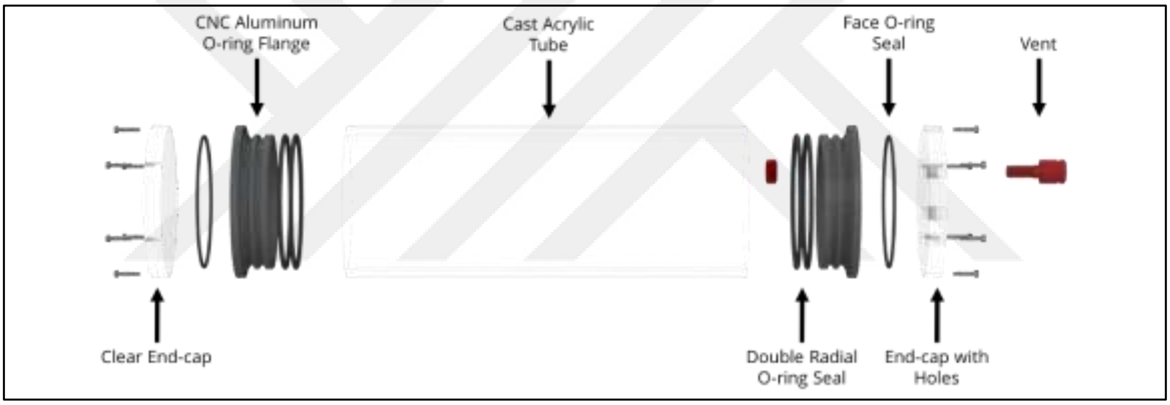

Figure 3.20: Electronic Tube.

3.5.5.4 Design iterations V thruster configuration.

In this iteration, the design shares the same thrusters configuration of iteration III, which by adding the extra thruster number 4, the AUV can carry extra weight while being able to roll.

3.5.5.5 Design iterations V flange design.

In order to design A proper watertight flange for the electronic box, proper O-ring calculations need to take place first. In this case, the O-ring dimensions and calculations were completed, and the flange must have a pathway for the compressed air to leave when inserting the flange in two the electronic cube; and the flange can then have multiple back covers based, needs, for example, a dome can be installed on the flange or in this case a back cover with seven differently sized holes can be found for the electric penetrators

Figure 3.21: Flange & Penetrators Back Cover.

3.5.5.6 Design iteration V prototype.

After the design was finalized, an initial prototype was manufactured to assess the usability of the design and evaluate its manufacturability, Figure 3:22 shows the completed prototype and figure 3:23 illustrates the electronics tube & avionics.

Figure 3.22: A Functional Pre-Optimization Iteration-V AUV Prototype.

3.5.5.7 Design iteration V avionics.

The avionics system of the Autonomous Underwater Vehicle (AUV) was initially designed around a Pixhawk flight controller shown in figure 3:23, a widely used open-source autopilot platform known for its reliability in autonomous navigation tasks. To handle onboard processing and higher-level control, a Raspberry Pi 3+ was integrated into the system. The Raspberry Pi provided sufficient computational power for tasks such as basic sensor data processing, communication, and system monitoring. However, as the AUV's requirements for real-time image processing and advanced computer vision tasks grew, the avionics system was upgraded to a more powerful Jetson Xavier NX. This upgrade was critical in enhancing the system’s image processing capabilities, enabling the AUV to perform more complex tasks such as object detection, obstacle avoidance, and environmental mapping using zed stero camera, which are crucial for autonomous underwater navigation [7].

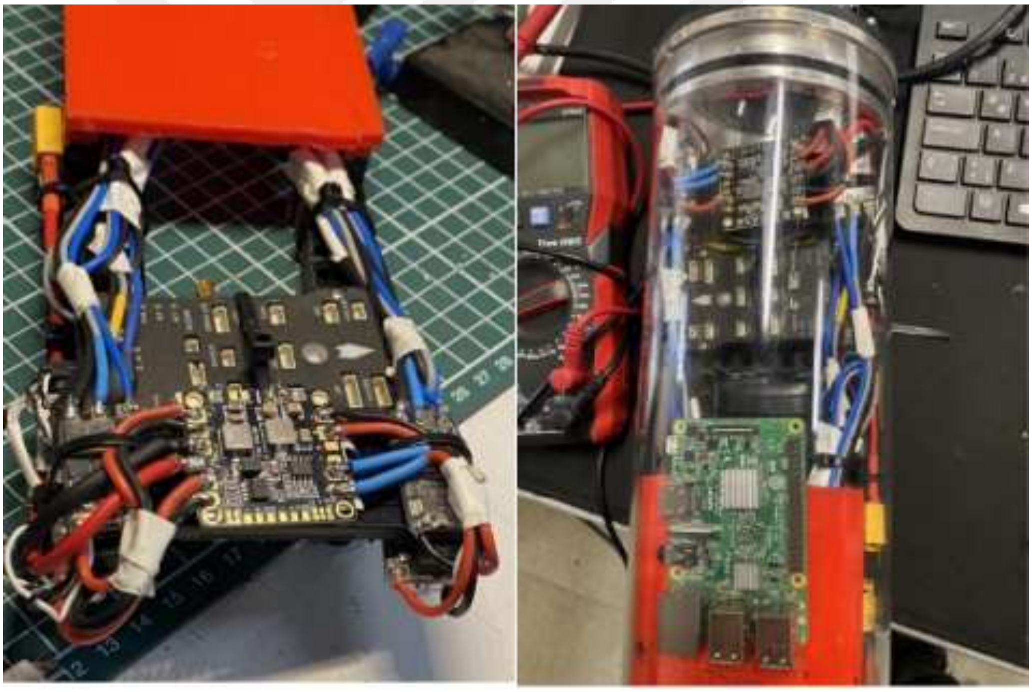

Figure 3.23: AUV Iteration V Electronics Tube.

For power management, the AUV was equipped with a power distribution board (PDB) that regulated power delivery from the onboard 6S 10,000mAh lithium polymer (LiPo) battery. This battery was selected to provide a high capacity, allowing the AUV to operate for approximately one hour under low-load conditions, the hardware was critical in meeting the power and computational demands of the AUV during missions in complex underwater environments [8].

3.6 MECHANICAL ANALYSIS

In The AUV design, the resistive force, also known as the drag force, started converging after around 250 running cycle s. The resistive force value is calculated as approximately 10N and is presented in Figure 42. Since the AUV is symmetrical, the design was sliced down in the symmetry line; therefore, the results show only half of the drag force. The resistive force started converging after around 300 running cycle s. The resistive force value is calculated as approximately 4.2N and is presented in the Figure 42 below.

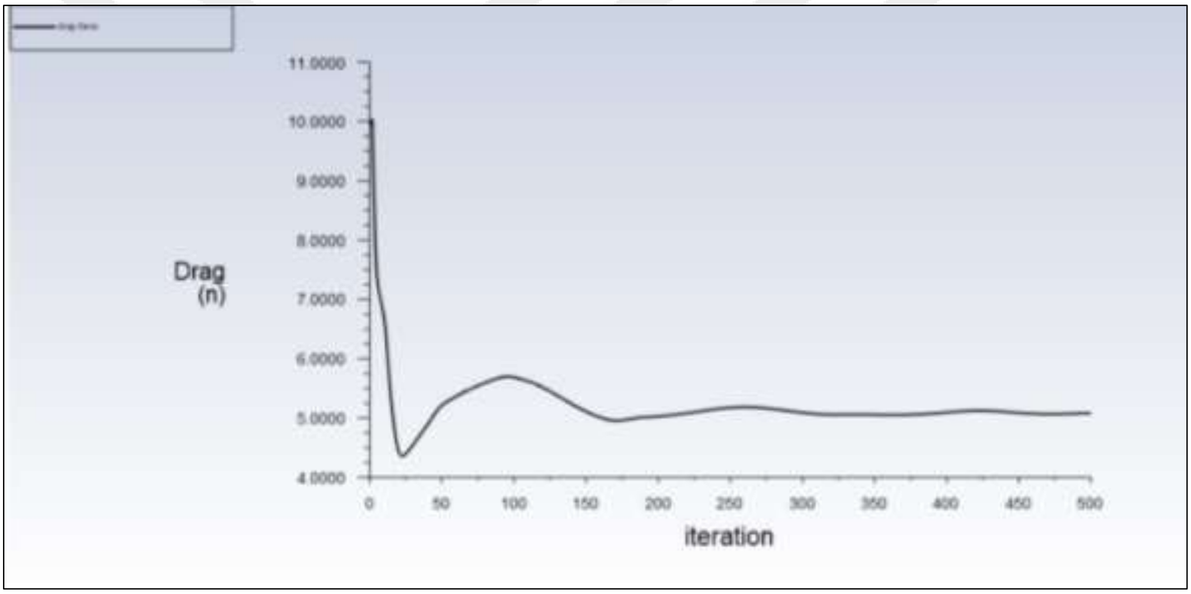

Figure 3.24: Drag Force to S graph, Resistive Force = 10.16 N.

In the following figure, the graph shows the relation between the drag coefficient and the convergence, which occurs after around 250 s to yield a cd of around 0.41, which is relatively high, even though for such a small-sized AUV, it would not have as big of an impact, since the drag force has an effect of only 10N on the body, having a good, streamlined design.

In below Figure, the Horizontal velocity streamlines are shown where the speed of the water was determined as 1.5m/s.

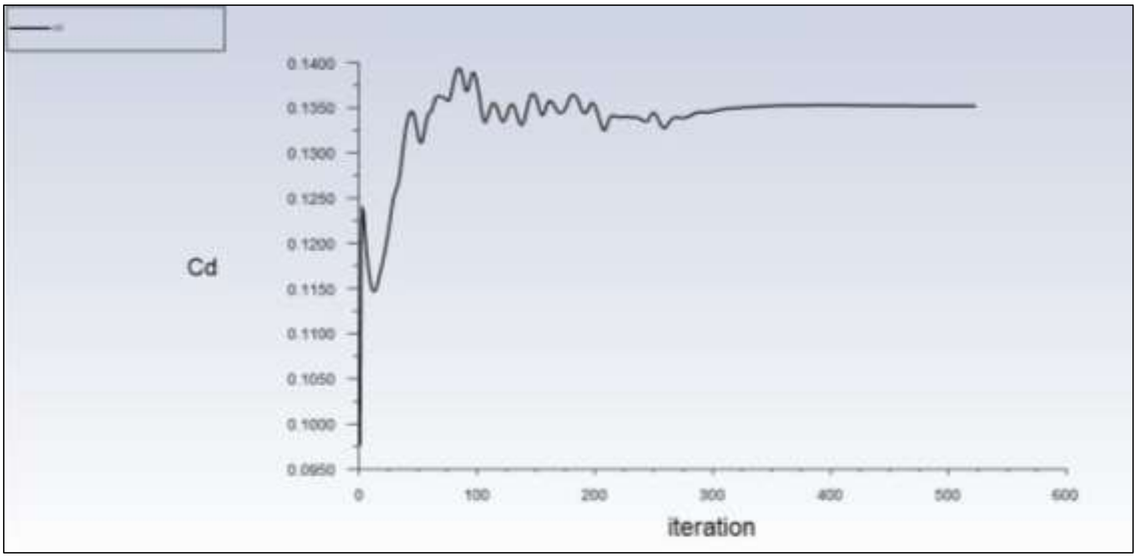

Figure 3.25: Drag Coefficient to S Graph V" ,Cd = 0.132.

Since the AUV is symmetrical, the design was sliced down in the symmetry line; therefore, the results show that only half of the drag force, In the following figure, the graph shows the relation between the drag coefficient and the convergence, which occurs after around 350 s to yield a cd of around 0.132, which is considered low.

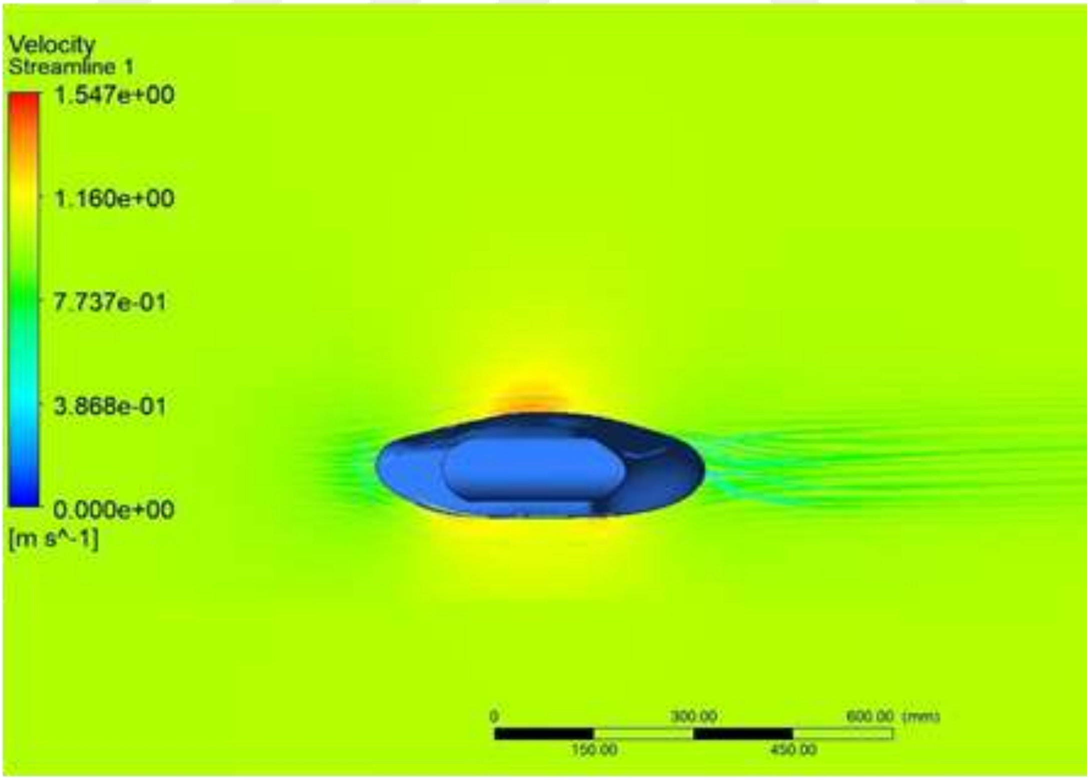

Figure 3.26: Streamline Cross Section Analysis.

A drag force equation can be used to predict the drag force experienced by an AUV as it moves through the underwater environment to recheck the CFD results, The drag force acts in the opposite direction to the AUV's motion and affects its speed and energy consumption where :-

$$F_d = \frac{1}{2}\rho v^2 C_d A \tag{3.1}$$

F_d is the drag force, measured in N (Newtons)

ρ is the fluid density, which in the case of an AUV in water is the density of water, measured in kg/m^3

v is the velocity of the AUV, measured in m/s

C_d is the drag coefficient, a dimensionless number that depends on the shape of the AUV and the roughness of its surface, as well as the fluid's viscosity

A is the reference area, which is usually taken as the cross-sectional area perpendicular to the direction of motion.

Given the density of water as 1000 kg/m^3, the drag coefficient of a half sphere as 0.47, the reference area as 0.0217 m^2, and the velocity as 1.5 m/s, the drag force experienced by an object in an underwater environment can be calculated as follows:

$$F_{drag} = \frac{1}{2} \cdot 1000\ \text{kg/m}^3 \cdot (1.5\ \text{m/s})^2 \cdot 0.47 \cdot 0.0217\ \text{m}^2 = 11.33\ \text{N}$$

Using the simplified equation as a reference , it can be concluded that the results found using the computer fluid analysis of 10.16 N is within a 10% error of the simplified equation results therefore we can approve the CFD analysis , further more the result are there since the exact AUV frontal cross section was not taken , but rather a rough area estimation , and the C_d “drag coefficient,” of half a sphere was taken since it had the closest resemblance to the AUV shape In conclusion, the drag force equation can be applied to AUVs in underwater environments to predict the drag force experienced by the vehicle as it moves through the fluid. Therefore, after the initial design validation and fluid analysis the design is ready for topology-lattice optimization [15].

Based on the static stress analysis results , a displacement heat map was generated in order to determine the weight reduction areas

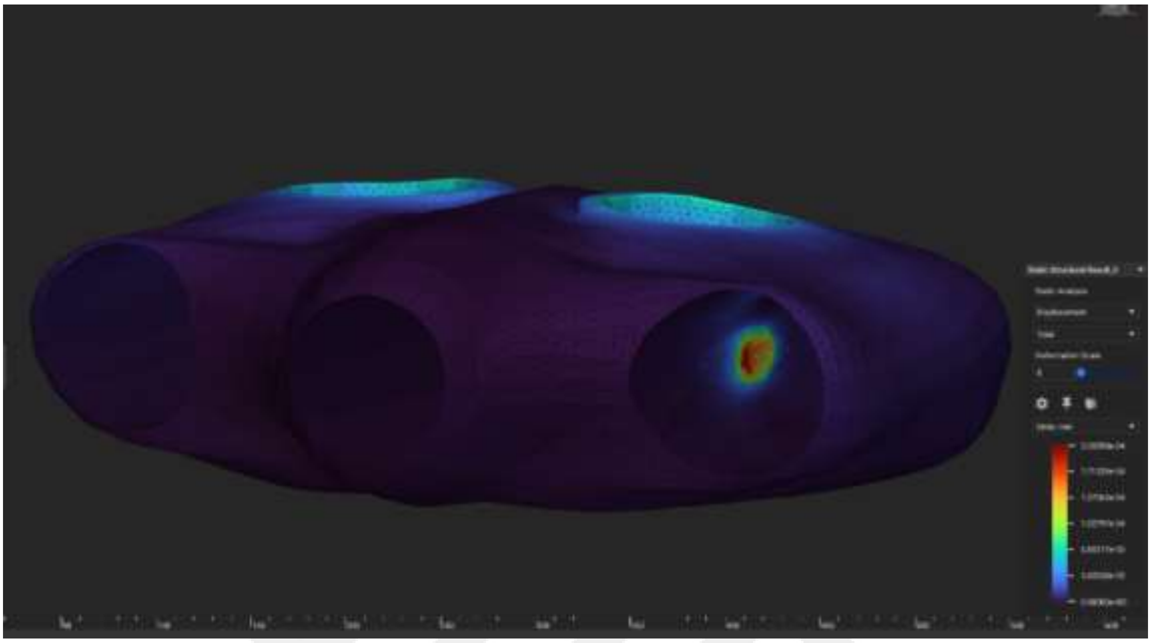

Figure 3.27: Static Analysis Displacement Results.

An extreme 85% reduction model shown in figure 3:25 was generated in order to study the design limits which was replaced later on by a more practical model later shown in figure 3:26

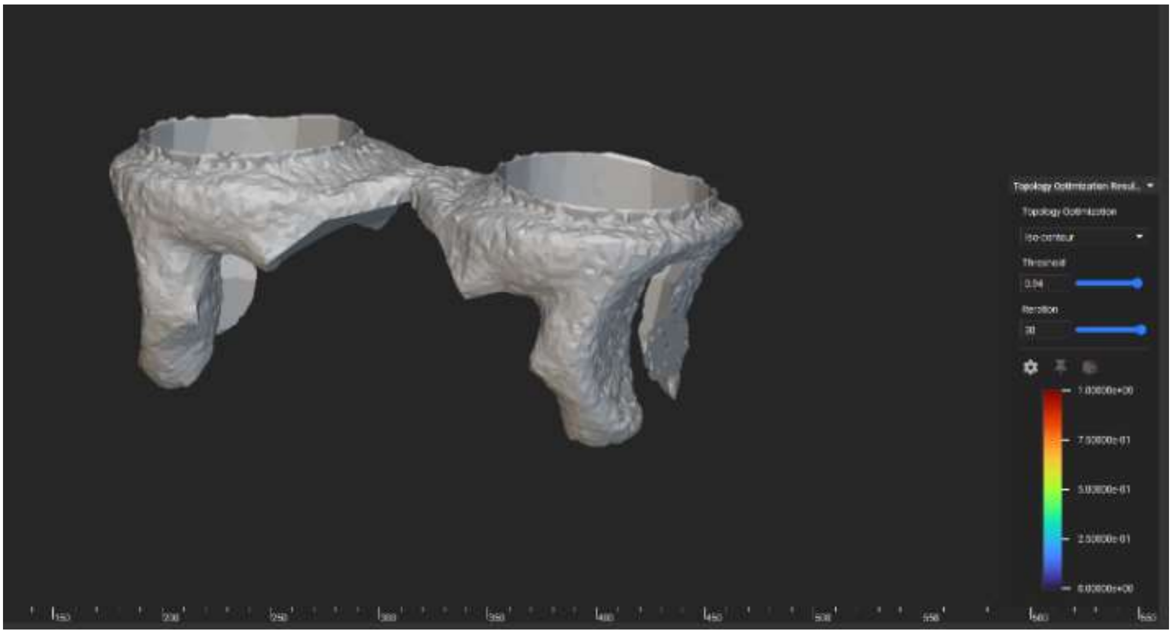

Figure 3.28: An Initial Extreme 85% Weight Reduction Model.

After setting up the boundaries and considering design constraints, for the project the next stage in the simulation involved performing topology optimization. During this step the goal was to identify the distribution of materials within the ROV framework while staying within the defined limitations and operational needs.

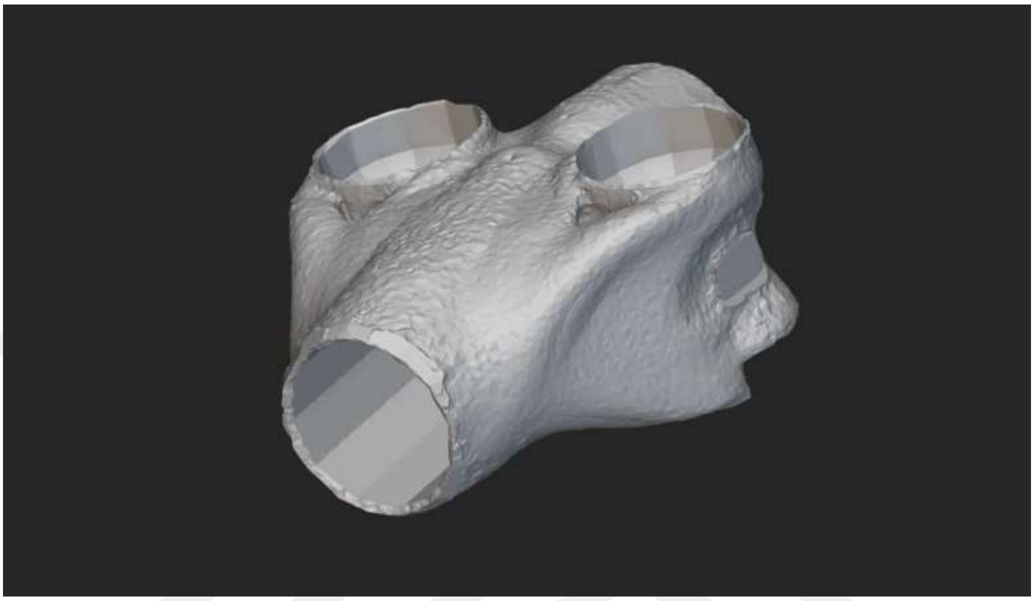

Figure 3.29: Topology Optimized Shell.

Through topology optimization it became possible to eliminate material thereby lowering the weight of the structure while ensuring its strength, in crucial load bearing areas, Subsequently after the topology iteration was completed the lattice optimization was utilized to improve the design by adding a lattice structure to key areas. This lattice helped strengthen

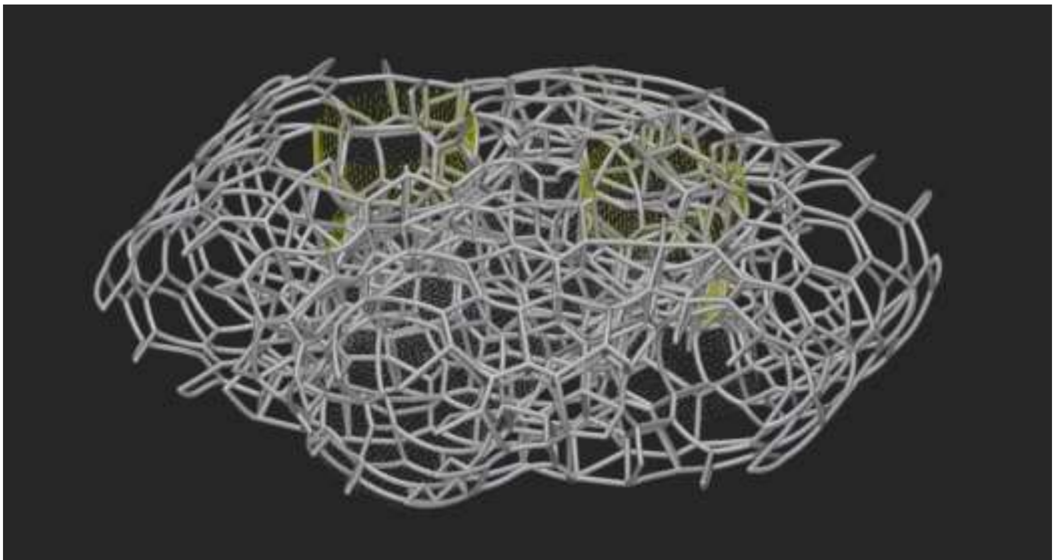

Figure 3.30: Lattice Optimized Shell.

the optimized layout. Maintained the form and functionality of the ROV while maintaining a balance, between durability and minimal weight. These enhancements collectively led to a built performing ROV design that is all set for real world application.

The structural design of the ROV was greatly enhanced by combining topology and lattice optimization techniques to create a process that integrated the strengths of both methods effectively. This hybrid optimization strategy allowed for an approach of minimizing material usage and adding reinforcement as needed without compromising the integrity of the ROVs structure or adding unnecessary weight [17] [18].

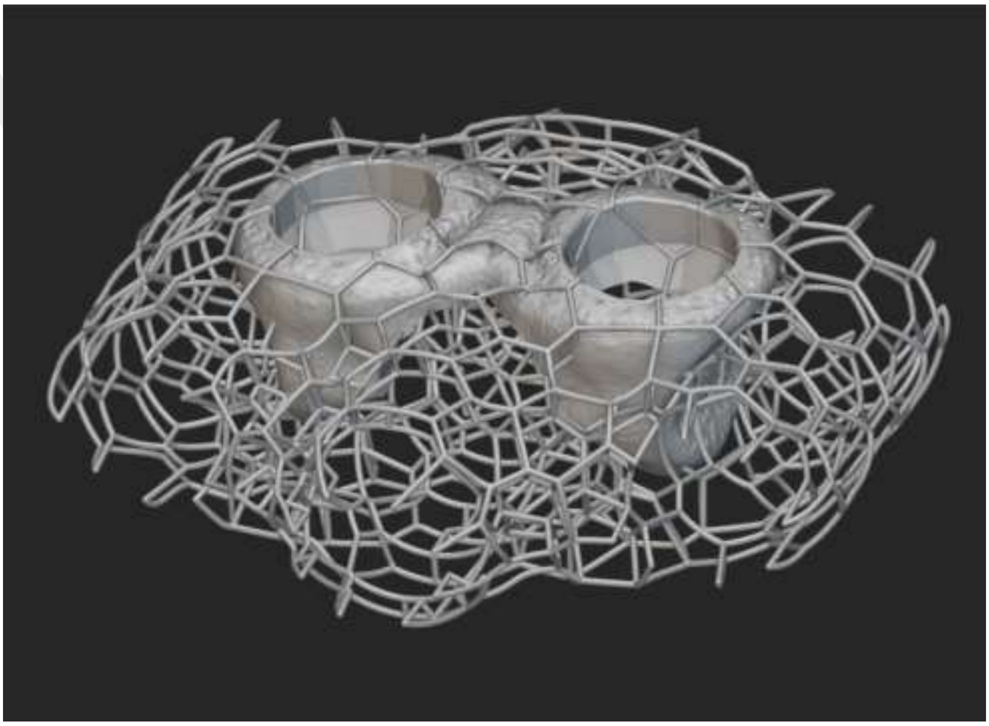

Figure 3.31: Topology & Lattice Optimized Shell.

By harmonizing principles from both topology and lattice optimization the ROV design achieved efficiency levels that would not have been possible with just one method alone. This guaranteed top notch performance, in real world operation scenarios[19] [20].

4. CONCLUSION

4.1 CONCLUSION

The concept of lattice optimization introduces a method, for creating Autonomous Underwater Vehicles (AUV) making them lighter and structurally efficient through buoyancy optimization techniques without the need for ballast weights commonly used in traditional AUV designs to achieve neutral buoyancy.

With lattice structures enabling adjustments to distribution and buoyancy based on material topology alone; the need for extra weights is eliminated, leading to reduced overall mass and potential energy savings. This setup helps the AUV stay out longer during missions and move better while carrying loads since its energy is managed efficiently. The lattice optimization also ensures that materials and structure are strengthened in areas to improve durability without sacrificing the AUVs efficiency in terms of weight.

Figure 4.1: Iteration V Shelled Completed Design.

The figures shown in this chart are approximations derived from simulations carried out using ANSYS software tools. These simulations were based on a hundred percent infill printing rate, for the ABS filament to model a material structure. Through ANSYS simulating the performance of the AUV (Autonomous Underwater Vehicle) we estimated the weight as the deformation and strain under various optimization scenarios, beginning from the initial design, to just topology optimization and ultimately topology combined with lattice optimization.

Table 4.1: Optimization Methods Used Comparison.

Metric	Before Optimization	Topology Optimization	Topology & Lattice Optimization
Weight (kg)	15.0	10.0	9.5
Weight Reduction (%)	-	33%	37%
Max Deformation (mm)	1.20	1.18	1.22
Deformation Change (%)	-	-1.7%	+1.7%
Max Strain (με)	800	810	815
Strain Change (%)	-	+1.25%	+1.9%

4.2 FUTURE DEVELOPMENT

In lattice design for underwater vehicles (AUVs) engineers could possibly use computational fluid dynamics (CFDs) as part of the design process to achieve multiple goals like maintaining buoyancy and structural strength while enhancing hydrodynamic performance efficiently with less energy consumption, in diverse underwater conditions.

Additionally, the utilization of lattice materials can be used to withstand external pressure or load. This can be useful for preserving structural strength and energy efficiency across different scenarios. Moreover, machine learning algorithms could contribute by expediting the optimization process through the examination of datasets from AUV missions to forecast optimal lattice arrangements. Furthermore progress, in manufacturing methods will enable the creation of more accurate and intricate lattice structures improving the precision of material distribution and facilitating a finer regulation of localized densities to customize buoyancy. These advancements may pave the way, for a wave of underwater vehicles (AUVs), with improved capabilities that allow for more extensive and efficient exploration of the ocean.

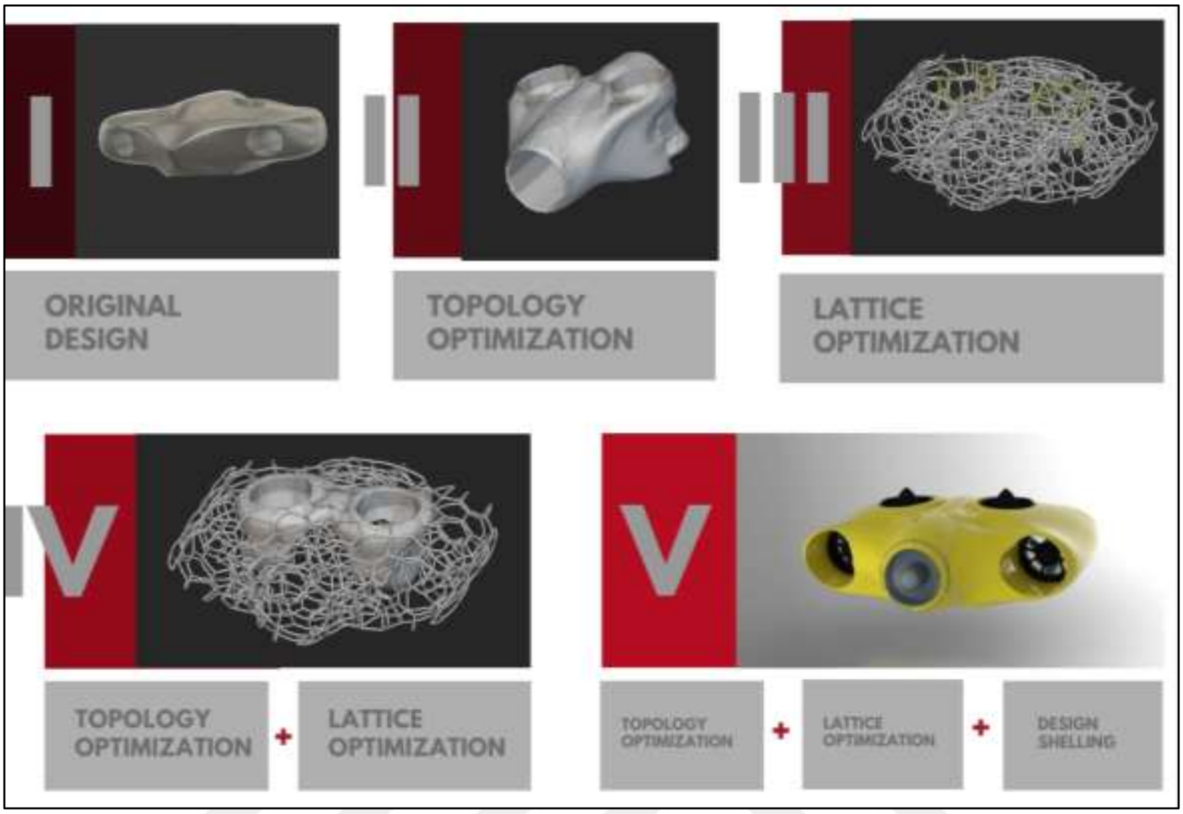

Figure 4.1: Design Iteration Road Map.

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