Design and Development of Unmanned Surface Vehicle Using System Engineering Principles

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MASTER OF SCIENCE

in

Systems Engineering

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August, 2023

7/9/23

Annex A to NUST Letter No.
0972/102/Exams/Thesis-Cert
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This thesis is dedicated to *my beloved parents & siblings.*

Declaration

I, *Nareeta Arshad* declare that my MS thesis titled ***Design and Development of Unmanned Surface Vehicle using Systems Engineering Principles*** is my own work and has not been submitted previously by me for taking any degree from this University "*National University of Sciences and Technology (NUST), Pakistan*" or anywhere else in the country/world.

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Acknowledgments

"Read. Read in the name of thy Lord who created; [He] created the human being from a blood clot. Read in the name of thy Lord who taught by the pen: [He] taught the human being what he did not know"

The importance of education lies in the first Revelation of the Quran and this proved to be my motivation. All praises to **ALLAH**, who bestowed me with the knowledge, patience, health and ability to complete this thesis.

First and foremost, I would like to sincerely thank my research supervisor Dr. Mian Ilyas Ahmad for his complete support and encouragement throughout my research, particularly in the dubious phases. His constructive advice and suggestions have allowed this research to move in the direction it moved and his support has also instilled confidence in me to become a self-dependent researcher. I would also like to acknowledge my GEC members Dr. Ammar Mushtaq and Dr. Salma Sherbaz for their advice and moral support.

I would like to offer my special thanks to my friends for their untimely discussions and advice which helped me get through the difficult phases of my research. The faculty and management of SINES, NUST proved to be extremely resourceful as well and have helped create a supportive and productive environment within the department.

Last, but not least, my deepest gratitude goes to my beloved parents who are the reason behind all my successes and also to my siblings for their endless prayers and love.

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Abstract

Unmanned surface vehicles (USVs) are remotely operated ships/boats without a crew and have applications in rescue operations, exploring deep-sea regions, coastal monitoring and defence systems. In this thesis, the focus is to identify an efficient design of unmanned surface vehicles using a system engineering process. The approach involves the identification of stakeholders and their operational needs, the development of operational scenarios highlighting system characteristics, functional architecture with detailed system characteristics, physical architecture and lastly implementation/integration of system components. This systematic approach allows us to identification of multiple design alternatives with no unwanted/redundant subsystems and each ensuring user requirements. Thus a set of design alternatives can be identified that are utilizing subsystems as per user requirements. The decision of selecting a specific the design is based on some economic and other non-economic criteria. The economic criterion is the total cost of the project including initial cost, maintenance cost, and salvage value and it is computed in terms of the present equivalent, future equivalent or annual equivalent of the project. The non-economic criteria may include flexibility, complexity and ease of integration. To utilize these non-economic criteria together with the economic criterion for multi-criteria decision-making, it is important to rank all the non-economic criteria on a scale by using past experience. The concept of decision evaluation display is used to select a better choice based on the given economic and non-economic criteria. The results are shown for an industrial-funded project where an efficient design of an unmanned surface vehicle is to be identified under economic and non-economic constraints. It is observed that for the given scenario, the system engineering process and evaluation leads to 27.7% improvement in terms of the total project cost, in addition to better ranking in other non-economic criteria. The improvement in non-economic criteria is qualitative and can be observed in comparison to other design alternatives.

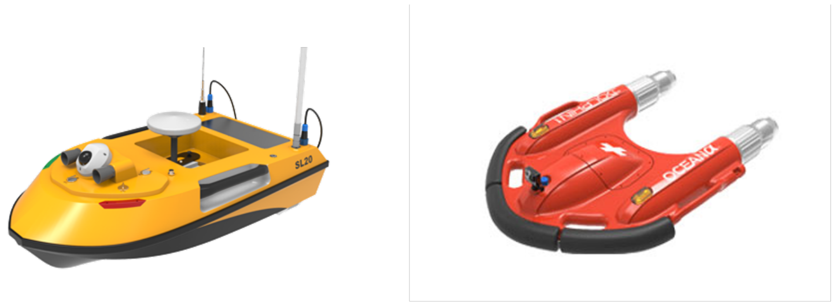
Chapter 1

Introduction

In this chapter, we briefly presented the importance of unmanned surface vehicles, their design and development stages, and the integration of associated subsystems. The problem statement and thesis objectives are highlighted along with the motivation of the research work.

1.1 Unmanned Surface Vehicle

Unmanned Surface Vehicles or Vessels (USVs) are boats/ships that are operated on the surface of the water without a crew, either from a remotely controlled device or in a completely autonomous mode, as shown in Figure 1.1.



Autonomous Survey USV

Remote Controlled Life Preserver USV

Figure 1.1: Autonomous and Remote Controlled USV

Typical USVs include servo motor systems, battery systems, sensors, cameras and other equipment mounted on them in order to perform a wide variety of tasks in different environments. Some well-used applications include rescue operations during floods [23], Passive Acoustic Monitoring (PAM) [12], exploring deep-sea regions [21], and coastal monitoring [28].

Different USV designs have been developed and tested in the above applications [19]. Each of them has its own advantages and disadvantages in terms of their limitation of the service area, stability in rough sea wave conditions, and sustainability, particularly in terms of service life. In this thesis, we will discuss some important and well-used USV designs and evaluate their alternatives at the component levels.

1.2 Components of USV

USVs are classified on the basis of their functionality (single or multiple functions/services), scale/size (small, medium or large size) and driving capabilities (Auto or remote controlled). In general, the most common components include the following:

- Hull
- Propulsion System
- Payload
- Communication System
- Ground Station
- Guidance Navigation and Control Systems

These components are shown in Figure 1.2 and are further discussed in the following subsections.

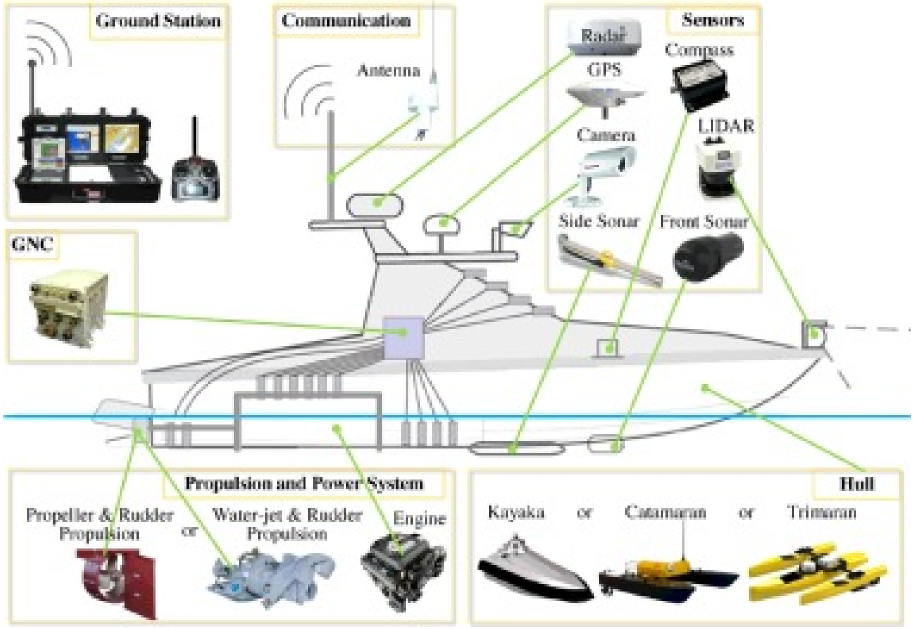


Figure 1.2: Basic Architecture of the USV

1.2.1 Hull

Hull is the body of the USV and its design has a significant impact on its stability, manoeuvrability, and hydrodynamic efficacy. It can be designed as a monohull, catamaran, trimaran, or other configuration, depending on the specific application and requirements. Commonly used hull construction materials include fibreglass, carbon fibre, aluminium, and composites to accomplish the desired strength-to-weight ratio and cost-effectiveness. The size of the hull is determined by the planned payload capacity, mission specifications, and operational environment. Often, they are designed with adequate space and mounting provisions that can hold a variety of sensors, cargo, and communication equipment.

The kayak and catamaran designs as shown in Figure 1.2 are popular due to their easy mounting and filling. The catamaran and trimaran USVs are useful because of their increased stability as they reduce the risk of capsizing in turbulent water [9]. In addition, these designs have high payload capacity and redundancy.

1.2.2 Propulsion System

The propulsion system produces thrust to push the hull forward. That is, water is accelerated in a backward direction by a rotor system powered by battery packs and the reaction to this acceleration produces a thrust or reaction force on the hull. The rotor system includes a propeller rotating in its plane and driven by an electric motor or other source of energy. The power source of the system is selected on the basis of power requirements and the duration of the service.

The steering of the hull about its centre of gravity is provided through the control of the rudder placed at the stern or aft-most part of the USV behind the propeller. In some cases, especially in the catamaran hull design, the steering is provided by differential thrust from two independent motors. In some cases, the total number of actuators available is less than the degrees of freedom (DOF) in the motion of the USV. This poses a significant difficulty for the safe and accurate control of underactuated USVs. Other fully- and over-actuated USVs are simpler to operate than under-actuated USVs, but they are more expensive [7].

1.2.3 Guidance Navigation & Control System

The guidance navigation and control system often includes a single-board computer, an inertial measurement unit (IMU) with global positioning system (GPS) capability, a tilt-compensated digital compass and a radio frequency (RF) transceiver. The IMU/GPS is a sensor that measures the position and orientation of the hull during operation. The digital compass is used to record vehicle heading, and the radio-controlled (RC) receiver allows us to manoeuvre the USV under remote manual control or autonomous navigation. The information from the sensors and RC receiver are passed on to the single board computer, where the manoeuvring data is logged and the control code is implemented. The control action on the actuators generates the required forces and moments. All these important roles are presented in Figure 1.3.

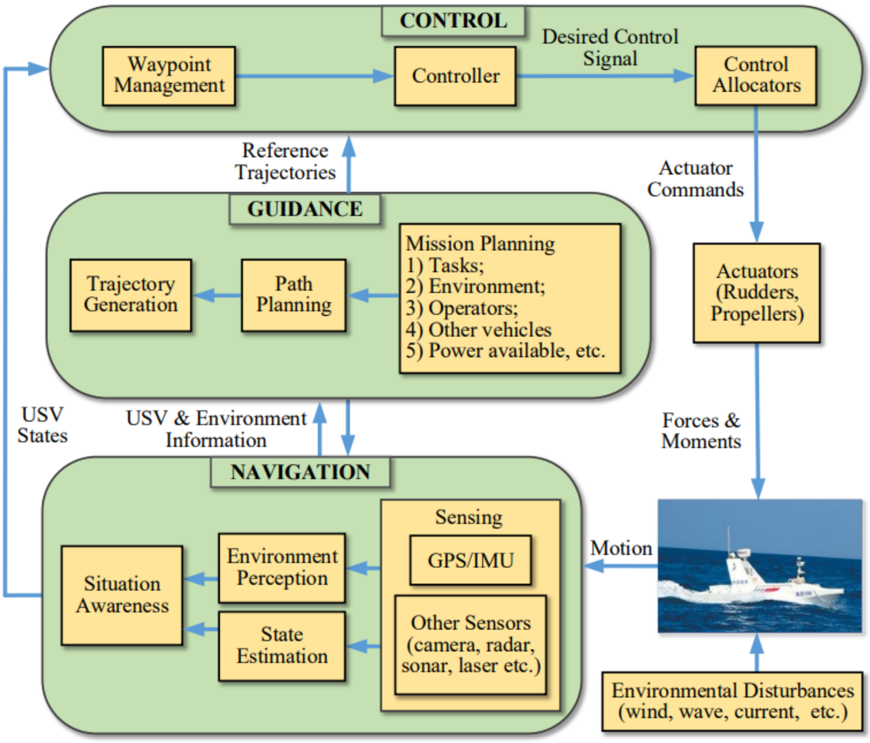


Figure 1.3: Guidance, navigation, and control of USV

1.2.4 Payload

USVs are frequently outfitted with a variety of payloads and sensors to accomplish specialised functions. Initial payloads for USVs are communication devices that allow vehicles to communicate with other human or unmanned platforms and transmit remotely gathered ISR (Intelligence, Surveillance, and Reconnaissance) data to a processing or decision-making entity. Cameras and optical sensors are other common sensors for remotely operated vehicles, while others may be used depending on the purpose. The combination of payload and sensors enables the USV to gather data, undertake inspections, and perform other mission-specific functions.

1.3 Systems Engineering Process

Systems engineering utilizes systems thinking for complex systems where the system's properties as wholes are considered, in addition to the properties of associated subsystems and focus on the design, integration, and management of complex systems over their life cycles. In the design of complicated systems, it is important to know the role of different subsystems or components and how they are integrated to achieve all the requirements of end users, what possible design alternatives satisfy user requirements, which design alternative is cost-effective and will work as expected over the entire life cycle. All these important knowledge areas lie in the domain of Systems Engineering.

The system engineering process emphasizes requirements-driven design and testing. All design elements and acceptance tests are traceable to one or more system requirements. The V-diagram as shown in Figure 1.4 visually represents the systems engineering process.

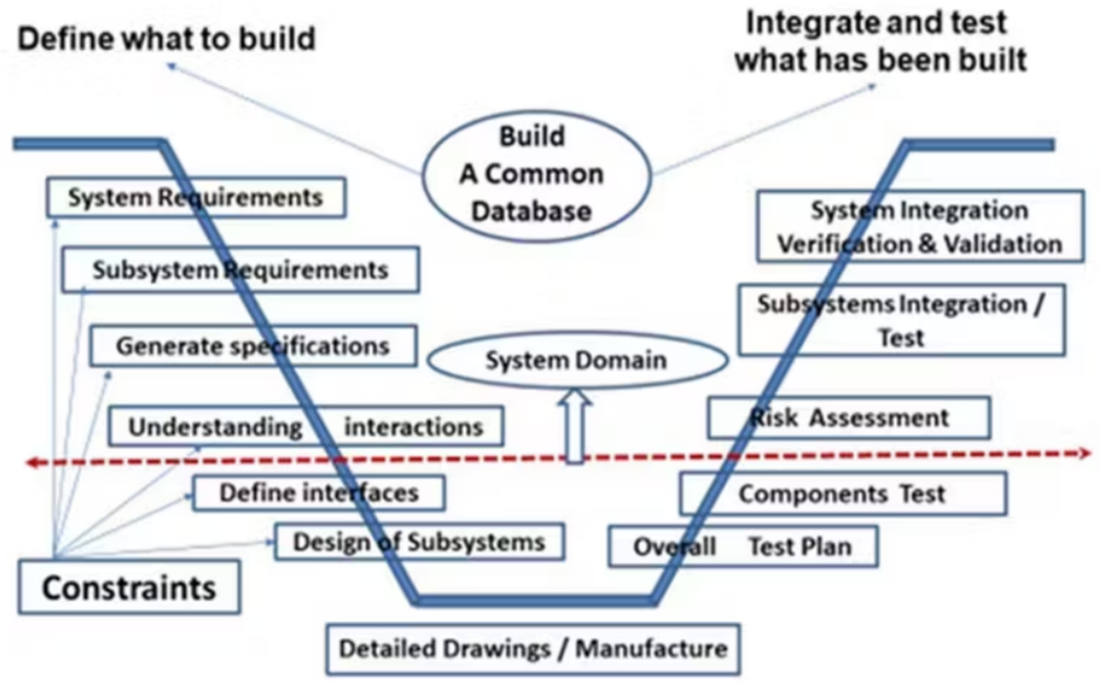


Figure 1.4: V-Diagram of a System

The process includes the initial design requirements at the system and subsystem level on the left and the corresponding testing of the developed design at the system and subsystem level on the right. The manufacturing and realization of the system with the required specifications and interfaces are observed in the middle of the system engineering process. The complete step-by-step system engineering process may include a definition of the problem, constraints and assumptions, stakeholder/user identification, stakeholder analysis, use cases, statement of customer needs, requirement analysis, structure and functions, subsystem integration, system architecture, testing, implementation, transition, verification & validation and disposal life cycle.

1.4 Problem Statement

The design and development of an unmanned surface vehicle (USV) ensuring all the interactions as per user requirements is a difficult task that involves a number of operational considerations and design possibilities. The importance of the systems engineering process in the design and development of USV and the evaluation of design alternatives based on economic and non-economic factors is the focus of this thesis. In particular, the problem is to study design alternatives for USVs using system thinking with end-user requirements ensured at the system and subsystem level and based on the system engineering process identify efficient design alternatives for USVs in terms of economic and non-economic factors.

1.5 Research Objectives

The following objectives have been designed for conducting the proposed research work:

- Utilizing System Engineering process to design and develop an unmanned surface vehicle.
- Identifying economic and non-economic factors for design alternatives
- Ranking of design alternatives based on non-economic criteria
- Identifying Optimal design Alternative based on Economic and non-economic criteria

1.6 Area of Application

USVs have been utilized in multiple operations and some of the applications studied in the literature are listed below:

- Ocean Resource Exploration: Oil, gas and mine exploration[26] [24]

- Military Application: Port, harbour, and coastal surveillance, reconnaissance and patrolling[30]
- Environmental Missions: Environmental monitoring, samplings, and assessment [8] [25]
- Transportation [15]
- Rescue Operation [29]

1.7 Thesis Overview

The overall work of the thesis is divided into five chapters. Chapter 1 provides the overview, objectives, and problem statement of the research. Chapter 2 focuses on the literature review providing the work that has been done on the unmanned surface vehicle and how it is controlled. Chapter 3 depicts the complete methodology starting from the need analysis to the system integration. Chapter 4 discusses the basis on which the design alternative is selected. Chapter 5 entails the conclusion and future work.

Chapter 2

Literature Review

In the last two decades, extensive research has been done on unmanned surface vehicles that can be operated autonomously or remotely through remote controllers or in hybrid mode. In this chapter, we present different research contributions in the design and development of USVs and some well-used system engineering approaches for complex systems.

2.1 USV Design and Development

The design of USVs has evolved with their applications, particularly from the integration of different sensors' points of view and the design of the mechanical structure. The controller design and the manoeuvrability of USV also vary with applications but the advancement in these areas can be grouped in separate sections.

2.1.1 USV Designs and Applications

As discussed before, USVs have been used in various applications each with different system characteristics and constraints. In this subsection, we will discuss the evolution of USVs in terms of both technology and applications. USVs were first developed in 1993 at MIT Sea Grant Institute and the initial designs were targeting simple remotely controlled manoeuvrability-specific missions. The first USV was named as ARTEMIS and was used to collect bathymetry data in a river [27]. The issue with ARTEMIS was its small size and hence stability, which limited its usage. A kayak platform was then utilized with an acoustic tracking system to utilize the USV for following a tagged fish [11]. These early developments of USVs were extended to other applications, particularly by the US Navy [18] in the defence sector. For more details on the development of USVs, we refer to a review paper in [20].

The introduction of more sophisticated navigation systems, including GPS and inertial navigation and advancements in sensor technology and integration such as cameras, radar, and sonar led to enhanced capabilities of USVs. These advancements in navigation and sensors enabled better environment sensing, target identification, collision avoidance, and enhanced situational awareness. The integration of AI and machine learning allowed USVs to make real-time decisions, adapt to dynamic environments, and optimize routes. AI-powered algorithms enabled tasks like anomaly detection, adaptive path planning, and even learning from experience. Advances in energy-efficient propulsion systems, including electric and hybrid-electric systems, increased operational endurance and reduced environmental impact. Some USVs incorporated renewable energy sources like solar panels to extend mission duration. Also, USVs became integral parts of networked systems, enabling coordinated operations with other USVs, UAVs, and control centres. This connectivity facilitated information sharing, distributed intelligence, and collaborative missions, such as swarm behaviours.

The evolution of USV technology expanded its applications to various sectors: In defence and security sector, USVs are used for mine countermeasures [17], surveillance, anti-piracy operations, and maritime border protection. For research and exploration, USVs contribute to oceanography, marine biology, hydrography, and underwater archaeology by collecting data from remote or hazardous locations. In the field of environmental monitoring, USVs are employed for tasks such as pollution detection, oil spill response, marine life tracking, and climate change research. In search and rescue operations, USVs assist in locating and rescuing people in distress at sea, using sensors and AI to scan large areas quickly. Finaly for commercial operations, USVs are used for offshore resource exploration, pipeline and cable inspection, and autonomous cargo transport.

For long-duration operations, the study in [14] suggests a hybrid USV system that links an unmanned surface vehicle (USV) with a remotely operated vehicle (ROV) through a tether connection, enabling the transmission of GPS data and a reliable power source. The ROV has been fitted with sub-aquatic sensors for the real-time capture and transmission of topographic and underwater images. While the ROV is doing underwater operations, the USV can navigate autonomously due to line-of-sight navigation and dynamic positioning algorithms. The efficiency of the hybrid system has been proven by simulation and real sea testing. While the winch system controls ROV depth, the USV has position and dynamic positioning control utilising GPS and AHRS sensors. It is shown that in comparison to integrated USV/AUV platforms, the suggested system delivers accurate positioning and is cost-effective. Also, the hybrid system successfully tracks circular way-points and keeps a tiny position error between the USV and ROV.

2.1.2 USV Controller Design

In a normal boat with a crew, the boat is guided and controlled by the crew member by first considering its present position and course of flow and then compare it to the desired position and course and take action accordingly by choosing a specific speed and heading. These parameters, heading and position are checked periodically and appropriate corrections are made to maintain the course of the boat. A USV is expected to perform the same operations efficiently without direct on-board human interactions. This problem can be divided into three parts: navigation, guidance and control. Navigation estimates the current state by fusing measurements from multiple satellites through GPS receivers. Guidance determines the desired position and orientation trajectories of the USV. Control commands the actuators according to tuned algorithms that ensure the desired state is closely tracked.

In [22], a working prototype of a boat is presented that is powered by a rechargeable battery and is operated on an RF remote to control the boat's movement. Using geared motors, it can drive forward, reverse, and make sharp left- and right-hand turns. LPC2148, DC Servomotors, RF Technology, and the L293D H-Bridge to drive the DC Servomotor are some of the system's components. An interfaced, high-sensitivity camera is used to record the surroundings and send the video to a ground station. Data transfer is facilitated by the RF modules. Positional data is provided via switches that are linked to the RF transmitter through the RF Encoder. As the wireless sources are easily accessible, the proposed system is cost-effective and economical. The system may be used to interface RF modules and controllers, making it particularly appropriate for marine research centres.

It was then followed by another approach [4] the GSM (Global System for Mobile Telecommunication) technique to operate the vehicle. The approach addresses the limitations of the traditional wireless control method where RF circuits, an extended working range, and no interference with other controllers were well known issues. Dual Tone Multi-Frequency (DTMF) signalling is used to get around these problems. This paper represents the four-bit data streams for remote transmission for USV control. The Dual Tone Multi-Frequency (DTMF) function of the mobile phone is utilised, and a microcontroller-based circuit is used to demonstrate wireless data communication to control the vehicle. The results show that the system has a high level of accuracy and user-friendliness. The developed unmanned surface vehicle (USV) overcomes the restrictions of RF circuitry and has a streamlined circuit architecture, a user-friendly interface, and enhanced cost-effectiveness. Moreover, it needs five motion commands. Training expenses are kept to a minimum since even novices can operate USVs without understanding their internal circuitry.

With the advancement of technology, most developers started using the PID controller technique as an alternative to operating the USV, providing a simple yet effective method to manoeuvre the vehicle. in this paper, explanation of the PID control set of rules hired in the ASV. Details of the experimental setup, consisting of the ASV platform and sensor systems Overview of the PID tuning technique and parameter choice The goal of this study is to create an ASV navigation system that makes use of GPS, a compass, a PID control system, Arduino UNO boards, and thrusters. The mechanism enables the ASV to navigate precisely with an accuracy of less than one metre at speeds of 3–4 m/s. Due to its bendy structure, onboard payload location, and powerful thrusters, this platform can effectively accommodate the integration of numerous sensors and scientific devices for a wide variety of packages associated with water sampling, temperature, and salinity measurements to frame patrol and tracking, regardless of weather conditions. [10]

2.1.3 USV Components and accurate Manoeuver

Developing a USV requires a multidisciplinary approach that will aid in achieving a seamless integration of the components and an accurate manoeuvring system. The main components in building a USV require it to operate in a complex environment so that it can navigate accurately. Opting for the correct components is very important when developing a USV, as it is essential to achieving the desired capabilities of the USV.

To present a framework for guidance, navigation, and control (GNC) of marine vehicles, focusing on unmanned surface vehicles (USVs) for high-accuracy measuring tasks. The framework incorporates a modular control scheme, including guidance, navigation, and control components. The desired manoeuvring path is defined and delivered to the guidance system, which employs an extended Kalman filter for navigation and estimation of unmeasurable states. The control system consists of a cascade structure, with the inner loop responsible for velocity control and the outer loop adaptable to different missions. Model parameters are estimated using a subspace identification method based on data from a measuring vehicle. The framework's effectiveness is demonstrated through a model for a path-following mission, considering unknown currents and measurement disturbances. The paper emphasizes the interconnection of the GNC components and addresses the design and application of each component. Key points include the modular control scheme, the use of an extended Kalman filter for navigation, and the demonstration of the framework's effectiveness in a path following mission. The use of an expanded Kalman filter for navigation and the demonstration of the framework's performance in a path-following mission are key components of the modular control method.[16]

Moreover, the design and parts of an autonomous surface vehicle (ASV) are covered in this article. The ASV is built like a catamaran and has several pieces of gear, including thrusters, an IMU, a GPS, and a power system. The main computer running Windows 10 at the ASV is a Lenovo Thinkpad. The VectorNav 200 Rugged is a GPS and INS module that offers better velocity, location, and altitude accuracy than a standalone GPS. The ASV is equipped with a safety circuit, a camera for object identification, and a T200 thruster propulsion system. Moreover, mathematical models and controllers for the direction and waypoint control of the ASV, as well as information on the usage of vacuum infusion in boat building have been discussed. [3]

Besides, designing and developing a low-cost, modular, autonomous surface robot for inland water applications are the main topics of this work. Software design, electrical and electronic design, and mechanical and electro-mechanical design are all parts of the design process. A rudder that is controlled by servo motors steers the robot. The onboard computer uses Robot Operating System (ROS) software, along with ground station software for keeping tabs on the robot's position, enabling autonomy. The designed system was put to the test in the field, and it was compared to other designs. The deck space of the robot and its modular software design makes it simple to integrate different sensors and mechanical components for uses including environmental monitoring, surveillance, and patrolling. To minimise expenses, the system uses off-the-shelf hulls, electric trolling motors, and an off-the-shelf two-hull design. Field experiments were carried out to assess the system, showing both its affordability and scalability.[6]

Thus, to address the challenges related to the accurate manoeuvring of unmanned surface vehicles, in this paper, vector field guidance and a characteristic model-based approach are combined for the controller. The second-order characteristic model is used whose parameters are estimated using the technique of forgetting factor recursive least squares (FFRLS). Moreover, the controller to track the heading angle and speed is designed using an intelligent adaptive control method. The vector field guidance law and the characteristic model-based heading angles and speed controller serve as the basis for the development of the path-following controller. Moreover, the results from the experiments show the controller's accuracy and efficiency. The characteristic model-based approach performs better than the alternative approaches as it is flexible and adaptable to different navigation environments. [1]

A cloud-based system for the planning and management of unmanned surface vehicle missions. It outlines the proposed framework's system architecture, components, and features. The utilisation of a cloud server, remote client software, local vehicle interface, and controlled vehicles in the system is highlighted. The primary data handler is a cloud server that offers a web interface for transmitting and receiving data. The remote client program has modules for interacting with the cloud server, instructing boats on missions, and keeping track of the state of the boat. The local vehicle interface communicates with the cloud server through the remote client to receive orders, and a heartbeat mechanism keeps the server in touch. It explains the advantages of the suggested approach, such as centralised synchronisation and decentralised communication. Moreover, It offers a suitable cloud-based architecture for coordinating the control of autonomous surface vehicles and offers early outcomes to validate its efficacy. [2]

2.2 Systems Engineering Principles

Systems Engineering is an interdisciplinary field that includes how to design and develop a complex system by translating the customer's needs into a prototype that can be operated and tested in various environments to achieve the desired capabilities. The systems engineering principles provide a framework that could be followed to achieve the successful development of the USV. Starting from the need analysis, why do we need to develop the system? Followed by a requirement analysis that will explain the capabilities of the USV in relation to the environment in which it will operate. Next is the system architecture, in which the electrical components, mechanical parts, communication and control, and software parts of the USV are finalized. Furthermore, testing and evaluation of the USV have been done in various environments to see that its functional requirements meet the customer's needs. After that, the prototype that has been developed is deployed into the environment to operate.

In this paper, the prototype of the autonomously guided vehicle (AGV) has been designed using the systems engineering principles. Different phases of the design process have been explained such as the concept development phase, system-level design, detailed design testing and refinement. Moreover, the customer requirements are translated to the House of Quality (HOQ) matrix to help them achieve them. Besides that, the mechanical and electrical design of the AGV has been discussed. The designed prototype is then tested to evaluate the performance and capabilities of the vehicle. [13]

In this paper, the four main factors are identified to implement systems engineering effectively, that includes Stakeholder Value-Based System Definition and Evolution, Incremental Commitment and Accountability, Concurrent Multidiscipline System Definition and Development, and Evidence-Based and Risk-based Decision Making. A comparison of these factors with Lean Systems Engineering and Hitchins had been done in this paper. Whereas, the traditional approach of systems engineering approach is no longer relevant as the trends change and ICSM (Incremental Commitment Spiral Model) has a flexible framework. Moreover, it focuses on early verification, concurrent engineering, risk prioritization, and integrated development. The four principles of the ICSM give adaptability and success to the project.[5]

2.3 Research Gap

A prominent difference we can see that exists in the literature is the use of a multi-disciplinary approach of system engineering principles to develop an unmanned surface vehicle. There has been done extensive research on the USV over the last few years, but a minimal focus on a compact design, engineering methodologies for building small USVs, and integrating indigenous knowledge. Addressing this gap, we are doing an indigenous development of unmanned surface vehicles (USV) using systems engineering principles and techniques. It will enable to formulate a USV that will tailor to the needs of the customers/stakeholders and achieve the desired functional capabilities. Moreover, it will improve the efficiency of the USV design and ensure the seamless integration of the components and subsystems. This study will help to fill the void the literature has and follows the well-coordinated and holistic approach to designing and developing a USV.

Chapter 3

Methodology

3.1 Systems Engineering Process for USV Design

Multiple design alternatives for USVs have been considered in the literature, each with its own importance, interactions, functionalities and hardware/software requirements. A systematic approach or guideline for the selection, implementation, and testing of design alternatives is crucial for the development of efficient USV design. A clear guideline helps us have a clear vision of the system's life cycle and a final product that fulfils the user's requirements. In this section, we will discuss the system engineering process for the design and development of USVs using the following steps:

- Need Analysis
- CONOPS Development
- Requirement Analysis (Define technical specifications, System Preferences and functional requirements)
- Conceptual Design Studies (Define system architecture and specifications)
- Verification and Validation
- Implementation
- Integration

These stages of Systems engineering are discussed in the following sections for USV design and development.

3.2 Need Analysis

In need analysis, we define the operational need, possible risks, and end-users of the product. In our case, the need is to develop an indigenously designed unmanned surface vehicle that can be operated remotely within a specific range. Such a product will be of interest to defence organisations, researchers on marine life or the environment, and rescue organisations. Some possible risks are an interruption in communication links, maintaining stable operation, especially in adverse weather conditions, and accurate navigation or collision avoidance.

3.3 CONOPS Development

The concept of operations (CONOPS) is a document that discusses the proposed concept of USV and how that concept will operate in the intended environment. The proposed system is a small USV that is a lightweight vessel equipped with a GPS system for navigation and an onboard sensor suite to measure water quality parameters or other parameters as required. The USV is powered by a rechargeable battery and can be remotely controlled or operated autonomously. As shown in Figure 3.1, thus the typical components of USV include

- Ground station
- Hull or USV body
- Propulsion System
- Navigation System
- Onboard Sensor Suite
- Rechargeable Battery

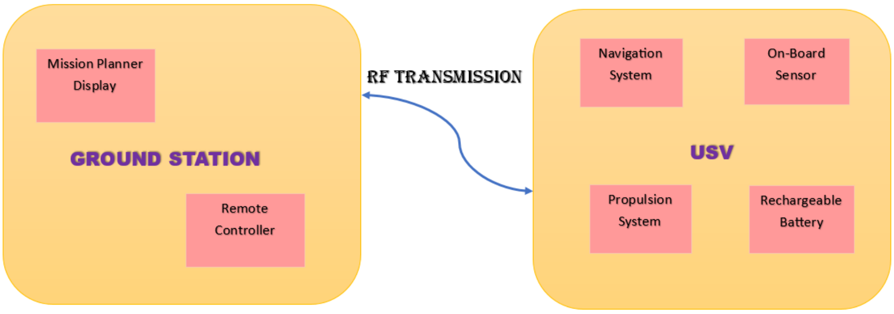


Figure 3.1: CONOPS Diagram

The operational Scenarios of the USV are to deploy the system in coastal or pool waters and navigate it along a predefined route to cover targeted monitoring areas. The USV will conduct data collection missions, returning to the base for data retrieval and battery recharging. The operators at the ground station will be responsible for mission planning, USV launch and recovery, and monitoring its operation. Maintenance personnel will handle routine maintenance and ensure the USV is in optimal condition for each mission.

3.4 Requirement Analysis

Requirement analysis focuses on what the system should do and what features it should have, to be successful. It is different from CONOPS in the sense that CONOPS outlines the high-level operational concept and approach for the system while requirement analysis focuses on identifying and defining the specific requirements and functionalities of the system. Customer requirements or Voice of Customer (VOC) define the characteristics or properties of the system that are really important to the customers, clients, partners or suppliers. Identifying VOC and translating them into technical characteristics is the first task in requirement analysis and the second task is to define the functional role of the system and subsystems.

3.4.1 House of Quality (HoQ)

A structured approach known as Quality Function Deployment (QFD) can be used to define and translate VOC and design specifications into a planning matrix. QFD helps in incorporating all the customer needs/requirements into the final product at the early stages of the design phase. A key part of the Quality Functional Deployment technique is the house of quality (HOQ) which involves collecting and analyzing the VOC and linking them to the product requirements.

There are many ways to develop the HoQ but in general, it includes customer requirements, priorities of customer requirements, product requirements or technical characteristics, the interaction of product requirements, correlation between product requirements and customer requirements and importance rating. The House of Quality is a nice bridge between customer requirements and engineering variables.

As a first step, customer requirements are defined and listed in Table 3.2 along with a description.

Requirements	Priority	Description
Cheap	4	The development process of the complete USV should be inexpensive
Maintenance	2	The maintenance of the USV should be easily possible.
Safety	3	The USV should be safe to work with.
Autonomy	5	The system should be able to operate autonomously.
Distance	3	The system should be able to cover distances up to a maximum of 1km to 1.5km.
Remote Operation	5	The system should be able to move to a specific point through remote operation.
Four Manoeuvre	4	The System should be able to move in 4 directions: backwards, forward, right and left.

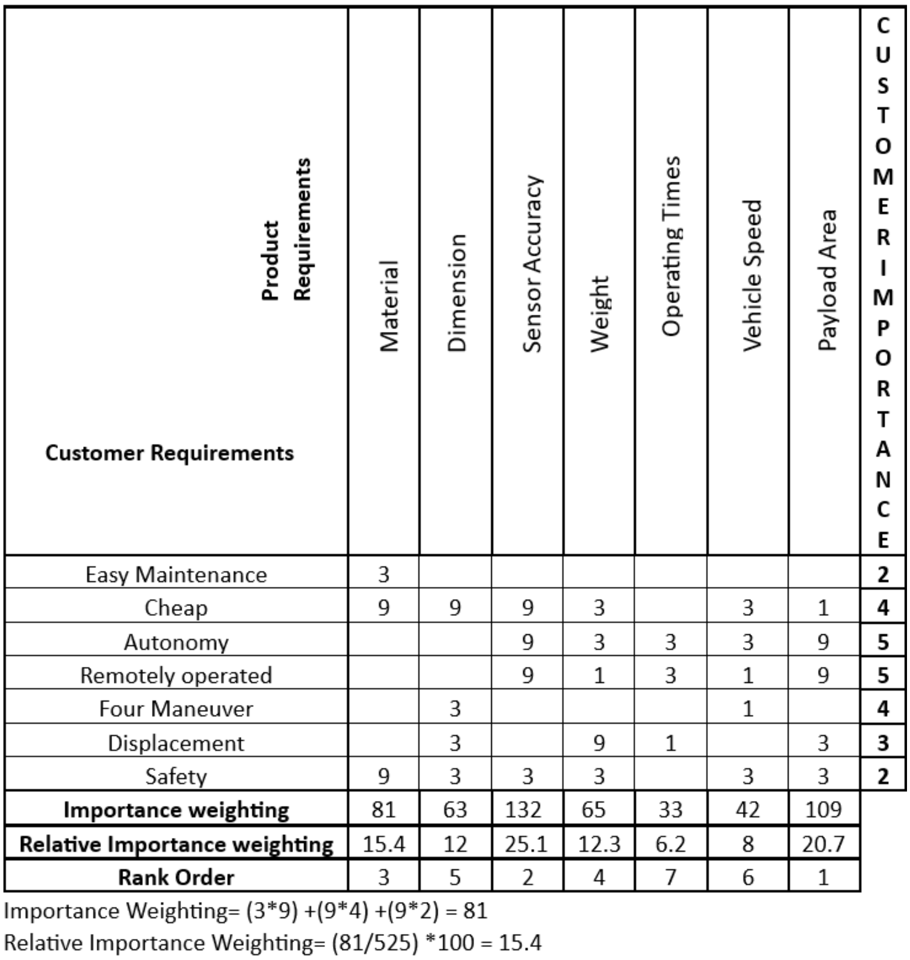
Table 3.1: Customer Requirements

The next step is to prioritize the customer requirements by assuming the importance of each of these USV characteristics. For example, what is more, important according to the customers in comparison to other customer requirements? If we use a scale of 1 to 5, with 5 being the most important and 1 being the least, the above customer requirements can be prioritized as shown in Table 3.2.

The next thing to figure out is the engineering parameters that we need to design the USV and have the largest effect on the customer requirement factors of the USV. The following list shows the engineering parameters selected for the design of the USV:

1. Weight
2. Dimensions
3. Material
4. Vehicle speed
5. Sensors Accuracy
6. Payload area
7. Operating time

Now that the requirements and characteristics have been identified, the house of quality (HoQ) for the USV can be presented as shown in Figure ??.



Product Requirements **Customer Requirements**	Material	Dimension	Sensor Accuracy	Weight	Operating Times	Vehicle Speed	Payload Area	**CUSTOMER IMPORTANCE**
Easy Maintenance	3							**2**
Cheap	9	9	9	3		3	1	**4**
Autonomy			9	3	3	3	9	**5**
Remotely operated			9	1	3	1	9	**5**
Four Maneuver		3				1		**4**
Displacement		3		9	1		3	**3**
Safety	9	3	3	3		3	3	**2**
Importance weighting	81	63	132	65	33	42	109	
Relative Importance weighting	15.4	12	25.1	12.3	6.2	8	20.7	
Rank Order	3	5	2	4	7	6	1	

Importance Weighting= (3*9) +(9*4) +(9*2) = 81

Relative Importance Weighting= (81/525) *100 = 15.4

Figure 3.2: House of Quality of the USV

Note that all the boxes in the product requirement columns are using a ranking system where a value of 9 is used for strong, 3 for medium, and 1 for weak relationships with customer requirements.

3.4.2 Functional Requirements

Functional requirements for a USV outline the specific capabilities and functionalities that the vehicle must possess to fulfil its intended mission and operation. The main functional requirements of the USV are:

1. The USV should have a stable lightweight body with room for electronic components.
2. The USV must be equipped with sensors to measure various environmental parameters, such

as water quality, temperature, salinity, and currents, and collect relevant data during its missions.

3. The USV should have a power source to manoeuvre the USV and operate on-board sensors/electronic components
4. The USV should be capable of autonomous navigation to follow predefined routes, and waypoints, or perform tasks without direct human intervention.
5. The USV should have reliable communication systems to establish a seamless link with remote operators or control centres for real-time data transmission and remote control capabilities.

Similarly, specifications for each subsystem can be obtained by breaking down the USV into functional components like propulsion, navigation, communication, sensing, mission planning, and control. This aids in the definition of interfaces between subsystems and makes sure that they function properly.

In terms of energy, material, or signals, it is important to explain how electrical energy is provided to the system and how it is transformed into mechanical energy for steering the boat in four different directions: forward, backwards, left, and right. What are the products that will be required for these functionalities? Also, how the energy requirements of multiple sensors attached to the boat are fulfilled for their operation All these subsystems performing the required functionality with specific requirements should be identified and analysed to get a clear picture of the required design. The functional representation of the USV is shown in Figure 3.3.

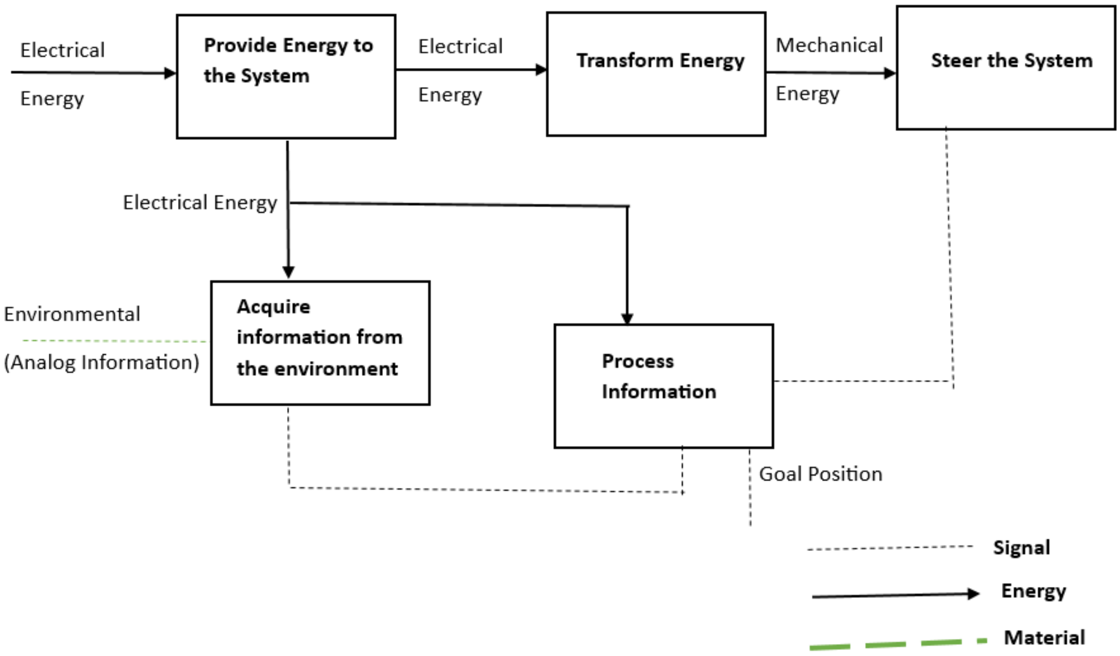


Figure 3.3: Functional Representation of the USV

The functional requirements show that the following components will be required for USV design:

1. Hull or Body of USV: A stable and lightweight catamaran hull can be selected.
2. Measurement devices on USV: Various sensors, such as GPS, IMU, digital compass, sonar, and cameras, which gather data about the environment and the USV's internal state are required
3. Operational power of USV: An electric motor driving a propeller with a rechargeable battery as a power source is essential for the movement of USV. In some cases, a battery management system may also be required.
4. Path following Capability of USV: An onboard computer is required to receive the USV's mission objectives and process sensor data to make decisions about the path/route of the USV. The onboard computer contains the autonomous control algorithm and is linked to the electric motor to control the speed and heading of the USV.
5. Communication Link of USV with the ground: A reliable bidirectional data transmission allows remote control, monitoring, and mission planning of the USV from the ground station.

The link can use RF, satellite, or wireless communication. Real-time telemetry and sensor data are sent to the ground, while mission commands and adjustments are sent to the USV.

6. Integration of USV components

3.5 Conceptual Design

Functional requirements help us identify the characteristics of USV and the interactions of subsystems. These characteristics and interactions are defined in detail in the conceptual design of USV. In the following, we present the conceptual design of the USV by discussing the physical architecture and software architecture of the USV.

3.5.1 Physical Architecture

A modular diagram based on the functional characteristics of USV is shown in Figure 3.5.1.

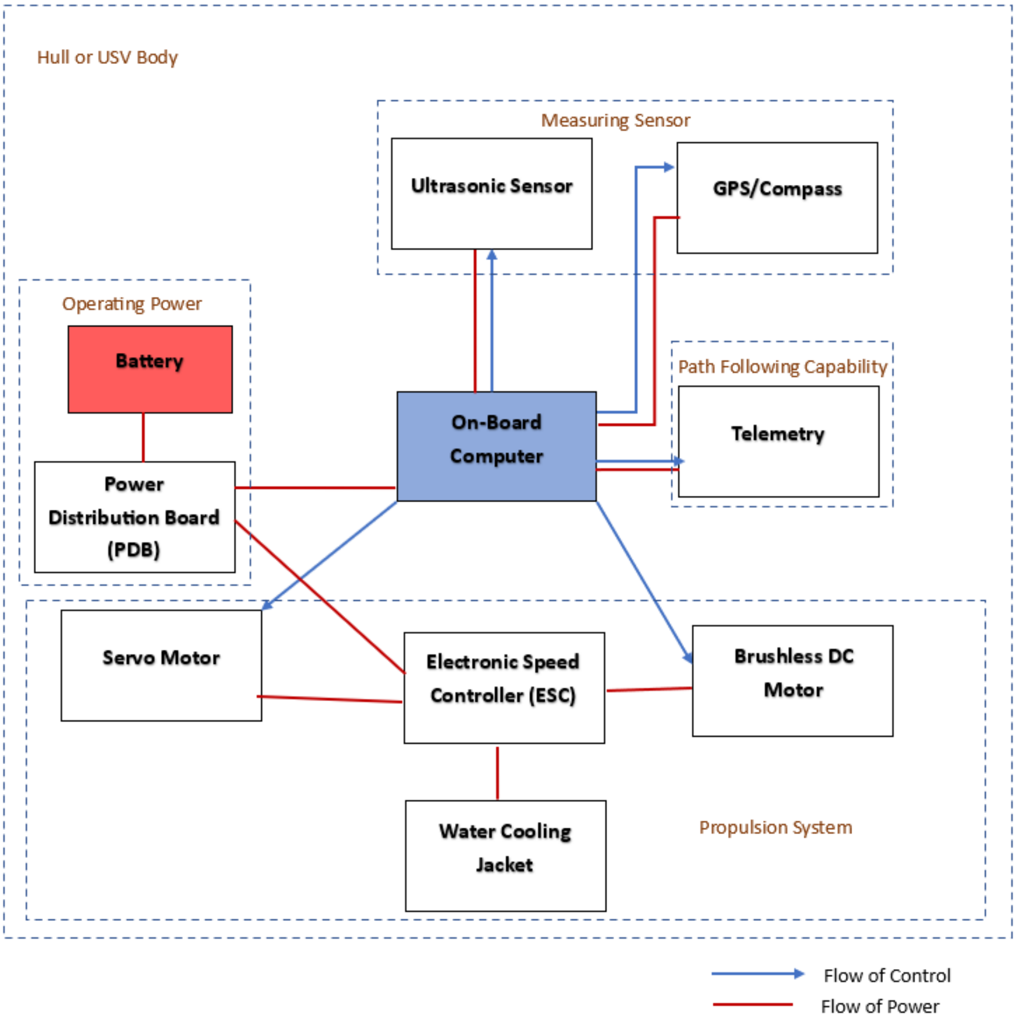


Figure 3.4: Modular diagram

Note that the operational power of the USV includes a rechargeable battery connected to two brushless DC motors. These motors are used because they provide more torque and speed as compared to brushed motors and are less noisy. They also have superior efficiency and performance in terms of reliability and cost. Each of these motors is required to manoeuvre the boat, and the associated ESC (Electronic Speed Controller) controls the power requirements to ensure a specific motor's speed. A cooling pump is also required to avoid overheating the propulsion system. This is possible by utilising an internal cooling loop that circulates water via a heat exchanger on the hull's surface. Rudders are also required for a boat to change direction. Two strong servo motors are therefore required with ratings of 3.0 and 3.5 kgf/cm to offer effective control. These servos can endure the water's resistance thanks to the comparatively large rudders. We can install the servo motors within the boat's hull and link them to the exterior rudders with thin wires threaded through a hole. The rechargeable battery provides power to the servo motors and other electronic devices as well.

The onboard computer serves as the brain of the USV as it receives all the measurements and signals for control of USV operations, stores the data, communicates with the base stations, and outputs signals to drive the motors as required. The rechargeable battery is connected to all these electronic devices through a power distribution board. For our requirements, among multiple options, two possibilities are shortlisted for an onboard computer that will be analysed further based on economic and non-economic criteria. These include 1) Pixhawk 2.4.8 and 2) Arduino.

as well as other components like servo motors, GPS modules, Ultrasonic sensors, and an ESC that uses BEC (built-in circuitry inside the ESC for safe power distribution) for powering the BLDC and servos. The red line in Figure shows the transfer of power, and the blue line shows the transfer of control. from the battery to the Pixhawk and ESC, and from the Pixhawk and ESC to the other modules. The Pixhawk is linked to the M8N GPS/Compass, which is directly attached to the Pixhawk through a clearly labelled GPS connection. It will provide location and navigation information for the boat. An ultrasonic sensor is used to measure the distance between two objects and is linked directly to an I2C port.

The Pixhawk flying controller will connect with the Mission Planner software via telemetry, which uses the MAVLink protocol by default. This module wirelessly transmits boat status, sensor readings, and GPS data to a base station running Mission Planner software. The open-source program Mission Planner, which collects and analyses telemetry data, may be used to monitor, control, and plan missions for the Pixhawk-based autonomous vehicle in real-time.

3.5.2 Software Architecture

Mission Planner is open-source software to autonomously operate the USV from a ground station. It is an application that is compatible with Windows, and it helps define the mission plans of USV by fixing waypoints and parameters and configuring the various driving modes from the ground station. There are various key features of the Mission planner; some of which are listed below:

- **Interactive Maps:** It allows us to view and edit the waypoints we have defined on an interactive map such as Google Maps or Sygic Maps. Live telemetry, such as GPS location, heading, speed, and altitude, can be overlaid, which is helpful in mission planning and keeping track of development. Graphical mission planning tools make it simple to set up waypoint missions, search grids, survey patterns, and other missions. With just one click, missions can be uploaded to auto-mode.

- **Initial Setup and Configuration:** Setup wizards guide users through downloading autopilot hardware, loading the most recent firmware, calibrating sensors, and fundamental configuration for various vehicle types such as multi-copters, fixed-wing aircraft, boats, etc. The detailed configuration permits fine-tuning important parameters such as PID gains, setting of waypoint navigation, and fail-safe behaviours, among others. Configurable advanced features include geofencing and control of the camera.

- **Simulation and Testing:** An integrated UAV simulator enables the testing of aerial vehicles in a SITL (software in the loop) environment without hardware. Manually practise flying with rate controls or let the autopilot conduct missions. An excellent method for testing configurations without risk. Simulation integrates with the Software in the Loop Environment (SITL) to test firmware builds for ArduPilot. For broader testing, custom MAVLink Protocol telemetry can be simulated.

- **Flight Monitoring and Analysis:** Real-time telemetry show critical flight data such as attitude, coordinates from GPS, sensor data, battery life, flight modes, and warnings. Rapidly monitor the status of mission execution. During flights, detailed logs can be recorded, replayed, and evaluated to find performance problems, fine-tune PID gains, and debug issues. Telemetry plots allow for in-depth diagnostics. Assistance for integrating multiple Ground Control Stations to oversee shared vehicles for larger teams is Beneficial for expert operators.

3.6 Implementation

The detailed design of the subsystems proposed in the conceptual design is presented in this part. The mechanical design is discussed first, followed by the material used in building the boat hull and the design considerations. Finally, the electrical design and proposed control system are given.

3.6.1 Hull or USV Body

A catamaran is a multi-hulled boat with two parallel, equal-sized hulls. It is a geometry-stabilized craft, and rather than a ballasted keel like a monohull boat, it gets its stability from its wide beam. In comparison to monohulls of equivalent length, catamarans often have a smaller displacement, a shallower draught, and a smaller hull volume. Additionally, the combined hydrodynamic resistance of the two hulls is frequently lower than that of equivalent monohulls, necessitating less propulsion force from either sails or engines. In comparison to a monohull, the catamaran's wider stance on the water can lessen heeling and wave-induced motion as well as reduce wakes.

The following Table 3.3 illustrates the structural efficiency of a range of materials that could be employed in bending and compression (for example, in a strut).

Material	**Young's Mod E(GN/m^2)**	**Density (g/cm^-3)**	**Spec. Stiffness E/ρ**	$\sqrt{E}/\rho$
Steel	210	7.8	26.9	5.2
Titanium	120	4.5	26.7	5.2
Aluminium	73	2.8	26.0	5.1
High Strength CRFP	138	1.6	86	9.3

Table 3.2: Effectiveness of Diverse Materials

It should be emphasized that the specific stiffness (E/ρ) of the bulk of traditional structural materials—steel, titanium, aluminium - is constant, but CFRPs provide significantly greater efficiency for stiffness or deflection essential constructions. When supporting a compression load, such as in a column, the efficiency of the structure is regulated by ($\sqrt{E}/\rho$), demonstrating yet again the value of adopting carbon fibre composite materials. While the fundamental stiffness of steel is significantly greater than that of carbon fibre-reinforced plastic (CFRP), the massive weight savings that can be achieved through the utilization of the material provide a substantial incentive to select (CFRP).

Design Consideration

Several factors must be considered while designing a catamaran-shaped USV composed of carbon fibre:

- **Size and Weight:** The USV's dimensions are critical to its operation. The maximum length of 30 inches achieves a good mix of mobility and solidity. To accomplish buoyancy and manoeuvrability, a weight of 7 to 8 kg should be optimized.

- **Hydrodynamic Efficiency:** The hull design is essential for reducing drag and increasing hydrodynamic efficiency. With two parallel hulls, the catamaran shape improves stability and decreases resistance, allowing for faster speeds and better fuel economy.
- **Structural Integrity:** Carbon fiber is used because it has a high strength-to-weight ratio. The hull should be built to endure a variety of sea conditions, including waves, hits, and vibrations, without sacrificing structural integrity. To ensure durability and lifespan, reinforcements along with proper bonding processes should be used.
- **Payload and Sensor Integration:** To integrate electronic components, sensors, communication systems, and other payloads, adequate space and appropriate mounting arrangements must be incorporated into the design. The carbon fibre frame enables customization and flexibility in incorporating the necessary equipment.

Types	Catamaran Shape Hull
Length	30 Inches
Material	Carbon Fibre Sheet
Weight	6-7.5 kg

Table 3.3: Hull Specification

The catamaran-shaped USV built of carbon fibre can provide a resilient and adaptable platform for unmanned operations in aquatic settings by concentrating on size, weight, hydrodynamic efficiency, structural integrity, and payload integration. The summary of the above discussion has been represented in tabular form in Table 3.4.

3.6.2 On-board Computers

A USV's integrated computer system is a crucial component. It is responsible for processing information collected from sensors, executing control algorithms, and making manoeuvring decisions for the vehicle. The complexity of the onboard computer system will depend on the difficulty of the required control functions.

Our endeavour will utilise a Pixhawk 2.4.8 flight controller. Pixhawk is a highly capable SBC (single-board computer) designed particularly for unmanned vehicles. The use of Pixhawk version 2.4.8 in the construction of a USV is intended to provide a dependable and flexible platform for managing and directing the flight and navigation of the vehicle. Pixhawk serves as the USV's central processing unit, gathering data from various onboard sensors, analyzing that data, and making decisions according to predefined instructions or input from the user. It employs advanced algorithms and control methods that ensure accurate and stable navigation.

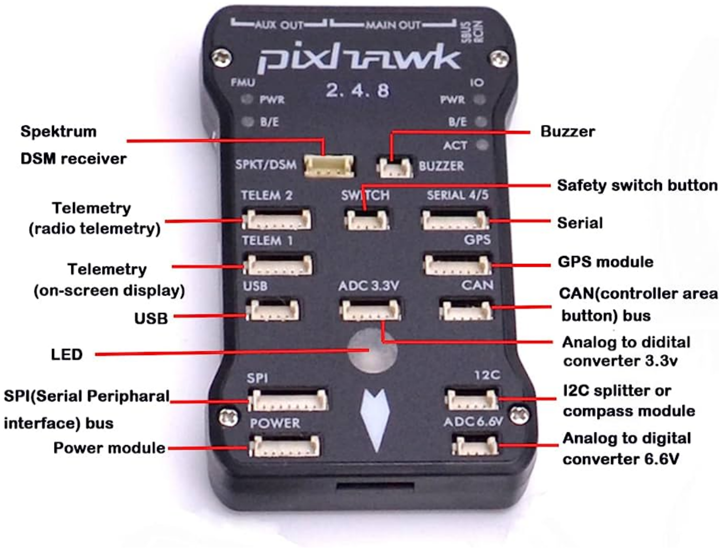


Figure 3.5: Pixhawk Flight Controller 2.4.8

Pixhawk version 2.4.8 provides a variety of essential features and functionalities for operating a USV as shown in Figure 3.5. These consist of:

- **Flight Controller:**Pixhawk is responsible for controlling the USV's propulsion system, steering mechanisms, and other actuation elements. It controls the speed, direction, and manoeuvrability of the vehicle.
- **Navigation:** Pixhawk is equipped with GPS, a compass, and other positioning sensors to identify the location and monitor the movement of a USV. It uses this data to navigate along predefined routes or follow specified coordinates.
- **Autonomy:** Pixhawk enables the autonomous operation of the unmanned surface vehicle, allowing it to execute pre-planned missions or complete duties without direct human intervention. It can adhere to mission plans, navigate autonomously, and adapt to changing environmental conditions.
- **Sensors Integration:** Pixhawk integrates with a variety of sensors, including GPS/compasses, and ultrasonic sensors, to collect key data about the USV's surroundings. This information is used for navigation and obstacle avoidance.

- **Communication:** Pixhawk supports various communication protocols and interfaces, allowing it to interact seamlessly with ground control stations and other external devices. It permits data transmission in real-time, remote control, and mission monitoring.

The Pixhawk has an integrated Safety Switch, shown in Figure 3.6 switch that enables the user to manually enable or disable the motor-controlling output signals. This switch provides a crucial layer of protection and safety.

Figure 3.6: Pixhawk Safety Switch

When enabled prior to operation, the Pixhawk will send output signals to the ESCs to power the motors when armed. After completing the mission, the user can deactivate the switch to stop all motor output signals, even if the Pixhawk is still powered on. Additionally, the safety switch functions as a visible indicator of whether or not the outputs are live. Typically, a red switch indicates that the operation is disabled, while a green switch indicates that the operation of the vehicle is enabled. The switch has sufficient resistance to prevent inadvertent state changes due to vibrations. A physical hardware safety switch provides a direct layer of protection against software bugs or errors that could cause the outputs to be activated inaccurately. It enables the user to confidently disable motor control.

The Pixhawk autopilot includes an integrated Safety Buzzer that alerts the pilot to critical flight events, warnings, and changes in vehicle status, shown in Figure 3.7. It emits a tone upon startup to confirm its functionality. Unique sequences of beeps affirm whether a vehicle is armed or disarmed, eliminating any ambiguity. It will alert the user with a repeated beep if the battery level falls perilously low, allowing them to land immediately.

Figure 3.7: Pixhawk Safety Buzzer

Major failures are signalled by rapid, continuous beeping, prompting the user to deactivate and address problems. It will emit a warning prior to arming if the pre-arm tests detect any issues. The buzzer can also announce programmed events such as geofence violations or missing waypoints. When critical events occur, the Pixhawk's integrated alarm provides intuitive audible confirmation. Along with LED indicators, it functions as a redundant safety mechanism. The clear audible feedback enhances the user's situational awareness, which is particularly beneficial when the vehicle is far away or when the user is distracted. This evident communication between the vehicle and the driver increases confidence and safety.

3.6.3 Measuring Sensor

The M8N GPS/compass module is a component that is frequently used in combination with Pixhawk flight controls as shown in Figure 3.8. It provides credible global positioning system (GPS) performance, allowing unmanned vehicles to perform precise positioning and navigation.

Figure 3.8: Gps M8n ublox built-in compass

The ultimate accuracy of the Ublox GPS NEO-M8N is 0.6 metres, which is over 0.9 metres more than the previous generation NEO-7N's 1.4–1.6 metres accuracy. The integrated compass is critical for orientation and control algorithms since it gives heading information. The M8N module guarantees better location accuracy by supporting various satellite systems, including GPS, GLONASS, Galileo, and BeiDou. It interfaces with the Pixhawk flight controller using SPI or UART protocols, allowing for smooth integration and efficient data transmission between the GPS/compass module and the Pixhawk system.

When the USV is driving autonomously, an ultrasonic sensor is typically employed for obstacle avoidance, shown in Figure 3.9. It identifies things in the vicinity of the USV and offers distance estimations to help avoid collisions.

Figure 3.9: A22 Ultrasonic Sensor

They calculate the distance to the target by transmitting focused ultrasound waves into the air and measuring the time it takes for the reflected waves to return. When voltage is applied, the sensor's piezoelectric transducer generates ultrasonic pulses. The transducer also functions as a microphone to pick up echoes. A control circuit toggles the transmit and receive modes of the transducer. The sensor emits a short ultrasonic pulse when instructed to take a measurement. If this encounters an object, the reflected signal is detected by the sensor. Using the speed of sound in the air and precise measurement of the time between transmitting the pulse and receiving the reverberation, the distance can be calculated. If there is no object present, the waves continue to travel until they dissipate and no echo is received. The narrow beam width of ultrasonic waves enables the precision targeting of particular objects as opposed to the entire environment. They can operate effectively in filthy, humid, foggy, and other low-light environments. Ultrasonic waves are unaffected by object colour, transparency, or surface texture, in contrast to optical systems.

Name label	A22 ultrasonic sensor waterproof

Table 3.4: Ultrasonic Sensor Specification

3.6.4 Propulsion System

A Brushless DC (BLDC) motor is an electric motor that uses direct current (DC) but lacks the brushes and commutators present in conventional brushed DC motors. Instead, electronic commutation is used to control the rotation of the motor. This electronic commutation entails changing phase currents within the motor at precise intervals in order to generate torque.

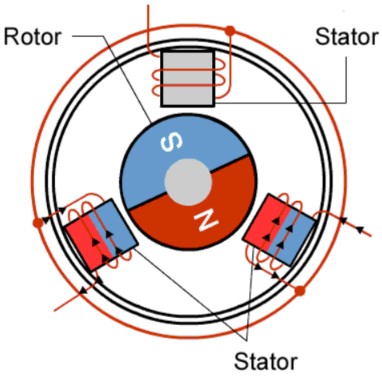


Figure 3.10: Operation of the Brushless DC motor

As shown in Figure 3.10, BLDC motors use electrical commutation with a permanent magnet rotor and a stator containing a series of coils. Permanent magnets rotate within this motor, whereas current-carrying conductors remain stationary.

KV(RPM/Volt)	3250 kV
RPM	60000
Watt	1200 W
No load current	3.8 A
Max Voltage	14 V
Diameter	36 mm
Length	60 mm
Shaft	5 mm
Connector	4 mm golden banana connector
Weight	208.5 g
Wires	Hold 60 A current

Table 3.5: Brushless DC Motor (BLDC) Specification

Servo motors as shown in Figure 3.11 enable precision position control and are used to steer and operate other mechanisms on boats. A small electric actuator is coupled to a position sensor and control circuitry.

Figure 3.11: Servo Motor

Based on autonomous commands, the servo will rotate to the desired angle position. This enables the boat to be reliably steered to precise headings. Servos offer the precision required for navigation, as opposed to a fixed rudder. Servos are indispensable components of boat autonomy and remote control systems due to their simple position modulation, quick response, and small size.

Label	Weytoll 30KG Motor Servo
Peak Stall Torque	29.5kg.cm - 32kg.cm
Gear	Metal
Voltage	4.8V - 7.4V
Size	40.0*20.5*40.5mm
Weight	2.96 ounces
No Load Speed	0.24sec/60° - 0.17sec/60°

Table 3.6: Sevo Motor Specification

An ESC (Electronic Speed Controller) is an electronic circuit used to control the speed and direction of motors in unmanned surface vehicles (USV) by connecting the motor, battery, and flight controller, particularly brushless motors. The ESC functions as an intermediary between the flight controller and the electric motor, regulating the power transmitted to the motor based on the flight controller's signals. It interprets the control signals, which are typically pulse-width modulation (PWM) signals and transforms them into the voltage and current levels necessary to control the speed and direction of the motor. In the case of unmanned vehicles, ESCs play a crucial role in ensuring precise and responsive motor control, which has direct effects on the vehicle's stability, mobility, and performance. By changing the amount of power supplied to the motors, the ESC enables the unmanned surface vehicle to accomplish a variety of patterns.

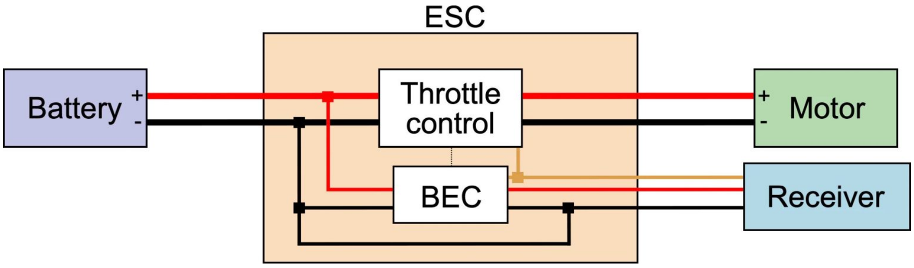


Figure 3.12: Electronic Speed Controller (ESC) Working

As discussed in Figure 3.12 ESCs regulate the rotation of the motor by transmitting a timed electrical signal that is interpreted as a speed change. First, the signal is transmitted from a radio transmitter, which is received by a telemetry receiver attached to the unmanned vehicle. The received signal is then sent to the flight controller, which generates a compatible signal and forwards it to the ESC/BEC, which, depending on the strength of the signal, accelerates the motor.

Label	90A Brushless ESC with 5.5V/3A BEC
Cont. Current	90 A
Burst Current	110 A (10 s)
BEC	5.5V/3A
Voltage	5-18 NC / 2-6 Li-Po
Size	80 * 50 * 23mm (without cables)
Weight	122 g

Table 3.7: Electronic Speed Controller (ESC) Specification

3.6.5 Path Following Capability

Telemetry, as shown in Figure 3.13 is the recording and transmission of data and measurements from USV to a receiver for analysis. During operation, it permits continuous monitoring of status parameters such as position, speed, performance of the engine, orientation, and temperature, which indicate that it operates correctly. Using radio communications links, telemetry entails sensing, digitizing, and transmitting key parameters.

Figure 3.13: 3DR Radio Telemetry 433mhz 433 1000MW Data Telemetry pixhawk apm

Connected sensors in a telemetry system measure necessary parameters and convert them into electrical signals that are then digitally encoded for transmission. This stream of digital data is transmitted wirelessly to a computer at a ground station, which collects, processes, and displays the received data. Advanced telemetry systems enable bidirectional communication for altering settings and parameters remotely. When human observation is problematic due to distance, environment, or complexity, telemetry allows for tracking and monitoring. By detecting unusual parameters, telemetry allows for early warning of upcoming problems.

Name Label	3DR Radio Telemetry 433mhz 433 1000MW Data Telemetry TTL & USB Port
Air data rates	up to 250kbps
Weight	under 4 grams without antenna
Receiver sensitivity	Receiver sensitivity
Frequency	433 MHz
Protocol	MAVLink protocol framing and status reporting

Table 3.8: Telemetry Specification

3.6.6 Operating Power

Power distribution boards are essential for cleanly routing power from the main battery to all electrical components. Onboard voltage regulators generate optimal steady voltages for each type of device from the single battery input. For example, 5V for sensors, 12V for servos, and higher voltages for ESCs Dedicated channels isolate sensitive electronics like flight controllers from electrical noise induced by motors and ESCs using separate power domains. Adjustable current limiting on each channel prevents single device failures from overdrawing current and taking down other electronics. Automatic shutdown activation on overload and short circuit faults also contain damage. Reverse polarity protection blocks damage from connecting batteries incorrectly.

Name label	HB-04-03-PDB-Board-X500

Table 3.9: Power Distribution Board Specification

Battery Specification

Name label	Two 6S Li-Po at 2500 mAh

3.6.7 Electrical Wiring

A power source and connected components like motors, ESCs, a telemetry module, a GPS module, an RC receiver, and other peripherals power this propulsion system. The batteries are connected to Pixhawk, which acts as the brain, and other components such as Servo motors, GPS modules, and UV sensors. They are also connected to the ESC using BEC (a built-in circuit inside the ESC for safe power distribution) to power the BLDC and servos. These connections include the wiring connections of these components. These components are wired through a specific scheme that follows the specific port numbers of Pixhawk for the specified functions.

The battery is to be connected to the Power Distribution Board (PDB) at suitable input ports. PDB acts as the central distributor of power across the whole system. PDB is connected to the Power Module by connecting the output leads of PDB with the input ports of the Power Module. Also, connect the current sensor port of the PDB with the current sensor port of the Power Module. It will help Pixhawk monitor the current consumption. To connect the Power Module with the Pixhawk, connect the Power Module's 6-position DF13 or other compatible connector to the "Power 1" port on the Pixhawk. Make sure to connect the corresponding "+", "-", and "S" ports with each other. It will power up the Pixhawk.

The Pixhawk board should also be connected to PDB so that it can monitor the voltage level of the battery, which is necessary information. Connect the Power 2 port of the Pixhawk with the PDB's port. Connect the specific output port of the PDB with the ESC, which is further connected to the motor. A signal wire from the ESC to the motor should be connected to Pixhawk port 'M' or 'Motor'. There are 8 to 16 pins on the motor port; Pin 1 should be connected to Motor 1, and Pin 2 should be connected to Motor 2. It will control the motor's speed. Connect the RC receiver with the 'RC' port on Pixhawk to remotely control the USV. The GPS module should be connected to the GPS port on the Pixhawk. Telemetry peripherals have a 6-wire connector that can be connected to the 'TELEM 1' or 'TELEM 2' ports labelled on the Pixhawk. Safety switches and buzzers should be connected in ports 'SWITCH' and 'BUZZER' of Pixhawk, respectively.

Safety Measures

There are certain precautionary steps that need to be taken while connecting these peripherals so that the Pixhawk and other peripherals do not explode.

- Install the buzzer at least 5cm away from the flight controller to avoid disrupting the accelerometers.

- All the components should be connected before connecting the battery. The battery should be connected in such a way that the negative wire should be connected first and then the positive wire so that extra current can run through the closed circuit without exploding the Pixhawk or any other peripheral with excess voltage.
- Before turning on the rover, double-check all connections to verify they are proper and secure.
- Calibrate the Pixhawk sensors and compass according to the instructions included with the Pixhawk.

3.6.8 Systems Communication

The telemetry radio is critical for communication between the USV and the ground control station. The Pixhawk flight controller is widely used in unmanned vehicles such as USVs as an open-source and adaptable platform. It supports bidirectional connections, allowing for uninterrupted conversation and data exchange.

The MAVlink protocol is the default communication protocol for the Pixhawk telemetry system. MAVlink is a simple communications protocol used to communicate with unmanned devices. It allows the USV and the ground control station to exchange instructions, telemetry, and other data in a standardised manner. The ground control station may transmit orders to the USV via the MAVlink protocol, such as establishing waypoints, altering speed, or starting specified operations. At the same time, the USV may transmit telemetry data to the ground control station, such as GPS location, sensor readings, battery status, and vehicle health information. MAVlink provides a dependable and efficient communication link between the USV and the base control centre at ground level. It provides operators with situational awareness in real-time of the USV's activities, allowing them to monitor its status make pre-planned missions and execute decisions.

The telemetry radio serves as the physical link between the USV and the ground control station, wirelessly broadcasting and receiving MAVlink signals. It offers a reliable and strong link, allowing operators to manage the USV remotely and receive critical data in real-time.

Overall, the Pixhawk flight controller, telemetry radio, and MAVlink protocol provide a robust communication system for USVs. It allows for effective remote administration, monitoring, and information exchange, increasing the USV's operating capabilities and autonomy in a variety of applications.

3.7 Subsystems Integration and Interfaces

Integrating and connecting the many subsystems is a critical part of the complex process of designing and building a modern boat using systems engineering principles. This phase involves seamlessly combining the various separate systems and parts, each with its own purpose, into a unified, well-functioning whole. Effective subsystem integration requires thoroughly understanding the complex relationships between the different boat design elements. This includes not only physical connections, but communication protocols, data exchange, and collaborative functions too. This section examines the systematic approach taken to harmoniously bring together the electrical wiring, components, and communication systems within the boat's structure. By exploring the intricate web of connections and interfaces, we reveal how these integrated subsystems contribute to the overall efficiency, reliability, and performance of the boat. It highlights the key role thoughtful design plays in achieving a successful outcome.

3.7.1 Propulsion System Integration

Integration of BLDC with Pixhawk

Connect brushless motors to the Pixhawk autopilot in a systematic manner is required for integration. The main battery power input will be received by a power distribution device, which will then distribute power to all BLDC motors. Brushless motors are not physically connected to the Pixhawk. Each motor is instead connected to an ESC (electronic speed controller) that modulates the power to the motor in response to control signals. The ESCs will receive power from the distribution board, and their signal cables will be connected independently to the Pixhawk's motor output pins to receive PWM signals for varying motor speeds. In addition to receiving power from the power board, the servos' individual control wires will connect to the Pixhawk's designated servo ports to receive position control pulses. This architecture enables the Pixhawk to independently send control commands to the ESCs for brushless motor speed regulation and to the servos for position control via a clean, managed power configuration via the distribution board.

Remember to observe both the BLDC motor and ESC manufacturer's guidelines and instructions. Proper configurations and connections are required for secure and reliable operation. Before deploying BLDC motors with Pixhawk in actual applications, initial tests and inspections must always be conducted in a controlled environment.

Integration of ESC with Pixhawk

Integration of the Pixhawk autopilot with other components, such as ESCs, servos, and motors, demands a systematic approach to the connections for reliable functioning. A power distribution board will receive the primary battery power, filter it, and distribute it to the components via integrated BECs. The Pixhawk receives its own regulated power from the flight controller system's dedicated output on the distribution board. The distribution board powers the ESCs that regulate the brushless motors, and they independently connect their signal cables to the Pixhawk's motor output pins to receive PWM signals for variable motor speeds. The power board also supplies power to servos, and they connect their control cables to the Pixhawk's designated servo pins to receive position control pulses. This allows the Pixhawk to simultaneously send commands to the ESCs to control motor speeds and servo positions, respectively. The power board manages the high power requirements of the actuators and provides robust power delivery to electronics such as the flight controller. With these connected components, the Pixhawk can coordinate and command motors, servos, and other actuators for autonomous flight in a safe, dependable, and precise manner.

Integration of Servo with Pixhawk

To incorporate servos with other components and the Pixhawk autopilot, the power distribution board will serve as the central hub for battery power distribution. The Pixhawk flight controller will receive its own regulated power from the distribution board's dedicated power output. The ESCs that control each brushless motor will be directly connected to the motors and will also receive power from the distribution board. Their individual signal wires will connect to the Pixhawk's motor output ports to control motor speeds. Additionally, the servos will receive power from a servo wire on the power distribution board. Each servo's control wire will then be connected independently to a designated servo port on the Pixhawk in order to receive PWM position control signals. Through these signal connections, the Pixhawk can send position-actuation commands to the servos. Therefore, the servos receive pure power from the distribution board as well as control signals from the Pixhawk. This architecture enables the Pixhawk to independently and simultaneously control ESCs, brushless motors, and servos for autonomous operation.

3.7.2 Measuring Sensor

Integration of Ultrasonic Sensor with Pixhawk

The Pixhawk can be connected to ultrasonic sensors to provide obstacle detection and range data for a boat. The Pixhawk has dedicated ports for connecting I2C ultrasonic sensors. Attach the ultrasonic sensor's ground wire to one of the Pixhawk's ground ports to establish a common ground. Connect the sensor's SDA (data) and SCL (clock) lines to Pixhawk's SDA and SCL pins, respectively. These components serve as the I2C interface between the Pixhawk and the sensor. The ultrasonic sensor will also require power, which can be supplied directly from the battery or a BEC; these cables do not need to pass through the Pixhawk. With the ground, SDA, and SCL lines connected, the ultrasonic sensor can use the I2C protocol to transmit distance data to the Pixhawk. The Pixhawk firmware can be configured to initiate ultrasonic measurements and receive distance readings for the rover's obstacle avoidance or mapping functions. Multiple ultrasonic sensors can be connected together on the I2C bus to increase the rover's coverage area.

Integration of GPS/Compass Module with the Pixhawk

The GPS M8N module can supply Pixhawk with position data for autonomous navigation. Establish common ground by connecting the GPS's ground wire to one of the Pixhawk's ground terminals. Next, connect the TX pin of the GPS receiver to the RX pin of the Pixhawk for serial communication. If you need to alter GPS settings on the Pixhawk, you can connect the GPS RX pin to the Pixhawk TX pin. The GPS will also require power, either from the Pixhawk 5V rail or, preferably, a distinct 5V BEC to prevent interference. The M8N is equipped with a USB interface, but its use is limited to initial configuration and not during flight. The GPS will begin transmitting standard NMEA 0183 navigation sentences over the serial connection, which the Pixhawk will parse to derive latitude, longitude, altitude, and other navigation data. The Pixhawk can use this GPS data for autonomous missions and sophisticated flight modes that require a precise global position.

3.7.3 Integration of Operating Power

The power distribution board is the central component for connecting the Pixhawk automation system's components. It will receive the primary input connections for battery electricity. The distribution board then supplies all devices with regulated and filtered power. The Pixhawk flight controller itself will receive power from the flight controller system's dedicated power output. The distribution board will provide power to the ESCs controlling the brushless motors, while their individual signal wires will be connected to the Pixhawk's motor ports. In addition to receiving power from the distribution board, the servos' control wires will connect to the Pixhawk's servo pins. This architecture enables the Pixhawk to independently send control signals to the ESCs for motors and servos for actuation, while the power board manages higher power demands and noise isolation between components. The battery eliminator circuits on the board provide stable voltage sources regardless of battery voltage fluctuations. The distribution board is the platform for integrating the Pixhawk, ESCs, motors, servos, and battery into a dependable and efficient system.

3.7.4 Integration of On-Board Computer

The Pixhawk autopilot features an integrated safety buzzer that alerts the user to changes in flight modes, warnings, and vehicle status. The alarm requires no external connections to function. It is integrated into the Pixhawk circuit board and soldered to the GPIO pins of the processor at the factory. The microprocessor can directly activate the buzzer because it receives power from the Pixhawk's internal power channels. The firmware of the microcontroller operating on the Pixhawk is programmed to activate the buzzer for events such as initialization beeps on startup, arming/disarming tones, low battery warnings, and more. Firmware allows for the complete configuration of tonal patterns, durations, and triggers. Therefore, when the programmed conditions are met, the microprocessor merely toggles the control pin of the buzzer to produce the required audible alert. The built-in alarm provides intuitive audible feedback without the need for additional external components or wiring, thereby enhancing safety and convenience.

The Pixhawk has an integrated safety switch that enables the motor/servo output signals to be manually enabled or disabled. This switch is embedded in the Pixhawk circuit board and requires no additional cabling. It is connected to one of the GPIO ports of the microprocessor, which can digitally toggle the switch's state. When the user enables the safety switch prior to flight, the Pixhawk's output signals can be transferred to the ESCs and servos to control the motors and actuators. After landing, the user deactivates the switch that completely disables these signals, preventing accidental spin-ups. The switch has LEDs that illuminate to signify whether it is enabled or disabled. The Pixhawk's firmware reads the digital state of the safety switch's pin to determine whether outputs should be permitted or blocked. Since the safety switch is embedded in the circuit board, no additional connections are required. Flipping the switch regulates the Pixhawk's hardware layer directly, providing a crucial manual safety feature with ease.

3.7.5 Path Following Capability

Telemetry enables remote data exchange and communication between a Pixhawk autopilot, and off-board systems such as ground-based systems. The Pixhawk has dedicated serial interfaces for telemetry via MAVLink protocols. A radio modem or wireless module can be connected to the Pixhawk's serial port to establish a telemetry link in order to integrate telemetry. The modem on the receiving end connects to the destination system or computer. Software APIs such as MAVlink and serial libraries permit the parsing of the telemetry stream on both ends, facilitating the exchange of meaningful data. The Pixhawk transmits telemetry data such as GPS coordinates, system health, and battery status, while the ground station can transmit commands for control, configuration changes, and mission updates. Advanced cellular or satellite telemetry enables operation beyond the line of sight. Multiple remote systems can even connect to a centralized ground station computer in order to consolidate telemetry data transfers across the entire autonomous system. With properly incorporated telemetry via suitable links, the Pixhawk and connected platforms can exchange vital data continuously, enabling safe, efficient, and intelligent autonomous operation.

A compatible RC receiver in the boat receives radio signals sent by the remote control transmitter. The Pixhawk's RC input port, which is typically a PPM-Sum or S.Bus connection, is where this receiver is connected. The radio pulses are transformed by the RC receiver into a digital signal that the flight controller can understand. The remote control channel mappings are set up in the flight controller firmware to specify what each transmitter stick or switch does, such as throttle, steering, or mode switching. When the switches are engaged, the firmware's RC override functionality enables the manual RC inputs to take preference over autonomous flight modes. This enables manual guided control in addition to autonomy by allowing the transmitter to immediately deliver throttle, steering, and mode signals to the flight controller as needed.

Chapter 4

Results and Discussion

In this chapter, our goal is to show the evaluation of design alternatives based on economic and non-economic criteria. For simplicity, we fixed two design alternatives that were identified using systems engineering principles, as discussed in Chapter 3, with each alternative ensuring user requirements. The cost analysis of each design alternative is shown by computing the present, future, and annual equivalents of the expenses. The non-economic criteria are ranked on a scale and together with the economic criterion, the decision evaluation display is used to identify the design alternative that is better on the basis of multiple criteria.

4.1 Cost Calculations

In this section, we show the component level costings of two selected USV design alternatives and calculate the total cost of the system. The costs are taken from available online shops such as Smart Hobby and Aliexpress. The quantity of the components is as per user requirements. The first alternative is named a Flight controller-operated USV and the second alternative is named as Robot Operating System (ROS) based USV.

4.1.1 Flight Controller Operated USV

In this design, the onboard computer is a flight controller, PixHawk 2.4.8 (Chinese copy), with telemetry devices and GPS/Compass as required. The flight controller uses its built-in code for control to follow the way-point tracking. The cost details along with a description of the components are shown in Table 4.1.

Material	**Description**	**Qty**	**Price (PKR)**	**Total (PKR)**
Brushless Motor	Rocket 3660 3250 KV Motor	2	9,786	19,572
Servo motor	Weytoll 30KG Motor Servo	2	8,922	17,845
Electronic Speed Controller (ESC)	90A Brushless ESC with 5.5V/3A BEC	2	10,658	21,317
Telemetry	3DR Radio Telemetry 433mhz 433 1000MW Data Telemetry pixhawk apm	1	22,500	22,500
GPS/ Compass	Gps M8n ublox built-in compass for Pixhawk	1	6,650	6,650
Ultrasonic Sensor	A22 Ultrasonis sensor Waterproof	2	3,823	7,647
Power Distribution Board	HB-04-03-PDB-Board-X500	1	3,271	3,271
Flight Controller	Pixhawk 2.4.8 (Chinese copy)	1	30,000	30,000
Battery	2500mAh 6S 35C (22.2 V) Lithium Polymer Battery Pack (Li-Po)	2	7,882	15,764
Remote controller	Radiolink AT9S (Radiolink Electronics, Guangdong, China)	1	23,757	23,757
Other electrical and mechanical parts	Plastic enclosure boxes, cables, connectors, screws etc.	1	15,000	15,000

Table 4.1: Cost Analysis of Flight Controller Operated USV

Based on the above table, the total initial cost of the flight controller-operated USV design is PKR 183,322.

4.1.2 ROS Operated USV

The second design alternative is utilizing an Arduino micro-controller as an on-board computer and the control software is a robot-operated system.

Material	**Description**	**Qty**	**Price (PKR)**	**Total (PKR)**
Brushless DC Motor	Rocket 3660 3250 KV Motor	2	9,786	19,572
Servo motor	Weytoll 30KG Motor Servo	2	8,922	17,845
Electronic Speed Controller (ESC)	90A Brushless ESC with 5.5V/3A BEC	2	10,658	21,317
Telemetry	3DR Radio Telemetry 433mhz 433 1000MW Data Telemetry pixhawk apm	1	22,500	22,500
IMU	BNO055 9 DOF Absolute Orientation IMU Module	1	9,891	9,891
GPS/Compass	Gps M8n ublox built-in compass for Pixhawk	1	6,650	6,650
Ultrasonic Sensor	A22 Ultrasonis sensor Waterproof	2	3,823	7,647
Arduino	Arduino Mega 2560	1	4,200	4,200
Raspberry Pi	Raspberry Pi 4	1	55,000	55,000
Power Distribution Board	HB-04-03-PDB-Board-X500	1	3,271	3,271
Memory Card	SanDisk Ultra 64GB	1	1,690	1,690
Battery	2500mAh 6S 35C (22.2 V) Lithium Polymer Battery Pack (Li-Po)	2	7,882	15,764
Remote controller	Radiolink AT9S (Radiolink Electronics, Guangdong, China)	1	23,757	23,757
Other electrical and mechanical parts	Plastic enclosure boxes, cables, connectors, screws etc.	1	25,000	25,000

Table 4.2: Cost Analysis of Flight Controller Operated USV

The total initial cost in this case is PKR 234,103.

4.2 Cost Analysis for Flight Controller Operated USV

The cash flow diagram displays the inflow and outflow of the cash during a system life cycle. As discussed in Section 4.1, the total initial cost of the project is PKR 183,322 for the specific design alternative utilizing a flight controller. Assuming that the project requires PKR 50,000 annually for the operational and maintenance cost (O&M) of the USV and the salvage value of the USV is PKR 120,000 after 4 years, then the cash flow model for the flight controller-operated USV is shown in Figure 4.1.

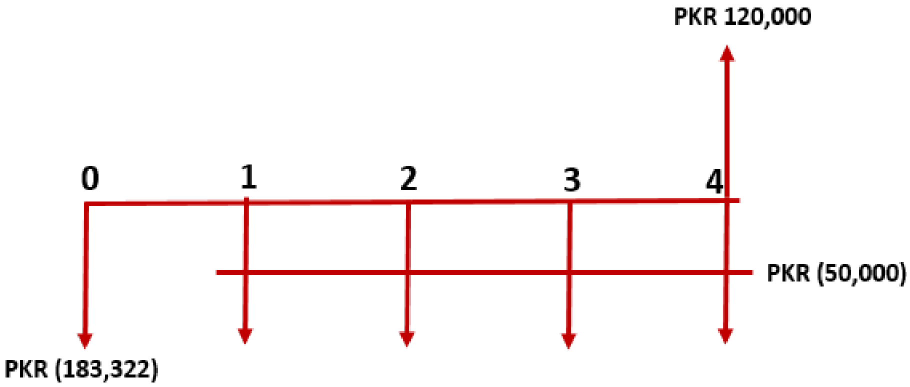


Figure 4.1: Cash Flow diagram of Flight Controller Operated USV

4.2.1 Present Equivalent

The sum of all the costs and benefits during the system life-cycle after projecting them to the present time incorporating the impact of inflation or interest rate is called the present equivalent cost or benefit of the system. This is an important parameter which can be used to compare two different design alternatives. The present equivalent of the annual cost A for n years with an inflation rate of $i\%$ can be written as

$$P_A = A\Big[\frac{((1+i)^n - 1)}{i(1+i)^n}\Big] \tag{4.2.1}$$

In case of the flight controller-operated USV design, $A = 50,000$ and $n = 4$. The inflation rate i is assumed to be 15%. This implies that

$$P_A = 50000\Big[\frac{((1+0.15)^4 - 1)}{0.15(1+0.15)^4)}\Big]$$

$$P_A = 142,775$$

Similarly, the present equivalent of the future cost or benefit F after n years with inflation rate i can be written as

$$P_F = F\Big[\frac{1}{(1+i)^n}\Big] \tag{4.2.2}$$

For the flight controller-operated USV design, the salvage value after 4 years is 120000 so $F = 120,000$ is a benefit not cost, $n = 4$ and $i = 15\%$ as used before. This means that

$$P_F = 120000\Big[\frac{1}{(1+0.15)^4}\Big]$$

$$P_F = 68,610.$$

Now, the present equivalent of all the costs and benefits can be calculated by simply using

$$P_E = P + P_A - P_F$$

$$P_E = 183322 + 142775 - 68610 = 257487$$

Thus the present equivalent cost of the flight controller-operated USV design is PKR 257,487.

4.2.2 Annual Equivalent

The sum of all the costs and benefits during the system life-cycle after projecting them to the annual cost/benefit incorporating the impact of inflation or interest rate is called the annual equivalent cost/benefit of the system. Although present equivalent can be used for comparing two design alternatives, annual equivalent show the cost or benefit of a design from another angle and can be used for comparing two different designs alternatives economically. The total annual equivalent and total present equivalent are related through the following expression:

$$A_E = P_E\Big[\frac{i(1+i)^n}{(1+i)^n - 1}\Big] \tag{4.2.3}$$

In case of the flight controller-operated USV design, present equivalent is $P_E = 257487$, $n = 4$ and $i = 15\%$, so the annual equivalent becomes

$$A_E = 257487\Big[\frac{0.15(1+0.15)^4}{(1+0.15)^4 - 1}\Big]$$

$$A_E = 90,189$$

Thus the annual equivalent cost of the flight controller-operated USV design is PKR 90,189.

4.2.3 Future Equivalent

The sum of all the costs and benefits during the system life-cycle after projecting them to the future cost/benefit after n years, incorporating the impact of inflation or interest rate is called the future equivalent cost/benefit of the system. The total future equivalent and total present equivalent are related through the following expression:

$$F_E = P_E(1+i)^n \tag{4.2.4}$$

In case of the flight controller-operated USV design, present equivalent is $P_E = 257487$, $n = 4$ and $i = 15\%$, so the future equivalent becomes

$$F_E = 257487(1+0.15)^4$$
$$F_E = 450344$$

Thus the future equivalent cost of the flight controller-operated USV design is PKR 450,344.

4.3 Cost Analysis for ROS Operated USV

In case of ROS operated USV design, the initial cost of the USV is PKR 234,103 that is computed after adding the cost of all associated components. The operational and maintenance cost is PKR 50,000 annually as before. The salvage value is now PKR 140,000 with the project life of 4 years. These details are shown in the cash flow model in Figure 4.2.

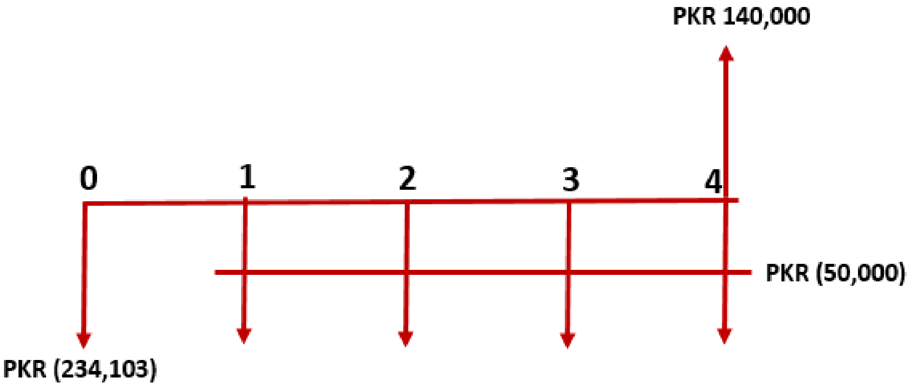


Figure 4.2: Cash Flow diagram of ROS Operated USV

4.3.1 Present Equivalent

The present equivalent of ROS operated USV design can be computed by using the same expression as in Subsection 4.2.1 but with a different P and F values. The present equivalent of the annual cost is the same because A is equal in the two design alternatives. That is $P_A = 142,775$. For the present equivalent of the future value, we use (4.2.2) with $F = 140,000$ to obtain

$$P_F = 140000[1/(1+0.15)^4]$$
$$P_F = 80046$$

Now, the present equivalent of all the costs and benefits becomes

$$P_E = 234103 + 142775 - 80046 = 296832$$

Thus the present equivalent cost of the ROS-operated USV design is PKR 270,819.

4.3.2 Annual Equivalent

For the annual equivalent, we can use (4.2.3) to get

$$A_E = 296832\left[\frac{0.15(1+0.15)^4}{(1+0.15)^4 - 1}\right]$$
$$A_E = 103970$$

Thus the annual equivalent cost of the ROS-operated USV design is PKR 103,970.

4.3.3 Future Equivalent

Similarly for future equivalent, we can use (4.2.4) to obtain

$$F_E = 296832(1+0.15)^4$$
$$F_E = 519159$$

Thus the future equivalent cost of the ROS-operated USV design is PKR 519,159.

4.4 Design Comparison Analysis

We are evaluating two design alternatives under different criteria. There is a design comparison based on these non-economic factors and economic factors, as there are various methods through which we can control the unmanned surface vehicle, and here is a comparison between them in Table 4.1.

Factors	**ROS-Operated USV**	**Pixhawk-Operated USV**
Sensors Integration	Integrate a wide range of sensors	Primarily designed for specific sensors setup
Built-in Sensors	No Built-in Sensors	Include some Built-in Sensor
Flight Tested Firmware	Custom Development Needed	Established and Tested
Actuator Interfacing	Complex Interfacing, adaptable to	Designed with Standard actuator Interfaces
Vehicle Health Monitoring	Custom Implementation Needed	Robust Built-in Monitoring
Price	Potentially Higher	Affordable Pixhawk Controller
Community Support	Strong ROS Community	Dedicated Pixhawk Community
Stability in Rough Conditions	Depends on Implementation	Known for Stable Performance
Reliability	Implementation-Dependent	Proven
Computational Power	Requires Powerful Onboard Computation	Optimized for Autonomy
Autonomy Level	Highly customizable autonomy algorithms	Limited by Pixhawk's autonomy capabilities

Table 4.3: Comparison of Design Alternatives for Unmanned Surface Vehicles

4.5 Decision Evaluation Display

Decision-making in Systems Engineering helps select the best possible outcome. It provides a logical technique to opt for better design alternatives among others based on facts.

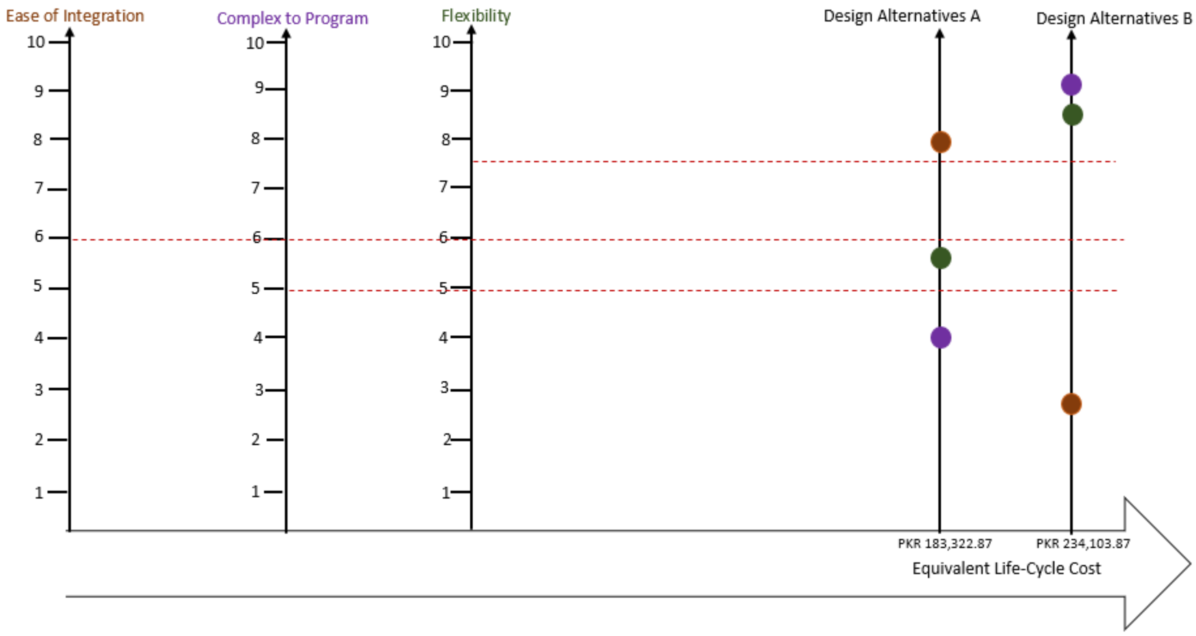


Figure 4.3: Decision Evaluation Display for Alternatives

Considering the design evaluation display of the alternatives as illustrated in Figure 4.3. If the customer doesn't have a preference for the specific configuration of the USV's structure, then the decision can rely solely on economic factors. Design A is being evaluated without restrictions, while Design B is being assessed under constraints. This evaluation is primarily focused on the initial cost estimates.

Now, assuming Design A has certain unfavourable aspects, such as limited adaptability when compared to Design B, Specifically, suppose that the flexibility adapts the rate to only 4 on a 10-point scale versus Design B which stands at 9. Moreover, it will be difficult for the customer to develop custom behaviours and interactions, making it their choice to have a highly flexible and adaptable platform for developing a wide range of scenarios to operate the boat.

The rating for ease of integration and complexity of programming, as shown in Figure 4.3 helped to make the decision to go with Design A. Therefore, the total cost of PKR 183,322 is no longer the only factor on which we have based our decision.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

In this thesis, we showed the use of system engineering principles in the design and development of unmanned surface vehicles, starting from customer needs to requirements, scenario generations, functional analysis, logical architecture and finally physical architecture. In this way, multiple design alternatives can be identified each ensuring user requirements and validating the scenarios or constraints of the system. The design alternatives are classified by using a multi-criteria and multi-alternative decision making method. The criteria include both economical and non-economical parameters. To explain the decision evaluation process, two different design alternatives and four different criteria have been taken for selecting a better USV design alternative. The economic factor we have considered is the total amount of cost in building a USV and the non-economic factors we have considered are the ease of integration, the complexity of the implementation, and the flexibility in design of USV. With these details, the framework of deciding a better design alternative is discussed. Overall the following observations are noted:

- The system engineering principles can specify design alternatives efficiently with USV components essential for required scenario and ensuring all user requirements.
- The decision making of selecting optimal design alternative in terms of economic and non-economic criteria can be highly beneficial. In case of the two design alternatives considered for decision evaluation, the USV operated by a flight controller is 27.7% cheaper than the one operated by the robot operating system.

5.2 Future Work

There are multiple future directions of this work. One of the most important extension of this work is to perform model based system engineering on USV design and development. This will allow us to add additional features in the USV design without effecting the basic user requirements. Another important direction is to perform practical testing of all sub-systems and validate the USV's capabilities through field trials in various settings. Establishing a robust communication link between the USV and the ground control station will enable real-time monitoring and precise remote operation.

Mathematical quantification of the non-economic criteria on a scale that can be used to compare design alternatives require further research work.

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