DEVELOPMENT OF REAL-TIME NAVIGATION SYSTEM BY USING PURE PURSUIT GUIDANCE FOR UNMANNED SURFACE VEHICLE

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ABSTRAK

Sistem navigasi berfungsi sebagai rujukan penting Kereta Permukaan Air tanpa Pemandu (USV), memanfaatkan penerima GPS dan penderia permulaan untuk menentukan dengan tepat koordinat geografi dan orientasi arahnya. USV telah menerima sokongan penuh daripada sistem navigasi dalam menentukan pose semasa dan masa hadapannya di antara dua titik, manakala kedudukan semasanya ditentukan oleh beberapa penderia untuk menganggarkan arah ke arah sasaran atau laluan berikut. Walau bagaimanapun, USV menghadapi kesukaran untuk menjejaki kedudukan semasa sasaran di atas air semasa bergerak ke arahnya, disebabkan oleh pengehadan dalam pengaturcaraannya untuk menavigasi berdasarkan arahan pengiraan awal seperti tajuk dan jarak. Oleh itu, algoritma Pure Pursuit akan dibangunkan untuk membantu USV menjejaki kedudukan sasaran, memastikan kenderaan akan mengikut maklumat laluan baharu dan meningkatkan prestasi masa nyata USV kerana ia menjejaki kedudukan semasa sasaran berdasarkan arahan keluaran. Penyelidikan ini bertujuan untuk mencipta algoritma penjejakan masa nyata untuk membimbing USV ke sasaran menggunakan kaedah Pure Pursuit, dan untuk menguji sejauh mana ia mengurangkan ralat sisi dan mencapai sasaran. Sistem USV dilengkapi dengan konsep dan kaedah pengesanan yang melibatkan penentuan jarak dan sudut tajuk antara dua koordinat (Sasaran dan USV). Untuk mengikuti trajektori laluan semasa, panduan Pure Pursuit telah dilaksanakan dalam sistem. Ringkasnya, menjelang 75s, USV mencapai kedudukan sasaran terakhir, menunjukkan navigasi yang berjaya di sepanjang laluan trajektori. Kejayaan ini disebabkan oleh penyepaduan kaedah pengiraan mati dengan bimbingan Pure Pursuit, yang mengemas kini kedudukan dan orientasi USV secara berterusan menggunakan penderia onboard. Algoritma Pure Pursuit berfungsi dengan memfokuskan pada laluan berdekatan berbanding dengan kedudukan USV, membimbingnya dengan arah stereng berdasarkan kedudukan dan orientasi semasanya. Dari 40s hingga 70s, USV mengikut sasaran, mencapai kedudukan terakhir yang diketahui pada 75s, menunjukkan cara algoritma penjejakan berkesan membimbing USV menggunakan bimbingan Pure Pursuit. Panduan Pure Pursuit membantu USV kekal di landasan dengan melaraskan sterengnya untuk menyasarkan ke arah titik sasaran di sepanjang laluan yang dirancang. Ini mengurangkan ralat sisi, iaitu jarak antara USV dan laluan. Sistem sentiasa melaraskan berdasarkan maklum balas penderia, memastikan USV mengikut laluan dengan rapat dengan ralat yang minimum. Ia akan memudahkan penyesuaian kepada sasaran dinamik, memastikan prestasi yang boleh dipercayai dalam keadaan yang berubah-ubah dan manuver tangkas melalui pertimbangan yang teliti dan strategi mitigasi yang sesuai.

ABSTRACT

The navigation system was serving as the Unmanned Surface Vehicle (USV) cardinal reference, leveraging GPS receivers and inertial sensors to precisely determine its geographical coordinates and directional orientation. The USV was receiving full support from the navigation system in determining its current and future poses between two points, while its current position was being determined by several sensors for estimating the heading towards the target or the following path. However, the USV encountered difficulty in tracking the target's current position on the water while moving towards it, due to limitations in its programming to navigate based on initial computation commands such as heading and distance. Therefore, a Pure Pursuit algorithm will be developed to assist the USV in tracking the target's position, ensuring that the vehicle will follow the new path information, and enhancing the real-time performance of the USV as it tracks the target's current position based on the output commands. This research aims to create a real-time tracking algorithm for guiding the USV to the target using the Pure Pursuit method, and to test how well it reduces sideways errors and reaches the target. The USV system was equipped with a tracking concept and method involving determining the distance and heading angle between two coordinates (Target and USV). To follow the trajectories of the current path, the Pure Pursuit guidance was implemented in the system. In summary, by 75s, the USV reached the last target position, demonstrating successful navigation along the trajectory path. This success was attributed to the integration of the dead reckoning method with Pure Pursuit guidance, which continuously updated the USV's position and orientation using onboard sensors. The Pure Pursuit algorithm works by focusing on the nearby path relative to the USV's position, guiding it with steering directions based on its current position and orientation. From 40s to 70s, the USV followed the target, reaching its last known position at 75s, showing how the tracking algorithm effectively guides the USV using Pure Pursuit guidance. Pure Pursuit guidance helps the USV stay on track by adjusting its steering to aim towards a target point along the planned path. This reduces sideways errors, which is the distance between the USV and the path. The system constantly adjusts based on sensor feedback, ensuring the USV follows the path closely with minimal errors. It will facilitate adaptation to dynamic targets, ensuring reliable performance in changing conditions and agile maneuvering through careful consideration and suitable mitigation strategies.

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LIST OF SYMBOLS

D'Lat	Distance in Latitude line
M'Lat	Mean in Latitude line
D'Lng	Distance in Longitude line
X_C	Latitude Current Coordinate
Y_C	Longitude Current Coordinate
Θ_c	Angle of the Current Coordinate
V_x	Velocity Vector on the x-axis
V_y	Velocity Vector on the y-axis
X_g	Latitude of Target
Y_g	Longitude of Target
X_v	Latitude of USV
Y_v	Longitude of USV
θy_c	USV's Current Course Angle
θy_u	USV's Last Course Angle
Lat_c	Current Latitude
Lng_c	Current Longitude

LIST OF ABBREVIATIONS

AUV	Autonomous Underwater Vehicle
DGPS	Differential Global Positioning System
DOF	Degree of Freedom
DR	Dead Reckoning Method
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
MIO	Maritime Interdiction Operations
MIT	Massachusetts Institute of Technology
NGC	Navigation, guidance, and control system
SWIMS	Shallow Water Influence Mine-sweep System Technology
SCOUT	Surface Craft for Oceanographic and Undersea Testing
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle
VO	Velocity Obstacle

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CHAPTER 1

INTRODUCTION

This chapter emphasizes the comprehensive research studies, including the background and problems faced based on the area studies' current situation. Additionally, this study's research topic and aims are suggested in light of a discovered research gap. Also, this chapter will address the nature of the issue and the importance of this study.

1.1 Research Background

An Unmanned Surface Vehicle (USV) is one of the water surface drone for harvesting at the water surface, which autonomously operates to take the data and patrol the harsh area. In addition to working autonomously, most USVs can be operated manually or remotely on the water's surface. Liu et al. (2016) reported that climate change, environmental anomalies, manpower needs, and national security concerns lead to a substantial demand for new USV development from commercial, scientific, and military crews. Furthermore, since the USV does not require personnel onboard, it is smaller and more manoeuvrable in hazardous water surface areas than conventional ships (Effendi & Kadir, 2021). Hence, all the benefits improved personnel safety and allowed USV to perform hazardous and challenging tasks besides saving lots of time and power (Tanakitkorn, 2019a).

The future advancement of USVs is contingent upon the development of complete autonomy, which enables USVs to operate autonomously in any unstructured or unpredictable environment. The navigation, guidance and control (NGC) system is vital to developing a functional USV. These three critical components ensure the USV's capacity to perform the tasks. According to Naeem et al. (2008), NGC systems must be installed in autonomous vehicles, and these systems must communicate to function optimally. Liu et al. stated that developing this autonomy is particularly challenging since it requires the development of effective and reliable USV systems, such as reliable communication systems, stability of hull design, and powerful NGC techniques (Liu et al., 2016a). The defects in one system diminish the efficiency of another.

Besides, controlling USVs safely and efficiently necessitates a navigation system capable of sensing, state estimation, perception of the environment, and situation awareness. The failure of communication, sensor, and actuator of the fully automated USV will complicate the mission to complete on time and cause the high cost. For this reason, the consumption of a semi-autonomous USV gains more demand than the fully automated USV due to the challenges on the automated system and the reliability of the navigation system. Further development of fully autonomous USVs is necessary to minimize both the requirement for human control and the repercussions of a human mistake on the practical, safe, and reliable operation of USVs (Campbell et al., 2012a). For instance, Mousazadeh et al. (2018) stated that many USVs are equipped with NGC algorithms due to the inherent human error in manual surface vehicle navigation (Mousazadeh et al., 2018).

The navigation system delivers target-related information, which the guidance system processes reference headings. Some research has highlighted that the navigation system, which collects environmental data, is responsible for most of the safety of the USV's functioning (Asgharian & Azizul, 2020). The navigation system is responsible for recognizing the USV's current and future states (such as position, direction, velocity, and acceleration) and its surrounding environment, based on the USV's previous and current states and environmental states data obtained via onboard sensors (Liu et al., 2016a). In addition, the compass and GPS are the most often used sensors for monitoring the condition of a vessel in surface vessel navigation, but inertial sensors, such as an IMU, are also utilized. For instance, the sensor's control module uses GPS and a digital compass to calculate the necessary heading and speed corrections for following the USV's onboard system's waypoints (Ahmad et al., 2011).

The waypoints of the autonomous vehicle are defined as the waypoints the vehicle would take in a particular situation. Samuel et al. (2016) said that the primary operational process is that the USV first detects the environment, positions itself according to necessary sensors, such as GPS, IMU, cameras, sensors, and then navigates with global and local planners. As a result, the vehicle drives itself autonomously by executing the necessary control command and following the given waypoints. Path-tracking controllers perform path following tasks by achieving a minimal lateral distance and the heading between the vehicle and the designated waypoint (Samuel et al., 2016). Path-tracking missions for USVs can be classified into two categories: offline path-tracking in known environments and real-time path-tracking in unknown situations. The researcher has explained that offline path-tracking should optimize globally and applied offline. In the second situation, the trajectory should be near optimized locally, and the USV should address the software architecture and sensors. (Phanthong et al., 2014).

Path-tracking is a system for navigating and operating autonomous vehicles along a waypoint by continuously generating speed and steering orders that adjust for tracking error, primarily vehicle distance and heading deviations from the waypoint (Samuel et al., 2016). Besides, Amidi (1990) explained that the simpler tracking systems rely on geometric considerations between the current vehicle position and the path followed (Amidi, 1990). For example, a researcher has developed the USV platform for autonomous navigation in the paddy field using a least square method to autonomously navigate the predefined navigation map under the farming working requirement (Y. Liu et al., 2014). Giesbrecht et al. (2005) stated that USV's capabilities would be enhanced if other behaviours such as obstacle avoidance, path planning, or leader/follower augment control were implemented in the onboard system. Hence, the path-tracking algorithm should be flexible enough for suitable application in all these behaviours, working in concert with the other algorithms used.

1.2 Problem Statement

The movement of USV towards the one point to another is depends on the computation detail from the NGC system commands. Installing the GPS in the USV is essential in order to determine its current location that able to compute the distance between two locations, heading and the speed of the vehicle. In depth, various types of mathematical techniques have implemented in USV's NGC system to determine the initial reading towards the other position then, controlling USV's movement to that point. Based on this situation, several researchers have implemented the off-path-tracking system to guide USV towards the target and control the USV odometry by installing the known environment in the onboard USV. In order to guide USV to the target location, the desired position will be computed in advance and generate the trajectory path towards the target position (Liu et al., 2014).

However, USV has faced the constraint to track the target's current position on the water while USV move towards the target. This problem occurred due to the limitation of the USV's program to navigate itself by following the commands of the initial computation command such as heading and the distance before it moving (Larrazabal & Peñas, 2016). In depth, the real-time data cannot be processed by the controller because both parameters of the remaining distance and the current heading are not being computed in the program. The program will generate the trajectory towards the target based on the initial parameter received from the program command. Consequently, USV will stray from the target's current position because it has followed the trajectory commands that generate by the program.

Therefore, a Pure Pursuit algorithm that can assist USV for tracking the target position needs to be developed to ensure this vehicle will follow the new path information. This algorithm will enhance the real-time performance of the USV that track the target's current position based on the output commands. In-depth, the path information from the sensor will be used as the input commands to track the target's location by estimating the current distance and the heading between the target and the USV. In this situation, the movement of the USV will depends on the real-time information and commands from the onboard sensor to minimize real-time USV path-tracking error.

1.3 Research Question

i. How to determine the real-time tracking path based on the coordinate position of the target in the USV's navigation system?

ii. Why are initial distance and heading towards the target will improve the performance of USV to track the correct path towards the target?

iii. How will technique implement in the USV affects the heading of USV in minimizing the lateral error while it moving?

1.4 Objectives

The objectives of this research are:

i. To develop the real-time tracking algorithm that guides USV towards the target location using Pure Pursuit guidance method.
ii. To evaluate the algorithm's performance in minimizing lateral error and reaching the target location.

1.5 Scope of the Dissertation

The scope of the dissertation is summarized as follows:

i. To develop the real-time tracking algorithm that guides USV towards the target location using PP guidance method.
ii. This research will focus on the water surface, free from obstacles and nature distractions such as wind, rain, and the cluttered environment.
iii. This research will use Global Positioning System (GPS) as the main sensor to determine the coordinates and HC-12 transmitter as the connection between target and the USV.

1.6 Research Significance

The research findings will redound to the USV, considering that tracking scenario plays a vital role in the autonomous navigation area. The real-time tracking of the USV requires the proposed techniques to compute the lateral distance and position between the target and USV. This research proposed the path-tracking techniques that can guide USV without human intervention to catch the target location on the water. In the autonomous navigation system of USV, the nearest distance between the target and the USV needs the proposed technique to estimate the exact position of both platforms. The excellent proposed program has assisted with the Pure Pursuit guidance algorithm to guide USV tracks the target’s position by estimating the heading of the USV towards the target in real-time tracking.

1.7 Organization of the Chapter

The following is the flow of proposal representation by chapters:

i. Chapter 1 explains the three primary components of this research: current USV usage, navigation system, and path-tracking scenarios. This chapter also outlines the research's purpose and objective, the dissertation's scope, and the research's importance.

ii. Chapter 2 contains a literature review developed following the research’s keywords. These keywords include USV, navigation system, path-tracking scenarios, and contemporary USV navigation system methodologies.

iii. Chapter 3 describes the flow process of the development of the navigation system by implementing the selected technique in detail. This chapter also emphasizes the development of the USV platform and the target platform, including the subsystem’s development with the hardware connection.

iv. Chapter 4 shows the result of USV performance by implementing the proposed technique in real-time tracking. USV platform has to manoeuvre on the water surface to collect the tracking data of the vehicle to track the target’s position. The position (coordinates) of both platforms and the heading are addressed in this chapter.

v. Chapter 5 examines the conclusions drawn based on calculation and the results obtained in the previous chapter. The recommendation will also be addressed in this chapter.

Summary

This chapter describes the research issue that evolved with the real-time tracking performance in USV's navigation system which is; to track the target’s current position on the water while USV move towards the target.

CHAPTER 2

LITERATURE REVIEW

Chapter 2 explores the intricate terrain of real-time navigation system development for unmanned surface vehicles, concentrating on the utilisation of the Pure Pursuit Guidance algorithm. Through a comprehensive analysis of prior studies, the objective is to decipher the progression of navigation approaches for unmanned surface vehicles (USVs), evaluate the effectiveness of Pure Pursuit Guidance across various scenarios, and ascertain the obstacles and prospects that await in the future regarding augmenting the autonomy and adaptability of USVs. By conducting an extensive examination of the relevant literature, this inquiry aims to offer significant perspectives on the latest advancements, crucial areas of uncertainty, and prospective trajectories in the domain of autonomous marine navigation.

2.1 Overview of Unmanned Surface Vehicle

Unmanned Surface Vehicles (USVs) have emerged as pivotal assets within the maritime domain, offering autonomous or remote-operational capabilities devoid of onboard human presence. Rooted in the confluence of robotics, sensor technology, and maritime engineering, the genesis of USVs can be traced back to the latter half of the 20th century (Azzeri et al., 2015). Originally conceived for military endeavours, such as reconnaissance and surveillance, USVs swiftly transcended their initial scope, permeating diverse civilian and commercial sectors owing to their multifaceted utility and economic viability.

Notably, the Massachusetts Institute of Technology (MIT) has spearheaded the development of various USV prototypes within the United States of America (USA), such as the catamaran model AutoCat (1999) and SCOUT vessels (2004). Diverging from conventional manned vessels, USVs function autonomously or under remote guidance, obviating the necessity for human presence aboard. For instance, Larson et al.

transformed a fishing trawler-type vessel, scaled to 1:717, into a USV known as ARTEMIS (Larson et al., 2006). Similarly, in 2003, QinetiQ Ltd. engineered a semi-autonomous USV incorporating the Shallow Water Influence Mine-sweep System technology (SWIMS) to bolster military capabilities (Corfield & Young, 2006).

The progression of Unmanned Surface Vehicles (USVs) has undergone significant advancement throughout the years, originating from both military and civilian contexts. Early iterations primarily served military purposes, notably in mine countermeasures and reconnaissance operations. For instance, Bertram (2008) documents the utilization of USV models such as MUSCL, Stingray, and Silver Marlin in research endeavours aimed at developing surveillance and reconnaissance systems.

As technological capabilities advanced, USVs began to find applications in various fields including oceanography, environmental monitoring, and offshore industries, indicative of their versatility and capacity to adapt to a range of tasks. In 2007, a small-scale USV incorporating GPS-assisted guidance waypoints was developed to facilitate the recording of chlorophyll data, thereby enhancing capabilities in oceanographic surveying (Desa et al., 2007). Furthermore, previous studies have suggested that the trajectory of USV development in the future will be heavily influenced by advancements in underlying technologies (Campbell et al., 2012b).

In scientific realms, USVs assume a pivotal role, particularly within the realms of oceanography and marine biology. Equipped with an array of sophisticated sensors and data acquisition instruments, they facilitate comprehensive investigations into marine ecosystems, oceanic currents, and underwater topographies (Liu & Chen, 2016). Their autonomous operational prowess enables protracted missions, thereby enabling researchers to conduct extensive data-gathering endeavours across expansive maritime expanses, thereby advancing our comprehension of oceanic phenomena and ecological dynamics.

A collaborative research expedition led by oceanographic institutes aims to utilize USVs for conducting comprehensive surveys of marine biodiversity in remote oceanic regions. Equipped with state-of-the-art hydroacoustic and imaging sensors, the USVs autonomously navigate predetermined transects, collecting high-resolution data on marine species distribution and habitat characteristics. This research provides invaluable insights into the ecological dynamics of understudied marine ecosystems.

Commercially, USVs are increasingly harnessed for an array of applications including offshore exploration, subaquatic inspections, and environmental surveillance. Their cost-efficiency and adeptness in navigating challenging maritime environments render them preferred choices within industries such as oil and gas, where remote-operational modalities are inherently advantageous (Gaugue et al., 2019). Additionally, the integration of USVs into commercial endeavours yields discernible benefits encompassing diminished operational expenditures and reduced ecological footprints vis-à-vis conventional manned maritime vessels.

A multinational energy corporation invests in research initiatives to optimize the use of USVs for offshore oil and gas exploration and production operations. The research program focuses on enhancing the autonomy and reliability of USVs for conducting subsea infrastructure inspections, leak detection, and environmental monitoring tasks (Lewicka et al., 2022). Furthermore, the project explores the integration of USVs with unmanned aerial vehicles (UAVs) to provide comprehensive surveillance coverage of offshore assets.

Notwithstanding their myriad merits, USVs confront a gamut of challenges encompassing regulatory frameworks, cybersecurity vulnerabilities, and imperatives for sustained technological innovation. The resolution of these challenges is imperative for realizing the comprehensive potential of USVs and expanding their operational purview within diverse maritime domains (Barrera et al., 2021). Thus, concerted research endeavours and collaborative initiatives spanning industry, governmental, and academic domains are indispensable for propelling innovation and ensuring the seamless and efficacious integration of USVs within global maritime frameworks.

A leading maritime technology company undertakes research and development efforts to address cybersecurity challenges associated with USV operations. The research team designs robust encryption protocols and intrusion detection systems to safeguard communication channels and onboard systems from malicious cyber threats. Additionally, the project explores the use of artificial intelligence (AI) algorithms for proactive threat detection and mitigation in real-time USV operations (Singh et al., 2020).

The development of USVs has evolved significantly over the years, with roots in both military and civilian applications. Early iterations were primarily designed for defence purposes, including mine countermeasures and reconnaissance. For instance, Bertram (2008) lists MUSCL, Stingray, and Silver Marlin as the USV-type used in the research studies to develop surveillance and reconnaissance systems. As technology advanced, USVs found applications in oceanography, environmental monitoring, and offshore industries, reflecting their versatility and adaptability to diverse tasks. In 2007, small USV equipped with a GPS-assisted guidance waypoint is developed to record the data of chlorophyll formed, besides improving the oceanographic survey (Desa et al., 2007). Besides, previous research has indicated that USV in the future will influence by the advance of underpinning technology (Campbell et al., 2012b).

USVs come in various sizes and configurations, from small, agile crafts to larger vessels capable of extended missions. They are equipped with a variety of sensors, communication systems, and navigation tools, enabling them to operate in different maritime environments. In 2005, Curcio et al. developed a low-cost Surface Craft for Oceanographic and Undersea Testing (SCOUT) to improve the communication between AUV and the craft (Curcio et al., 2005). These vehicles often integrate advanced technologies such as GPS, radar, sonar, lidar, and computer vision to navigate, sense their surroundings, and execute tasks with precision. A Dynamical System and Ocean Robotic (DSOR) department developed DELFIM under the Institute Superior Technical (IST) supervision in Lisbon, Portugal. Using as collecting marine data and acted as an acoustic relay between a UUV and a support vessel (Alves et al., 2006).

The applications of USVs span a broad spectrum. In scientific research, they contribute to oceanographic studies, collecting data on marine ecosystems, weather patterns, and underwater topography. In defence, USVs are employed for tasks such as surveillance, reconnaissance, and mine detection, minimizing the risk to human personnel. By relying on USVs with sophisticated Navigation, Guidance, and Control

(NGC) systems, the precise and autonomous operation across diverse maritime scenarios can be applied (Wu et al., 2017). The cornerstone of these systems lies in Global Navigation Satellite Systems (GNSS) such as GPS, providing real-time and accurate positioning data globally. Complementing GNSS, Inertial Navigation Systems (INS) utilize accelerometers and gyroscopes to maintain navigation integrity in areas where satellite signals might be compromised (Luo et al., 2021).

2.1.1 Onboard System

USV epitomize forefront technological innovations in maritime domains, leveraging sophisticated onboard systems to facilitate autonomous or remotely controlled navigation. At the core of each USV lies a meticulously crafted array of systems meticulously engineered to enable safe and effective operation across diverse marine environments (Yeong-Ho et al., 2020). The navigation system serves as the USV's cardinal reference, leveraging GPS receivers and inertial sensors to precisely determine its geographical coordinates and directional orientation. This critical dataset feeds into the control system, coordinating propulsion and steering mechanisms, thereby empowering the USV to navigate water channels with utmost precision and manoeuvrability (Ccolque-Churquipa et al., 2018).

The navigation system of a USV is a complex amalgamation of cutting-edge technology designed to provide precise positioning, orientation, and velocity data crucial for safe and effective operation. GPS receivers serve as the backbone, ensuring accurate geographical coordinates even in challenging environments (Rovelli, 2002). Inertial sensors such as accelerometers and gyroscopes complement GPS data, offering redundancy and resilience against signal disruptions. Moreover, magnetometers enhance orientation estimation, providing reliable heading information essential for course plotting and maintaining trajectory accuracy, particularly in areas with magnetic anomalies (Fang et al., 2005). All the components mentioned formed a robust navigation system that not only ensures the USV stays on course but also adapts to dynamic environmental conditions with precision and reliability.

Equipped with GPS receivers, the USV precisely determines its geographical coordinates, allowing researchers to track its movement in real-time. Inertial sensors like accelerometers and gyroscopes provide additional data, ensuring accurate positioning even when GPS signals are intermittently obstructed by tall waves or cloud cover. Meanwhile, magnetometers help maintain course accuracy, compensating for magnetic anomalies that might otherwise distort directional readings (Specht et al., 2019). Hence, USV adheres to its designated research route, collecting valuable data on ocean currents and marine biodiversity.

Communication systems constitute another pivotal facet of USV architecture, facilitating seamless interaction between the vehicle and its operators, alongside other pertinent entities such as control stations or satellites. Whether employing radio frequency, satellite links, or underwater acoustic communication modalities, these systems ensure real-time data exchange essential for the successful execution of missions (Politi et al., 2024). Concurrently, the sensor payload equips USVs with a multifaceted suite of instruments, spanning cameras, radar, sonar, and environmental sensors. This amalgamation of sensor capabilities endows USVs with the capacity to comprehensively capture data for diverse applications encompassing marine research, environmental monitoring, surveillance, and defence.

The sensor payload of a USV encompasses a diverse array of state-of-the-art instruments meticulously chosen to meet the demands of its operational objectives. Using a visible light, infrared, and multispectral cameras provide the USV with comprehensive visual perception capabilities, crucial for situational awareness and target identification (Fan et al., 2022). Visualize a USV deployed in an ecologically sensitive marine sanctuary for environmental monitoring. Equipped with a comprehensive sensor payload, including visible light, infrared, and multispectral cameras, the USV captures high-resolution imagery of coral reefs and marine life (Yuan et al., 2023). Environmental sensors continuously monitor water temperature, salinity, and pollutant levels, providing valuable data for conservation efforts (De Camargo et al., 2023). By integrating these sensor modalities, the USV supports ongoing research initiatives and facilitates informed decision-making to protect fragile marine ecosystems.

The control system of a USV serves as its operational nerve centre, orchestrating propulsion, manoeuvrability, and response to external stimuli with unparalleled precision and efficiency. Drawing inputs from the navigation system, mission objectives, and user commands, the control system employs sophisticated algorithms to modulate propulsion mechanisms, such as thrusters or propellers, adjusting speed and direction seamlessly (Du et al., 2015). Steering mechanisms are meticulously calibrated to enable precise course alterations, ensuring the USV navigates along designated routes and avoids obstacles effectively. Furthermore, real-time feedback mechanisms and predictive algorithms enable the system to anticipate and respond to environmental changes swiftly, maintaining optimal performance even in challenging conditions. In essence, the control system embodies the USV's adaptability and responsiveness, essential qualities for accomplishing a wide range of maritime missions (Wang et al., 2024).

In depth, the control system receives inputs from the navigation system, radar, and camera sensors to assess maritime traffic patterns and identify potential threats. Based on this data, the system dynamically adjusts the USV's speed and heading, optimizing its surveillance coverage while avoiding collisions with other vessels (MahmoudZadeh et al., 2022). Additionally, predictive algorithms anticipate changes in weather conditions or incoming vessels, enabling proactive course adjustments to maintain operational effectiveness (Liu & Chen, 2016b). As a result, the USV seamlessly monitors coastal activities, enhancing maritime security without human intervention.

The autonomy and control software represent the intellectual centre underpinning USV operations, orchestrating intricate algorithms for path planning, obstacle avoidance, and mission coordination (Yang et al., 2024). These algorithms imbue USVs with cognitive capabilities to autonomously navigate dynamic environments, adeptly adapting to fluctuating conditions while optimizing operational efficiency and safety. Complemented by robust safety systems, as well as data processing and storage functionalities, USVs stand as formidable assets in maritime endeavours, offering unparalleled versatility and reliability amidst a continually evolving technological landscape (Asgharian & Azizul, 2020). As advancements continue to push the boundaries of unmanned maritime systems, USVs are poised to play an increasingly pivotal role across myriad maritime applications, propelling advancements in efficiency, safety, and environmental sustainability across global waterways.

Picture a USV navigating through congested waterways to deliver supplies to remote coastal communities. Powered by advanced autonomy and control software, the USV autonomously plans its route based on real-time data from the navigation system and onboard sensors (Sotelo-Torres et al., 2023). As it encounters dynamic obstacles such as drifting debris or changing tide patterns, the software dynamically recalculates the optimal path, ensuring efficient and safe navigation. Additionally, mission optimization algorithms manage onboard resources, adjusting propulsion and energy usage to maximize operational efficiency and minimize environmental impact (Xiong et al., 2021). Through adaptive decision-making and continuous learning, the USV safely completes its delivery mission, demonstrating the efficacy of its autonomous capabilities in real-world scenarios.

2.1.2 USV Degree of Freedom

In the context of Unmanned Surface Vehicles (USVs), the concept of "degrees of freedom" typically refers to the range of motion and control capabilities these autonomous or remotely operated vessels possess (Breivik et al., 2008). The degrees of freedom of a USV encompass various aspects, including its propulsion system, manoeuvrability, sensors, and onboard systems. The degrees of freedom of a USV can be categorized into translational and rotational motions. Translational degrees of freedom relate to the vessel's ability to move forward/backward, left/right, and up/down on the water surface. This involves the propulsion system, which can include propellers, waterjets, or thrusters.

Rotational degrees of freedom refer to the vessel's capability to rotate around its own axis or pivot. This rotational control allows the USV to change direction, turn, and adjust its orientation to navigate effectively. The axes of motion for a USV are delineated based on linear and rotary motion, as depicted in Figure 2.1, denoted as x, y, and z. Linear motion encompasses surge, sway, and heave, while rotational motion encompasses roll, pitch, and yaw. Consequently, the motion of the vessel adheres to the six Degrees of Freedom (DOF), namely surge, sway, heave, roll, pitch, and yaw (Sonnenburg & Woolsey, 2012).

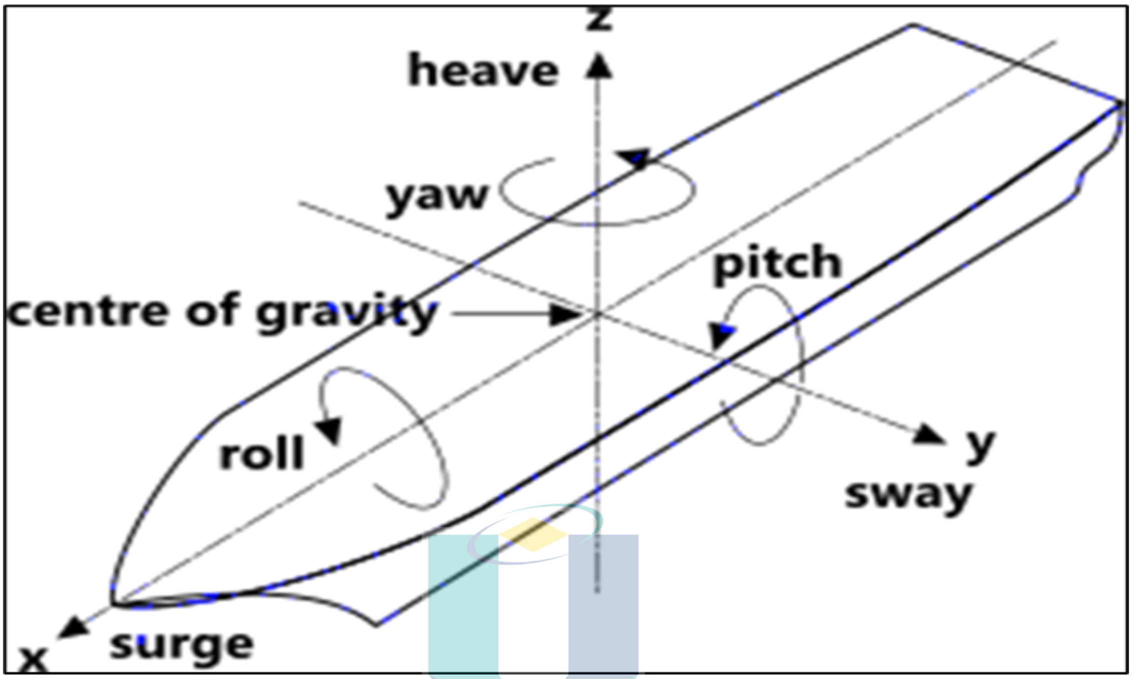

Figure 2.1 USV’s Degrees of Freedom
Source: Breivik (2010b)

Table 2.1 shows USVs possess degrees of freedom (DOF) that characterize their mobility and operational capabilities. These DOF encompass both translational and rotational movements. Translational DOF include surge (x), which represents forward/backward motion, sway (y) for lateral movement, and heave (z) for vertical displacement (Wan et al., 2019). Each of these translational DOF is typically measured in meters (m) and influences the vessel's ability to navigate effectively in different water conditions.

Rotational DOF encompass yaw (φ), representing rotation around the vertical axis, pitch (θ) for rotation around the lateral axis, and roll $(\emptyset)$ for rotation around the longitudinal axis. These rotational DOF are typically measured in degrees (°) and affect the vessel's stability, manoeuvrability, and ability to maintain course. Together, these degrees of freedom define the agility, versatility, and operational performance of USVs across a range of maritime missions, from surveillance and reconnaissance to environmental monitoring and offshore operations (Sonnenburg & Woolsey, 2012).

Table 2.1 Vessel Six-Degrees of Freedom

DOF	Transfer Function	Phase Angle
Surge (m)	x	DOF_x
Sway (m)	y	DOF_y
Heave (m)	z	DOF_z
Roll (◦)	$\emptyset$	$DOF_{\emptyset}$
Pitch (◦)	θ	DOF_{θ}
Yaw (◦)	Ψ	DOF_{Ψ}

Source: Sonnenburg & Woolsey (2012)

2.2 Real-time Navigation System

USVs represent an autonomous or remotely operated class of watercraft navigating aquatic environments devoid of human presence. Their navigation systems are pivotal components facilitating safe and efficient traversal across water bodies (Jovanović et al., 2024). The navigation paradigm of USVs is typically characterized by the amalgamation of sensor suites, communication frameworks, and intricate control algorithms. USVs rely on an array of sensors encompassing GPS, Inertial Measurement Units (IMUs), radar, lidar, and cameras to ascertain their surroundings and acquire pertinent data for navigation (Bovcon et al., 2017).

The importance of a robust navigation system in autonomous vehicles cannot be overstated, as it serves as the cornerstone for precision and safety in their operations. Accurate navigation is essential for ensuring that the vehicle can precisely determine its location in real-time, allowing it to navigate through complex and dynamic environments with confidence (Hashemi & Karimi, 2014). This precision is crucial for avoiding obstacles, adhering to traffic rules, and making timely decisions to ensure the safety of both the vehicle and its occupants.

Navigation systems play a pivotal role in the decision-making process of autonomous vehicles. By providing real-time information about the USV's surroundings and the broader environment, these systems enable the vehicle to make intelligent decisions based on the current situation. The adaptability of autonomous vehicles to unforeseen circumstances, such as road closures, traffic congestion, or dynamic obstacles, relies heavily on the accuracy and responsiveness of the navigation system. For example, an effective navigation system enhances the overall operational efficiency of USV (Hashali et al., 2024). By optimizing routes and making informed decisions about lane changes, turns, and speed adjustments, the vehicle can navigate more efficiently through traffic, reducing travel time and energy consumption.

Navigation systems often work in tandem with a variety of sensors, such as lidar, radar, cameras, and GPS, through a process known as sensor fusion. This integration enhances the vehicle's perception of its environment, providing a comprehensive and multi-modal understanding (Líu et al., 2019). The synergy between navigation and sensor systems enables the vehicle to navigate effectively in diverse conditions, including challenging weather, low-visibility scenarios, or situations with high levels of traffic and pedestrian activity. A dependable navigation system contributes to a positive user experience, fostering trust in the vehicle's capabilities and, by extension, in the broader adoption of autonomous technology.

Commonly, USV's latest technology fitted in stratifying the respective task with the advance electronic system. The researcher and developer concentrate on hull consideration, engine development, propulsion system, communication-based system, navigation, guiding, and control (NGC). Due to the un-predict obstacle and the cluttered environment in the heavy traffic, the good setup and better safety onboard crew have improved the hulls, intelligent NGC system, and delicate sensor. Most USV is only experimental platforms used to evaluate communication, control algorithms, sensor systems, propulsion solutions, and hull designs (Setiawan et al., 2022).

Based on previous research, Northwind Marine Inc. developed SEAFOX, a rigid hull inflatable boat (RIB), to verify and test the obstacle avoidance algorithm (Colito, 2007). Coast Guard International Regulations installed a path-planning system for

Avoiding Collision as Sea (COLREGS) on the onboard's SEAFOX to deal with the heavy traffic. Besides, most of the naval operations use the RIB hull as the standard vessel diffusion due to the capability accommodated the large fuel tanks (Bremer et al., 2007) (Yang et al., 2011) (Caccia, 2006) (Navy, 2007). Furthermore, eleven meters of USV RIB-type consist of intelligence, surveillance, and reconnaissance systems (ISR) to perform maritime interdiction operations (MIO). Therefore, the MIO mission needs an enhanced awareness system to detect the scourge using various sensors and devices (Navy, 2007).

The NGC system is the autonomous vehicle's central system because it depends on its operation. An instalment of accurate and adaptable navigation hardware with the NGC system will help USV seamlessly switch the operational, autopilot, and manual driving modes. Naeem et al. (2006) analyze the NGC system using the Fuzzy Logic algorithm within Springer's onboard system in case of emergencies and unpredicted events (Naeem et al., 2006). The NGC system is divisible into three subsystems representing navigation, guidance, and control processes that instantly handle the USV's movement. It also can be called the USV's brain to track all sorts of situations and environments while controlling the USV to get away from the collision along the task journey. The NGC system is closely related, indirectly bringing importance to every movement in USV.

USV receives full support from the navigation system in determining its current and future poses between two points. Furthermore, USV's current position is determined by several sensors for estimating the heading towards the target or the following path. As example, Liu et al. (2016) stated the USV's current condition (position, acceleration, orientation, and velocity) determines by the navigation system, while the several onboard sensors trace current environmental awareness for decreasing the collision risk. In 2012, Naeem et al. mentioned that human intervention had been eliminated from the onboard, where USV will equip with a robust and reliable NGC system.

2.2.1 Importance and Challenge

The navigation system serves as a vital component for USVs, facilitating their safe and efficient navigation through water bodies. An efficient navigation system enhances operational efficiency by enabling optimal route planning, trajectory optimization, and reduced fuel consumption. Sophisticated navigation algorithms and control systems empower autonomous USVs to operate independently, diminishing the requirement for human intervention and allowing for extended mission durations without human supervision. Additionally, a robust navigation system enables USVs to adapt to diverse mission requirements and environmental conditions, facilitating effective performance in tasks such as surveying missions, maritime surveillance, or search and rescue operations across various maritime environments, including open seas, coastal areas, and congested waterways.

Nevertheless, the navigation system of USVs encounters various challenges. These encompass environmental variability, where the dynamic and unpredictable nature of maritime conditions, such as shifting weather patterns, water currents, and limited visibility, present obstacles to precise navigation. Additionally, sensor limitations can impede navigation effectiveness, as onboard sensors may be vulnerable to interference, signal degradation, or environmental influences. Communication constraints, such as bandwidth limitations and network congestion, have the potential to disrupt real-time data exchange between the USV and control centre, thereby affecting navigation performance and mission execution.

2.3 Celestial Navigation

Celestial navigation, an age-old technique utilized for determining maritime positions, involves the observation of celestial bodies such as the sun, stars, moon, and planets. Despite the ascendancy of Global Positioning System (GPS) technology in contemporary navigation practices, celestial navigation remains pertinent, particularly as a supplementary or alternative method when GPS signals are obstructed or inaccessible (Seidelmann et al., 1983). By adhering to the principles of celestial navigation, whereby celestial observations are meticulously recorded and analysed, USVs can substantiate their navigational autonomy and resilience in diverse maritime environments.

The radius of the Earth is a fundamental measurement representing the distance from the Earth's centre to its surface, often used in various scientific calculations, geodesy, and cartography. There are several ways to define and measure the Earth's radius, each providing slightly different values due to the Earth's non-uniform shape. One commonly used measure is the mean radius, which represents the average distance from the centre of the Earth to its surface. This value is approximately 6,371 kilometres (or 3,959 miles) (Seidelmann et al., 1983).

The Earth's radius plays a critical role in numerous scientific disciplines, including geophysics, astronomy, and navigation. It serves as a fundamental parameter in calculations related to gravity, atmospheric science, satellite orbits, and the study of the Earth's interior (Plag et al., 2009). Additionally, accurate knowledge of the Earth's radius is essential for cartographers and surveyors when creating maps and determining distances on the Earth's surface. Various techniques, such as satellite geodesy, gravimetry, and geometric surveys, are employed to measure and refine our understanding of the Earth's radius, contributing to advancements in both scientific research and practical applications.

2.3.1 Celestial Navigation Concept

In the realm of celestial navigation, the interrelation with the Earth's radius constitutes a foundational aspect within the mathematical frameworks utilized for positional determinations on the Earth's surface. Celestial navigation operates by capturing angular measurements of celestial entities relative to the observer's position, thereby facilitating the derivation of latitude and longitude coordinates. However, the efficacy of such angular measurements is contingent upon an appreciation of the Earth's curvature, an attribute intrinsically linked to its radius (Seidelmann et al., 1983).

Central to celestial navigation is the computation of an observer's position predicated upon the observed altitude of celestial bodies. The determination of latitude, for instance, is predicated upon the angular displacement of celestial bodies relative to the observer's position vis-à-vis the equatorial plane (Zhang et al., 2021). This correlation forms the bedrock of celestial navigation computations, where the observer's latitude is often inferred from celestial body altitudes employing trigonometric functions. The curvature of the Earth's surface, modulated by its radius, profoundly influences the angular dynamics between the observer and celestial entities.

Likewise, in ascertaining longitudinal coordinates through celestial navigation, precise temporal synchronization assumes paramount importance. The temporal differential between local time at the observer's locale and a reference standard, typically Greenwich Mean Time (GMT), establishes a direct correlation with the observer's longitudinal deviation from the Prime Meridian. This deviation, quantified in degrees of longitude, is directly commensurate with the Earth's radius (Zhang et al., 2021). Consequently, comprehension of the Earth's radius serves as a linchpin for converting temporal disparities into longitudinal differentials, thereby enriching the accuracy and efficacy of celestial navigation methodologies. This symbiotic relationship underscores the indispensability of spherical geometry and trigonometric principles in the meticulous determination of terrestrial positions within the context of celestial navigation.

The computation of distances on a spherical Earth involves several fundamental equations based on spherical geometry. One of the most used equations is the Haversine formula, which allows for the calculation of the great-circle distance between two points on the Earth's surface given their latitudes and longitudes (Seidelmann et al., 1983). The computation of distances on a spherical Earth involves several fundamental equations based on spherical geometry. One of the most used equations is the Haversine formula, which allows for the calculation of the great-circle distance between two points on the Earth's surface given their latitudes and longitudes. The Haversine formula is expressed in equation 2.1.

$$D = 2r \times arcsin\left(\sqrt{hav(\Delta lat) + \cos lat_1 \times \cos(lat_2) \times hav(\Delta lon)}\right) \tag{2.1}$$

d is the distance between the two points along the surface of the sphere (typically in kilometres or nautical miles). r is the radius of the Earth (in the same units as the distance). Δlat is the difference in latitude between the two points (in radians). Δlon is the difference in longitude between the two points (in radians). lat_1 and lat_2 are the latitudes of the two points (in radians). $hav(\theta)$ denotes the haversine of an angle θ, calculated as $hav(\theta) = sin^2\left(\frac{\theta}{2}\right)$.

2.3.2 Dead Reckoning Method

The relationship between dead reckoning (DR) methodology and celestial navigation epitomizes a symbiotic association within maritime navigation, particularly under circumstances where celestial observations prove challenging or impracticable. DR methodology entails the extrapolation of a vessel's position from a known point, employing courses and speeds over elapsed time intervals. Conversely, celestial navigation relies upon the precise determination of a vessel's position through observations of celestial bodies (Kao, 1991).

In practical application, dead reckoning serves as a foundational mechanism for approximating a vessel's position during periods characterized by limited visibility or when celestial sightings encounter obstructions, such as inclement weather conditions. It entails the continual updating of the vessel's estimated position, integrating factors such as course deviations, speeds, wind influence, and current drift (Bruyns, 2013). Nonetheless, the accuracy of dead reckoning diminishes over time due to inherent navigational errors and environmental variances. The amalgamation of dead reckoning with celestial navigation engenders a synergistic approach to maritime navigation, blending the continuous position estimation capability of dead reckoning with the precision afforded by celestial observations.

Dead reckoning is a navigation technique where a vessel's position is estimated based on its previous known position, course, speed, and time elapsed. It provides continuous situational awareness, especially when celestial or electronic navigation aids are unavailable (Kao, 1991). While prone to errors due to factors like wind and currents, dead reckoning remains crucial for maintaining navigation during adverse conditions. The concept is rooted in continuously updating the vessel's position by integrating its heading (direction) and speed over time intervals. The fundamental formula for dead reckoning is mentioned in equation 2.2.

$$EP = Previous\ position + (Speed \times Time \times Direction) \quad (2.2)$$

Estimated Position (EP) is the USV calculated position at the present time. Previous Position is the last known position fix. *Speed* is the USV's speed through water, typically measured in knot. *Time* is the elapsed time since the last position fix, usually expressed in hours. *Direction* is the vessel's heading or course, represented as an angle relative to a reference point, typically measured in degrees clockwise from true north (Bruyns, 2013).

When researcher applied this formula, they could approximate the USV's current position based on its predicted movement from the last known position. However, it was important to note that dead reckoning inherently accumulated errors over time due to factors such as changes in speed, wind, currents, and navigational inaccuracies. As a result, dead reckoning was often supplemented or corrected by other navigation methods, such as celestial navigation or satellite-based positioning systems like GPS, to maintain accuracy during extended voyages.

2.4 Pure Pursuit Guidance

The pure pursuit algorithm represents a frequently employed guidance technique within the domain of robotics and autonomous vehicular systems, utilized for directing a vehicle towards a predetermined objective or target. Fundamentally, the essence of pure pursuit lies in the ongoing adjustment of the vehicle's trajectory towards a designated point along its path situated at a predetermined distance ahead of its current position. Termed the "lookahead point," this focal reference is established through an analysis of the vehicle's existing spatial coordinates and orientation.

2.4.1 Definition and Concept

Pure pursuit is a guidance algorithm commonly used in the field of robotics and autonomous vehicles to navigate a vehicle toward a specific goal or target. The basic idea behind pure pursuit is to continuously steer the vehicle towards a point on the path that is a certain distance ahead of the vehicle. This point, often referred to as the "lookahead point," is determined based on the vehicle's current position and orientation.

The lookahead point is calculated based on the current position and orientation of the vehicle. It is positioned along the path at a fixed distance ahead of the vehicle. The choice of this distance is a crucial parameter in the algorithm and depends on the dynamics and speed of the vehicle. Determine the point on the path that is closest to the lookahead point. This point is the target point that the vehicle aims to reach. The steering command is then computed based on the difference between the current orientation of the vehicle and the direction toward the target point.

The steering angle is often determined using trigonometric functions, such as the arctangent of the ratio of the lateral distance to the lookahead distance. In a complete system, adjustments to the vehicle's speed may be made to ensure smooth and stable navigation. The formula for calculating the steering angle in a basic pure pursuit algorithm can be represented in equation 2.3:

$$a = \tan^{-1}\left(\frac{2L\sin(\delta)}{L_{wheelbase}}\right) \tag{2.3}$$

where; a is the steering angle, L is the lookahead distance, δ is the angle between the vehicle's heading and the line connecting the vehicle's position to the target point and $L_{wheelbase}$ is the wheelbase of the vehicle.

This formula assumes an Ackermann steering system, where the steering angle of the wheels is dependent on the turning radius. In order to operationalize this algorithm for an Unmanned Surface Vehicle (USV), integration must be undertaken with due regard to the particular dynamics and control framework of the vehicle in question. This necessitates meticulous attention to various parameters, encompassing the determination of maximum steering angles, velocity regulation mechanisms, and strategies for obstacle circumvention.

2.4.2 Overview of Existing System

The existing Unmanned Surface Vehicle (USV) systems utilizing Pure Pursuit guidance provide a robust platform for autonomous marine operations. These systems typically integrate various components, including sensors, control algorithms, and communication systems, to enable efficient and reliable navigation in diverse maritime environments (Samuel et al., 2016). At the core of these systems lies the Pure Pursuit guidance algorithm, which facilitates precise path following and waypoint navigation. Sensors such as GPS, inertial measurement units (IMUs), and environmental sensors provide essential data on the USV's position, orientation, and surrounding conditions.

The Pure Pursuit algorithm utilizes this sensor data to calculate steering commands, guiding the USV along predefined paths or towards specified waypoints with minimal lateral error. Communication systems allow for remote monitoring and control, enabling operators to supervise USV missions and intervene if necessary (Shamsuddin & Mansor, 2018). These USV systems are employed in a wide range of applications, including maritime surveillance, environmental monitoring, oceanographic research, and offshore operations. By leveraging Pure Pursuit guidance, these systems offer a reliable and effective solution for autonomous marine navigation, contributing to advancements in both academic research and real-world applications in marine industries.

Pure Pursuit guidance constitutes a fundamental algorithm employed in robotics, particularly within the domain of autonomous navigation and path tracking. Its principal objective is to steer a vehicle or robot towards a predetermined target or trajectory by iteratively adjusting its heading relative to the target's position vis-à-vis the vehicle's current location (Breivik et al., 2008). The algorithm relies on the delineation of a specific target, typically defined by a sequence of waypoints or a continuous path represented by mathematical formulations. For effective implementation, the vehicle must possess means of localizing itself within the environment, often facilitated through sensors like GPS, encoders, or inertial measurement units (IMUs).

Pure Pursuit guidance epitomizes a foundational algorithm integral to autonomous navigation systems, notably within the fields of robotics and vehicle control. The conceptual underpinning of Pure Pursuit entails orchestrating the movement of a vehicle or robot along a designated trajectory by perpetually adjusting its course to pursue a predetermined target point. This methodological approach involves prognosticating the vehicle's forthcoming position along its current trajectory and ascertaining the point on said trajectory that exhibits the closest proximity to the desired target (P. N. F. M. Shamsuddin et al., 2021). Subsequently, the algorithm computes the requisite steering command essential for steering the vehicle towards this identified target point, typically by discerning the curvature of the path necessary to intercept it.

The operationalization of Pure Pursuit necessitates the iterative refinement of the target point contingent upon the vehicle's positional updates, facilitating the requisite adjustments in steering to sustain the vehicle's trajectory alignment. Renowned for its inherent simplicity and efficacy, Pure Pursuit is ubiquitously embraced across manifold autonomous systems, catering to diverse functionalities encompassing path tracking, waypoint navigation, and target pursuit (Ma et al., 2021). Moreover, the integration of feedback mechanisms can fortify Pure Pursuit's resilience against environmental perturbations and uncertainties, thereby engendering a framework conducive to precise and dependable autonomous navigation across a spectrum of real-world scenarios.

Summary

In summary, advanced navigation algorithms and control systems enable USVs to function independently, reducing the need for human intervention and enabling prolonged mission durations without direct human oversight. However, sensor limitations can hinder navigation effectiveness due to vulnerabilities such as interference, signal degradation, or environmental factors affecting onboard sensors. The interconnection between dead reckoning methodology and celestial navigation exemplifies a mutually beneficial relationship in maritime navigation, especially in situations where celestial observations are difficult or unfeasible. Integration of Pure Pursuit guidance with higher-level planning algorithms in Unmanned Surface Vehicles (USVs) offers a multitude of advantages, including mission customization, dynamic path planning, path replanning, mission coordination, task allocation, and fault tolerance. By seamlessly integrating Pure Pursuit guidance with higher-level planning systems, USVs can adapt their navigation behaviour to meet specific mission objectives, respond to dynamic environmental conditions, avoid obstacles, and coordinate with other vehicles. This integration enables USVs to achieve enhanced autonomy, adaptability, and effectiveness in accomplishing complex missions such as surveillance, reconnaissance, search and rescue, and environmental monitoring. Overall, leveraging higher-level planning capabilities empowers USVs to navigate with efficiency, reliability, and responsiveness in diverse maritime environments.

CHAPTER 3

METHODOLOGY

Chapter 3 will emphasize the methodology of this research to achieve the objectives of the studies. In order to accomplish the research objectives, the method and technical strategy implied is the most critical disciplined need to be concerned. There are two stages are arranged in chronological based on how this experiment has conducted, which consist of navigation system design and system testing.

Figure 3.1 shows the flowchart of the methodology process to archive the study's research objectives, Figure 3.2 is continuous from Figure 3.1. The author is developing a navigation system design (write the source code, invention of electronic circuit and wiring the circuit) for two platforms: target and the USV. Both platforms are re-undergoing the system testing for analyse the system developed and collected the data when this vehicle is exposed to the water.

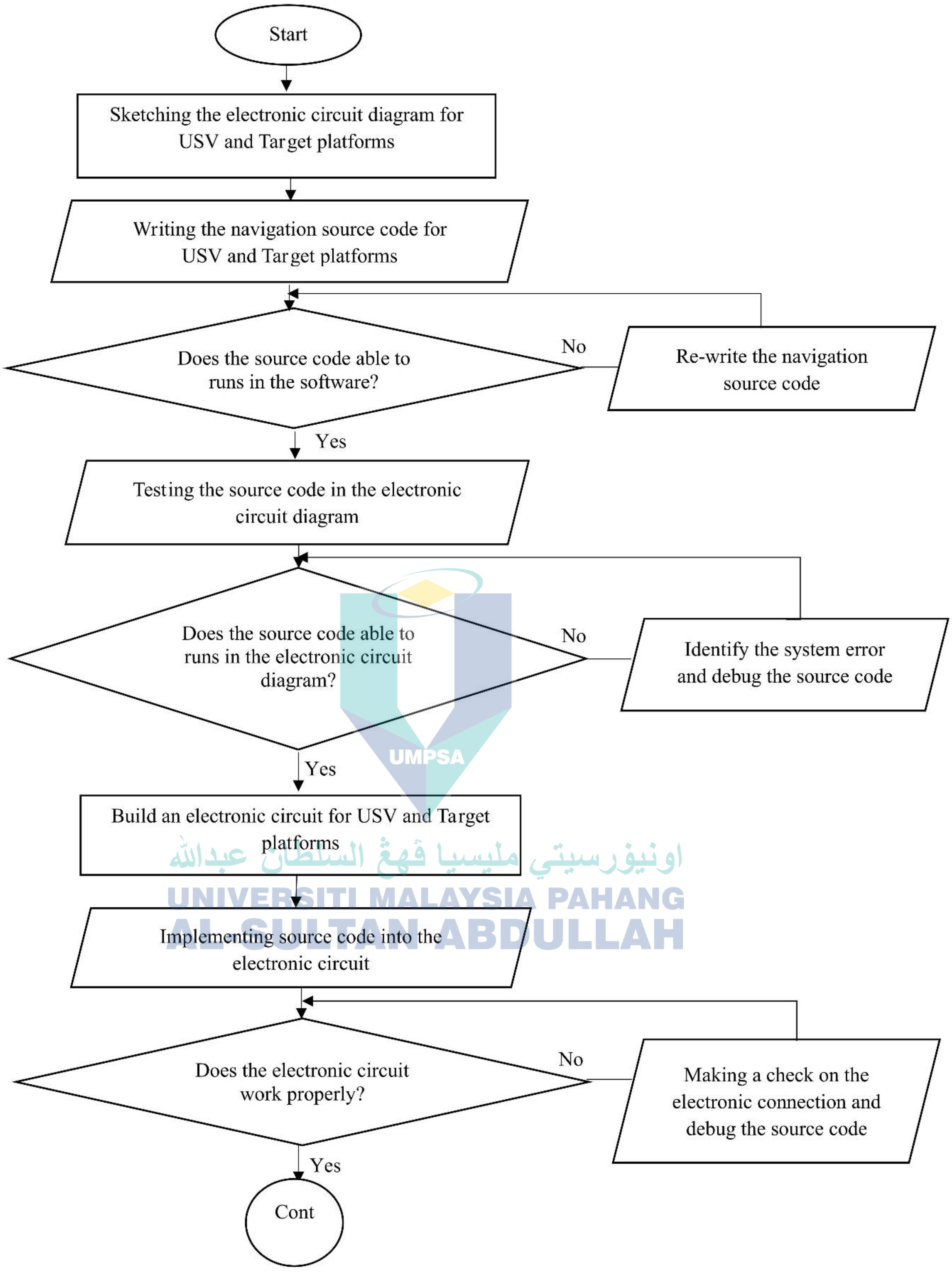

Figure 3.1 Flow Process of the Methodology

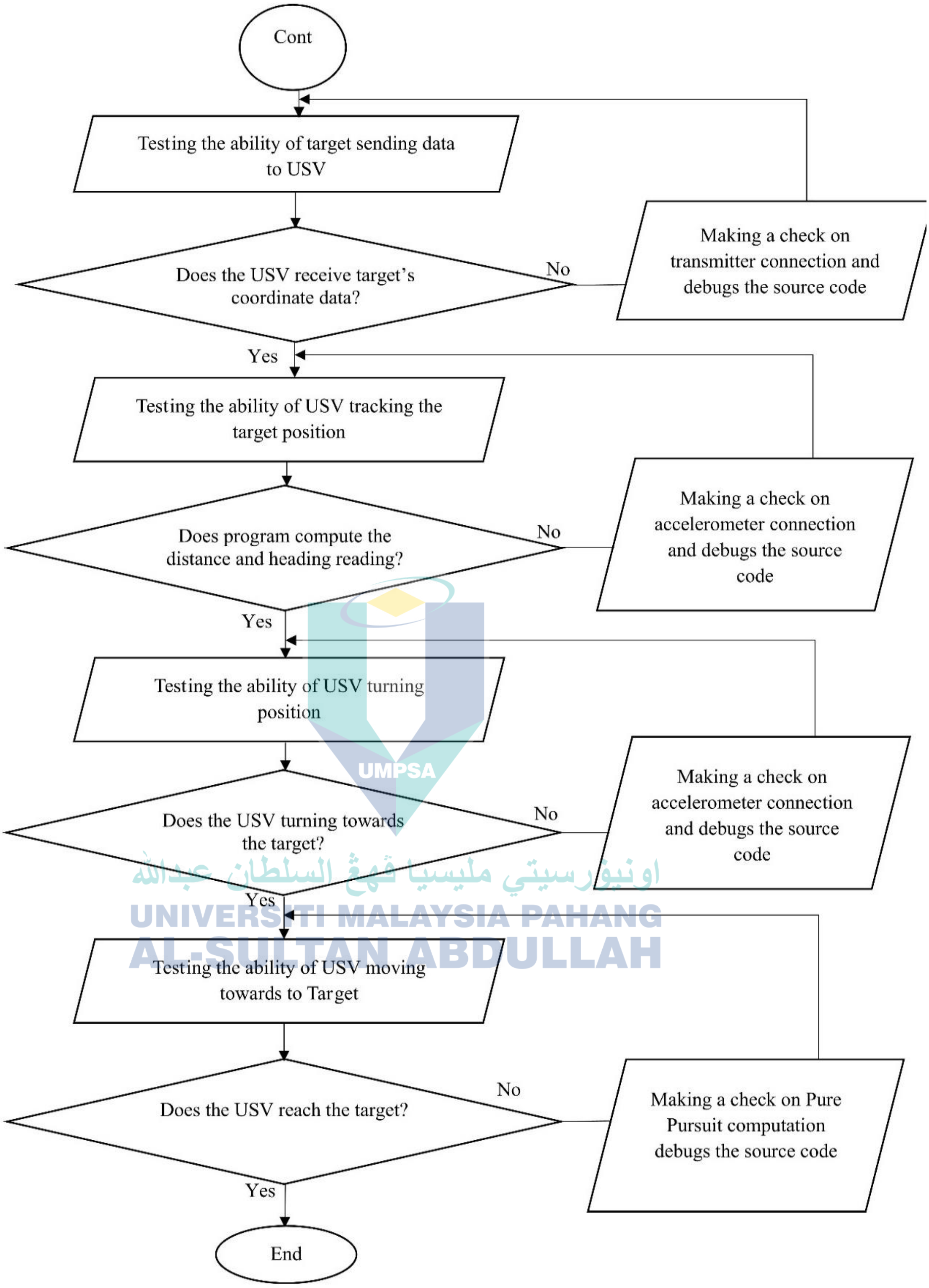

Figure 3.2 Continued

3.1 Navigation System Design

In this research, USV has been designed to follow predefined path accurately and dynamically. In order to track the position of target platform, USV needs to adjust the vehicle's control inputs in real-time to ensure it stays close to the planned path. The author is used pure pursuit guidance as the feedback control strategies to adjust the USV's trajectory based on sensor measurements (such as GPS, inertial sensors, and vision systems). The author used the transmitter sensor to play the roles of the vision system, by transmitting the data from the target to the USV.

Figure 3.3 shows the block diagram of the Target platform that consist of initial sensor and transmitter for sending the data to USV. Firstly, the GPS receiver get a signal from satellite and communicate with the Arduino controller. Then, the Arduino will transmit the target coordinate (X_g, Y_g) via the RF Transmitter. USV is in the standby mode until it received the signal from the target platform.

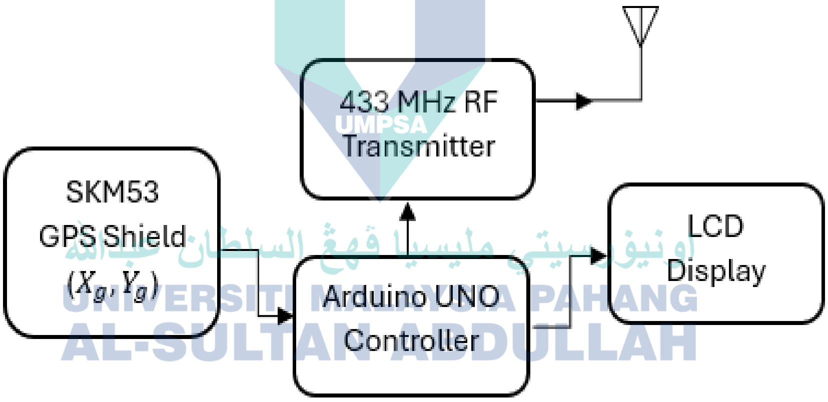

Figure 3.3 Target Platform Block Diagram

Figure 3.4 illustrated the USV Platform block diagram which consist of embedded sensors (such as SKM54 GPS Shield, transmitter HC12, QMC5883 Digital Compass, and Encoder sensor module). While USV receive the data from the transmitter, the Arduino Mega has stored the target coordinate in the SD Card. Then, GPS receiver has received its signal as USV coordinate (X_u, Y_u) then stored in the SD Card. After that, a Compass module communicate with Arduino Mega to read angle of the USV (θ_b). Then, all the value of the coordinates needs to convert in radian by multiplying with the π rad.

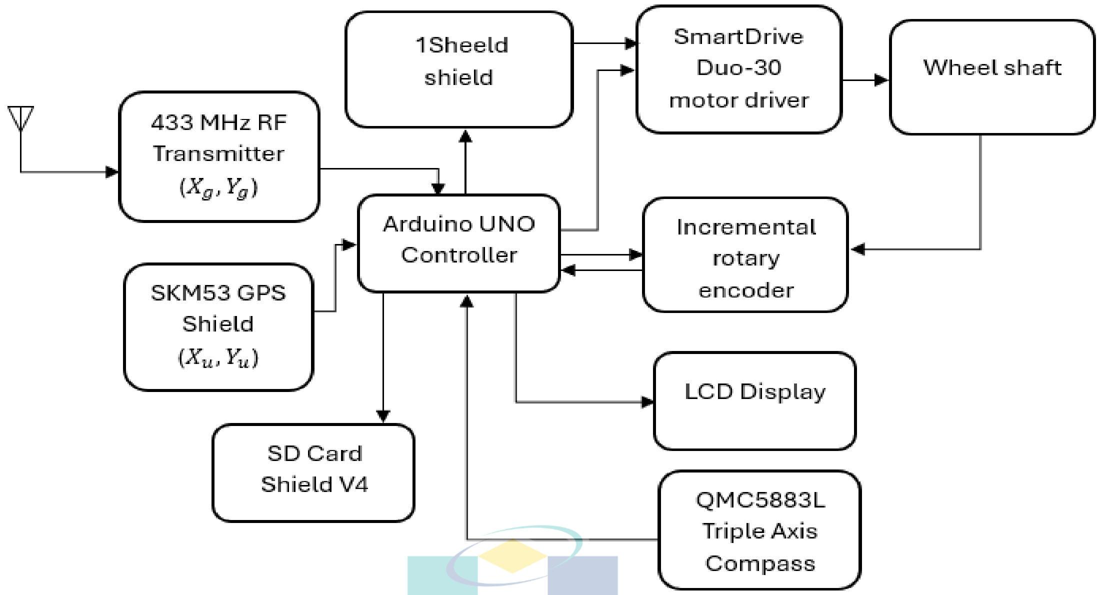

Figure 3.4 USV Platform Block Diagram

Next, the latitude (X_u, X_g) and longitude of both location (Y_u, Y_g) are subtracted together to get the distance of latitude and the longitude for both coordinates. In the navigation system of USV, the distance between the latitude line and longitude line are multiplied with the meridional radius of curvature (R_M) and radius of curvature in the prime vertical (R_N), respectively.

$$R_M = \frac{1 - e^2}{1 - e^2 sin^2 \emptyset} \tag{3.1}$$

$$R_N = \frac{a}{\sqrt{1 - e^2 \sin \emptyset}} \tag{3.2}$$

Based on the equation 3.1 and 3.2, 1-e^2 is the common ellipse equation where *e* represents as value of eccentricity. The value of Ø is represents as value of latitude of USV a represents as circle of the earth. After that, the value of R_M will multiply with distance between two latitudes to compute known as Radius of Curvature in meridian (*dN*), while R_N will multiply with distance between two latitudes and cos of USV's latitude known as Radius of Curvature in the prime vertical (dE). Then, the distance (D) between two coordinates is compute as shown in equation 3.3.

$$D = \sqrt{(dN)^2 + (dE)^2} \tag{3.3}$$

Next, triple axis Compass communicated with the controller for getting the data of USV's heading angle. After converting the input angle into the radian, the value of cosine latitude of USV is multiplied with the distance between two longitudes, then divided the value with the distance between two longitude and arctan of the out value. The output value of USV heading ($\boldsymbol{\Psi}_h$) has compared the reading with the compass after converted it into the degree form. Figure 3.5 illustrates the two coordinate frames relative to the position and orientation of the USV.

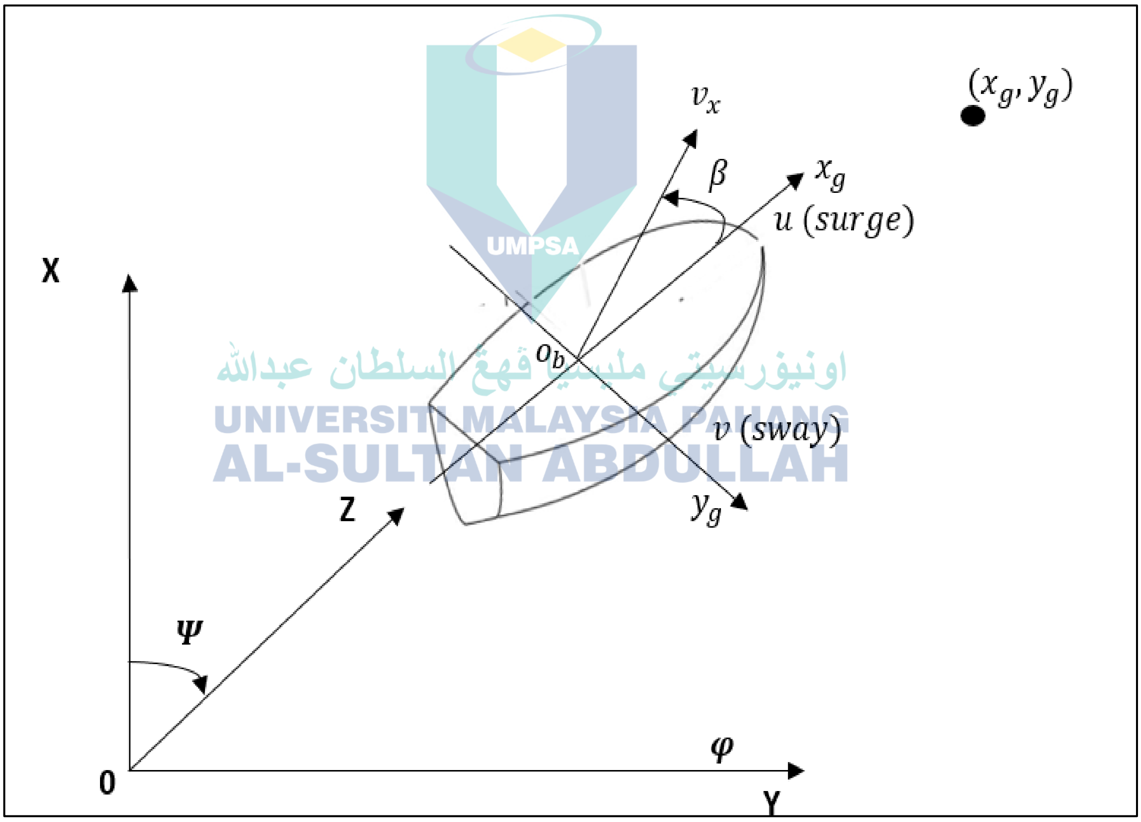

Figure 3.5 Oreintation Error in USV (Self Collection)

(X, Y, Z) coordinates are represent the earth coordinate frame (inertial fixed frame) with origin O, and the body coordinate frame, which is fixed to the USV and moves along with it, with b origin and (x, y, z) coordinates. The output value of the heading is converted to the positive degree value. The true heading is identified by subtracting the current course angle of USV ($\boldsymbol{\Psi}_{b}$) and the $\boldsymbol{\Psi}_{h}$ as shown in equation 3.4.

$$\Psi_t = \Psi_h - \Psi_b \tag{3.4}$$

Figure 3.6 shows the summarization of USV tracking process. USV has identified its direction towards the target the by comparing Ψ_t in the concept of earth's magnetic field. Each angle output represents a different orientation of eight cardinal, namely North, Northeast, East, Southeast, South, Southwest, West, and Northwest, respectively. Then, the primary function will classify the heading output as either needs to turn right, left, or straight movement.

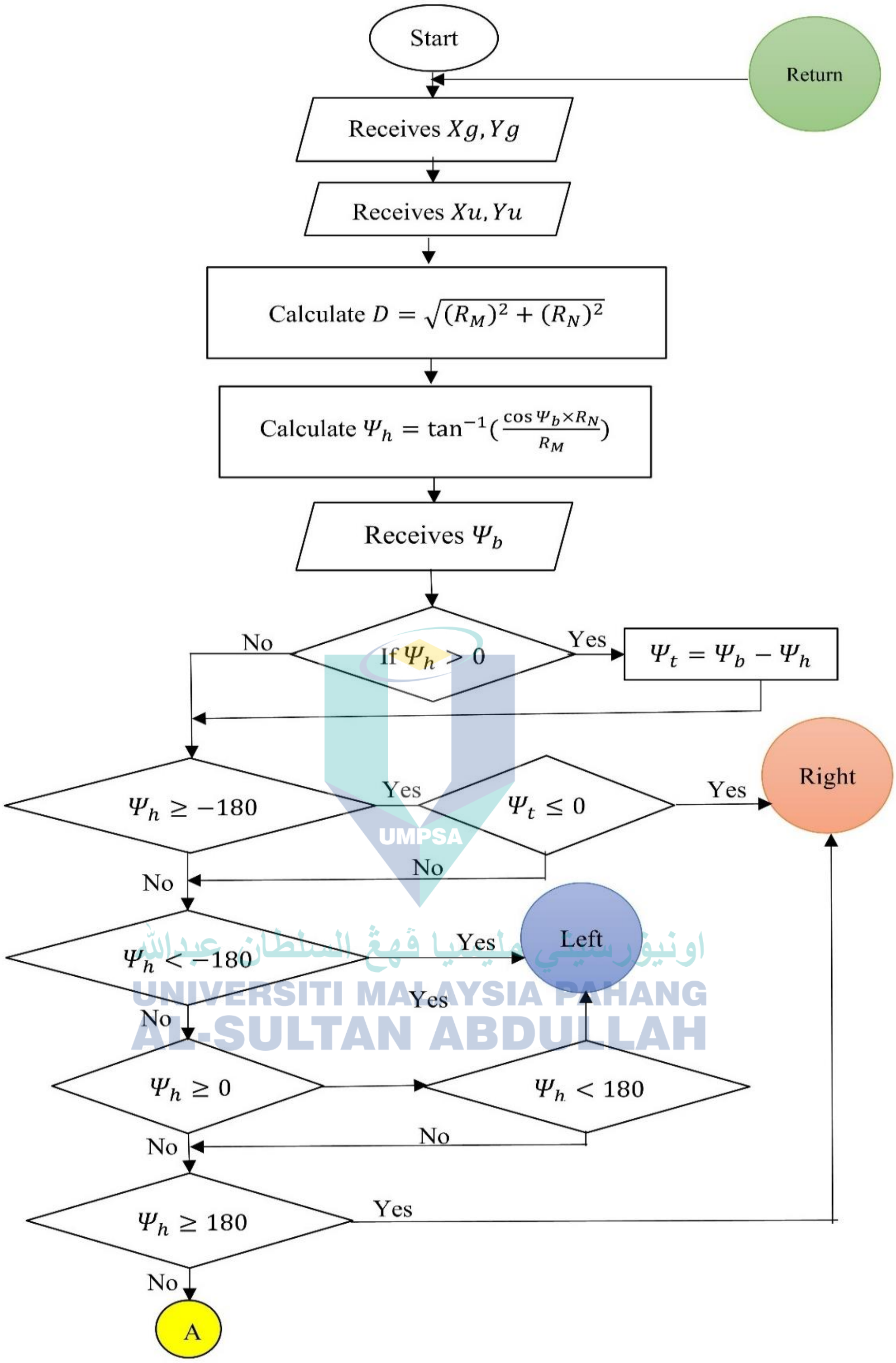

Figure 3.6 Main Flowchart for Navigation System's Computation Process

Figure 3.7 conceptual block diagram illustrates the flow of information and control commands through the various modules of a pure pursuit guidance system in an USV. The basic idea behind pure pursuit is to continuously steer the vehicle towards a point on the path that is a certain distance ahead of the vehicle. This point, often referred to as the "lookahead point," is determined based on the vehicle's current position and orientation.

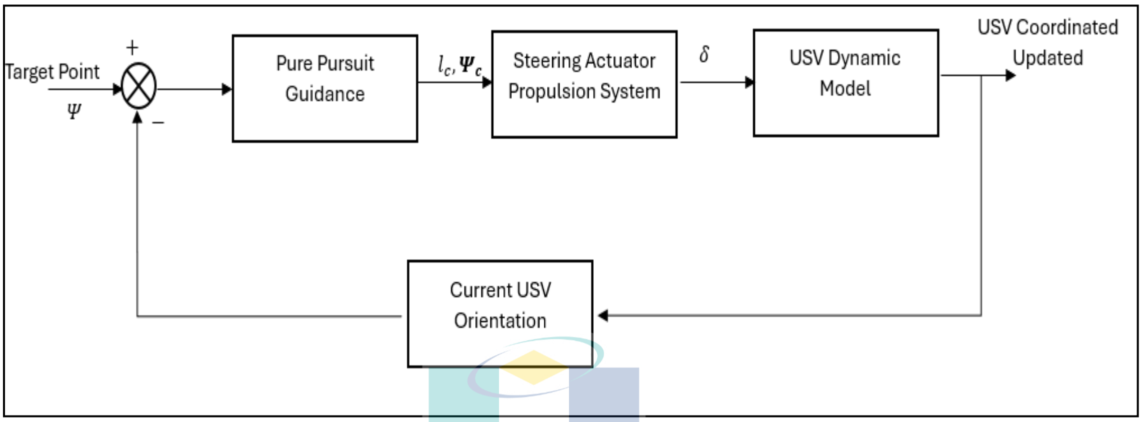

Figure 3.7 Block Diagram for USV's Navigation System (Self Collection)

Equation 3.5 and 3.6 shows how the controller computes the left and right shaft's movement (δ_v), to identify the update latitude and longitude of USV *(Lat_c, Lng_c)* using a dead reckoning computation. The pure pursuit method extends this approach by fitting a smooth circular curve from the vehicle to the target point for the vehicle to follow.

$$Lat_c = Lat_u + [(\delta_v) \times cos(\Psi_b)] \quad (3.5)$$

$$Lng_c = Lng_u + [(\delta_V) \times \sin(\Psi_b)] \quad (3.6)$$

$$\Psi_c = \left(\frac{2 \times (\Psi_t - \Psi_u)}{\delta_V}\right) \quad (3.7)$$

The implementation of the PP guidance waits until it receives the Ψ_t from the controller before moving to the next position. Using the rule of sine involving D and the angle $\boldsymbol{\Psi}_c$, each update from the GPS unit triggers the algorithm to check whether it has reached the current waypoint or not. Equation 3.7 shows the computation detail updated of current true heading angle (Ψ_i). The author has summarized the overall process in the figure 3.9 and figure 3.10.

Figure 3.9 shows the turning right flowchart that controls the movement of USV yaw based on the odometry concept and the Pure Pursuit controller method. When the motor rotates, the compass will detect the current direction of the vehicle. The change that occurred in the left (δ_e) and right encoder (δ_n) will be added together and divided into two to calculate the average and find the current distance of the vehicle travelled from the orientation position. Besides, the output value of the distance travelled is multiplied with the velocity vector (v) of the heading angle of the USV to estimate the new position of the latitude and longitude of USV.

In all the current locations of USV, the curvature of vehicle turned are run in this loop body before the curvature of the vehicle's angle is less than or equal to 0˚. Then, the primary function will classify the current heading ($\boldsymbol{\Psi}_i$) as either returning to the primary function or looping the right function again. Figure 3.10 shows the turning left flowchart that controls the movement of USV yaw and its concept is same with the turning right flowchart.

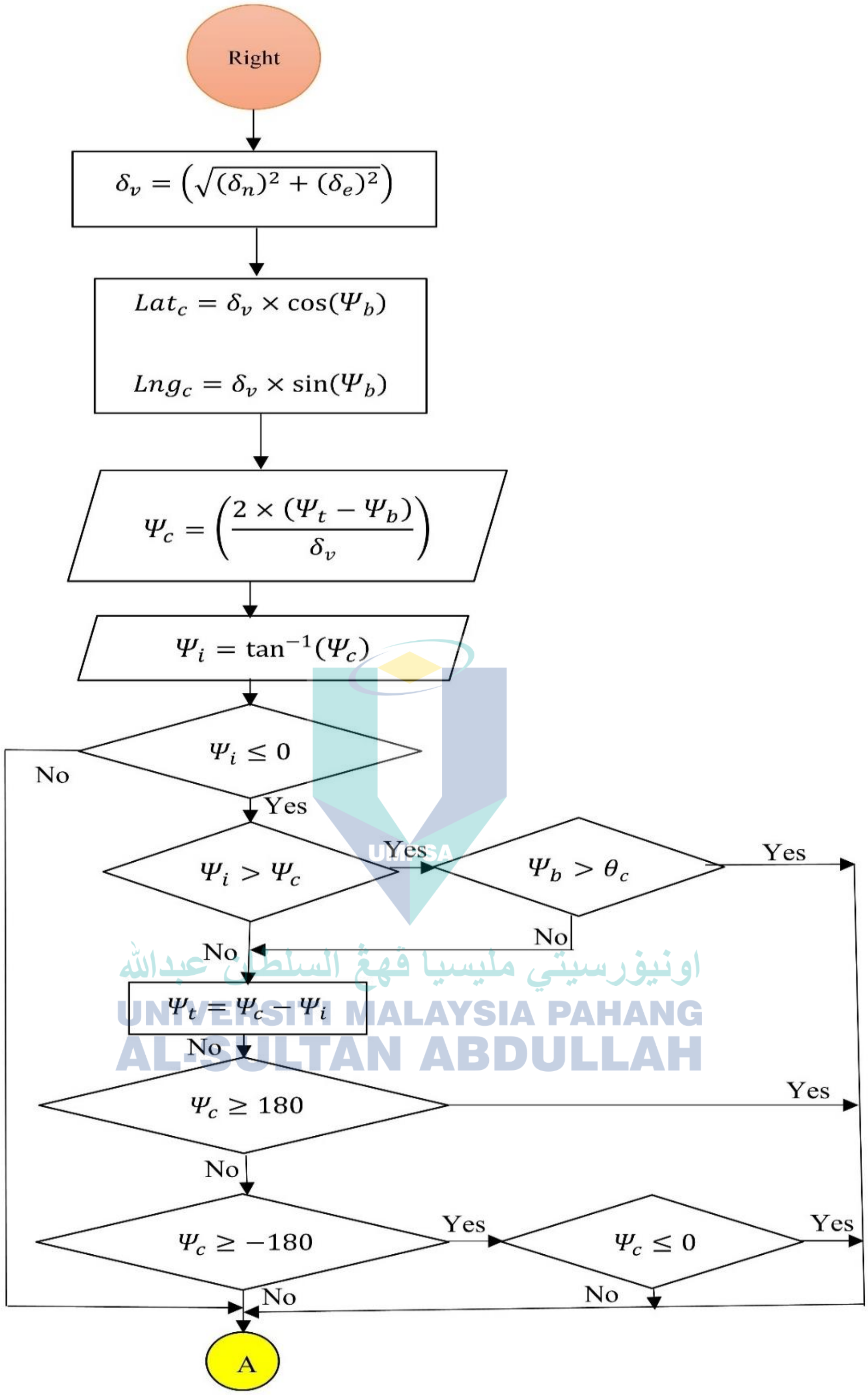

Figure 3.8 Continued R from the Main Flowchart

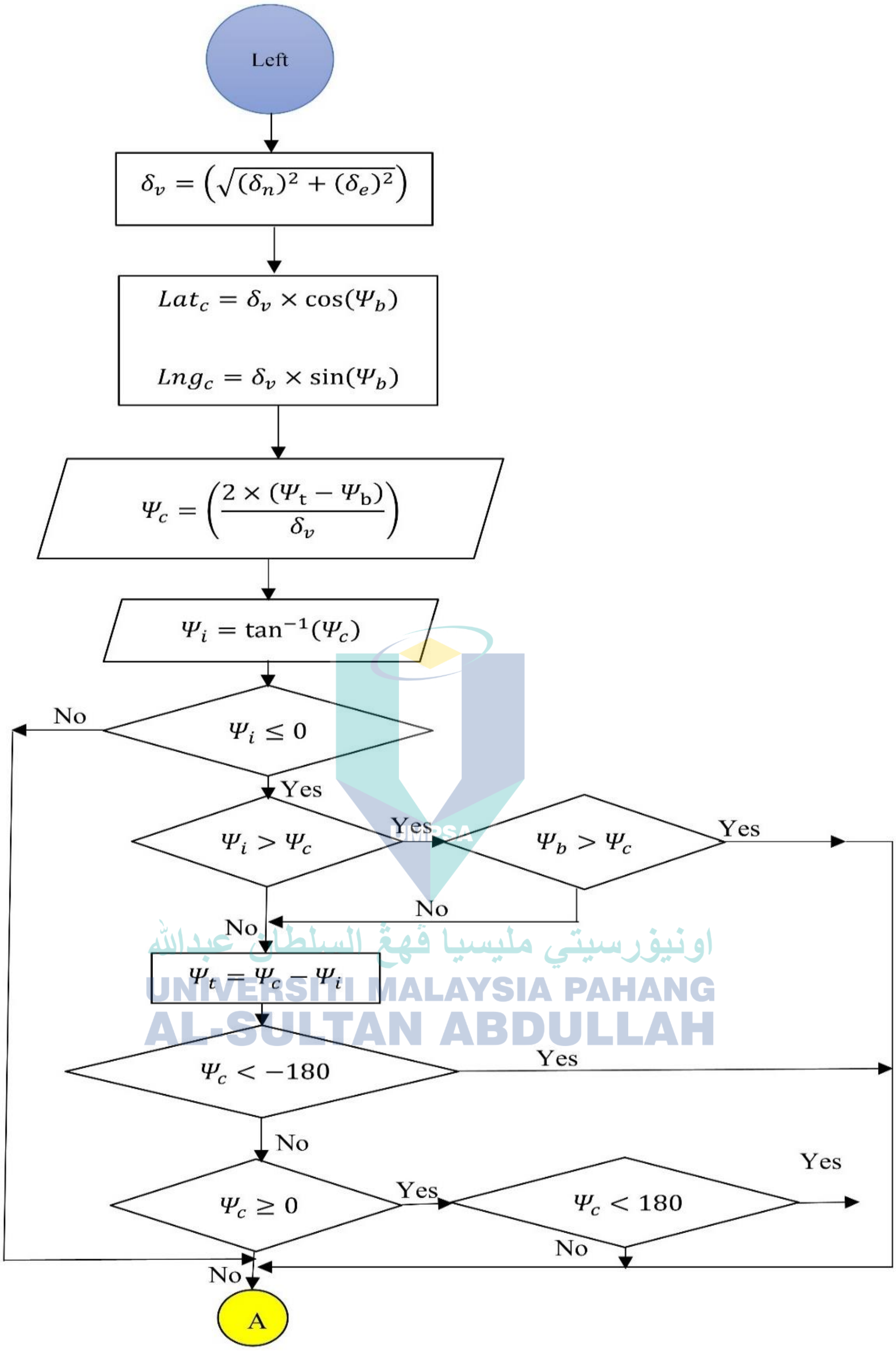

Figure 3.9 Continued L from the Main Flowchart

After that, the controller will undergo the while looping until the button pin in the 1Sheeld is high. If the gamepad is pressed in the manual control function, the USV will be guide by the human manually using the phone. While looping, the controller will compute the remaining distance of the USV towards the target position. The orientation distance of USV is subtracted with the command of USV's current distance by time, then the value with the vehicle's velocity with the differential of time travelled. If the remaining distance of the USV is less than one meter, both motors will stop, and the latitude and longitude of the target will be transformed to the USV position. If the button pin in the 1Sheeld is high, the controller's mode will change to controlled by the user. This step is crucial as the precaution step if the USV does not move in the correct direction. the computation process for this stage has emphasized in figure 3.10.

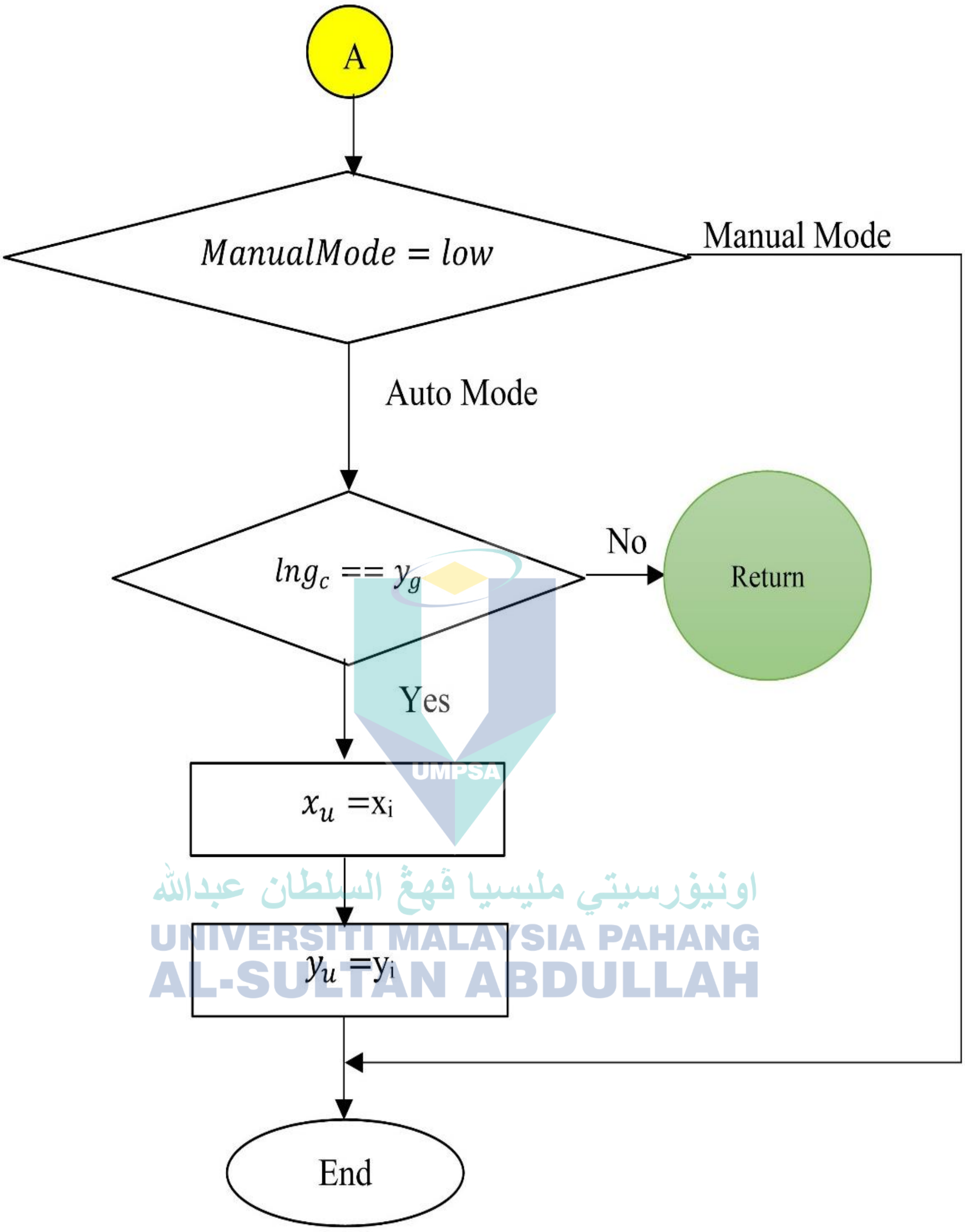

Figure 3.10 Continued A from the Main Flowchart

3.2 System Testing

There are several experiments undergoing by the USV to test the ability of the system tracking performance. Firstly, the author has tested the ability of receiving the data from the target platform. By examine the problem on the transmitter connection, the receiving source code has been re-written because the program could not receive the longitude of the target (y_g). Then, the author has re-write the computation of distance(D) source code due to the distance output value does not accurate with the exact distance.

Then, the author is observed the movement of the USV to track the target's location at the edge of the pool. At the beginning of the experiment, the movement of USV strayed from the target position because of magnetometer error. The part of azimuth source code has changed to determine exact true heading output by using computation of equation 3.4. By converting the output heading into a degree positive angle according to the compass reading, USV is turned and move towards the target location better than the first attempt, as shown in figure 3.11.

Undergo USV on the pool gave several benefits to control an unpredicted turning or movement within the testing process. The USV is turned on in auto mode, and the smartphone's Bluetooth connection to the vehicle is also turned on. After ensuring the USV able to receive signal from the target, it was released two meters on the centre of the pool to test the ability of moving. Based on the observation, USV is slightly stray away from the exact path while it moved. The author has checked the Pure pursuit guidance source code and make a change on encoder computation.

After all the problems are being traced and solve by the author, USV is departed on the fishing lake at Batu Kapor Village, Mentakab, Pahang. Within two hour of experiment process, the target platform was departed around ten meters from the waterfront while USV was on standby at the waterfront before the system was started. Based on figure 3.12, USV has departed from the water's edge while the target has been departed earlier before the navigation system has been activated on the water. Then, the author has monitored all the movement of the USV when it was moving towards the target.

Figure 3.11 USV Moves on the Pool Towards the Target

Figure 3.12 USV's Location Departure

USV and the target has been located of ten different locations, (namely W1-W10) as mentioned on Table 3.1. Each waypoint represents a key location that the USV needs to reach or pass through during its mission. All the output command (value of target coordinates, USV coordinates, heading angle, true heading angle, distance of two platform) has been computed and will discuss on chapter 4. The author has tested the same waypoint with Dead Reckoning method and Dead Reckoning with implementation of Pure Pursuit Guidance to analyse the efficiency of the tracking control method.

Table 3.1 Initial Position of USV and the Target

Waypoint	**Target Platform**		**USV Platform**	
	Latitude (X_g)	**Longitude** (Y_g)	**Latitude** (X_u)	**Longitude** (Y_u)
W1	3.5087966	102.3313165	3.5087888	102.3313131
W2	3.5088573	102.3313076	3.5087969	102.3313164
W3	3.5088722	102.3304922	3.5088570	102.3313069
W4	3.5088999	102.3304956	3.5088720	102.3304989
W5	3.5089031	102.3304989	3.5088990	102.3304950
W6	3.5089482	102.3305111	3.5089029	102.3304986
W7	3.5089484	102.3305121	3.5089479	102.3305109
W8	3.5089489	102.3305195	3.5087480	102.3305123
W9	3.5088660	102.3305032	3.5089485	102.3305193
W10	3.5088882	102.3305002	3.5088662	102.3305029

Summary

In summary, there are two procedures needs to be achieved; design the navigation system and test the ability of USV performance with the system. USV system has implemented with tracking concept and method by determining the distance and heading angle between two coordinates (Target and USV). For following the trajectories of current path, the Pure Pursuit guidance has implemented on the system.

The platform has undergone the experiment, to test the ability of USV movement towards the target. The coordinates have been recorded for ten waypoints as the initial position of both platforms. Two procedures needed to be accomplished: designing the navigation system and testing the USV's performance with the system. The USV system was equipped with a tracking concept and method involving determining the distance and heading angle between two coordinates (Target and USV). To follow the trajectories of the current path, the Pure Pursuit guidance was implemented in the system.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter will analyse the outcome USV navigation system result where it divided it two parts: initial point tracking computation and Analyzation of USV performance with navigation system developed. The sub chapter 4.1 interprets the location listed in table 3.1, by listed the orientation of USV (distance, heading and the bearing angle). The analysation of waypoints (W1-W10) is discussed in the sub chapter 4.2 based on the technique implementation.

4.1 Initial Point Tracking Computation

Table 4.1 shows the computation of navigation system for determine the distance between two locations (D), heading angle (Ψ_h), USV's bearing angle (Ψ_b), and true heading angle (Ψ_t). The value of D is determined based on the changing occurred on the latitude line (dN), and distance of the surface of the sphere in longitude line (dE). Based on the result recorded in Table 4.1, the system able to compute the distance between USV and the target for each waypoint. The result shows W7 is the nearest waypoint (0.12m) while W6 is the longest waypoint (10.93m) when the system computed the computation of distance. There are no output commands on the motor at W5 and W7 due to the distance of USV is nearest to the target platform. Hence, the author is selected a point of W1 and W6 to discuss about the ability of USV navigation control path while the other waypoints result is included in appendices.

Table 4.1 Computation of Navigation System in USV

Waypoint	**Computation Output**					
	$\boldsymbol{dN}$ $(\boldsymbol{\pi})$	$\boldsymbol{dE}$ $(\boldsymbol{\pi})$	**D** $(\boldsymbol{m})$	$\boldsymbol{\Psi_h}$ (°)	$\boldsymbol{\Psi_b}$ (°)	$\boldsymbol{\Psi_t}$ (°)
W1	0.0018839	-0.0000045	1.88	24	87	64

Table 4.2 Continued

Waypoint	Computation Output					
	dN (π)	dE (π)	D (m)	Ψ_h (°)	Ψ_b (°)	Ψ_t (°)
W2	0.0023910	-0.0000118	2.39	42	65	24
W3	0.0036693	-0.0010882	3.83	90	109	20
W4	0.0067343	-0.0000044	6.73	7	49	43
W5	0.0009894	-0.0000052	0.99	44	225	181
W6	0.0109315	-0.0000167	10.93	15	88	73
W7	0.0001206	-0.0000016	0.12	67	24	-44
W8	0.0050495	-0.0000096	5.05	19	199	180
W9	0.0066579	-0.0000082	6.66	12	301	289
W10	0.0053104	-0.0000017	5.31	3	99	95

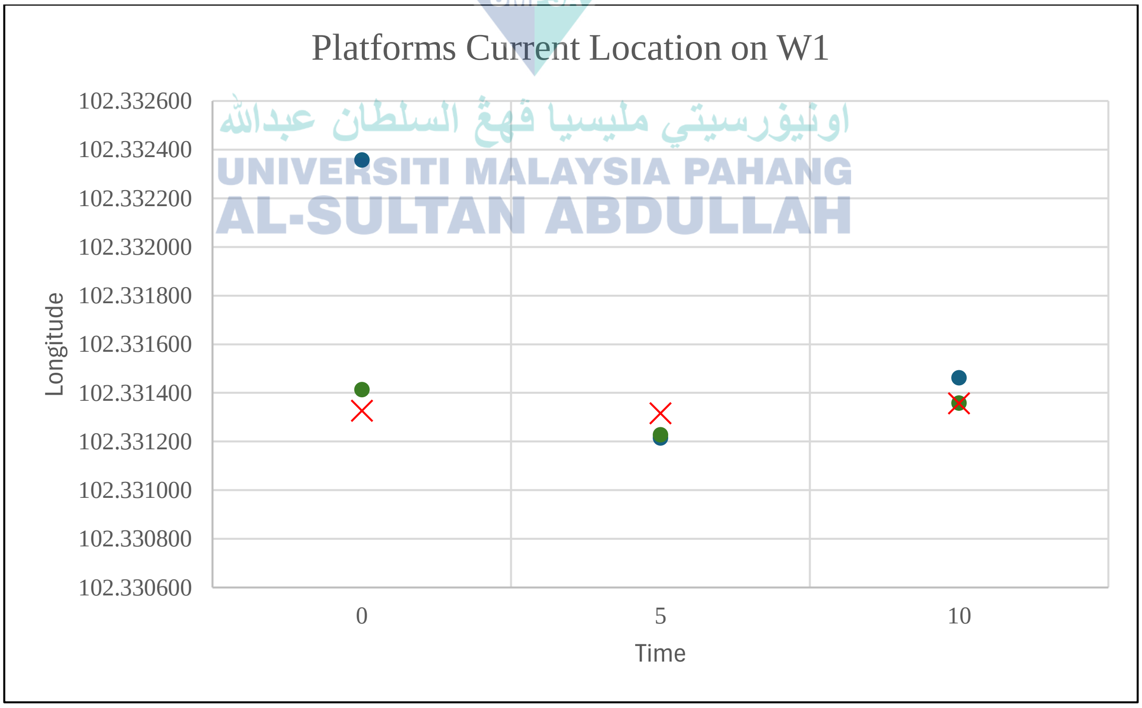

Figure 4.1 Location of both platform for W1

Figure 4.2 shows the graph coordinate of USV with the target position based on time in second, T for W6. The initial distance between both platform is 10.93 meter while the true heading is 73˚. At 0s until 30s, the green and blue dots are approaching the red cross while, at 40s until 75s, green dots catch the red cross coordinates and blue dots are scattered from the red cross respectively. At 75s, USV (3.508868, 102.330530) catch the path last target position (3.508888,102.330500). Based on the observation, dead reckoning method with Pure Pursuit guidance command support USV followed the trajectory path on W6.

This is due to USV continuously updates its position and orientation using onboard sensors. Hence, Pure Pursuit guidance used the information feedback into the Pure pursuit algorithm to achieve accurate navigation along the local path. The path segments are initially defined in global coordinates for tracking the next position, but then transformed into local coordinates for real-time navigation using Pure Pursuit. This feedback loop commands USV to stay on course and adjusts its trajectory as needed to reach the desired waypoints. The system developed has minimized the lateral error at point 0s until 30s, and controlling the shaft command (δ_v).

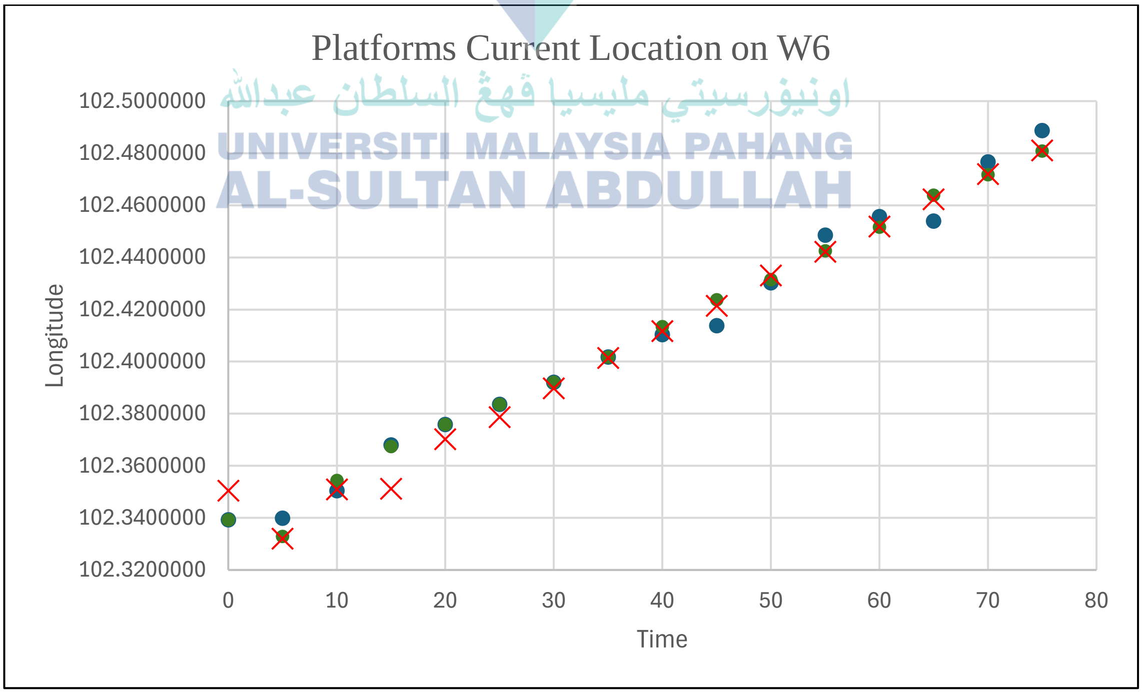

Figure 4.2 Location of both platform for W6

4.2 Analyzation of USV performance with Navigation System Developed

In order to determine the performance of USV using program developed, the author has compared differentiation of latitude ($\Delta\varphi$) and longitude ($\Delta\lambda$) using dead reckoning method and implementation of Pure Pursuit guidance with the Dead Reckoning Method. The displacement of the last position (Target platform and USV platform) computed by using equation 4.1 and 4.2:

$$\Delta\varphi = \varphi_{i-}\varphi_t \qquad 4.1$$

$$\Delta\lambda = \lambda_i - \lambda_t \qquad 4.2$$

Equation 4.1 is used to calculate latitude distance by subtracting the latitude of the USV last position φ_i from the latitude of the Target φ_t ,while Equation 4.2 is used to calculate longitude distance, where λ_i represents as longitude of the USV last position and longitude of the Target (λ_t). The full computation detail (W1-W10) is attached on appendix. Table 4.2 and 4.3 listed the displacement coordinates ($\Delta\varphi, \Delta\lambda$) and lateral error ($e_l$) by using Dead Reckoning computation and Pure Pursuit Guidance with Dead Reckoning method respectively.

Table 4.3 Displacement and Lateral Error of Dead Reckoning Implementation

Waypoint	**Difference (Dead Reckoning)**		**Lateral Error (e_l)**
	$\Delta\varphi$	$\Delta\lambda$	
W1	0.000658	0.001042	0.000677
W2	0.000891	-0.000520	0.001032
W3	-0.001340	0.000089	0.001343
W4	0.003682	0.000868	0.003783
W5	0.000551	-0.000112	0.000563
W6	0.003638	0.000318	0.003652
W7	-0.000168	-0.000278	0.000325
W8	0.003149	0.000366	0.003170
W9	0.001486	0.000057	0.001487
W10	-0.001640	0.001220	0.002045

Table 4.4 Displacement and Lateral Error of Dead Reckoning and Pure Pursuit

Waypoint	Difference (Pure Pursuit Guidance)		Lateral Error (e_l)
	$\Delta\varphi$	$\Delta\lambda$	
W1	0.000200	0.000028	0.000202
W2	0.000000	0.000056	0.000056
W3	0.000000	0.000000	0.000000
W4	-0.000009	0.000003	0.000009
W5	0.000010	-0.000030	0.000032
W6	-0.000910	0.000011	0.000910
W7	-0.000002	0.000020	0.000020
W8	0.000000	0.000040	0.000040
W9	-0.000040	0.000090	0.000098
W10	-0.000020	0.000002	0.000020

Overall, the lateral error in Table 4.2 is extravagant than Table 4.3. This result occurred due to the Pure Pursuit guidance enhance the control performance by implementing the information feedback (current location and orientation of USV) updated and transform global coordinates to the local coordinates for real-time navigation. This information feeds back into the Pure Pursuit algorithm to ensure accurate navigation along the local path. The lookahead point is determined along the local path, and the USV steers towards this point by adjusting its heading.

Based on the Table 4.2 and 4.3, the value of W1 lateral error is greater than W6. The rapid change in steering commands is affecting the USV to accurately follow the desired path. The precision of path following in short-distance scenarios is also influenced by the dynamics of the USV and the response of propulsion systems. Besides, with a limited lookahead distance, the vehicle may not have enough time caused anticipate subtle deviations in the path, leading to suboptimal tracking performance.

Summary

In summary, by 75s, the USV reaches the last target position, demonstrating successful navigation along the trajectory path. The USV reaches the last target position, demonstrating successful navigation along the trajectory path. This success is attributed to the integration of the dead reckoning method with Pure Pursuit guidance, which continuously updates the USV's position and orientation using onboard sensors. The lateral error in Table 4.2 (dead reckoning method) is larger compared to Table 4.3 (dead reckoning with Pure Pursuit Guidance), primarily due to the Pure Pursuit guidance system enhancing control performance through real-time feedback of the USV's location and orientation. Besides, restricted lookahead distance hampers the vehicle's ability to anticipate subtle deviations in the path, leading to suboptimal tracking performance, especially in short-distance scenarios.

CHAPTER 5

CONCLUSION

This chapter examines the conclusion that reflects on the research's specified aims. This chapter discusses the contribution of this study to academia. In addition, the chapter addresses the recommendations for future study and the enhancement of the research.

5.1 Conclusion

This paragraph will answer the first objective which is: to develop the real-time tracking algorithm that guides USV towards the target location using Pure Pursuit guidance method. The Pure Pursuit algorithm functions by directly engaging with the nearby path (x_i, y_i), which is determined in relation to the USV's position. It computes steering directives according to the USV current position and orientation relative to this proximate path. Based on the Figure 4.2, USV is meet and followed the target location at time 40s until 70s, then, catch the last current position of the target at time 75s. Hence, the tracking algorithm able to guide USV towards the target location by using Pure Pursuit guidance.

This paragraph will answer the second objective which is: To evaluate the algorithm's performance in minimizing lateral error and reaching the target location. Pure Pursuit guidance minimizes lateral error in USV by continuously adjusting the steering angle to direct the vehicle towards a target point along a waypoint. By converging towards the predefined path and the target point, the USV naturally reduces lateral error, which is the perpendicular distance between its position and the path. Operating in a closed-loop fashion, Pure Pursuit utilizes feedback from sensors to make real-time adjustments to steering commands, ensuring precise path following and minimizing lateral errors.

5.2 Contribution

The application of Pure Pursuit guidance in USVs has made significant contributions to academic research It serves as a tracking algorithm for studying autonomous navigation and control in marine environments, providing researchers with a reliable method for path following and waypoint navigation. The algorithm developed allowing USVs to autonomously navigate along predefined paths or towards specific waypoints with high accuracy by minimizing the lateral error. Additionally, the algorithm developed enables USVs to adapt to dynamic target by continuously adjusting their trajectories based on real-time sensor feedback, ensuring robust performance even in changing conditions.

5.3 Recommendation

By carefully considering these constraints and employing appropriate mitigation strategies, Pure Pursuit guidance can be adapted to achieve precise path following in short-distance navigation scenarios by employing advanced control strategies or higher-level planning algorithms to enable agile and responsive manoeuvring in dynamic environments

Summary

The developed real-time tracking algorithm guides USVs toward target locations using Pure Pursuit guidance, interacting directly with nearby path coordinates relative to the USV's position. Demonstrated in Figure 4.2, the USV effectively reaches and follows the target location, showcasing the algorithm's efficacy. Pure Pursuit continuously adjusts steering angles, minimizing lateral error by integrating sensor feedback for real-time adjustments, ensuring precise path following with minimal errors. This method significantly contributes to studying autonomous navigation in marine environments, enabling accurate navigation along predefined paths or waypoints. It facilitates adaptation to dynamic targets, ensuring reliable performance in changing conditions and agile manoeuvring through careful consideration and suitable mitigation strategies.

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APPENDICES

Appendix A: Target Platform Source Code

```
void loop() {

  do {
    while (gpsSerial.available() > 0) {
      if (gps.encode(gpsSerial.read()))
      {
        Serial.println ();
        Serial.println("Target Pose: ");
        if (gps.location.isValid())
        {
          TargetLngLoop = TargetLngLoop + 1;
          Serial.print(F("Longitude: "));
          double Longitude = gps.location.lng();
          Serial.println(Longitude, 6);
          TargetLngString = String(Longitude, 6);
          HC12.print("R" + TargetLngString + "T");
            }
}
```

Appendix B: USV Platform Source Code

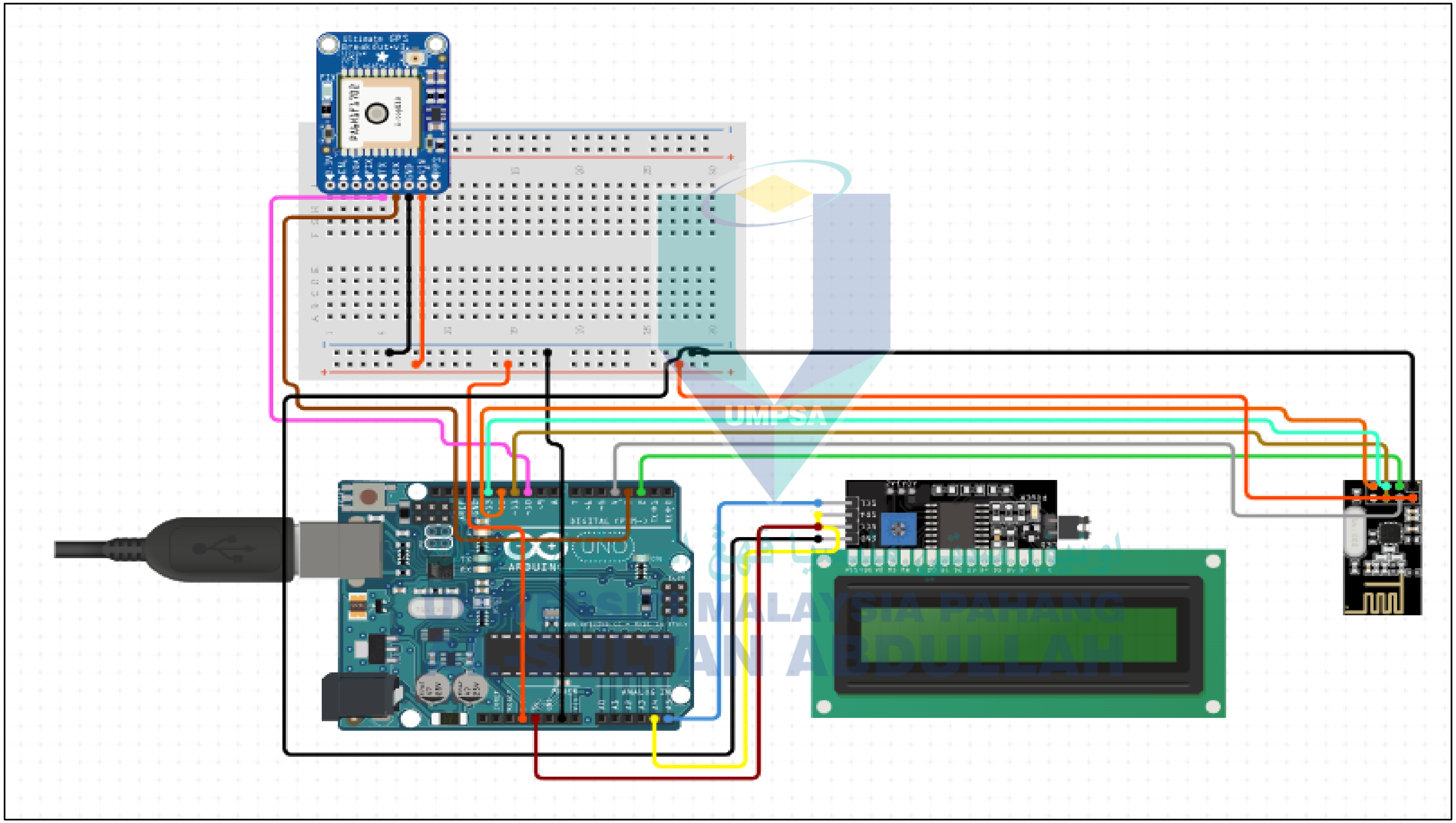
```
void loop()
{
  double recalTargetPose = Target_Waypoint();
  delay (100);
  compass.read();
  USVCourse = compass.getAzimuth();
  Serial.println();
  Serial.println("***USV's Course***");
  Serial.print(USVCourse);
  Serial.println();
  WritingUSVCourse_inSDCard(USVCourse);
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Course:");
  char Coursestr[4];
  dtostrf(USVCourse, 2, 0, Coursestr);
  lcd.setCursor (7, 0);
  delay (10);
  lcd.print(Coursestr);

  double recalValRad = CoverttoRad ( USVCourse,  USVLat,  USVLng,
LatTarget,  LngTarget);
  Dis2Lat = abs(RadLatTarget - RadLatUSV);
  Dis2Lng = abs(RadLngTarget - RadLngUSV);
  MLat = RadLatTarget - RadLatUSV / 2;
  double recalValDist = Convert(USVLat, USVLng, Dis2Lat, Dis2Lng);
  float distance = sqrt((pow(distance_North, 2)) + (pow(distance_East,
2)));
  distance = distance * 1000  ;
  Serial.print ("Distance: ");
  Serial.print(distance, 4);
  Serial.println (" m");
  WritingDist_inSDCard(distance);
  lcd.setCursor(0, 1);
  lcd.print("Distance:");
```

```
delay (1000);
RadHeading = atan2( cos(RadLatUSV) * Dis2Lng, Dis2Lat), 2 * M_PI;
heading = RadHeading * 180 / 3.1415926535;
int head = heading;
if (head < 0)
{
  heading += 360;
}
Serial.print("Heading: ");
Serial.println(heading);
Writingheading_inSDCard(heading);
lcd.setCursor(0, 2);
lcd.print("Heading:");
char Headstr[4];
dtostrf(heading, 2, 0, Headstr);
lcd.setCursor (8, 2);
delay (10);
lcd.print(Headstr);

ErrHead = USVCourse - heading;
Serial.print("Error: ");
Serial.println(ErrHead);
delay (1000);
lcd.setCursor(0, 3);
lcd.print("Error:");
char Errstr[4];
dtostrf(ErrHead, 2, 0, Errstr);
lcd.setCursor (6, 3);
lcd.print(Errstr);

int turn;
int HC = USVCourse;
if (ErrHead >= -180) {
  if (ErrHead <= 0) {
    turn = 8;              //set turn =8 which means 『right』
  }
}
```

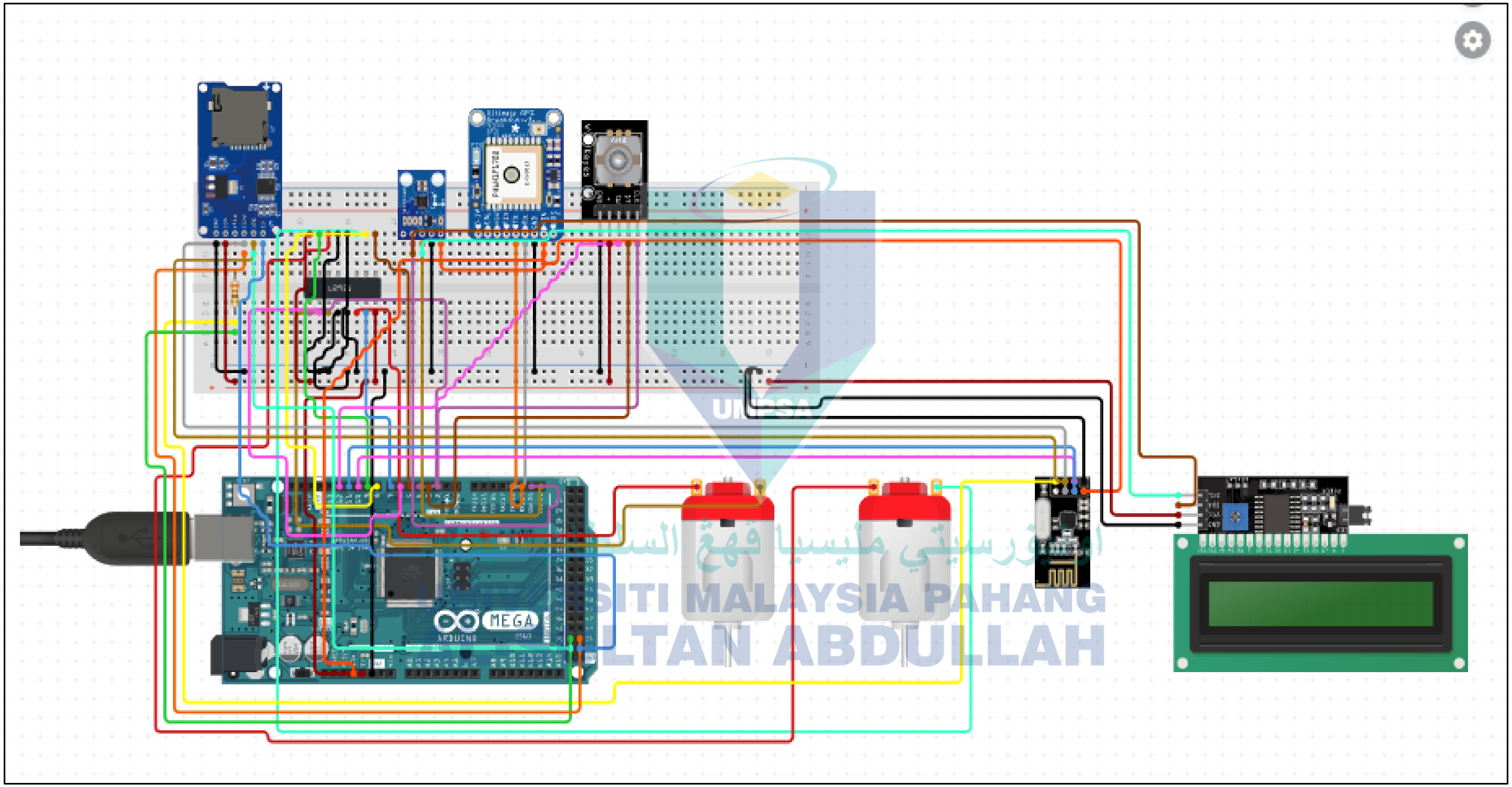
```
  if (ErrHead < -180) {
    turn = 5;                //set turn = 5 which means 『left』
  }
  if (ErrHead >= 0) {
    if (ErrHead < 180) {
      turn = 5;              //set turn = 5 which means 『left』
    }
  }
  if (ErrHead >= 180) {      //set turn =8 which means 『right』
    turn = 8;
  }
  if (HC == heading) {
    turn = 3;                //then set turn = 3 meaning go
『straight』
  }

  StanbyMode();

  if (turn == 3) {
    Serial.print(″Move:″);
    Serial.println(″straight″);
    lcd.setCursor(0, 2);
    lcd.print(″******Straight******″);
  }
  if (turn == 8) {
    lcd.clear();
    Serial.print(″Move:″);
    Serial.println (″Right Turn″);
    lcd.print(″****Right Turn****″);
    rightturn(USVCourse, heading, ErrHead);
  }
  if (turn == 5) {
    lcd.clear();
    Serial.print(″Move:″);
    Serial.println (″Left Turn″);
    lcd.print(″****Left Turn****″);
    leftturn(USVCourse, heading, ErrHead);
```

```
}

lcd.clear();
lcd.setCursor(0, 0);
lcd.print("Catching Target:");
smartDriveDuo30.control(40, 40);
interim_USVLat = USVLat;
interim_USVLng = USVLng;

while (digitalRead(buttonPin) == LOW) {
  if (millis() - Time_old >= 1000) {
    Time_old = millis();
    dt = millis() / 1000;
    Serial.print(dt); Serial.println(" ");
    double Velocity_meter = 4;
    float Current_Distance = Velocity_meter * (dt / 60);
    Serial.print ("Current_Distance: ");
    Serial.print(Current_Distance, 4);
    Serial.println (" m");
    Diff_Distance = distance - Current_Distance;
    Serial.print ("Remaining_Distance: ");
    Serial.print(Diff_Distance, 4);
    Serial.println (" m");

    if ( Diff_Distance < 1) {
      smartDriveDuo30.control(0, 0);
      delay (100);
      USVLat = LatTarget;
      USVLng = LngTarget;
      break;

    }
    else {
      delay(100);
      Current_Distance ++;
    }
```

Appendix C: Schematic Diagram (Target)



Appendix D: Schematic Diagram (USV)



Appendix D: Testing Process

Figure i: Executing the Program into the Arduino Microcontroller

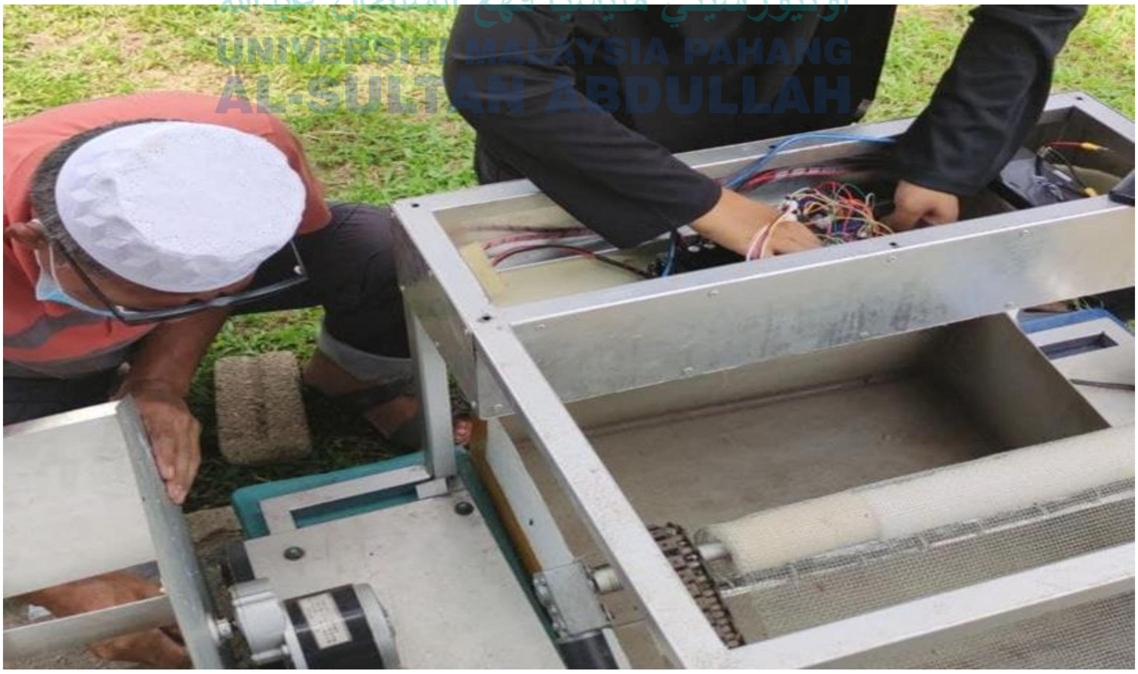
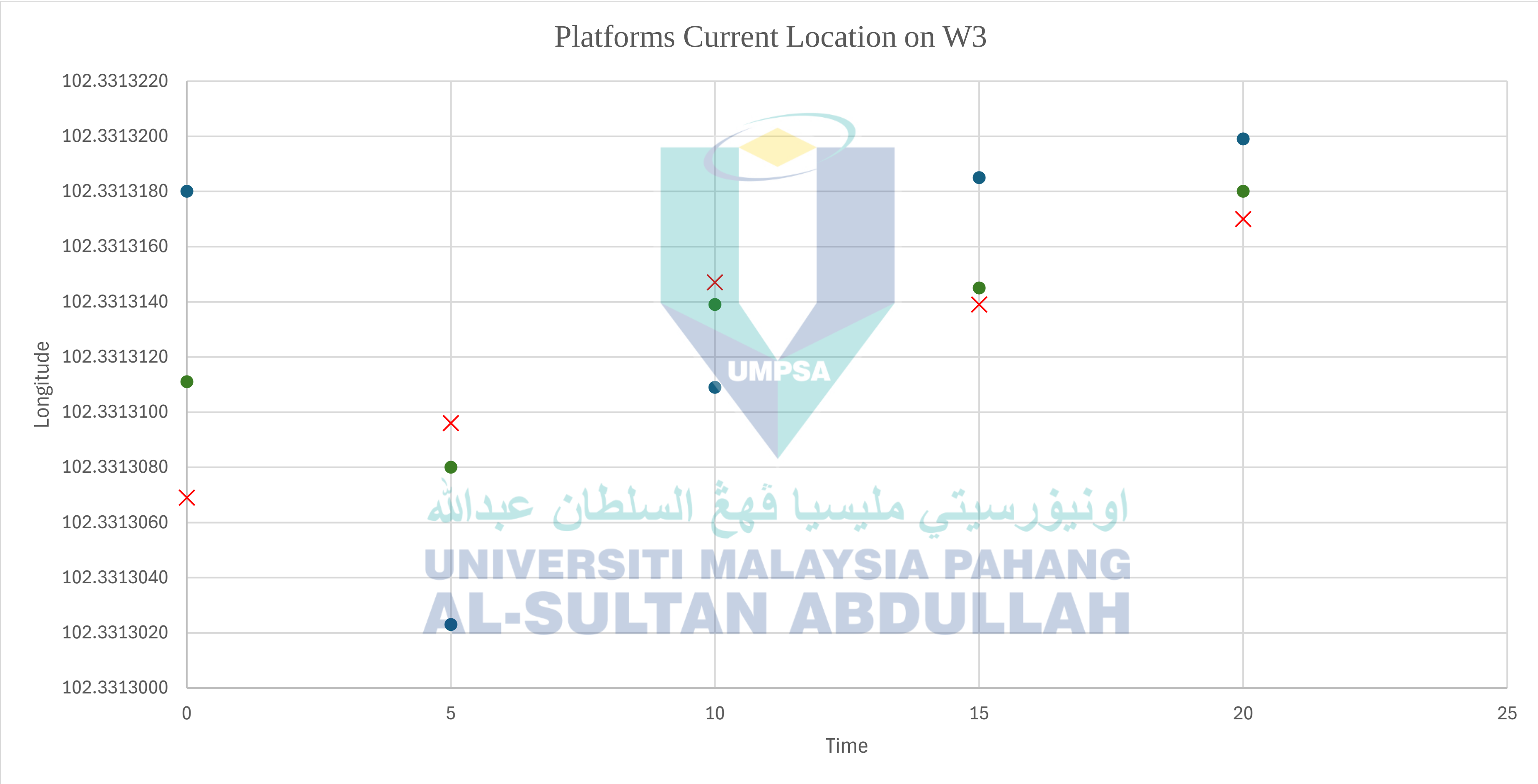
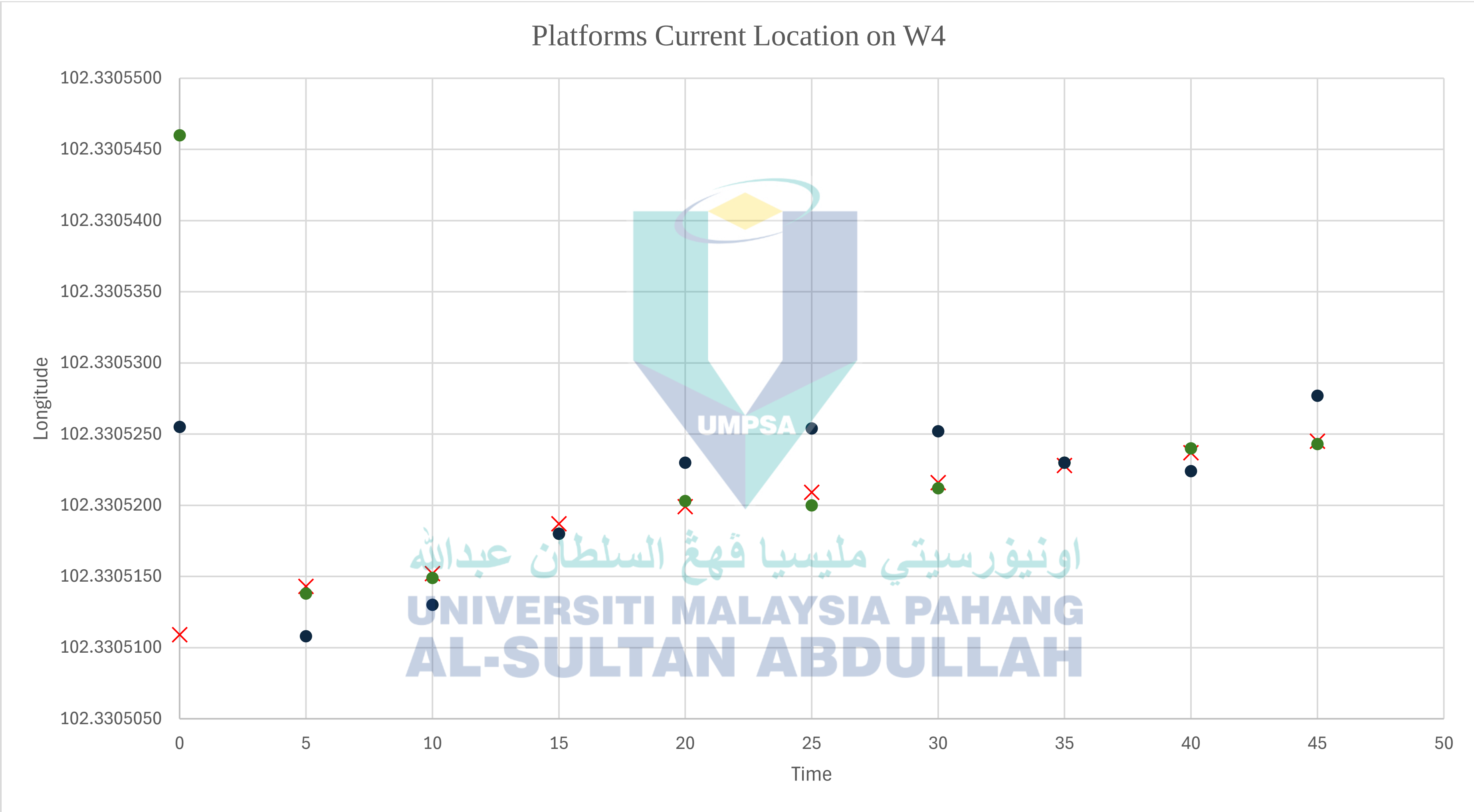


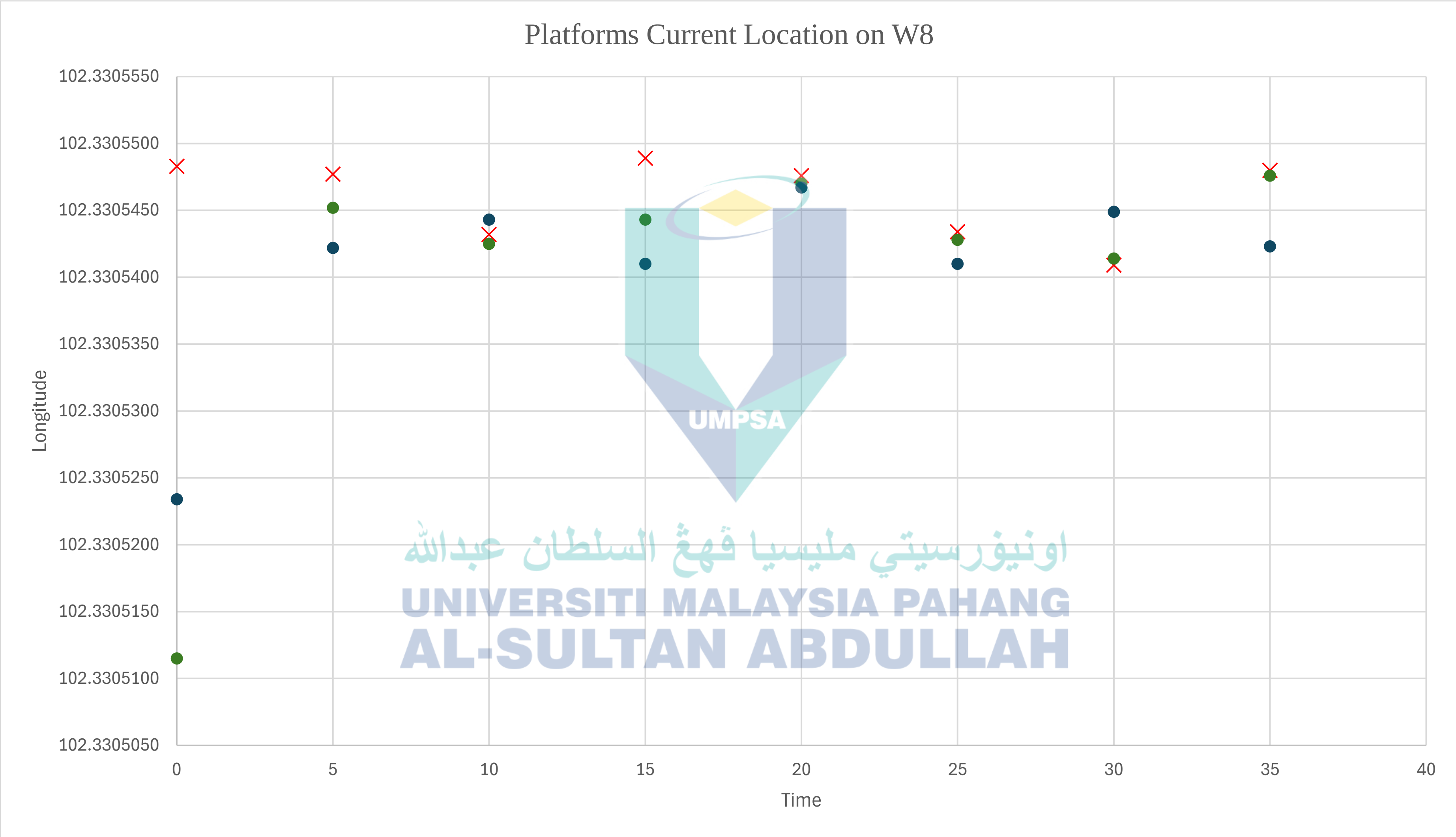
Figure ii: Installing the Arduino microcontroller into the USV

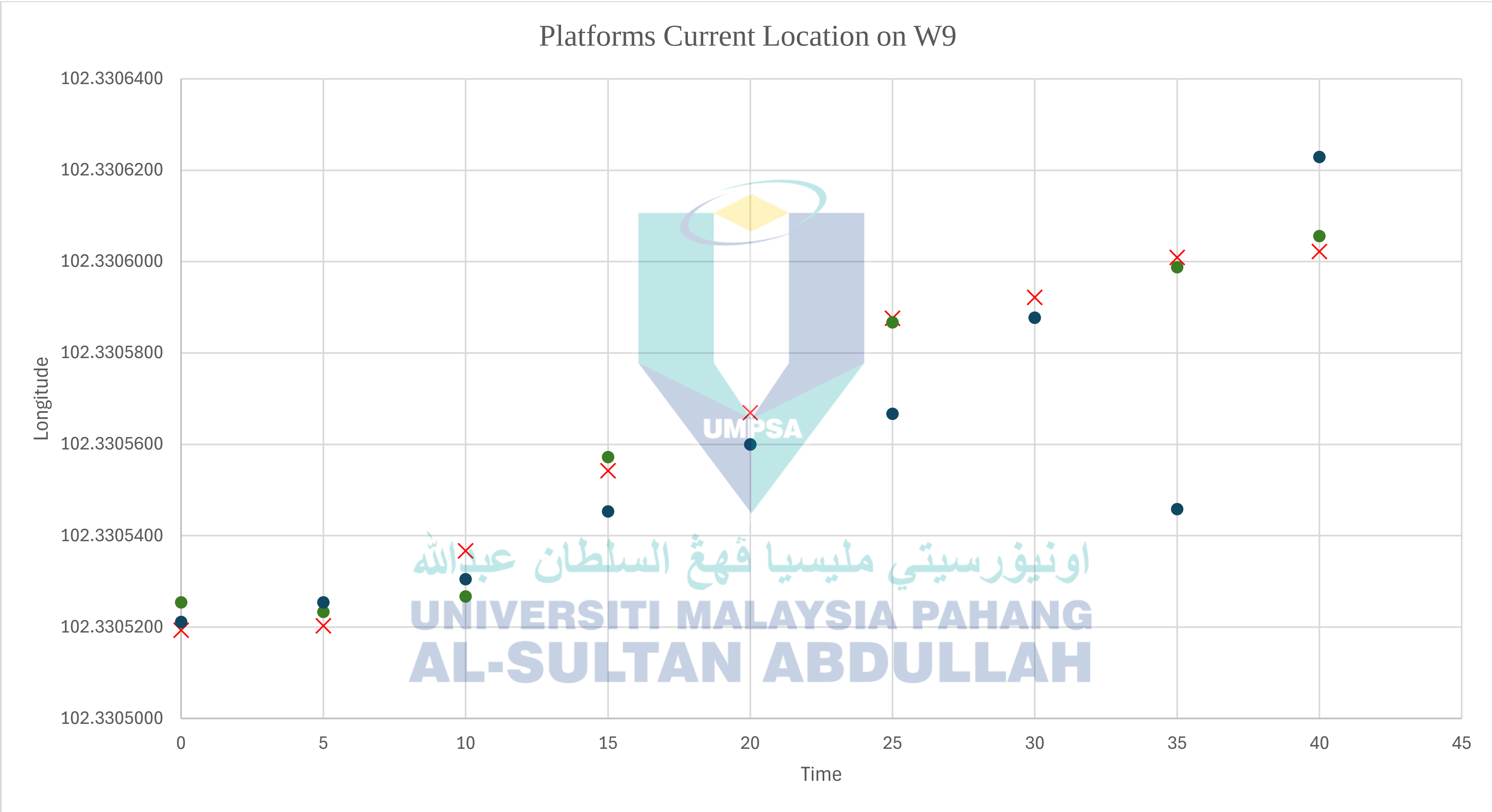
Figure iii:Testing the Program before Running it in the real situation

Appendix D: Waypoint Graph

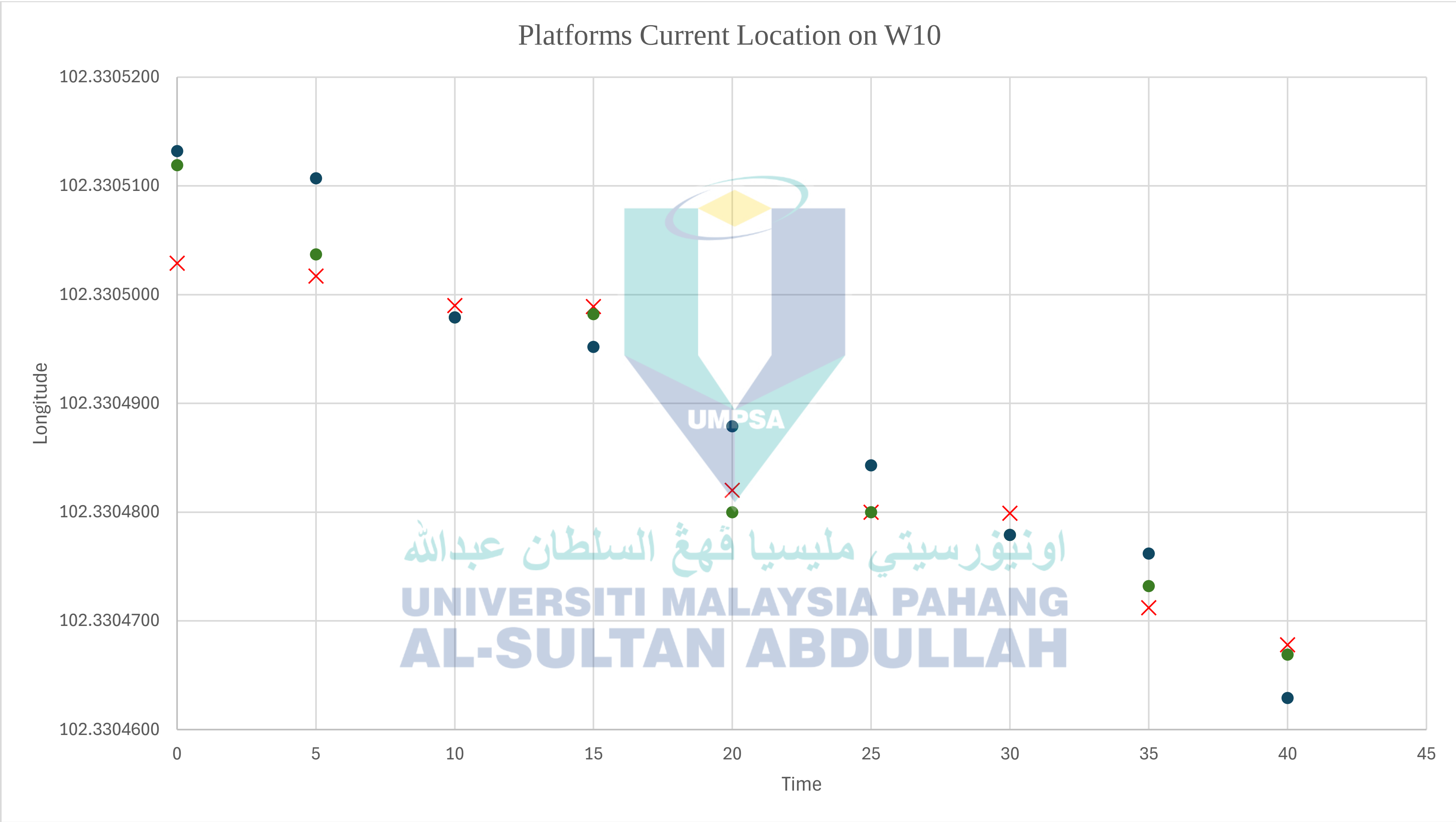



Platforms Current Location on W4
Longitude
102.3305500
102.3305450
102.3305400
102.3305350
102.3305300
102.3305250
102.3305200
102.3305150
102.3305100
102.3305050
0
5
10
15
20
25
30
35
40
45
50
Time


Platforms Current Location on W8
Longitude
102.3305550
102.3305500
102.3305450
102.3305400
102.3305350
102.3305300
102.3305250
102.3305200
102.3305150
102.3305100
102.3305050
0
5
10
15
20
25
30
35
40
Time



Platforms Current Location on W9
102.3306400
102.3306200
102.3306000
102.3305800
102.3305600
102.3305400
102.3305200
102.3305000
Longitude
0
5
10
15
20
25
30
35
40
45
Time


Platforms Current Location on W10
Longitude
102.3305200
102.3305100
102.3305000
102.3304900
102.3304800
102.3304700
102.3304600
0
5
10
15
20
25
30
35
40
45
Time