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Evaluation of the utility and performance of an autonomous surface vehicle for mobile monitoring of waterborne biochemical agents

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Submitted to the Faculty of
Mississippi State University
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in Agriculture
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2021

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Real-time water quality monitoring is crucial due to land utilization increases which can negatively impact aquatic ecosystems from surface water runoff. Conventional monitoring methodologies are laborious, expensive, and spatio-temporally limited. Autonomous surface vehicles (ASVs), equipped with sensors/instrumentation, serve as mobile sampling stations that reduce labor and enhance data resolution. However, ASV autopilot navigational accuracy is affected by environmental forces (wind, current, and waves) that can alter trajectories of planned paths and negatively affect spatio-temporal resolution of water quality data. This study demonstrated a commercially available solar powered ASV equipped with a multi-sensor payload ability to operate autonomously to accurately and repeatedly maintain established A-B line transects under varying environmental conditions, where lateral deviation from a planned linear route was measured and expressed as cross-track error (XTE). This work provides a framework for development of spatial/temporal resolution limitations of ASVs for real-time monitoring campaigns and future development of *in-situ* sampling technologies.

DEDICATION

I would like to dedicate this work to my husband, Clint. There were many stressful and long days, but you have encouraged me through all of this since day one. This process would have been much harder to go through if I did have you to support me. Thank you for everything you have done for me. I love you!

I would also like to dedicate this work to my parents, Barry and Kim, and my brother, BJ, for believing in me and supporting me throughout not only this project but throughout my life. Each of you always believed in me, pushed me to better myself, and knew I was capable of anything if I put my mind to it. I love y'all!

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To my committee members, Dr. Lowe, Dr. Turnage, and Dr. Dash. Thank you for devoting your time and effort the past couple of years. I am grateful for each of your guidance and expertise that helped me gain much knowledge and experience throughout this project.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1 Unmanned Systems

An unmanned system (US) is a broad term characterizing a class of vehicles that are technologically capable of being powered and operated from a distance without a human directly onboard. Commonly referred to as Unmanned Vehicles (UVs), these machines integrate and utilize sophisticated data processing systems, telemetry and guidance systems, sensors, cameras, payload capacity, and other technologies to perform tasks and execute missions otherwise limited by human presence and/or machine size and spatial constraints (Liu et al., 2016). These scaled down and/or miniaturized machines serve as vehicular tools to perform tasks in severe and/or hazardous conditions that are deemed too dangerous or inconvenient for a human to perform (Ferreira et al., 2009). Furthermore, they are proportionately designed to be operational in confined or inaccessible locations (i.e., harmful pathogens or chemical spills) that prevent the possibility of human entry. In these situations, USs serve to reduce operational, labor and maintenance costs, while increasing safety, efficiency, and productivity (Association for Unmanned Vehicle Systems International, 2021). Historical accounts of US utilization dates as far back as 1849 where military forces utilized balloons as a vehicle to carry timed fuse incendiary devices to targeted locations (McKenna, 2016). Pilotless radio-controlled aircrafts were developed shortly after World War I and utilized in World War II and the Vietnam war as aerial torpedoes, target drones, and reconnaissance drones (Imperial War Museums, 2021). In the

current twenty-first century digital age, developments and technological advancements of USs have evolved rapidly with seemingly limitless capabilities and applications across a plethora of civilian, commercial, and military applications.

USs are controlled, navigated, and/or maneuvered in various ways ranging in level of technical complexity and autonomy. The levels of control are broadly characterized as remote operations, teleoperation, semi-autonomous operation, and fully autonomous operation (Huang et al., 2004). Remote operation requires direct line of sight (LOS) and directionally oriented responsive control by a human operator through a handheld interface or controller (Huang et al., 2004). A robust two-way data communications link is required to prevent disruption and/or loss of communication. A major disadvantage of remote operation is limited device range due to law restrictions, sight restriction, or loss of communication. According to FAA 107 laws, small UAS (<55 lbs.), or "drones", are not allowed to operate beyond LOS of the operator nor fly at an altitude above 400 feet above ground level (AGL) or the top of an object without appropriate permits or waivers (Federal Aviatin Administration, 2020). USs not equipped with cameras, GPS navigation, or re-homing safety features are spatially limited and problematic when beyond LOS of the operator, resulting in loss of communication and control, damage to the craft and property, recovery efforts, and risk of injury to bystanders. Moreover, recovery efforts can prove challenging in restricted and/or inaccessible areas. Teleoperation is an advanced mode of US remote operation that does not require direct LOS, where the human operator inputs directionally oriented responsive control and/or assigns incremental goals on a continuous basis by means of an interface via camera or GPS guidance (Huang et al., 2004).

Semi-Autonomous is a mode of US operation requiring various levels of human/robot interaction. The mission is planned and conducted by the human operator and the US is capable

of executing goals and maneuvers autonomously while allowing human interactions to interfere when necessary (Huang et al., 2004; Thomasson et al., 2020). Travel between pre-defined waypoints is a characteristic of semi-autonomous operation. Operators must remain engaged when operating USs in semi-autonomous mode to avoid loss of control, objects, and/or hazardous situations.

Fully Autonomous is a mode of operation wherein the US accomplishes its assigned mission and/or goals without human intervention. Fully Autonomous vehicles are capable of decision based operational control through integrated sensing and perception of their environments to make safe and necessary decisions in real time such as obstacle avoidance, problem solving, and dynamic variables reaction (Huang et al., 2004). Advancements of autonomous technologies used in civil, agricultural, research, and military applications is rapidly increasing. Autonomous tractors, passenger vehicles, commercial trucking, drones, and autonomous mobile robots used in warehouse and factory systems are common examples. Driverless or driver assisted vehicles must sense and adapt to operational and environmental conditions, select appropriate routes, and navigate to their destinations. To perform these tasks, they must recognize objects including lights, road signs, other vehicles, and pedestrians.

Autonomous vehicle control and software architecture, based on artificial intelligence technology, is broadly partitioned into sensing, perceiving, decision making, and acting/execution (BlackBerry QNX, 2021; Huang et al., 2004). Sensing involves gathering informational data from various sources including sensors (speed, accelerometer, wheel/rudder angle, etc.), cameras, communications (V2X, DSRC, RF, 5G, cellular, satellite, etc.), flight data (LiDAR, radar, ultrasonic, etc.), and vessel position (GPS, charts/maps, landmarks, etc.). Perception and understanding are the organization, interpretation, and classification of the sensed

data which includes signal and image processing to detect features, classification of data (obstacles, pedestrians, signs, etc.), tracking of obstacles, and vessel localization (geo-referenced location of vehicle). Decision making is the process of carrying out operational determination relative to the perceived and classified data. This includes route/trajectory planning, mobility awareness (safety), and physical dynamics of planned maneuvers. Finally, the plan or mission is executed through dynamically controlled actuation of the vehicles locomotion and steering systems (motors, drivetrain, accelerator, brakes, rudder, etc.) (BlackBerry QNX, 2021). This process is executed iteratively and requires a significant level of advanced computing technology and software, which is a major cost driver for autonomous systems. Operator confidence, system cost, safety, reliability, and liability concerns present challenges with consumer adoption of autonomous vehicle/system technology (Yeomans, 2014). However, McKinsey & Company (2016) reported up to 15% of new cars sold in 2030 could be fully autonomous, if technological and regulatory issues have been resolved.

Reliable wireless communication systems are critical in support of US remote operation. These systems facilitate the transfer of mission critical data and commands to and from the US, maintaining safe and efficient operation. Data from cameras and sensor payloads can be transmitted in real-time. Common communication platforms include radio frequency (RF), cellular, and satellite. RF communication is a reliable and cost effective means of signal communication but limited at transmitting large amounts of data. Also, RF is generally limited to LOS and does not support over the horizon operations. Cellular communications are capable of supporting over the horizon operations and support relatively large data transfers. However, a cost is associated with cellular communications, and areas of operation are limited to those with cellular service. Satellite communication systems also support over the horizon operations and

are more reliable in remote locations such as rural landscapes and open ocean areas. However, increased cost is associated with satellite communications than with the other communication options.

Application and utilization of US technologies are mission and/or terrain dependent and are broadly separated into three distinguishable categories: 1) terrestrial, 2) aerial, and 3) marine/aquatic. Terrestrial USs are robotic systems capable of navigation and operation on land or solid terrain. Autonomous tractors, passenger vehicles, and autonomous mobile robots used in warehouse and factory systems are common examples. Aerial USs are a class of unmanned aircraft. Generally classified based on altitude range, endurance, and weight, these systems support a wide range of sensor payloads and cameras for aerial observation and tactical planning applications (Narayanan & Ibe, 2015). Marine/aquatic USs are a class of vessels designed for operation and navigation in marine or freshwater environments. These systems can operate on the surface of the water, sub-surface, or a combination of the two (Zolich et al., 2018). Marine unmanned technologies are generally ruggedized, corrosion resistant, and designed for operation in harsh weather and environmental conditions (Snyder et al., 2020). With the expanding technological frontier, applications of land, air, and marine unmanned technologies are rapidly expanding across military, civilian, and commercial sectors.

1.2 Unmanned Ground Vehicles

USs utilized in terrestrial applications, referred to as Unmanned Ground Vehicles (UGV), are characterized by their ability to navigate diverse landscapes and terrains. UGVs serve to extend human capabilities in unreachable or unsafe locations. UGV locomotion systems are dependent on contact with solid or semi-solid surfaces to propel the vehicle forward and are

typically observed as legged, wheeled, or tracked all-terrain platforms (Figure 1.1) (Odedra et al., 2009).

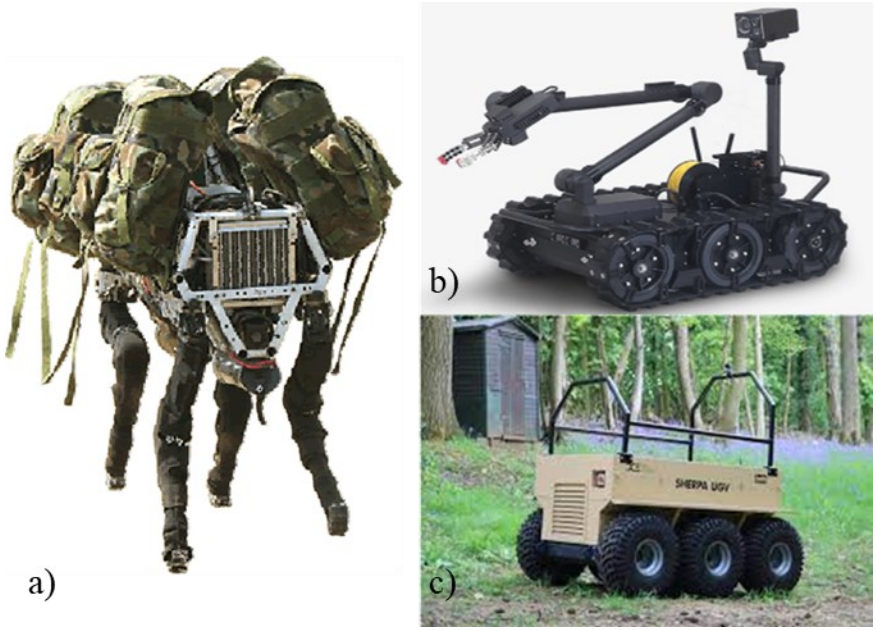

Figure 1.1 Illustration of UGV locomotion systems; a) legged (Boston Dynamics, 2008), b) tracked (Teledyne FLIR LLC, 2021), and c) wheeled (Smith Engineering, 2018).

UGVs utilized in military defense and security applications are designed for the battlefield's dangerous and hazardous conditions, and are equipped with sophisticated tactical, imagery, and navigational technologies and sensors. Military applications include transportation of machinery and equipment, surveillance of military bases or areas in battle, communication between the military and UGV, and search and rescue of troops trapped in a dangerous situation.

Civilian and commercial applications of UGVs include transporting for supply chains, search and rescue in dangerous environments, surveillance in restricted areas, and harvesting of agriculture crops. UGVs can replace humans that are working in a dangerous environment or assist them to make their operation easier or safer. Shipping departments use USs to receive items in stock for workers filling sale orders, creating a faster packaging process, while factory

industries use UGVs to transport products to the desired location without human intervention or assistance to prevent worker injuries.

1.3 Unmanned Aerial Vehicles

USs utilized in aerial applications, referred to as Unmanned Aerial Vehicles (UAVs) or drones, are aircraft that are flown and/or hovered above the landscape. UAVs have the ability to cover large areas in short time and reach inaccessible areas as compared to dispatching humans to survey areas on foot. UAVs come in various configurations and sizes. Most UAVs host lightweight and compact designs due to FAA regulations but can be similar in size to manned aircraft and helicopters in some security and defense applications where increased payload capacity is needed. UAV classification schemes exist based on operational characteristics and capabilities including weight, altitude, speed, range, and degree of autonomy. Additionally, they are broadly categorized as either fixed wing, rotary wing, or a hybrid vertical-take-or-landing (VTOL) design (Figure 1.2).

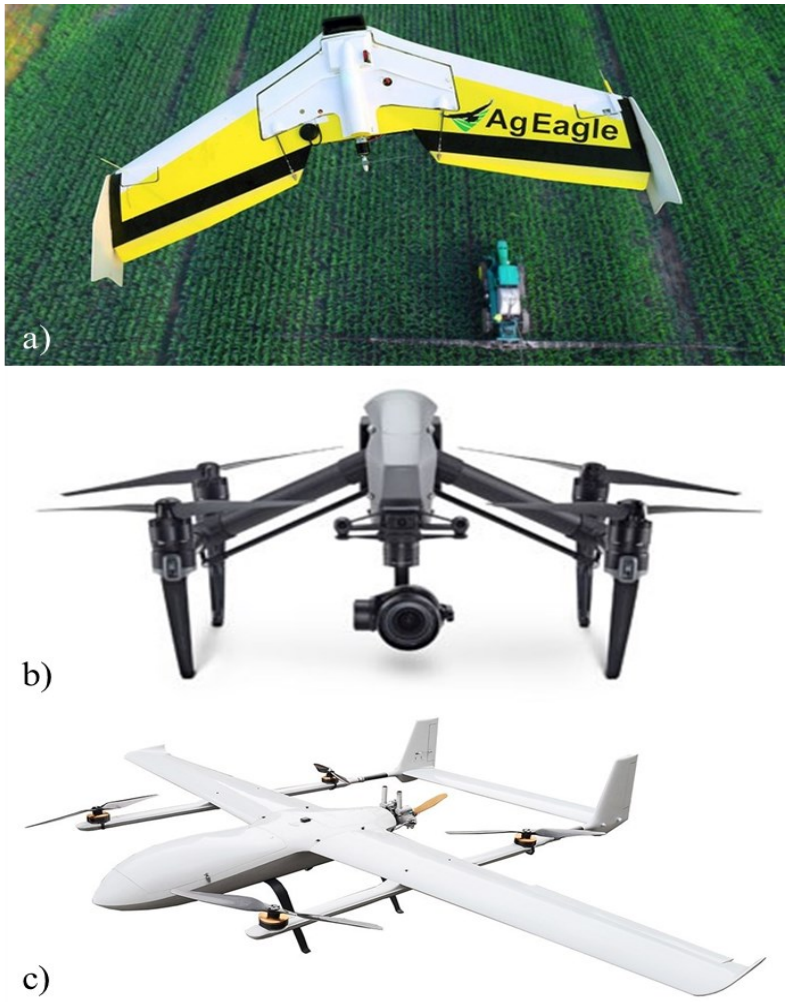

Figure 1.2 Illustrations of UAV systems; a) fixed wing, b) rotary wing (Mississippi State University Extension Service, 2021b), and c) VTOL (Fly Dragon Drone Tech., 2021)

Fixed wing craft are comparable to manned winged aircraft which only fly nose forward and typically lack vertical and/or stationary flight capabilities (Figure 1.2a). Energy is used to generate thrust for forward momentum while the fixed wings generate lift. This characteristic optimizes energy consumption and provides an extended energy budget to power other instrumentation and sensors during flight, extending mission endurance and altitude capabilities.

Other advantages include the ability to carry heavier payloads, reduced noise during operation, and the ability to cover larger geographic areas than rotary wing or hybrid UAVs. This makes fixed wings more efficient for high altitude missions such as mapping, photography, and surveillance. Other fixed wing missions include flying weaponry/explosives and delivering supplies and packages. Some fixed wing UAVs may be susceptible to crash due to the need for a catapult to launch and/or a runway to launch and land them safely. Also, the inability for true vertical and/or stationary flight can be a disadvantage in locations lacking enough room for take-off and landing. There is, however, a rare instance where fixed wing aircraft flights are conducted into the wind so that wind speed negates aircraft velocity. This allows sequential images to be collected over the same location with a fixed wing aircraft; the process is called 'kiting'.

Rotary wings generate vertical lift by rotating a propeller or other pitched device designed for creating lift around a vertical shaft. They can be single rotary wing, like a helicopter, but most are multirotor in design, providing for greater stability and increased lift capacity over single rotary wing. The quadcopter (4-rotor) design is widely adopted among enthusiast and professionals (Figure 1.2b), but varying rotor configurations are available, such as the hexacopter or octocopter. Multirotor flight control is determined by independently varying rotor speed and direction to dynamically control roll, pitch, and yaw, which results in precision navigational control and maneuverability. Rotary wing flight control is generally easier to master due to their ability to launch, land, and operate in confined spaces. Multidirectional, vertical, and stationary flight are also major advantages. Unlike fixed wing craft, endurance, speed, altitude, and payload capacities are restricted for rotary wing due to limited battery life. They are, however, less likely of crashing compared to fixed winged craft due to precise flight control,

vertical takeoff/landing capabilities, and the ability to compensate for single-engine failure on multi-engine UAVs (Mississippi State University Extension Service, 2021a; Tkáč & Mésároš, 2019). Rotary wing mission capabilities are generally characterized as low altitude and low endurance and are typically used for aerial imagery, surveillance, and videography. VTOL UAVs are a combination of rotary and fixed wing craft, which have the capability to shift between the two during flight (Figure 1.2c). They can take off vertically and land without a launcher or runway. VTOL aircraft have extended flight time capabilities compared to rotary wings but have less flight time (aerial coverage) than fixed wings. Also, they host more moving parts which can malfunction and support less instrumentation weight capacity due to their changing center of gravity. UAV technologies and applications are growing rapidly and provide significant contributions to military and civilian sectors due to their ease of deployment, relatively low operational cost, and high mobility.

1.4 Waterborne Unmanned Technologies

Akin to their terrestrial and aerial counterparts, a class of unmanned technologies exist for operation and navigation in marine environments and provide an essential link between sea, land, and space. Marine USs provide a platform designed to support a plethora of sensors and payload configurations to address needs across marine military, research, and commercial industries. Utilization of marine USs in military and research is established. Commercial and civilian US utilizations and platforms marine multi-mission applications are emerging but limited. Utility and performance limitations may exist due to communication reliability, power requirements, and navigational accuracy. Military applications include operations to protect and inspect maritime zones and borders from threats of illegal activity, which include patrolling, target acquisition, minesweeping, communication links, and intelligence, surveillance, and

reconnaissance (IRS). Environmental assessments help support research and commercial applications including surveillance, oceanography, bathymetric and hydrographic surveys, and water quality monitoring. Use of marine USs minimizes the disturbance of the environment and improves spatial and temporal resolution of real-time data.

Two broad categories of marine USs exist. Autonomous Underwater Vehicles (AUVs) are used for subsurface applications and missions. Autonomous Surface Vehicles (ASV), also known as Unmanned Surface Vehicles (USV), are specifically designed for surface use only. However, marine unmanned technologies, like the Ocean Aero Triton, are emerging that are both surface and sub-surface mission capable. Marine USs serve a critical need by expanding capabilities across governmental, scientific, and business sectors for monitoring, managing, and protecting both oceanic and inland water resources and environments.

1.4.1 Underwater Vehicles

Underwater vehicles are used in oceanography to explore and monitor harsh environments and deep inaccessible locations. Applications for military defense and security include minesweeping, target acquisition, time-critical strikes, and anti-submarine warfare. Civil and commercial applications include oil and gas inspection and sea pipeline monitoring. Two categories of underwater vehicles exist: Remotely Operated Underwater Vehicles (ROV) and Autonomous Underwater Vehicles (AUV) (Figure 1.3).

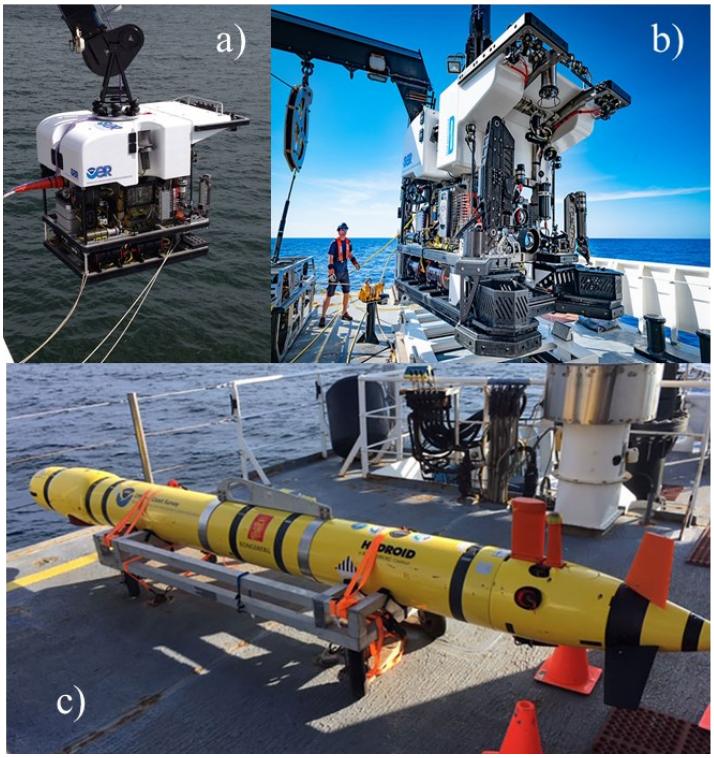

Figure 1.3 Illustration of ROV and AUV Underwater Vehicles; a & b) NOAA Deep Discoverer ROV tethered to a ship (NOAA Ocean Exploration, 2021a), and c) NOAA REMUS 600 AUV (NOAA Ocean Exploration, 2019).

ROVs are water maneuverable systems that are remotely operated by a pilot at the water surface (Figure 1.3a & b). ROVs are usually tethered to a ship or buoy by cabling that transmits operational commands and other data between the operator and the ROV. They range in size from small, compact units to units as large as a passenger vehicle and are typically equipped with cameras, lights, manipulator arms, and various levels of sampling instrumentation depending on the application (NOAA Ocean Exploration, 2021b).

AUVs are untethered autonomous underwater robots that operate independently of human responsive control (Figure 1.3c). Unlike remotely controlled ROVs, AUVs are programmed or controlled by operators on ships or land to execute pre-programmed missions for

sampling and data collection. AUVs host a variety of instrumentation and sampling equipment but are typically unable to transmit data like their ROV counterparts. Instead, they store data on onboard computers to be retrieved when the vessel surfaces or is retrieved. AUVs are generally torpedo shaped units and that vary in weight from less than 100 to more than 3000 pounds (Virginia Institute of Marine Science, 2021). Communication between a base station and AUV is critical, and barriers exist; these include transmission distortion, the use of acoustic waves instead of electromagnetic waves, causing one to two second delays in response, and environmental factors that disrupt communication due to reflection, refraction, or absorption of signals. Transmission of radio frequencies signals (i.e., GPS) in water is limited to short distances; The AUV must surface often to find GPS signals, but this repeated surfacing can cause missions to be interrupted (Taudien et al., 2020).

Most AUV technologies utilize battery power for propulsion, navigation, and sensing systems. Although battery technologies have made significant strides in endurance and capacity, the underwater application of AUVs restricts the ability to recharge batteries on the go and/or utilize solar power recharging technologies. This limitation impedes the use of AUVs for long endurance missions and persistent surveillance operations.

1.4.2 Surface Vehicles

ASVs are a floating marine class of unmanned technologies that provide capabilities for performing surface based multi-task missions in varying aquatic (riverine, estuarine, coastal, etc.) environments. ASVs can be generally characterized by their mobility, cost, and level of autonomy and intelligence (Peng et al., 2021). They are utilized across research, civil, and military applications where their implementation alleviates logistical constraints while improving the safety of working conditions and expanding operational working windows, especially during

adverse environmental and weather conditions (Peng et al., 2021). ASV military and security applications include minesweeping and harbor and border security through reconnaissance and surveillance. Civil and research applications include hydrographic surveys and water quality management.

Common ASV hull designs utilize twin hull or monohull style (Figure 1.4). Twin hulls, also referred to as catamarans, consist of two hulls connected by a wide beam, providing more stability and speed than a mono hull design (Figure 1.4a). They are designed with a wide stance to ease heeling and wave-induced movements and have shallower drafts compared to monohulls. These characteristics make catamarans advantageous for hosting large and/or heavier payloads, such as profiling instrumentation, that need to be raised and lowered into the water column for data collection. However, they are incapable of self-righting when capsized, creating a major disadvantage, especially for systems deployed to run extended missions at sea under potentially harsh environmental conditions and sea states. Monohull designs are compact and streamlined vessels (Figure 1.4b). They provide an efficient platform for navigating heavy seas and shallow water environments. Monohull ASVs have increased internal payload volume compared to catamarans, providing sealed payload capacity for onboard electronics, computers, and other moisture sensitive instrumentation and wiring. For solar powered ASVs, the continuous top deck of monohull vessels provides an efficient location for mounting solar panels. A major advantage of monohull vessels is their ability to self-right if capsized. These characteristics make monohull designs especially valuable for over the horizon long endurance missions in harsh marine environments and heavy sea states.

Figure 1.4 Illustration of ASV systems; a) HydroCat-180 twin hull (Seafloor System Inc., 2021) and b) SeaTrac SP-48 mono hull.

ASVs are normally larger than AUVs tolerating a larger payloads and improved battery capacity (National Oceanography Centre, 2021). ASVs can be powered by various types of energy sources including battery, internal combustion engine, solar, wind and/or some combined configuration of these. Solar-powered vessels utilize solar panels to harvest energy from the sun to store in batteries. Various solar powered prototype ASVs for research purposes have been designed and tested (Dunbabin et al., 2009; Karapetyan et al., 2019; Kimball et al., 2015; Specht et al., 2019), but commercially available solar powered ASVs designed to agnostically host sensor and instrumentation payloads for long duration multi-mission applications are limited (Peng et al., 2021).

Solar energy creates a viable energy source for ASV propulsion, equipment, and instrumentation, so long as battery storage capacity is sufficient to provide power during low

light period or at night. Internal combustion engines can be more powerful and have better endurance than electric systems, but can be hazardous, unreliable, and laborious, requiring frequent re-fuels disrupting monitoring operations (Reed, 2006). Most ASV propulsion systems include mechanically driven propellers but can be jet drive systems or mechanically actuated sail systems. Actuated rudder systems are commonly used for ASV steering and heading control. Dual independent propellers/thrusters and/or rotating Azipod propellers are also used. Precise steering and heading control can be challenging for ASVs due to environmental forces, such as wind, waves, and current, that may alter their trajectory.

The purpose of this research was to characterize the navigational performance of the commercially available multi-purpose solar powered ASV, SeaTrac SP-48, equipped with an integrated payload package of environmental monitoring sensors. The depth and breadth of this study is communicated in Chapter II of this manuscript.

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CHAPTER II

ASV PERFORMANCE EVALUATION

2.1 Introduction

Inland and coastal waters are valuable but limited and vulnerable resources. Use of these waters is essential for numerous reasons (i.e., drinking water, irrigation, industry, navigation, and recreation); thus, the quality and management of these waters is important for the survival of humans and aquatic ecosystems (Ferri et al., 2011). Therefore, importance of real-time monitoring of water quality in inland and coastal marine environments has increased due to increases in land utilization in support of agricultural, industrial, and civilian sectors which can negatively impact aquatic ecosystems due to surface water runoff (Anderson, 2009; Yang et al., 2018). Consequently, an emergent consensus towards development of sensing and operational robotic technology to aid in real-time monitoring of inland and coastal waters is apparent (Kutser et al., 2009). Conventional monitoring tasks, based on sampling at fixed locations, require the use of specialized manned vessel or ship-based sampling missions and/or *in-situ* monitoring stations. Manned vessel missions are 1) laborious and expensive due to the need for dedicated vessels, sampling equipment, and personnel, 2) are dependent on environmental and weather conditions, and 3) limited in the number of sampling locations attainable on a given day due to physical site characteristics (i.e., water depth) (Figure 2.1). Moreover, the subsequent laboratory analysis of collected water samples are also expensive and labor intensive. As a result, the spatial

and temporal resolution of the sample collection can be extremely low as compared to the spatio-temporal dynamics of the water quality parameters.

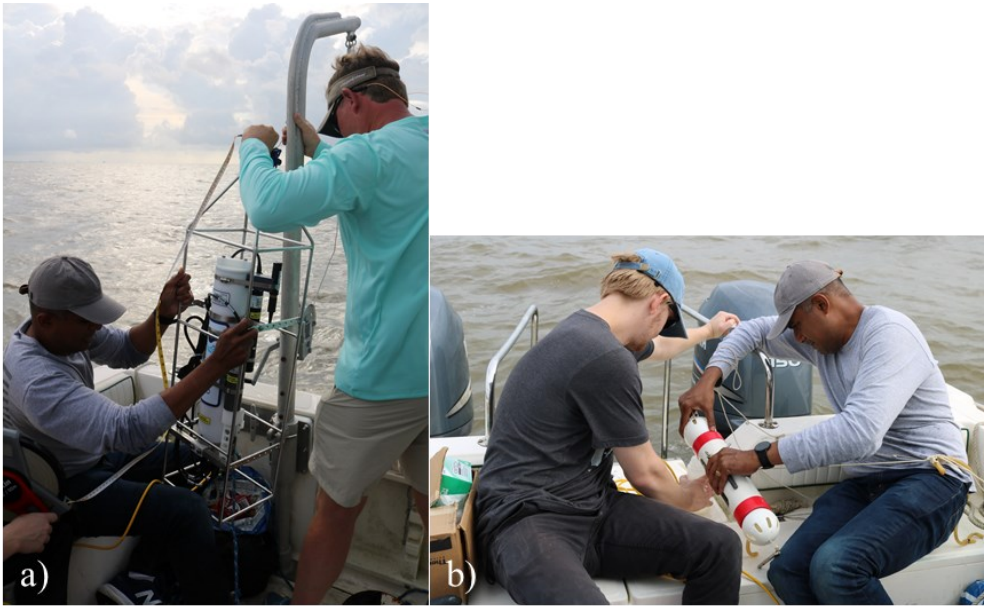

Figure 2.1 Illustration of manned vessel mission data collection activities; a) launch and recovery of CTD sensor and b) deployment of water sampling device.

In-situ monitoring stations (buoys) can provide real-time measurements of water quality with high temporal resolution using telemetry (Figure 2.2). However, significant costs are associated with station equipment and maintenance; therefore, spatial resolution can be limited with fixed stations (Ferri et al., 2011). These conventional monitoring methods may be infeasible for gathering high resolution data (spatial and temporal) needed for development of remote sensing algorithms, hydrodynamic models, and mobile adaptive sampling autonomy (Dunbabin et al., 2009).

Figure 2.2 Illustration of an *in-situ* monitoring station (buoy) (Vu, 2016).

In recent years, advancements in miniaturization of electrical systems/components, commercial availability, and affordability have yielded a plethora of water parameter sensors, sensing systems, and devices. This increase in available hardware, coupled with advancements in unmanned technologies for applications in dynamic aquatic environments, provides a relatively low-cost potential for collecting high spatial or temporal resolution data through continuous monitoring, while reducing operational costs associated with manned vessel logistical constraints (Ferri et al., 2011).

Autonomous surface vehicles (ASVs) are a marine class of unmanned technologies that provide capabilities for performing multi-task missions in varying aquatic (i.e., riverine, estuarine, coastal, etc.) environments. ASVs can be generally characterized by their mobility, cost, and level of autonomy and intelligence (Peng et al., 2021). ASVs are utilized across research, civil, and military applications where their implementation alleviates logistical

constraints while improving the safety of working conditions and expanding operational working windows, especially during adverse environmental and weather conditions (Peng et al., 2021).

For real-time water quality monitoring, ASVs provide a powered platform for water quality sensors, on-board computers, and data management systems because they serve as mobile sampling stations that enhance spatial and temporal data gathering capabilities (Ferri et al., 2011). Their compact design and relative low weight provide enhanced maneuverability and deployment capabilities for ASVs in shallow riverine, estuarine, and coastal areas where larger craft are operationally ineffective (Liu et al., 2016). Additionally, on-board computers for *in-situ* data analysis can increase decision making processes that aid in rapid identification and response to water quality impairments (e.g., harmful algal blooms and increased pollutant loading) and can contribute to further development of adaptive sampling autonomy.

ASV capacity to operate under varying conditional scenarios such as shallow water, hazardous locations, heavy current and sea states, and harsh weather conditions contributes to their usefulness for real-time monitoring. Their ability to conduct large-scale, extended-duration, and unsupervised missions is also advantageous, making solar powered systems desirable for these operations. Various solar powered prototype ASVs for research purposes have been designed and tested (Dunbabin et al., 2009; Karapetyan et al., 2019; Kimball et al., 2015; Specht et al., 2019), but commercially available solar powered ASVs designed to agnostically host sensor and instrumentation payloads for long-duration multi-mission applications are limited (Peng et al., 2021). Valuable solar powered ASV features for real-time water quality monitoring include ease of deployment and recovery, sensor payload capacity, the ability to self-right if capsized, a reliable data transmission/communications backbone for sensor and vehicle data, and an endurance of operation (battery life and management). Utility and performance limitations

may exist for ASVs due to communication reliability, operational power requirements, and navigational accuracy, all of which could negatively affect the accuracy and resolution of water quality data.

Precise and efficient navigational control is a fundamental issue when operating in dynamic aquatic environments and is especially complex for small ASVs. For large vessels, wind, current, and waves may not significantly alter trajectory; however, for smaller vessels such as ASVs, these environmental forces can greatly impact planned path trajectories and introduce spatial errors for *in-situ* sampling missions (Karapetyan et al., 2019). Another factor negatively influencing navigational control can be the payload (i.e., instrumentation, sensors, wiring, enclosures, etc.) hosted on board the ASV. ASV weight is increased by this payload , and hydrodynamic drag force may be introduced/altered/increased by sensors and objects (i.e., external bracketry, structures, sensor enclosures, etc.) that require surface/sub-surface contact with the water while in transit. To achieve efficient piloting, planning, and execution of planned missions, precise and efficient navigational control is critical.

The purpose of this research was to characterize the navigational performance of the commercially available multi-purpose solar powered ASV, SeaTrac SP-48, equipped with an integrated payload package of environmental monitoring sensors. More specifically, the objective of this study was to evaluate the payload laden vessel's ability to accurately and repeatedly maintain established A-B line transects under varying environmental conditions (i.e., wind, current, and waves), where lateral deviation from a planned linear route was measured and expressed as cross-track error (XTE).

2.2 SeaTrac SP-48 Autonomous Surface Vehicle

The SeaTrac SP-48 ASV, designed and manufactured by SeaTrac Systems, Inc., was evaluated in this study (SeaTrac Systems, Inc., Marblehead, MA) (Figure 2.3). The SP-48 is a compact, solar powered, long endurance ASV designed for surface navigation in inland, near shore, and open ocean environments for the purpose of conducting real-time monitoring, data collection, and intelligent reconnaissance surveillance missions. The SP-48's power system, payload capacity, and agnostic sensor design provide capabilities to host or tow a variety of sensors for multi-task/mission operations across a variety of civil, military, and research applications (SeaTrac Systems Inc., 2021). The SP-48 comes standard with a trailer for boat ramp launch and recovery and includes a built-in center lift point for ship or pier launch and recovery.

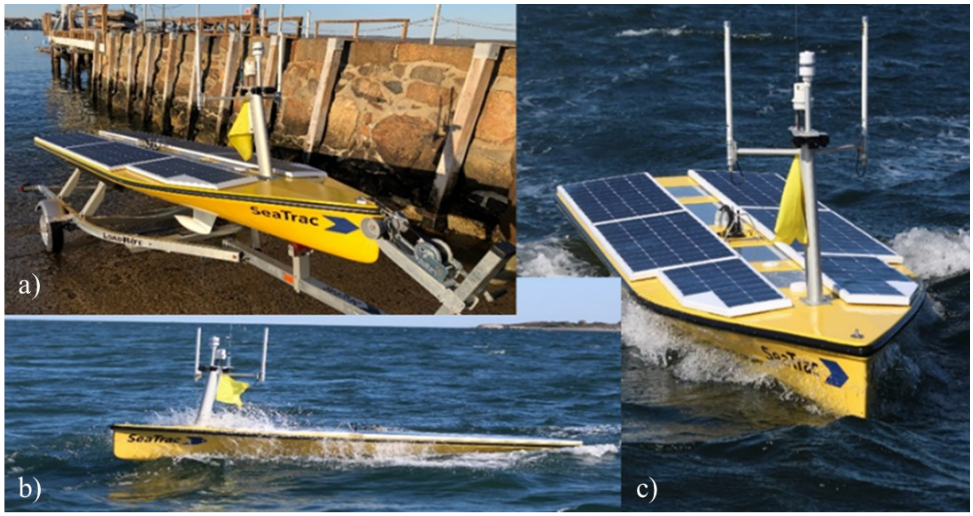

Figure 2.3 Illustration of SeaTrac SP-48 ASV and trailer (SeaTrac Systems Inc., 2021); a) trailered launch, b) port side view, and c) bow view.

2.2.1 Design

The SP-48 features a streamlined low profiled monohull design constructed of foam-cored fiberglass designed to provide physical characteristics capable of withstanding harsh open ocean conditions (Figure 2.4). The SP-48's ocean condition functionality is characterized as being operational in sea state conditions up to Beaufort Level 7 and survivable in conditions up to Beaufort Level 11 (Barua, 2005). The SP-48 is 4.8 m long, 1.39 m wide, and weighs approximately 250 kg (excluding additional payloads), with an additional payload weight capacity of approximately 70 kg. The SP-48's approximate freeboard and draft is 0.21 m and 0.42 m, respectively, which contributes to maneuverability and operation in shallow water conditions. A 22.9 cm diameter through-hull space moonpool serves as an external payload bay for the vessel and is strategically located center mass relative to the vehicle and provides stability for customized installations of sensors and/or deployment of profiling sensors and instrumentation. An internal, watertight payload bay provides space for sensors and instrumentation. Sealed, detachable aluminum hatch plates provide access to internal systems such as electronics, batteries, payloads, propulsion, and steering components. A strategically positioned weighted bulb keel contributes to stability and improve maneuvering via the stern rudder control and provides self-righting functionality if the vessel becomes capsized in high sea state conditions. A securely affixed anodized aluminum mast provides an elevated location for mounting antennas, sensors, cameras, and other associated hardware. Additionally, the hollow mast and sealed through-hull connection provides an integrated waterproof means of routing antenna and component wiring to electronics housed in the internal payload bay.

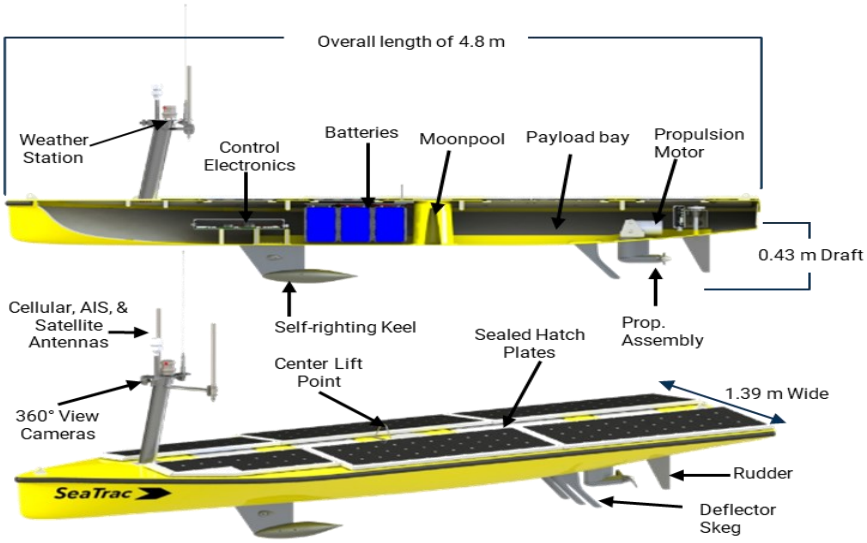

Figure 2.4 Illustration of SP-48 physical characteristics and dimensions (SeaTrac Systems Inc., 2021).

2.2.2 Propulsion

Propulsion is achieved via a 1000 W direct current brushless motor driving a single two-blade 25.4 cm diameter weedless propeller, designed to reduce the thrust necessary to cut through aquatic vegetation, thus preventing prop fouling. A knife-style deflector skeg array positioned afore the propeller safeguards both the propulsion assembly and rudder from underwater obstacles. The propulsion system provides a maximum speed of 5 knots with typical cruising speed at 3-3.5 knots. Steering control is provided through rudder deflection as the vessel moves across the water surface. Rotation of the aft located rudder is actuated by a second, position-referenced DC motor. The rudder can rotate 45° in either direction of center and variably adjusts direction based on controller feedback. Steering control responsiveness is proportional to vessel velocity and rudder angle, controlled via an embedded PID algorithm in the control system.

2.2.3 Power

ASV power is stored and supplied through twelve lithium-ion battery cells that provide up to 1000 W of continuous power with 6.75kWh capability, enabling long endurance operation through varying weather conditions. The cells are assembled into three packs of four cells each providing approximately 3.6 V per cell. Each pack is equipped with a charging/usage status board, providing active power balancing to redistribute energy from cells in each pack with a full charge to cells with a lower state of charge (SOC) to maintain balance between each. A microprocessor facilitates power balancing, cycling every five seconds to acquire cell status of voltage and temperature for each cell. The batteries are charged using six solar panels providing a maximum total of 750 W with 1 kW/m3 irradiance. The solar panels are securely affixed to the vessel deck and are independently wired. Additionally, a power distribution board provides blocks of 12, 24, and 36 V for sensors, instrumentations, and on-board computing and communications, as well as providing 36 V for the propulsion system motors. A visual output of the SOC and power management system is available to the ASV operator/pilot via the interface Dashboard software package used for SP-48 operation and control.

2.2.4 Sensor Package

The SP-48 comes standard with a built-in environmental and navigational sensor package including an anemometer, air temperature and pressure, and water temperature. Navigational system sensors provide the vessel's speed through the water, compass heading, GPS location, and speed and direction over ground. To provide critical awareness of leaks and/or condensation, an onboard humidity sensor is located in the internal watertight payload bay. Standard sensor data is logged to the onboard computer and transmitted to a cloud-based server. Data is

accessible for download and can be viewed on the user interface (via Dashboard software) in real-time.

2.2.5 Communications

The SP-48 is equipped with multiple means of communication links including LOS radio, cellular connection, and satellite uplink, enabling near-shore and beyond LOS operations supporting various mission requirements. The onboard communication board hosts an Automatic Identification System (AIS) Class B transceiver, a 3G cellular module with 2G drop-back capability, a satellite transceiver module, and a 900 MHz RF module; each is connected to an onboard LAN through a cellular router. Dual antennas for cellular transmission are located on the mast at the bow of the vessel. A very high frequency range (VHF) marine antenna is used for the AIS system. The LOS RF antenna is mounted inside the sealed hull compartment near the bow. The mast also houses the running lights, weather station, and the camera system.

2.2.6 Control and Autonomy

The SP-48 provides 3 modes of pilot control described as manual, supervised autonomy, and full autonomy. Manual mode is direct piloting via handheld remote in which an operator is making LOS navigation and maneuvering decisions. Manual control is used for maneuvering in launch and recovery operations, confined areas, or locations with little to no cell service when working alongside the ASV from a crewed vessel or dock/pier. In supervised autonomy mode, the SP-48 pilot uploads a mission to the on-board computer and the ASV operates independent of the pilot; however, the pilot is still supervising ASV performance and can override on-board ASV mission parameters if needed. In full autonomy mode the ASV autonomously executes pre-

programmed mission's over-the-horizon making decisions on its own (SeaTrac Systems Inc., 2021).

In supervised and full autonomy modes, missions consist of a series of waypoints that the ASV will traverse while collecting environmental and water quality data and recording navigational data. Pre-determined parameters can be pre-programmed into a mission such that the ASV will perform pre-determined tasks at specific waypoints (i.e., loiter time to collect data). When the ASV has satisfied pre-established waypoint conditions, it proceeds to the next waypoint along an A-B line transect. While traveling between waypoints along a transect, the navigation system will correct for external forces (wind, current, waves, etc.) that can alter ASV trajectory, so that the vessel stays in an acceptable range from the established track between waypoints. Lateral deviation from this pre-determined track is described as cross track error (XTE).

2.2.7 Dashboard Software Suite

The provided interfacing software, referred to as Dashboard, runs on a computer external to the ASV and provides remote wireless access to the boat's control and mission parameters as well as to sensor and instrumentation parameters (Figure 2.5). The Dashboard interface is also used for configuring and executing missions and provides chart-based and satellite imagery to visualize the ASV's path in real-time. Dashboard provides display and control of system parameters and settings, telemetry control, mission playback, and power management. A remote bridge provides a live link from the Dashboard to the vessel's control and data management systems to retrieve performance data and to send operational commands, allowing access to the ASV's real-time status and parameters including GPS position coordinates, heading, speed, and prop RPM, power production and usage, and battery SOC (SeaTrac Systems Inc., 2021). Telemetry link parameters

of the RF, cellular, and satellite communication systems are also displayed as link state (on/off), signal strength, and transmission and reception speed.

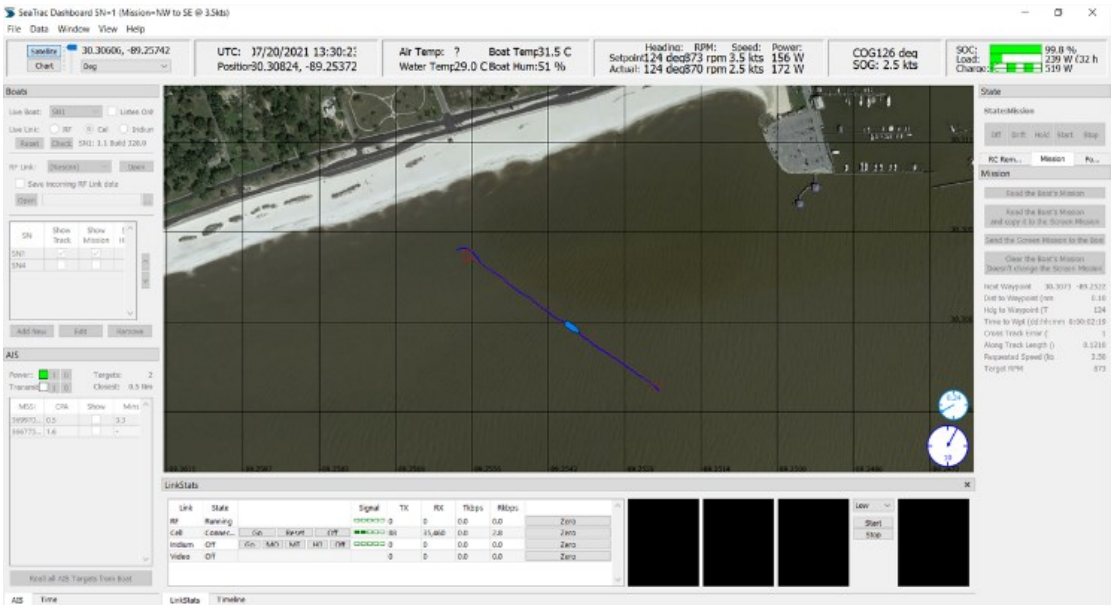

Figure 2.5 Illustration of the Dashboard software interface.

In addition to the SP-48, other vessels equipped with AIS transponders appear on the Dashboard, assisting with course planning and management and collision avoidance. The ASV control, mission, and built-in sensor data can be saved to the on-board database and/or transmitted via cell or satellite link to a cloud-based server (SeaTrac Systems Inc., 2021). SP-48 operators also have control over what data is saved and at what frequency. Previous missions and paths can be reviewed in the Dashboard through the historical data review timeline feature. Mission data is retrievable from the cloud-based server and can be downloaded in CSV format.

2.2.8 Surveillance

The vessel is also equipped with a ruggedized outdoor mobile surveillance camera system to aid in obstacle detection and safe navigation, especially in remote or limited-visibility

situations, and serves to deter and/or identify potential vandals. Four AXIS F1005-E cameras are utilized and affixed to the elevated mast at the 0° (bow), 90° (starboard), 180° (stern), and 270° (port) positions (Figure 2.6a). Each camera has a 113° horizontal field of view, providing a 360° view of the vessel and its surroundings when combined (Figure 2.6b). The cameras are routed through an AXIS F44 input unit, enabling 1080p video streaming and Wide Dynamic Range (WDR) forensic capture from the four cameras simultaneously. Designed for constant surveillance, this system provides the ability to record the camera data stream and can also be live viewed simultaneously through the Dashboard.

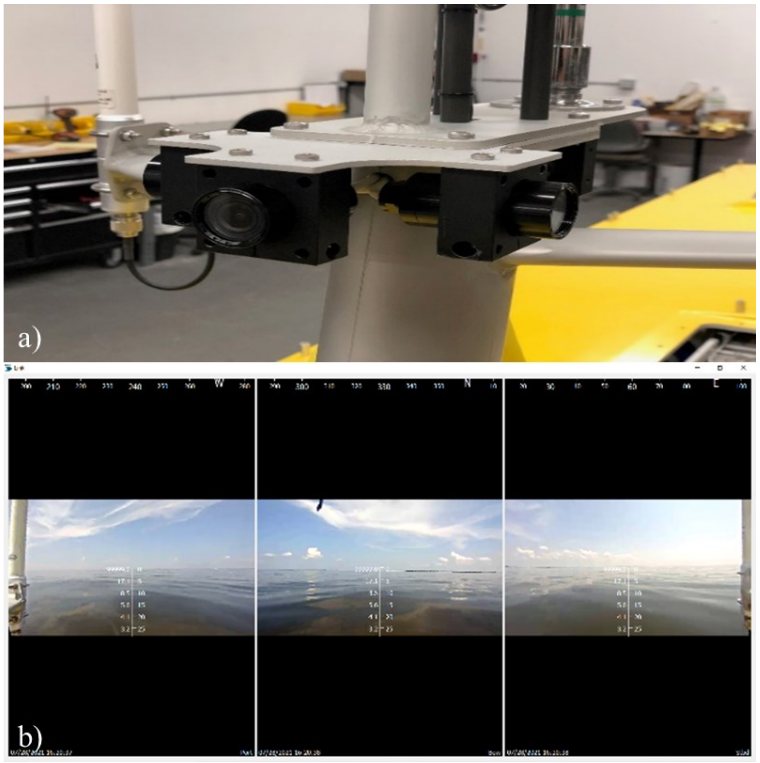

Figure 2.6 Illustration of the Axis F1005-E multi-camera video surveillance system; a) affixed to the SP-48 antenna mast and b) 360° view as displayed via Dashboard.

2.2.9 Integrated Payload Sensors

In addition to the standard onboard sensor package, the SP-48 sensor-agnostic platform supports a variety of payloads and a great range of sensor power consumption scenarios (SeaTrac Systems Inc., 2021). The SP-48 evaluated in this study hosts an integrated package of environmental monitoring sensors (Table 1). The payload sensor mounting components and fixtures were strategically designed to reduce weight and minimize hydrodynamic drag.

Table 2.1 Environmental sensors payload package hosted by the ASV platform.

Manufacturer	Sensor	Parameter	Sampling Method	Sampling Frequency (s)	Factory Accuracy
Sea-Bird Scientific	SBE 63	Dissolved Oxygen	Optical luminescence	1	Larger of ±3 µmol/kg or ±2%
	Eco Triplet 1	Chlorophyll a	Optical fluorescence	1	0.025 µg/L
		Phycocyanin	Optical fluorescence		0.09 ppb
		Phycoerythrin	Optical fluorescence		
	Eco Triplet 2	Backscattering	Optical scattering (470nm, 532nm, & 650nm)	1	0.003 m^{-1}
	Eco Triplet 3	Colored dissolved oxygen matter (CDOM)	Optical fluorescence	1	0.28 ppb
		Turbidity	Optical scattering (595nm & 700nm)		0.02 NTU
AML Oceanographic	Idronaut pH Sensor	pH	Blue glass membrane electrode	3	±0.01 [pH]
	CT Xchange	Conductivity	Resistance	0.04	±0.01 mS/cm [Conductivity]
		Temperature	Resistance		±0.005 °C
Pro-Oceanus System Inc.	CO_2 Pro CV	Carbon dioxide	Non-dispersive infrared (NDIR)	1	±5%

2.2.9.1 Moonpool Sensors

Located and affixed within the moonpool of the vessel with sensor faces mounted flush to the vessel bottom (Figure 2.7) are three Eco Triplets and a SBE 63 dissolved oxygen (DO) sensor

from Sea-Bird Scientific Inc. (Bellevue, WA) and a partial pressure of carbon dioxide (pCO2) sensor from Pro-Oceanus System, (Bridgewater, Nova Scotia, Canada). These sensors measure dissolved oxygen, chlorophyll a, phycocyanin, phycoerythrin, backscattering, colored dissolved oxygen matter (CDOM), turbidity, and carbon dioxide measurements in real time as the vessel traverses its path.

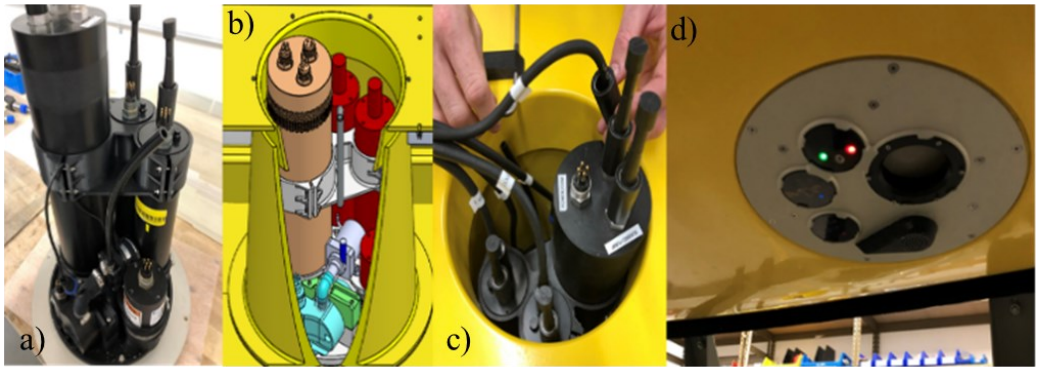

Figure 2.7 Illustration of integrated sensor suite (3 SeaBird Eco Triplets, a Pro Oceanus CO_2 Sensor, and a SeaBird SBE 63 (+Pump)); a) sensor suite configuration, b) cut away view of installed sensor suite, c) top view of installed sensor suite, and d) bottom view of installed sensor suite.

2.2.9.2 AML Sensors

An Idronaut pH sensor and a CT Xchange sensor, both from AML Oceanographic (Dartmouth, Canada), are located under the vessel housed in a hard-plastic sensor-fairing (Figure 2.8). These sensors measure levels of conductivity, temperature, and pH in the surrounding water. In total, the additional weight of the sensor payload (instruments, fixture components, wiring, enclosures, etc.) is approximately 15.4 kg.

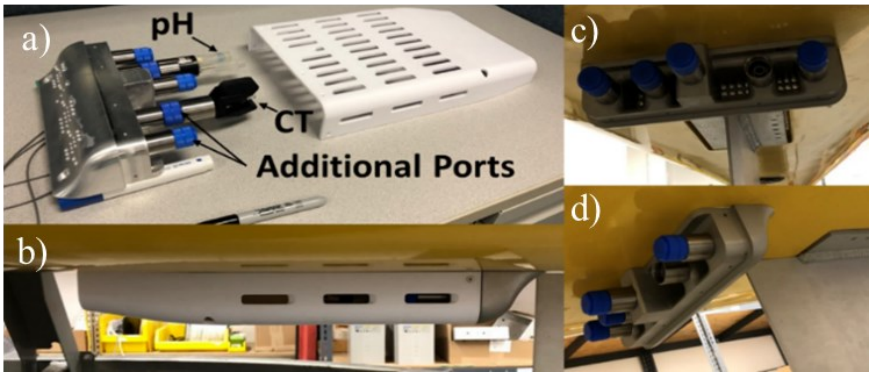

Figure 2.8 Installation of hydrodynamic sensor-fairing and bottom hull mounting location of AML CT and pH sensors; a) uninstalled sensor housing, sensors, and faring, and b) installed starboard view, and c) & d) bottom view of installed sensor housing.

2.3 Site Characteristics

To comprehensively evaluate the SP-48's ability to accurately and repeatedly maintain established A-B line transects under varying environmental conditions that could potentially alter ASV trajectory, three testing scenarios were considered based on operational conditions. Scenario 1 was calm/static conditions in an inland reservoir with no to minimal wind, water current, or waves present (Figure 2.9a). Scenario 2 was a riverine environment lacking wind and wave activity but having water current capable of altering ASV trajectory (Figure 2.9b). Scenario 3 was a near shore coastal environment with wind and waves but lacking major tidal current (Figure 2.9c). Depth in each Scenario was sufficient such that underwater obstacles were not a factor for ASV maneuverability and/or navigation.

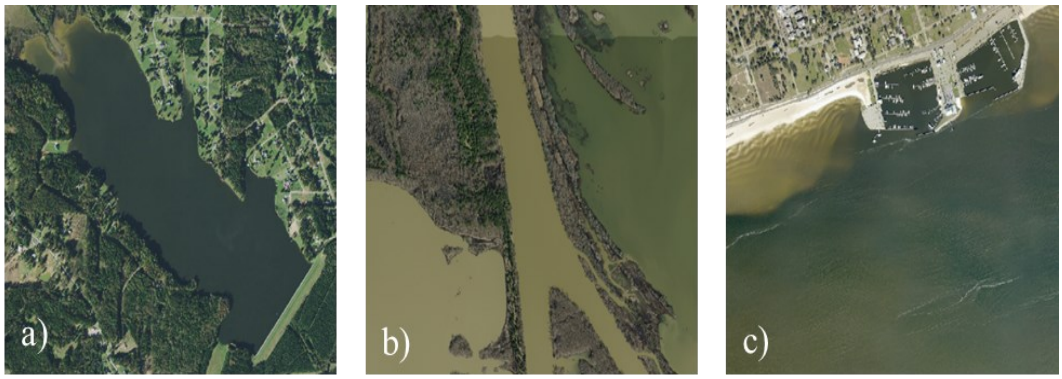

Figure 2.9 Aerial photos of site locations; a) White's Creek Lake, b) Tombigbee River, c) Mississippi Gulf Coast.

Three sites were strategically selected to meet Scenario conditions (Table 2.2) (Figure 2.9). Scenario 1 testing was conducted on May 20, 2021 at White's Creek Lake, a 113.3 ha reservoir located near Eupora, MS. No current was present on the day of testing and winds were light, averaging 4.35 knots from the SSW direction (Table 2.2). Scenario 2 testing was conducted on May 13, 2021 on a section of the navigational channel of the Tombigbee River Waterway located in Columbus, MS. Mean velocity of surface water current was 0.26 m/s and mean wind speed was 4.86 knots from the NNE direction (Table 2.2). Scenario 3 testing was conducted on June 1, 2021 on the Mississippi Gulf Coast (Mississippi Sound) adjacent to the Pass Christian Harbor near Pass Christian, MS. Mean wind speed was 10.34 knots from the ESE direction; wave height was 0.63 m from the ESE direction with a frequency of 3.61 sec (Table 2.2). The Gulf of Mexico is a microtidal system and the Mississippi Sound is protected by a series of barrier islands that limit water exchange between the shore and the Gulf such that water currents along the MS Gulf Coast are minimal; thus, water current along the coast was negligible. These conditions can be described as a Level 3 sea state on the Beaufort scale (Barua, 2005).

Table 2.2 Environmental Conditions of treatment locations.

Scenario	Site	GPS Coordinates *(Lat, Long)*	Wind *(Speed/Direction)*	Current *(m/s)*	Wave Measurements *(Mean Height/Period)*	Sea State *(Beaufort scale)*
1	White's Creek Lake	33.55524, -89.27731	~4.35 knots SSW	n/a	n/a	Level 1
2	Tombigbee River	33.51313, -89.49269	~4.86 knots NNE	0.26	n/a	Level 1
3	Mississippi Gulf Coast	30.30834, -89.25385	~10.34 knots ESE	n/a	.63 m 3.61 s	Level 3

2.4 Sampling Methodology

Testing procedures were designed in accordance with the ASABE/ISO standard 12188-2 (ASABE/ISO, 2019) for testing of satellite-based auto-guidance systems during straight line travel, where cross track error (XTE) is defined as the ASV's lateral distance deviation off the planned path (ASABE/ISO, 2019). To evaluate XTE for each treatment (Scenario vs. Direction), four 400 m A-B line transects (i.e., travel routes) were programmed as waypoint-to-waypoint missions within the ASV Dashboard interface, for a total of 4 missions per Scenario. The 400 m mission length was selected due to distance confinements associated with the Scenario 1 and 2 locations (inland lake and river). Each mission represented an A-B line travel route with different cardinal directions of travel: 1) NE to SW, 2) NW to SE, 3) SE to NW, and 4) SW to NE. Missions (Scenario X Direction) were repeated three times and were executed in supervised autonomy mode at 3.5 knots, considered to be a normal cruising speed for the ASV and an adequate sampling speed for the installed water quality sensor package. For each mission, the coordinates of the planned route (A-B line segment) and the ASV's actual route traveled were recorded from the SP-48 global navigation satellite system (GNSS) receiver, saved to a database in the ASV's onboard computer, and transmitted to a cloud server for future download. Routes

were recorded in Zone 16 North Universal Transverse Mercator (UTM) Cartesian coordinates and used to calculate XTE (in meters) between the planned and traveled routes. Because initial navigation along a route was affected by human navigation/positioning of the ASV to a location near the start-point of each route, the first 50 m of each route was considered a normalization zone for the ASV to navigate to its planned route; thus, this 50 m zone was removed from the dataset to reduce error in XTE attributed to human induced error (Figure 2.10).

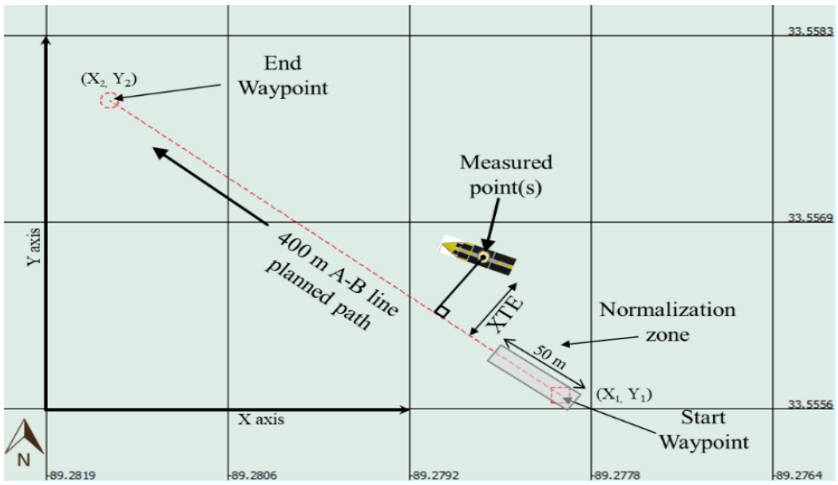

Figure 2.10 Figure showing conceptualized sampling transect and associated normalization zone.

2.5 Statistical Analysis

A two-way analysis of variance (ANOVA) was used to analyze differences in mean XTE among treatments using Direction and Scenario as fixed effects (R Core Team, 2021). Scenario ($p<0.0001$), Direction ($p<0.0001$), and the interaction of the two ($p<0.0001$) affected mean XTE; therefore, mean XTE of the interaction term (Scenario X Direction) was analyzed using a Tukey's post-hoc test to further separate differences in mean XTE. Additionally, controllability is a challenge for rudder steered vessels at low velocities as the effectiveness of rudder steering is

proportional to the vessel's velocity (Dunbabin & Grinham, 2010). Differences in mean XTE as a response to vehicle velocity (2, 3.5, and 5 knots) were also analyzed via ANOVA for Scenario 3 (R Core Team, 2021).

2.6 Results

2.6.1 Scenario 1: Calm/Static Conditions

In Scenario 1, mean XTE was 0.95 m and there was no difference in Direction ($p<0.0001$) (Table 2.3), suggesting that XTE is not affected by heading in calm/static environmental conditions. XTE values ranged from <0.50 to 3.67 m, the highest occurrence of XTE values were observed in the range 0.50-1.00 m, and 95% of the XTE values were less than 2.30 m (Figure 2.11).

Table 2.3 Mean XTE for each Scenario X Direction treatment; numbers in parentheses are SD, cells sharing the same superscript letter are not different at the alpha = 0.05 significance level (n=3) according to Tukey's post-hoc test.

Scenario	NE to SW	NW to SE	SE to NW	SW to NE
1	0.94 (0.68)^{C}	0.76 (0.56)^{C}	0.88 (0.62)^{C}	1.21 (0.62)^{C}
2	1.97 (1.16)^{AB}	0.82 (0.59)^{C}	2.39 (1.13)^{A}	0.64 (0.47)^{C}
3	1.06 (0.72)^{C}	1.26 (0.88)^{BC}	2.35 (1.39)^{A}	2.24 (1.27)^{A}

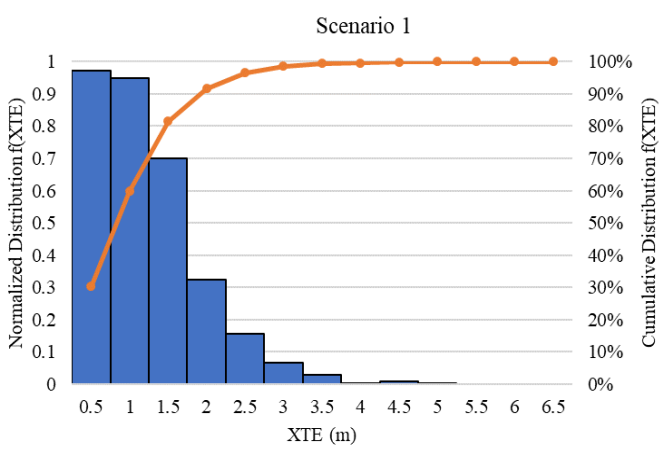

Figure 2.11 Histogram and cumulative distribution of XTE for similar transects; Scenario 1.

2.6.2 Scenario 2: Water Current

In Scenario 2, external environmental force (i.e., water current) was acting in a N to S direction while ASV routes were quartering into and away from water current on each side of the vessel (i.e., 4 travel routes). Mean XTE of transects ending on the western side of the water current (Westerly; SE to NW and NE to SW) were not different from each other. Similarly, mean XTE of transects ending on the eastern side of the water current (Easterly; NW to SE and SW to NE) were not different from each other. However, mean XTE of transects ending on the eastern side of the current (0.73 m) were 33.5% of the mean XTE of transects ending on the western side of the current (2.18 m; $p<0.0001$) (Table 2.3). This suggests that the environmental force of current acting on the starboard side of the ASV had a greater effect on mean XTE than forces acting on the port side of the vessel. The Easterly travel XTE data ranged from <0.50 to 3.00 m, the highest occurrence of XTE values were observed between <0.50-1.00 m, and 95% of the Easterly travel XTE was not greater than 2.00 m (Figure 2.12a). The Westerly travel XTE ranged from <0.50 to 5.50 m, the highest occurrence of XTE values in the Westerly travel routes occurred at the 3.00 m range, and 95% of the XTE values did not exceed 4.25 m (Figure 2.12b).

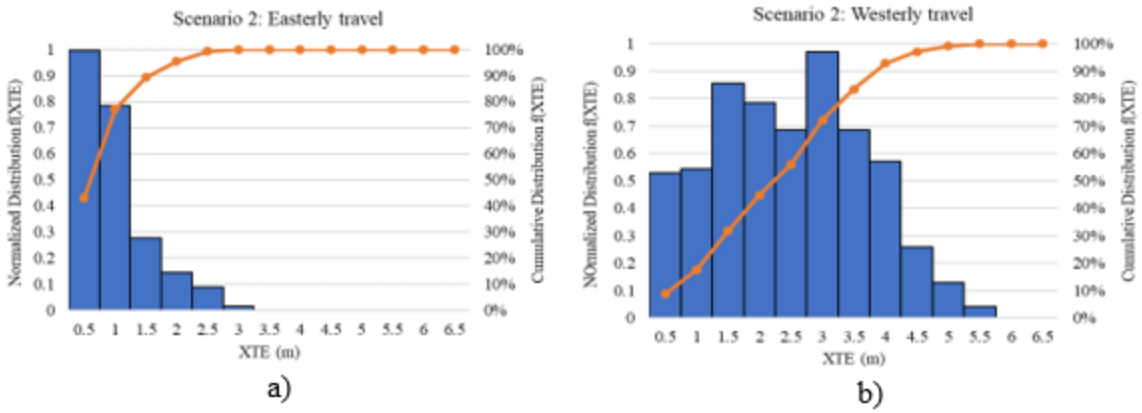

Figure 2.12 Histograms and cumulative distributions of XTE for similar transects; a) Scenario 2 - Easterly travel and b) Scenario 2 - Westerly travel.

2.6.3 Scenario 3: Wind and Waves

Environmental forces (i.e., wind and waves) were acting in a southeast direction while ASV routes were plotted parallel (bow and stern) and perpendicular (port and starboard) to these forces. Mean XTE of transects parallel to wind and waves (NW to SE [bow] and SE to NW [stern]) were different ($p<0.0001$), with forces acting on the bow of the vessel (NW to SE) having 53.6% less effect on mean XTE (1.26 m) than those acting the stern of the vessel (2.35 m; SE to NW) (Table 2.3). This suggests that forces acting in conjunction with the direction of propulsion have greater effect on mean XTE than those opposing the direction of propulsion. Mean XTE of transects perpendicular to environmental forces (SW to NE [starboard] and NE to SW [port]) were also different from one another ($p<0.0001$) (Table 2.3). Wind and waves acting on the starboard side of the vessel (SW to NE) yielded a greater mean XTE (2.24 m) than those acting on the port side (1.06 m; NE to SW) which is similar to results from Scenario 2. The Northerly travel XTE ranged from <0.50 to 5.00 m, the highest occurrence of XTE values ranged from <0.50 to 1.50 m, and 95% of the XTE was not greater than 2.75 m (Figure 2.13a). XTE for

Southerly travel ranged from <0.50 to 6.50 m, the highest occurrence of XTE values were observed at the 2.50 m range, and 95% of XTE values did not exceed 4.80 m (Figure 2.13b).

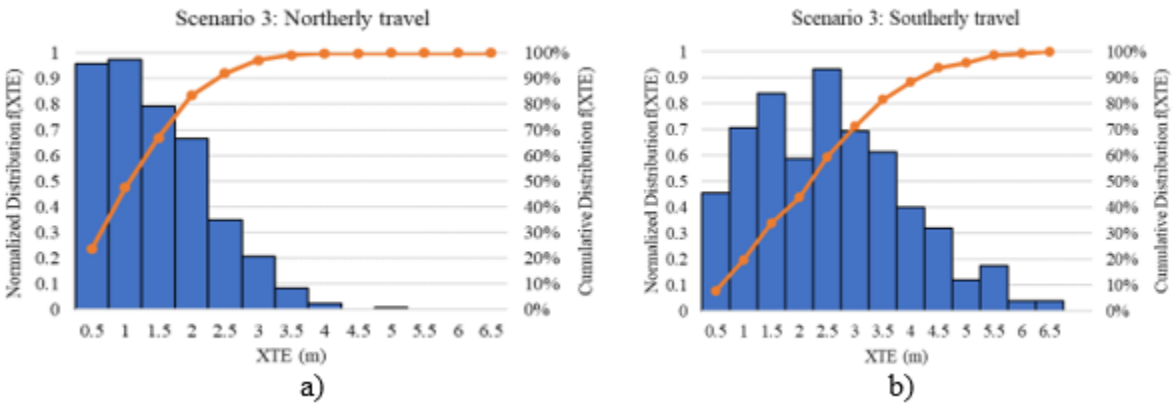

Figure 2.13 Histograms and cumulative distributions of XTE for similar transects; a) Scenario 3 - Northerly travel and b) Scenario 3 - Southerly travel.

2.6.3.1 Scenario 3: Vessel Velocity

Mean XTE at 3.5 and 5 knots. (1.73 m) was 57.6% lower than mean XTE at 2 knots. (3.0 m; $p<0.0001$). This suggests that lower speeds derived from internal propulsion provides less vessel control than the control achieved at increased speeds.

2.7 Discussion

Other studies have evaluated navigational accuracies of prototypical ASVs for navigated sounding profile routes and area coverage techniques for environmental monitoring where directional heading is changed, but the literature is depauperate regarding testing of straight-line tracking performance of commercially available ASVs under varying environmental condition scenarios (Dunbabin & Grinham, 2010; Karapetyan et al., 2019; Kimball et al., 2015; Peng et al., 2021; Specht et al., 2019). In this study, the ASVs ability to accurately and repeatedly maintain

established A-B line transects under varying environmental conditions was evaluated, where deviation from a planned linear route was measured and expressed as XTE. When environmental stressors are low, as in Scenario 1 (calm/static conditions), maintained accuracy was high and XTE was not significantly affected by heading/direction. In the riverine Scenario 2 where a slight current was present (0.26 m/s), statistical differences were found for XTE dependent upon heading/direction in relation to the water current's direction, where mean XTE for similar transects ending on the east side of the current and similar transects ending on the west side of the current were 0.73 and 2.18 m, respectively (Figure 2.14). For Easterly routes with current forces acting on the port side of the ASV, the repeated routes aligned well and mean XTE decreased, minimizing observable differences between the planned travel route and actual travel route (Figure 2.14a). For the Westerly routes with current forces acting on the starboard side of the ASV, an observable difference was present in alignment of the repeated routes with respect to the planned routes and mean XTE increased (Figure 2.14b).

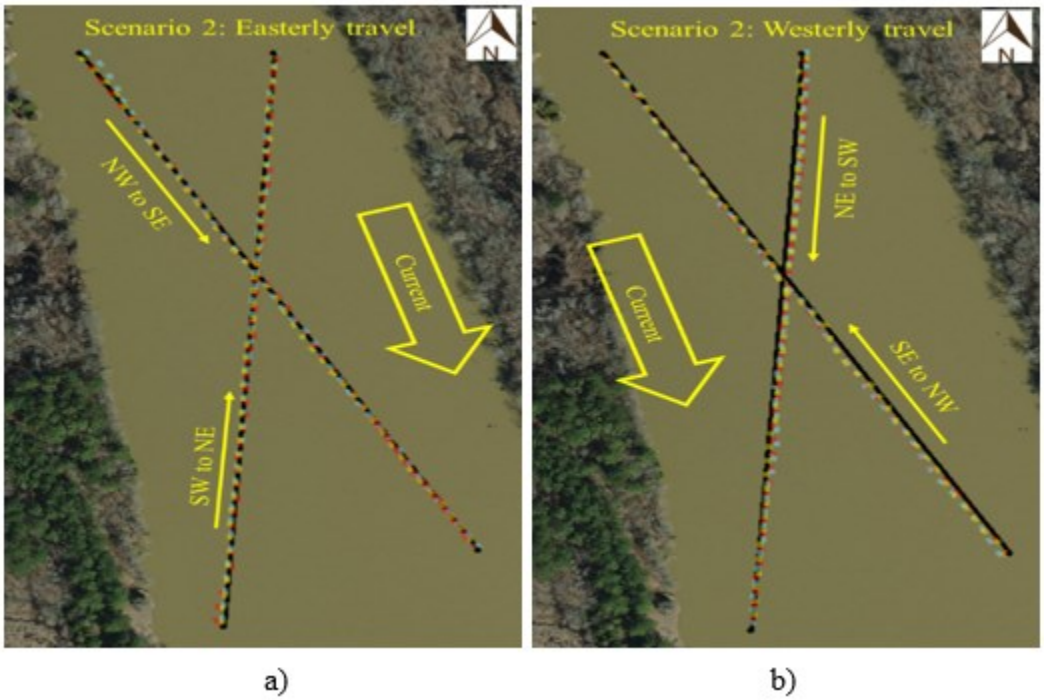

Figure 2.14 Riverine Scenario 2 measured trajectories on May 13, 2021; a) Easterly travel routes (SW to NE; NW to SE) and b) Westerly travel routes (NE to SW; SE to NW); solid black lines are planned A-B transects and dotted lines are actual routes traveled by the ASV.

In the coastal Scenario 3, substantial wind and waves (Beaufort scale Level 3) were present from the southeast direction (Figure 2.15). In the NW to SE transect, where wind and wave forces acted upon the ASV bow, mean XTE (1.26 m) was reduced (Figure 2.15a) and was likely attributable to an autopilot increase in ASV propulsion (RPM) to maintain vessel speed by providing additional thrust to overcome the environmental forces acting upon the bow and increased rudder deflection steering control of the vessel. Alternatively, in the SE to NW transect (Figure 2.15b) where environmental forces were acting on the stern of the vessel, mean XTE (2.35 m) was 86% greater than when forces acted upon the bow of the ASV. In this case, the wind and wave forces acting upon the stern have the potential to contribute to an increased vessel velocity, causing the autopilot to reduce propulsion RPMs to maintain the targeted speed,

resulting in a dampening effect for the steering control due to the manner in which the propeller thrust/rudder deflection steering system operates.

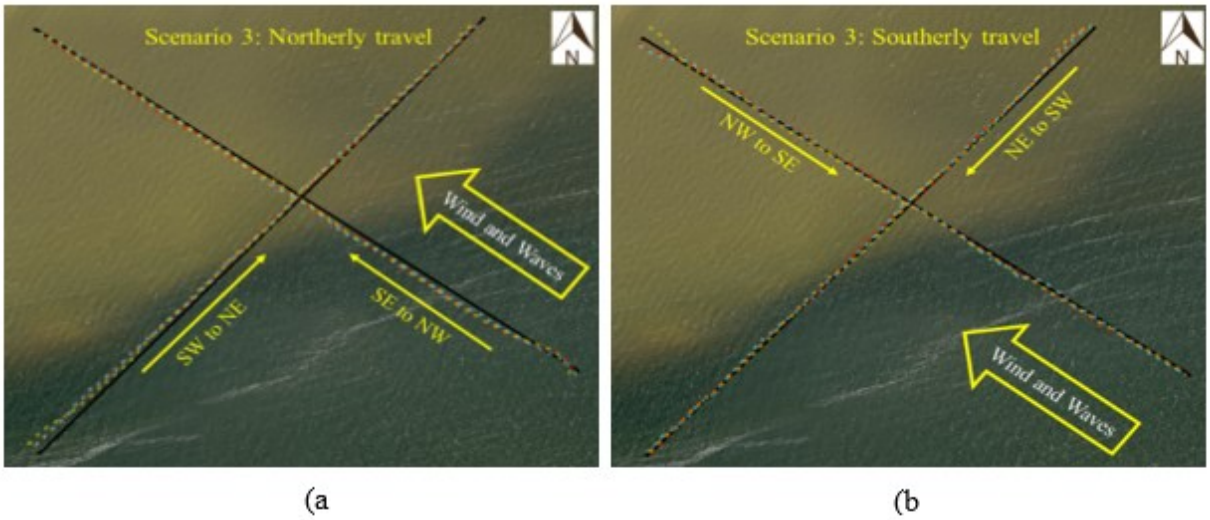

Figure 2.15 Coastal Scenario 3 measured trajectories on June 1, 2021; a) Northerly travel routes (SE to NW and SW to NE) and b) Southerly travel routes (NE to SW and NW to SE); solid black lines are programmed A-B transects and dotted lines are actual routes traveled by the ASV.

In summary, when the vessel's heading was traveling into (opposing) the direction of forces that could alter trajectory, autopilot heading control was observed to be easier to maintain. Alternatively, when the vessel's heading coincided with the direction of environmental forces causing them to act upon the stern of the vessel, autopilot controllability became more uncertain and mean XTE increased. This concept was further supported by lower XTE at higher velocities (3.5 and 5 knots) versus the higher XTE produced at a lower ASV velocity (2 knots). Commensurate with Scenario 2 results, wind and wave forces acting upon the starboard side of the vessel (SW to NE) (Figure 2.15a) affected XTE to a greater degree than the same forces acting upon the port side (NE to SW) (Figure 2.15b). It is unclear why forces acting on the starboard side of the vehicle had greater effect on XTE, but this pattern was clearly repeated

among Scenario's 2 and 3 and was also visually observable in the GPS data logs for each Location (Figures 2.14 and 2.15). Possible causes of the difference in XTE for environmental forces acting on opposite sides of the vessel may be attributed to potential inconsistent position accuracy in the GNSS system/receiver, directional differences in autopilot dynamic steering control algorithms, ASV hull hydrodynamic characteristics, imbalanced weight distribution of the payload and/or internal hardware, imbalanced hydrodynamic drag of the payload (sensor fixtures/enclosures) causing steering control discrepancies, or differences in rudder steering control responsiveness by turn direction.

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CHAPTER III

SUMMARY

3.1 Overall Conclusions

This study demonstrates the capability of the SeaTrac SP-48, a commercially available ASV equipped with a multi-sensor payload to operate autonomously with a high degree of navigational accuracy, to maintain repeatable straight line transects under varying environmental conditions (wind, current, and waves). Across all scenarios of environmental conditions, where straight line autopilot XTE was measured, mean XTE did not exceed 2.39 m. It should be noted that the ASV manufacturer stated autopilot XTE for the SP-48 ASV is ±5 m, with the vessel rarely exceeding this mark throughout the tested scenarios (maximum recorded XTE was 6.5 m). However, this deviation is well within the spatial accuracy needed for sampling large basin surface waters.

Precise and efficient travel is critical to efficient planning, piloting, and execution of ASV missions for real-time water quality monitoring. These findings support the use of ASVs to compliment conventional water quality monitoring tasks and overcome the spatial and temporal challenges associated with manned vessel sampling missions and *in-situ* monitoring stations. This evaluation also provides a conceptual framework for the development of spatial and temporal resolution constraints for ASVs in real-time monitoring goals such as water quality monitoring and assessment, conducting bathymetric surveys, and in surveillance or other missions where spatial and/or temporal data are important to the overall success. Lastly, these

data provide a navigational performance baseline for future development of remote sensing algorithms, hydrodynamic models, obstacle avoidance technology, and adaptive sampling autonomy. Future investigation should evaluate XTE response to environmental forces during autonomous station-keep operations, coverage/grid pattern maneuverability, and long distance/endurance missions.

3.2 Future Work

Unlike UGVs or UAVs, the ability to maintain or hold a georeferenced position with a high degree of accuracy is particularly challenging for rudder-steered ASVs due to the forward momentum needed to perform maneuvers steering and external environmental forces (wind, waves, and current) that may cause it to drift from its location. Therefore, future research is needed to evaluate the ASV's ability to hold its position or "station keep" at an assigned location for the purpose of mooring and/or fixed position sampling. The SP-48 dashboard hosts the ability to establish "hold position" waypoints. These hold position waypoints consist of programmable parameters including delay time, circle radii (inner and outer), and vessel speed settings. Delay time establishes how long the ASV will stay at the "hold position" waypoint before moving to the next waypoint, and time range can be set for as little as a few seconds to multiple hours. An inside and outside radius is established around the "hold position" waypoint; These radii can be set as zone boundaries for mooring or *in-situ* sampling at certain locations. Hold position operation is such that when the vessel is positioned inside of the inner zone radius parameter, it is in drift mode and no propulsion/steering is engaged. When the ASV drifts past the outside radius, it will autonomously maneuver back towards the set waypoint. Once the vessel has reached the inside radius boundary, it will transition back into to drift mode. The speed setting controls the ASV's speed when maneuvering back to the set waypoint. This process is iterative,

and precise positioning in relation to a way point varies depending on vessel speed, zone resolution, and environmental forces that may alter ASV trajectory (Figure 3.1). In a calm condition scenario, absent of wind waves and current, the vessel would remain inside the inner zone and near the target waypoint for an extended time-period before eventually drifting off target. In a wavy, windy, or current scenario, the vessel should constantly drift out of the established radii zone and away from the target waypoint. A performance evaluation of the SP-48's ability to "hold position" under varying environmental scenarios of wind, waves, and current is necessary to establish baseline performance and expected resolution of the system for *in-situ* sampling and monitoring schemes.

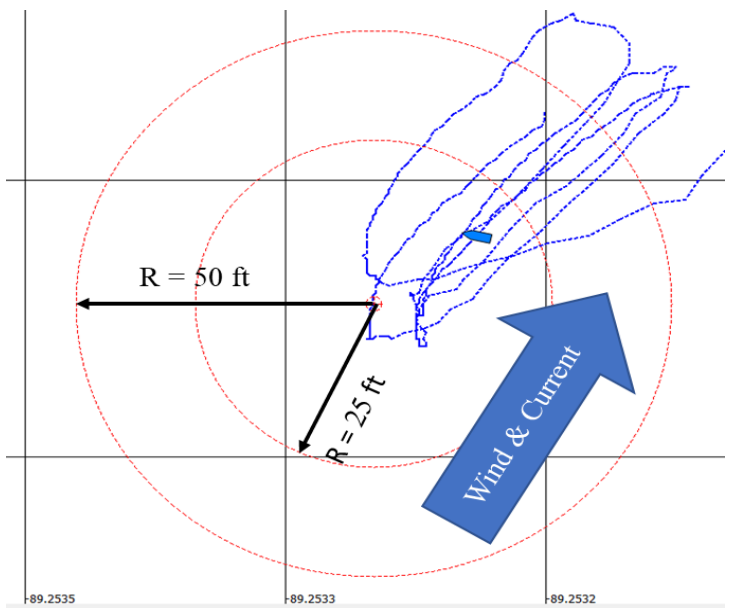

Figure 3.1 Dashboard track of the SP-48 "hold position" test mission conducted at the Mississippi Gulf Coast, near Pass Christian, MS.