Evaluation of Unmanned Surface Vessel (USV) Technology for Bathymetric Surveying of Inland Environments

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UNIVERSITY OF NORTH CAROLINA CHARLOTTE

RESEARCH & DEVELOPMENT

Evaluation of Unmanned Surface Vessel (USV) Technology for Bathymetric Surveying of Inland Environments

FINAL REPORT

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16. Abstract

This research project aimed to improve NCDOT's capabilities in collecting high-quality bathymetric survey data using unmanned surface vessels (USVs), focusing on evaluating current technologies, supporting their adoption by NCDOT, and tailoring tools and workflows to NCDOT's specific use cases. A comprehensive literature review was conducted to assess the state-of-the-art in USV technology. This review explored the history and regulation of USVs, their integration with sonar systems and how similar technologies have been used by other state transportation departments. A detailed database of 91 commercially available USVs with bathymetric capabilities was created, and the vessels were compared based on criteria such as weight class, country of origin, hull design, speed, endurance, and sensor configurations. Standard parameters for sonar systems, GNSS sensors, and communications technology were also outlined. Eleven potential NCDOT use cases were identified, and each was matched with suitable USV criteria. A commercial hydrographic survey USV—the HyDrone from Seafloor Systems—was also purchased and used to gain hands-on experience with its deployment, operation, and maintenance. Several enhancements were made to the USV, including the integration of a third-party RTK GNSS receiver, a connection to the North Carolina CORS network, and the addition of a first-person-view (FPV) camera system. The FPV system significantly improved the operator's ability to safely navigate around structures and debris, especially in situations where traditional remote control or pre-programmed missions would be limited. A detailed workflow was developed for planning and executing survey routes using HYPACK software and for processing the collected bathymetric data in ArcGIS to produce depth contour maps and triangulated irregular network (TIN) models. Over the course of the project, the HyDrone was deployed 25 times across 10 unique sites, resulting in 41 hours of total in-water survey time. These tests demonstrated the ability to collect and visualize bathymetric data in the field for rapid assessment, and they generated datasets that provide insights into key operational parameters. These include battery consumption rates, the impact of GNSS signal quality with distance from structures, vehicle maneuverability, and overall setup and deployment logistics. The team recommended a deployment workflow. In addition, a specialized coverage-path planning (CPP) algorithm was developed to optimize USV missions in shallow water environments. The algorithm incorporates prior bathymetric knowledge and a statistical model of the vehicle's path-following performance to reduce the risk of collisions. It outputs a set of optimized waypoints that maximize area coverage while maintaining a predefined safety margin.

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Chapter 1. EXECUTIVE SUMMARY

The North Carolina Department of Transportation (NCDOT) needs a diverse set of cost-effective, reliable, and efficient tools to periodically map the bathymetry of various bodies of water across the state. Bathymetric data collection is used by NCDOT in several ways, including as input data for hydraulic modeling software (e.g., for floor risk assessment), to plan dredging operations, and to monitor scour around bridges. The long-term goal of this research is to improve the capability of NCDOT to efficiently and cost-effectively collect high-quality bathymetric survey data using unmanned surface vessel platforms in inland bodies of water. The specific research objectives are (1) experimentally evaluate a professional hydrographic survey unmanned surface vessel (USV) for NCDOT-relevant inland survey use cases, (2) transition USV survey capability to NCDOT, and (3) review USV/sonar technologies to envision and support current and future NCDOT needs.

A literature review was conducted to survey the state-of-the-art of USV technology. This included an overview of USV history, regulations, applications of sonar-equipped USVs, the outlook of large-scale autonomous cargo vessels, and a summary of USV studies and adoption by other state transportation agencies. A database was compiled of 91 commercially available USVs that have bathymetric capabilities. To compare the USVs, a weight-based classification system was proposed. The USVs were also compared based on country of origin, hull type, length, speed, and endurance. The typical parameters of single beam echosounders, GNSS sensors, and communication systems for USVs are outlined. Eleven potential NCDOT use cases were identified, and a series of platform rating/categorization scheme was applied to each use case. The findings and deliverables from this project will help support NCDOT selection and purchasing of USV platforms in various applications, including for monitoring bathymetry around bridges and other structures

The UNC Charlotte team also purchased a commercial hydrographic survey USV (the HyDrone from Seafloor Systems, Inc.) and gained expertise in deploying, operating, recovering, and maintaining the USV. Several modifications were made to the vehicle, including integration of a third-party RTK GNSS receiver, connection to the NC CORS network, and integration of a first-person-view (FPV) camera system. The camera allows surveying in closer proximity to structures and avoidance of in-water debris that is not possible with shoreside remote control or autonomous waypoint mission planning. A workflow has been developed to plan survey routes using HYPACK software and process recorded bathymetric data using ArcGIS to produce depth contour maps and triangulated irregular network (TIN) models. Extensive testing involved deploying the USV 25 times at 10 unique locations with a total survey in-water time across all testing of 41 hours. The team demonstrated the ability to gather data and visualize bathymetric maps on-site using for rapid assessment. Datasets were recorded that allow comparison and provide guidance to NCDOT on the use of echosounder settings, expected battery consumption, GNSS signal quality with distance from bridge, vehicle handling characteristics, and other logistics like time to set up. A recommended deployment workflow was developed.

Lastly, a coverage-path planning (CPP) algorithm was designed that is tailored towards supporting shallow water surveys. The algorithm uses prior knowledge of the bathymetry and a statistical model of the vehicle's path following performance to refine a survey plan such that the risk of collision is below a desired threshold. The output of the algorithm is a set of waypoints for the vehicle to traverse that maximize area coverage while maintaining safety.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 2. Introduction

2.1 Background

Uncrewed surface vessels (USVs) can augment existing data-collection technologies used by NCDOT and provide methods to survey shallow-water rivers or streams that are difficult to access or inconvenient/time-consuming to survey with traditional methods. One existing method currently used by NCDOT for shallow-water survey involves a pole-mounted SBES (Sonar Mite v5) that supports surveys from a flat-bottom boat (or possibly wading through the water with a handheld unit). Obtaining measurements in this way can be dangerous and difficult if there are strong currents, debris, or challenging vegetation/sediment. Flat-bottom boats can operate in a few feet of water or more, but they are difficult to maneuver in constrained spaces (e.g., a narrow river). Furthermore, flat-bottom boats may also be difficult to deploy when there is no convenient launch point or when the survey area is difficult to access, for example, in bodies of water with steep surroundings (such as a high-walled pond or quarry). A small, low-draft, and man-portable USV equipped with an SBES can potentially improve NCDOT's ability to efficiently and safely operate in these conditions. USVs are already routinely used for bathymetric surveying both in shallow inland and coastal water, but they have limitations in more extreme conditions of strong currents or when operating near structures that pose collision risk and degrade GNSS quality/availability. The benefits of USV-based surveys are the reduced workload on the operator, improvement in safety, and the ability to automate data collection. By following pre-planned survey tracklines, repeated measurements at the same locations can be obtained periodically over time, and reduce the burden on the operator. This project aims to address NCDOT's research need of understanding the practical aspects of operating a USV for inland surveys and characterizing when and where it is beneficial to use such systems, as well as how they should be operated and integrated into the NCDOT workflow and data processing.

Figure 1. An example single-beam echo sounder (SBES) that can be mounted to a boat for manual surveys. The image shows the CEESCOPE developed by HydroSystems. Image Source: https://ceehydrosystems.com

2.2 Research Objective and Scope

The long-term goal of this research is to improve the capability of NCDOT to efficiently and cost-effectively collect bathymetric survey data in inland bodies of water. The specific research objectives are to experimentally evaluate an unmanned surface vessel (USV) equipped with a single-beam echo sounder (SBES), develop a workflow for using the USV, transition the system into NCDOT use, and provide a broader technology assessment of sonar-based technologies and platforms for other future NCDOT uses. The research activities are organized into three tasks:

- **Task 1: Experimentally evaluate a professional hydrographic survey unmanned surface vessel (USV) for NCDOT-relevant inland survey use cases.** The UNC Charlotte team will gain expertise in deploying, operating, recovering, and maintaining a commercial hydrographic survey USV (the HyDrone form Seafloor Systems, Inc.) and develop a workflow for integrating and managing data collected with hydrographic survey software HYPACK ECHO. Extensive field testing will be conducted to develop expertise in operating this USV and characterize the performance and limitations of the system in select NCDOT use cases.
- **Task 2: Transition USV survey capability to NCDOT.** Based on field testing results in Task 1, a set of recommended vehicle mission planning, operating protocols, and data processing procedures tailored for NCDOT use will be developed. The UNC Charlotte team will support the transition of the USV to NCDOT by providing documentation, guidance, and field training with future NCDOT operators.
- **Task 3: Review unmanned marine craft and sonar technologies for future NCDOT acquisition support.** This task will identify other potential uses of sonar and USV technologies for NCDOT applications and provide a critical assessment in terms of the maturity of the technology, system cost, system complexity, logistical requirements, and other relative capabilities and limitations. The assessment and recommendations report will be compiled based on an extensive review of available literature and discussions with vendors and other users. The critical technology review will support NCDOT's future acquisition and/or novel research directions that extend beyond the scope of Tasks 1 and 2).

2.3 Report Organization

The remainder of the report is organized as follows. Chapter 3 presents an overview of uncrewed surface vessel (USV) technology, including the history of USVs, related terminology, and applications of sonar-equipped USVs, and use cases of USVs by other transportation agencies. Chapter 4 presents a survey of existing commercially available USVs on the market, including characterization of their physical properties (length, weight), performance (speed, endurance), and their countries of origin. A novel method to group USVs by weight is proposed and typical sonar sensors and positioning systems used onboard USVs are discussed. Chapter 5 discusses specific NCDOT use cases and a platform rating system. Chapter 6 describes work conducted to evaluate a commercially available USV (the HyDrone). Lastly, Chapter 7 presents the implementation and technology transfer plan.

Chapter 3. Overview of Uncrewed Surface Vessel Technology

3.1 History of Uncrewed Surface Vessels (USVs)

The early history of uncrewed surface vessels (USVs) dates back to the 1800s and involved well-known inventors such as Werner Siemens and Nikola Tesla. Initial USV developments were motivated by the need to improve the accuracy of torpedo weapon systems by providing a remote steering capability. Siemens demonstrated a remote-controlled USV sailboat equipped with a torpedo that had three steering states (left, right, center) in August 1870; the system used an electric circuit controlled from shore to inflate a rubber bag to control the tiller position. Later, in 1897, Tesla demonstrated a remote-controlled boat (see Figure 2) that leveraged the famous Marconi transmitter.

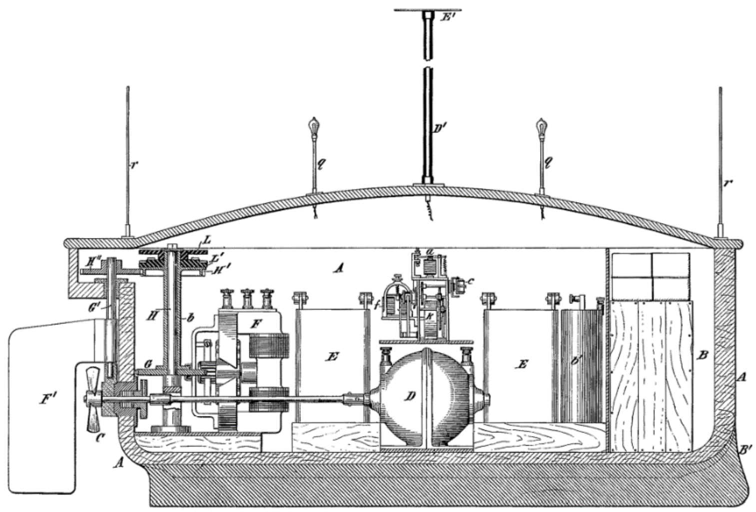


Figure 2. Nikola Tesla's remote-controlled boat design was the first ever wirelessly operated vehicle, predating wireless aircraft and ground vehicle demonstrations. Batteries are labeled "E" and the explosive charge is labeled "B". (Image Source: (Everett, 2015).)

A more recent overview of ASV technology spanning the years 1985-2016 is provided in (Liu et al., 2016; Manley et al., 2008). A prototype system for automated collection of bathymetric data was developed at MIT in 1996 (Vaneck et al., 1996) and is representative of earlier work in deploying USVs specifically for hydrographic data collection. Since then, numerous USVs have been developed in the last thirty years that are specifically tailored for survey work, both in calmer inland water as well as coastal surveys.

3.2 Terminology of USVs

The terminology used to refer to USVs varies across the literature, and several examples are shown below.

Table 1. Various terms used to refer to uncrewed surface vessels (USVs) or more general groups of aquatic vehicles that encompass USVs

Term	Acronym
Uncrewed/Unmanned Surface Vessel/Vehicle	(USV)
Autonomous Surface Vessel	(ASV)
Maritime Autonomous Surface Ships	(MASS)
Autonomous/Marine Surface Craft	(ASC/MSC)
Unmanned/Uncrewed/Autonomous Boat	–
Sea/Marine Drones	–
Aquatic/Marine Robots	–

3.3 Applications of Sonar-Equipped USVs

This section highlights several common applications of sonar-equipped with specific examples reported in the literature. These examples provide context for NCDOT to understand the state-of-the-art in USV technology in adjacent applications. The next section will focus specifically on transportation-relevant applications.

3.3.1 USV Platforms: Common Use Cases

Documenting Shipwrecks and Historical Heritage Sites. USV can be instrumented to survey areas that may contain shipwrecks or other underwater cultural artefacts. Multibeam echosounders provide high-resolution data that can be augmented by photographs to obtain 3D models. Figure 3 shows an example of a dataset used to map a shipwreck located in 3 m of water depth in the Bay of Gibraltar using a small man-portable USV (Solana et al., 2023).

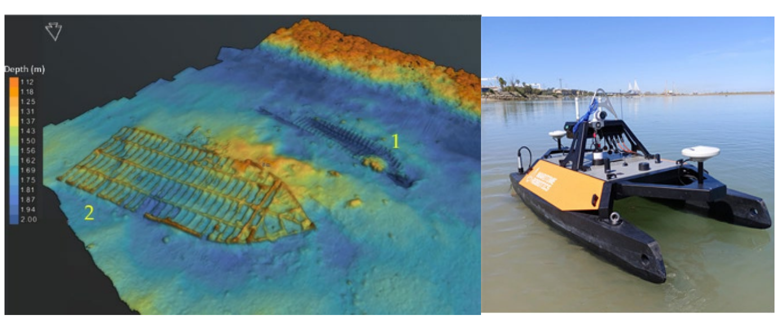


Figure 3. Example shipwreck data produced using HySweep module of the HYPACK software. Right: Data was collected using a Maritime Robotics Sea Otter USV equipped with a 700 kHz Norbit iWBMSe multibeam echosounder (Image Source: Solana et al, 2023)

3.3.2 3D Reconstruction of Offshore Structures

USVs have also been to monitor construction and offshore structures. Such applications may involve instrumenting the USV with both above-water sensors (e.g., LiDAR, cameras) as well as below-water sensors (e.g., sonar). For example, Figure 3 illustrates a dataset obtained by a small USV that was used to survey an offshore structure in South Korea. The USV was developed using a commercial kayak platform and used to gather point-cloud data above and waterline with a 3D LiDAR and below the waterline with an Imagenex 837B Delta T multibeam echosounder mounted in a tilted configuration (Han et al., 2018). Due to the degraded/unavailable GNSS, navigation was performed using a hull-relative framework with simultaneous localization and mapping (SLAM). Similar GPS-denied navigation schemes may be of interest to NCDOT when conducting surveys near bridges or other large structures that block or degrade GNSS signals.

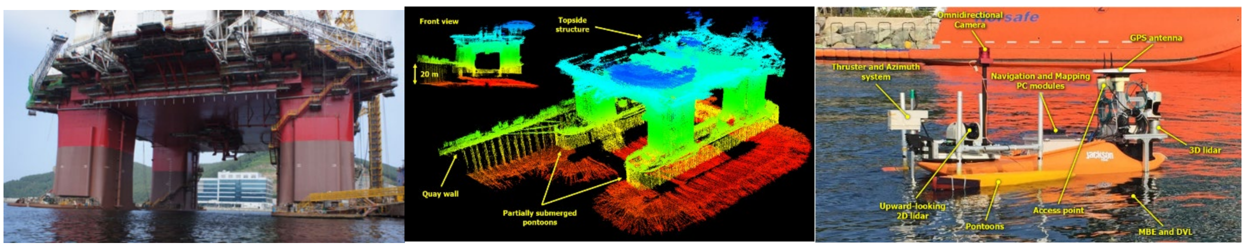


Figure 4. Left: A survey was conducted around a semisubmersible marine platform under construction in Okpo, South Korea. Middle: Resulting dataset including both 2D LiDAR, 3D LiDAR and below-water multi-beam point clouds. Right: Small custom-built kayak USV used during the survey. (Image Source: Han et al, 2018).

3.3.3 Water Quality and Environmental Monitoring

USVs have been used to monitor water quality and marine life by sampling the water to evaluate the extent of pollution or monitor and compare the effectiveness of various anti-pollution measures. Common water quality sensors collect data such as dissolved oxygen, pH, temperature, salinity, total algae, and turbidity. Sensors can also be purchased to detect specific chemicals of interest.

In some applications, obtaining a visual representation of the underwater environment is of interest. For example, USVs have been deployed with hyperspectral cameras in shallow water (Mogstad et al., 2019) for such purposes. The images can be stitched together to create mosaics with 0.5-cm resolution of the sea bottom (Mogstad et al., 2019). The data was then used to classify various parts of the image as belonging to several distinct classes, such as algae, invertebrates, and seafloor (Mogstad et al., 2019). Other work has also reported the use of USVs to monitor re-growth of invasive plants using an illuminating light, downward-facing camera, and a low-cost Blue Robotics echosounder (Codd et al. 2021). USVs can also assist with oil spill detection, monitoring, and cleanup (Guerrero et. al. 2016; Pu et al. 2020); however past projects focus on large-scale ocean oil spills.

3.3.4 Mine Survey

USVs can be used in applications where the location can be difficult to access with a conventional boat (e.g., a flat-bottom jon boat). In (Madusiok, 2019), the bathymetry of a flooded section of an open-pit mine was periodically surveyed during active extraction. The researchers used a hobby-grade Lowrance Mark-4 echo sounder. In addition to depth measurements, the acoustic energy was used to determine bottom composition. The authors reported that using a manned boat was rejected in this application due to the inefficiency and logistical difficulties of deploying one and because it could not reach all areas of the mine (Madusiok, 2019).

3.3.5 Bridge Inspection and Scour Monitoring

Bridges in the United States must be regularly inspected for safety. Deterioration of bridges can be caused by age, environmental attack, excessive loading, collision damage, or inadequate design or construction (Ellenrieder et al., 2016). Bridges on the coast near the “splash zone" where seawater repeatedly splashes and evaporates are particularly susceptible to corrosion (Ellenrieder et al., 2016). The Federal Highway Administration provide guidelines for underwater bridge inspection (Browne et al, 2010) and underwater bridge inspection is typically achieved by divers using visual or tactile examination (Ellenrieder et al., 2016). During visual inspection, divers use various tools to clean bridge surfaces prior to documenting them. When the water is too turbid to allow visual inspection, divers feel the bridge. Other methods of bridge inspection include non-destructive testing (e.g., using specialized acoustic, electrical, radar, mechanical impact techniques, infrared thermography, and/or radiographic/nuclear techniques), or destructive testing (material sampling/coring and analysis in the lab) (Ellenrieder et al., 2016).

Marine robots have the potential to assist in these activities that are often time and resource intensive and potentially dangerous for divers due to fast-flowing currents, waves, winds, and the presence of wildlife (Ellenrieder et al., 2016). In prior work, authors have shown that USV without GPS can inspect bridges using LiDAR and Camera and utilize neural networks to classify bridge cracks, exposed reinforcements, and spalling (Han et al., 2018). Several examples of transportation departments utilizing USVs for bridge inspection are described in the following section.

3.3.6 Transportation Infrastructure Inspection

Apart from bridge inspection and scour monitoring, USVs have also been used to inspect other transportation infrastructure, including long narrow aqueducts (Pang et al., 2016) and ports (Campos et al., 2022). For example, USVs were adopted as part of a two-vehicle system to inspect dams (Shimono et al., 2016). In (Shimono et al., 2016) the USV deployed a smaller remotely-operated vehicle (ROV) connected by a cable winch to dive and collect imagery.

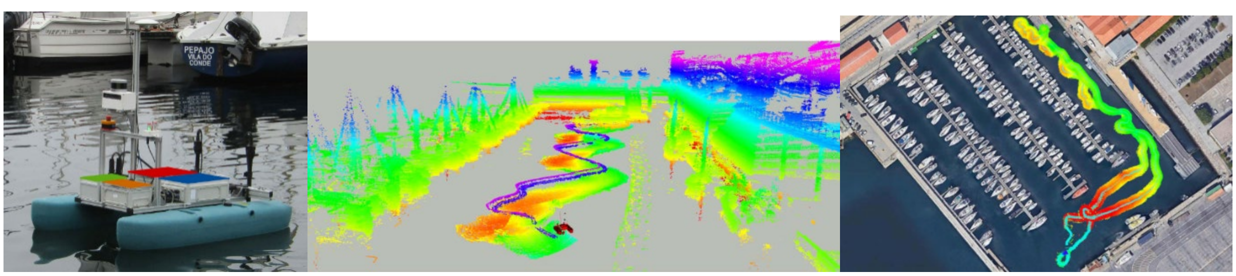


Figure 5: Left: A survey was conducted around a semisub-mersible marine platform under construction in Okpo, South Korea. Middle: Resulting dataset including both 2D LiDAR, 3D LiDAR, and below-water multi-beam point clouds. Right: Small custom-built kayak USV used during the survey. (Image Source: Han et al., 2018)

3.3.7 Monitoring Channels and Dredging Operations

High-traffic coastal waterways often require periodic dredging to enlarge channels for the safe passage of commercial vessels and ferries. Monitoring the width and depth of channels, as well as surveying both pre- and post-dredging activities, is important for planning, scheduling, and situational awareness of transportation agencies. Various sonar technologies are often used to accomplish these tasks by crewed vessels. However, USVs and other marine robots can potentially play a role in providing low-cost and efficient assessment of channels on demand. Prior work has demonstrated the use of USVs for this purpose. For example, the University of Michigan built a custom USV equipped with a Humminbird RF15 Wireless Fish Finder and used it to inspect the results of recent dredging activities in Harrisville, Michigan where it collected over 3,000 data points (Brown et al., 2010). A team from MIT demonstrated the ability of multiple USVs to coordinate their activities and localize and follow a deep trench in the Charles River in Boston, MA, using low-cost single-beam echosounders from Blue Robotics (Gershfeld et at., 2023).

3.3.8 Gathering Hydrology Data: Water Flow Velocity Measurement

Hydrodynamic models are important for evaluating riverine flooding, hurricane surge, bridge scour, and other hydrological phenomena that may impact roadways, NCDOT assets, the public, and the environment. To calibrate such models, measurements of water flow velocities can be used (Mahmutoglu et al., 2010), e.g., obtained using an acoustic Doppler current profiler (ADCP) or with other instruments. USVs can potentially serve as platforms that efficiently collect bathymetry and ADCP water velocity data. For example, prior work has demonstrated the use of automated boats (i.e., modified canoes with trolling motors and automatic controls) to map water velocity, bathymetry, and collect stratigraphy measurements in a tidal channel in Port Fourchon, Louisiana (Weeks et al. 2011). The boats were used in a cumulative survey in excess of 91 km (Weeks et al. 2011).

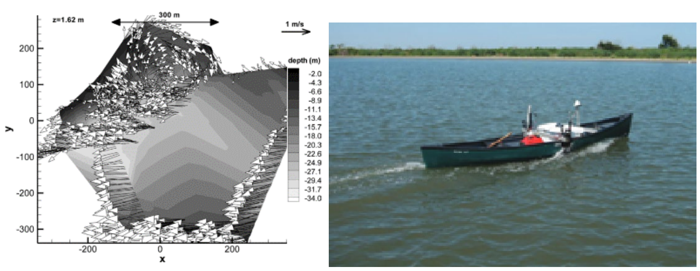


Figure 6: ADCP velocity vector data and bathymetry collected in Vermillion Bay, LA (left) by an automated boat (right). (Image Source: Weeks et al., 2011).

3.4 USV Studies and Adoption by Other State Transportation Agencies

Several transportation departments across the United States have explored the use of unmanned surface vessels, either through purchases of USVs or technology assessment studies (see Fig. 7). The departments of transportation (DOTs) exploring this technology include:

- California (Tom et al., 2022)
- Florida (Ellenrieder et al., 2016)
- Hawaii (Tom et al., 2022)

- Illinois (Tom et al., 2022)
- Michigan (Schroeder et al., 2019)
- Missouri (Tom et al., 2022)
- Montana (Tom et al., 2022)
- Texas (Murphy et al., 2011)
- North Carolina (i.e., the present study).

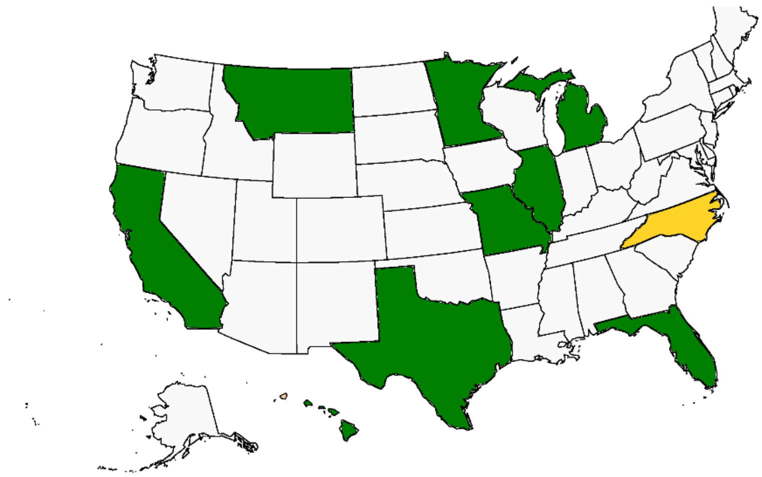


Figure 7: State-level DOTs that have purchased and/or supported research technology assessment studies related to the adoption of USV technologies are highlighted in green.

California Department of Transportation (CalTrans).

Interviews with CalTrans staff indicated the department is commencing a research project to explore a remote-controlled boat with single-beam or multi-beam sonar by identifying several options and whether they will work in flood conditions (Tom et al., 2022).

Illinois Department of Transportation (IDOT).

An IDOT research project provided a literature review and critical discussion of technologies that support assessing bridge safety during and immediately after floods (Tom et al., 2022). USVs were included as a case study among other technologies reviewed. The authors recommended further study to evaluate remote-control vessel systems for measuring scour at specific bridges of importance and proposed that USVs can be used as follow-on devices to augment low-cost tethered flotation-based sonar measurements (e.g., measurements obtained by a retail fish-finder lowered from a bridge) for rapid assessment.

Florida Department of Transportation (FDOT).

The FDOT sponsored a research project completed in 2016 that investigated the use of USVs for bridge inspection (Ellenrieder et al., 2016). The study included an analysis of requirements and recommendations for the use of USVs in on-water bridge inspection, including an investigation of control, dynamic positioning, and advanced navigation using robotics techniques under bridges and mapping of bridge features. A prototype vessel was developed based on the WAMV platform (see Fig. 8). The system was transported to field sites by a box truck and used a support boat deployed alongside the USV. Field experiments were conducted at several sites and demonstrated the ability of the system to detect possible scour in an imaging sonar unit.

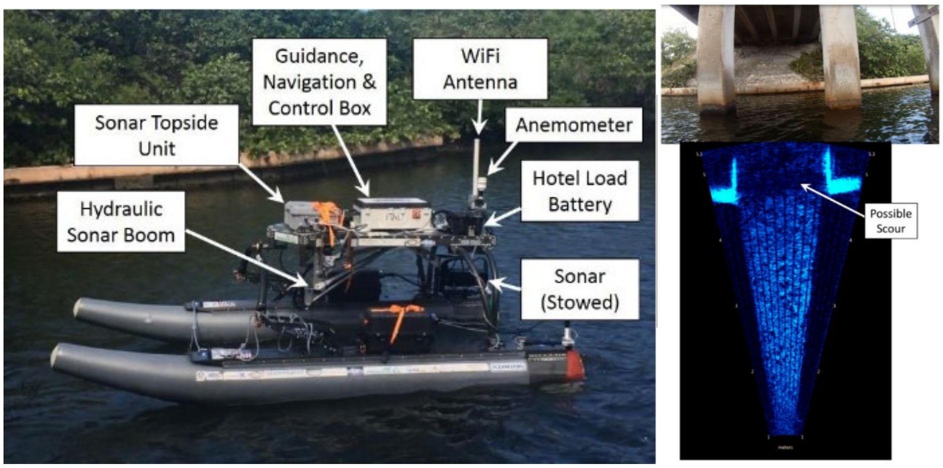


Figure 8: Custom-designed remotely operated vessel with a retractable imaging sonar unit (Aris 1800) and digital cameras used for bridge inspection during FDOT project. (Image Source (Ellenrieder et al., 2016))

Michigan Department of Transportation

This study evaluated the use of USVs equipped with different sonar technologies (including single-beam echo sounder, multi-beam echo sounder, and side-scan sonar) for monitoring bridge scour during high-flow events. Seven echo-sounder units, four GPS units, five side scan sonar units, six software packages, four data acquisition laptops, and six different USVs were investigated and comparatively rated. The authors visited various vendors to participate in in-water tests and report findings. An unmanned surface vessel from the company Hydronalix (model: Sonar EMILY), along with SAR Hawk post-processing software, was recommended.

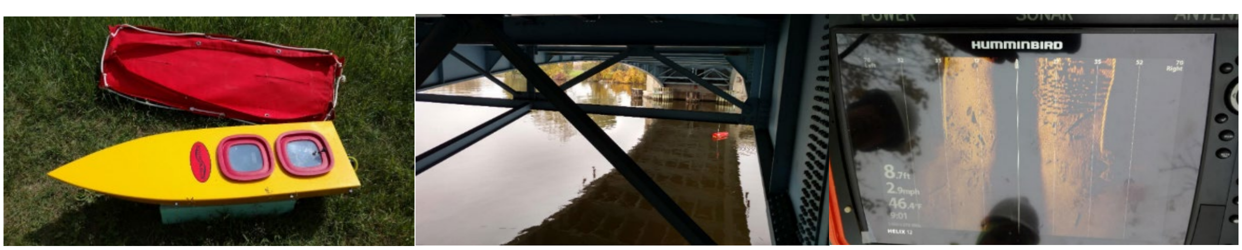


Figure 9: The Sonar EMILY system prior to deployment. Middle: Image of Sonar EMILY near a bridge site. Right: Example of commercial fish finder onboard the Sonar EMILY system and wireless transmitted to operators on shore.

Montana Department of Transportation

Montana DOT staff evaluated several competing unmanned survey boats and selected the CEE-USV for purchase (see Figure 10). The USV will be used to perform surveys near bridges and collect data for hydraulic modeling (Ceehydrosystems, 2024).

Figure 10:Left: The Sea-RAI with a DIDSON acoustic camera and other key components labeled. Right: Bridge scour appears as dark holes in front of pilings in the acoustic camera image. (Source: Ceehydrosystems, 2024)

Minnesota Department of Transportation

Bridge scour monitoring was performed during floods using a commercial fishing sonar (Humminbird 898c) attached to a pole or boogey-board (not shown) that was lowered by hand with a tethered cable into the water. Discharge measurements during the flood were also obtained using an OceanScience Riverboat SP equipped with a TRDI StreamPro acoustic Doppler current profiler (see Figure 11) (Barlet, 2017;Tom et at, 2022).

Figure 11: OceanScience Riverboat SP equipped with a TRDI StreamPro acoustic Doppler current profiler being deployed during a flood to measure discharge (Source: Bartelt, 2017)

Texas Department of Transportation

Texas DOT has also used various forms of low-cost flotation devices equipped with retail fish finders and wireless variants (e.g., Vexilar Sonar Phone) for over three decades. The devices record depth with time and have been attached to a water ski board (Tom et al., 2022). The Sea-RAI USV (see Figure 12) was used to inspect a bridge for scour in the aftermath of Hurricane Ike, along with the debris field from a damaged bridge (Murphy et al., 2011) by a non-profit organization (Center for Robot-Assisted Search and Rescue, CESAR) with coordination from Texas DOT.

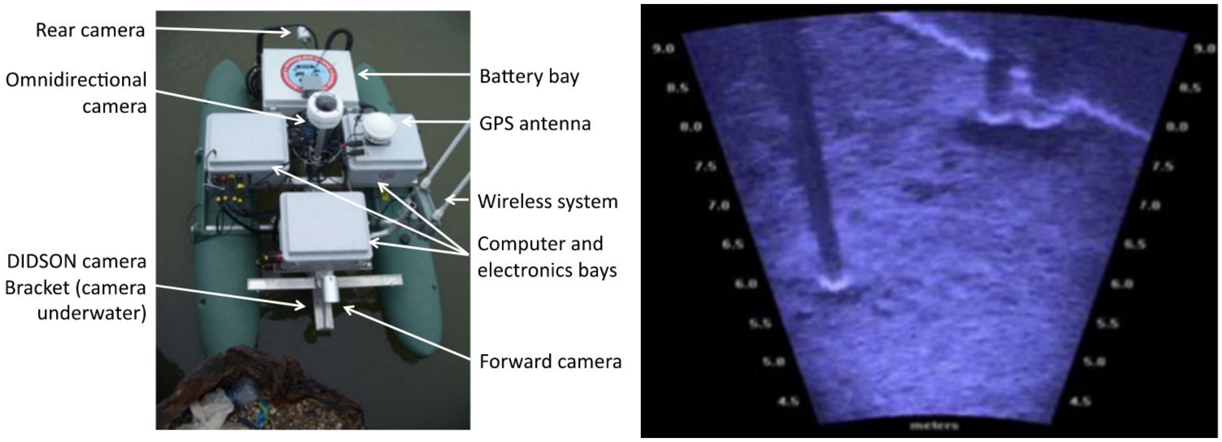


Figure 12: Left: The Sea-RAI with a DIDSON acoustic camera and other key components labeled. Right: Bridge scour appears as dark holes in front of pilings in the acoustic camera image. (Source: Murphy et al., 2011)

3.5 Regulations for USV Operations

International Regulations for Preventing Collisions at Sea (COLREGs) (Ventura, 2005) were established by the International Maritime Organization (IMO) in 1977 and provide regulations for the conduct of vessels at sea. These rules were established for crewed vessels, but modern interpretations apply them equally to uncrewed vessels. The COLREGs include requirements on how to determine safe speed, actions to take to avoid collision, right-of-way, obligations for crossing certain water features such as narrow channels, traffic separation schemes, and the requirements for a lookout. Some USVs have been designed to autonomously comply with the collision avoidance rules (Stankiewicz, 2020; Benjamin, 2006); however, there is a gray area regarding whether USVs can comply with all rules (USNI, 2024). For example, USVs with a remote sensor suite serving as a look-out to detect nearby vessels or land mass cannot satisfy the requirement from Rule 5 of COLREGs that requires a “proper look-out" which is interpreted as a physical human presence (USNI, 2024). Specifically, the Rule states that “every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision". COLREGs apply to “to all vessels upon the high seas and in all waters connected therewith navigable by seagoing vessel". The high seas are defined by international law as the regions of the ocean that are outside of a country’s exclusive economic zone. However, U.S. domestic law has extended these regulations to also apply to inland waters of the United States (33 C.F.R. § 83.01 (2022)) (ECFR, 2024). Lt. Chris Rabalais of the U.S. Coast Guard shared the following opinions about the operation of small USVs (Professional Mariner, 2024):

> *“If you’re operating them in the 100 percent remotely controlled mode, you’re basically the responsible skipper, even though you may be standing on the shore. Therefore, make sure that you operate them according to the vessel's Navigation Rules. If you do get involved in a collision, your vehicle probably won’t cause a great deal of damage to the other vessel involved. [...]. So, if you always have immediate control of these small ASVs and operate them in a safe manner according to the rules, you’re probably not going to incur a great deal of criminal or civil liability."*

For larger USVs (e.g., greater than 7 feet in length with speeds more than 7 knots), the collision concern is elevated. Close coordination with the manufacturer and Coast Guard, and other relevant authorities is recommended. In some cases, the USV may be equipped with an automatic identification system (AIS) and lights to support operation among other vessels.

3.6 Future Outlook of Large-Scale Autonomous Cargo Vessels

The development of new autonomous cargo vessels, often referred to as Maritime Autonomous Surface Ships (MASS), is being explored through several large-scale studies and projects (Kim et al., 2020). The International Maritime Organization (IMO) defines four degrees of autonomy for MASS (IMO, 2024):

- **Degree One:** Ship with automated processes and decision support. Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and at times be unsupervised, but with seafarers on board ready to take control.
- **Degree Two:** Remotely controlled ship with seafarers on board. The ship is controlled and operated from another location. Seafarers are available on board to take control and to operate the shipboard systems and functions.
- **Degree Three:** Remotely controlled ship without seafarers on board: The ship is controlled and operated from another location. There are no seafarers on board.
- **Degree Four:** Fully autonomous ship: the operating system of the ship can make decisions and determine actions by itself.

Many of the autonomous cargo vessels are being developed with alternative fuels, such as electric power or liquified natural gas (LNG) (Kim et al., 2020). For example, the *Yara Birkeland* is the world's first electric container vessel capable of autonomous operation (degree four). The container vessel officially entered service in Norway in 2022 and is undergoing a two-year trial period (see Figure 13). The vessel is expected to become certified and gradually transition into autonomous navigation and operations. It currently transports fertilizer between two ports (Maritime Executive, 2024; Nature, 2024). Uncrewed surface vessels are also being adopted by military and coast guard organizations. For example, the U.S. Navy expects that “by the middle of this century [...] up to 40 percent of the fleet will be unmanned” (LaGrone, 2023).

Figure 13: An all-electric container ship, the Yara Birkeland, is capable of operating in fully autonomous mode.

Autonomous cargo vessels incorporate features like those found in self-driving cars, including marine radar, GPS, LiDAR, infrared cameras, wind sensors, and high-resolution sonar (Kim et al., 2020). A new shipping paradigm that involves greater automation and integration of cyber-physical systems has been referred to as “Shipping 4.0" (Kim et al., 2020). Increased automation in shipping may potentially reduce costs, reduce the mental workload of crew, and improve safety and efficiency. However, with these advancements also come challenges—integrating autonomous vessels into regulatory frameworks, operating alongside crewed vessels, and security risk of cyber-attacks (Kim et al., 2020). Autonomous ships will also require ports to provide more services, such as interacting with crewless vessels to manage arrival, remote piloting, and tug coordination, berth allocation (Nature, 2024). New infrastructure may be required to support the refueling of ships that use alternative fuels (e.g., electric charging or LNG terminals).

While the routine use of autonomous cargo vessels is still decades away, the development of autonomous cargo handling at ports is already accelerating (Nature, 2024). For example, Singapore is constructing the world's largest autonomous terminal, known as *Tuas Port*, which is expected to be completed in 2040 (MPA, 2024). The port will use next-generation vessel traffic management systems, employ a private 5G network, and use electrified automated yard cranes and automated guided vehicles (AGVs) to transport cargo (MPA,2024). Other ports have already adopted some degree of automation; Rotterdam uses unmanned cranes and automated guided vehicles to unload to operate an entire container terminal with only 10-15 people (Nature, 2024).

Chapter 4. Survey of Commercially Available USV Platforms

4.1 Aims of Survey

Past surveys of USVs have focused on specific applications, such as USVs for disaster relief (Jorge et al., 2019), or USVs in coast guard missions (ENAS, 2020). The aim of this survey is to build a database of USVs that are tailored for bathymetric and hydrological data collection. The survey will provide an understanding of the capabilities of existing USVs to inform NCDOT on how they might be utilized effectively in the context of NCDOT work. The database of USVs can also be used to identify potential platforms to procure.

4.2 Data Collection Methodology

Data was collected primarily from online open-access resources by searching relevant keywords and browsing through public databases such as Geo-matching.com or AUVSI (Association for Unmanned Vehicle Systems International). The dataset collected includes only platforms that specify they can be used for the collection of bathymetric or hydrological data. A large subset of USVs are designed specifically for military operations and these were not included in the database. Platforms were only included if, at a minimum, the following data could be obtained: weight, length, and speed. Platforms exceeding 10,000 lbs were excluded. After downselecting the dataset based on the above criteria, the database currently includes 91 platforms. Since our aim was to provide recommendations for the entire gamut of NCDOT activities (including possible coastal surveys) we included platforms ranging from very small to large heavyweight vehicles. The dataset includes USVs that are either commercially available for purchase or that have been developed independently by various organizations and universities. Additional data recorded (where available) includes country of origin, a photo of the vehicle, a description of the hull (monohull, catamaran, or trimaran), width, endurance, manufacture type (industry or other state/non-profit/academia organization), and type of bathymetric sensor either single beam echosounder, side-scan sonar, or other (includes multibeam, ADCP, sub-bottom profiler). In some cases, the data was estimated based on engineering judgment and available information/images in brochures/datasheets.

4.3 USV Classification by Weight

To our knowledge, there exists no method of categorizing USVs by weight class (e.g., similar to the Group 1-5 based categorization used by the Department of Defense for uncrewed aerial vehicles). Thus, we propose the following categorization shown in Table 2.

Table 2: A group classification proposed by UNC Charlotte for categorizing USVs.

Group Classification	USV Weight Range	Description
Group I	<30 lbs	One-person portable (no boat ramp needed)
Group II	30-60 lbs	Two-person portable (no boat ramp needed)

Group III	60-500 lbs	comparable to jet ski / light aluminum jon boat
Group IV	500- 2000 lbs	comparable to small fishing or pontoon boat
Group V	> 2000 lbs	comparable to medium-size/larger boats

The rationale for the above choices is as follows. The Department of Defense defines “man-portable" as 30 lbs. This definition is adopted for Group I to indicate USVs that could potentially be deployed by one person. Group II considers a two-person deployable boat that is twice the weight of the Group I category. Both Group I and Group II boats can be deployed without a boat ramp or trailer. Group III boats are those where a boat ramp is likely to be needed and encompass boats that weigh less than 500 lbs. Many jet skis and aluminum jon boats are comparable in weight. Vessels in this group can be pulled by a Class One (I) hitch rated for a gross weight of 2000 lbs (including trailer). Group IV vessels are in the 500-2000 lbs range. Such vehicles can likely be pulled by a Class Two (II) hitch rated for 3000 pounds gross weight. Group V vessels are the largest USVs that likely require a Class Three (III) hitch or other heavier infrastructure for deployment/transport.

A histogram of group categorization of the dataset is shown in Fig.14. About 70% of the USVs are in the Group I-III category, and nearly half are 100 lbs or less. There are about twice as many Group III USVs (the most numerous of all) compared to Group I, and most of these are near the lower weight end of the Group III weight range.

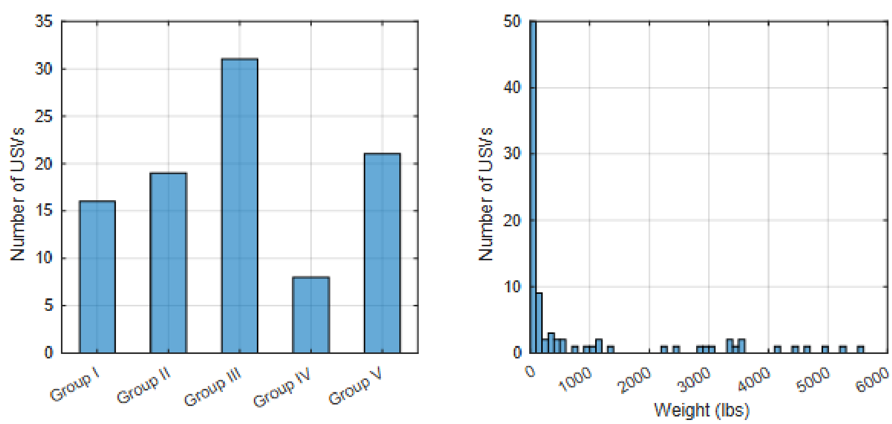


Figure 14: Categorization of USVs by weight. The histogram on the right bins USVs in intervals of 100 lbs.

4.4 USV Countries of Origin

The number of USVs by country of origin in the dataset collected is shown in Fig.15. A large number of USVs are from the United States (28 out of 91 USVs). and China (19 out of 91 USVs). Other countries represented with three or more USVs include Australia, Belgium, Canada, France, the Netherlands, Norway, the UAE, and the United Kingdom.

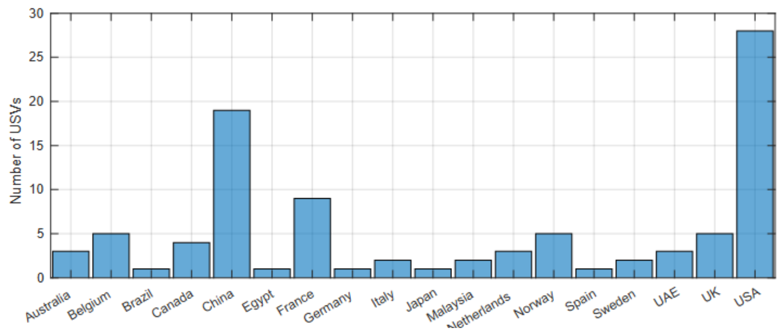


Figure 15: Categorization of USVs by country of origin.

4.5 USV Hull Types

Common designs for ASV hull geometries are the monohull (i.e., a single main hull), catamaran (twin hull) design, catamaran-SWATH (small waterplane area twin hull), and trimaran (triple hull). These different designs differ in their water resistance, stability properties, and method of construction. Monohulls are often described as either displacement hulls (designed to move at slow speeds and typically are more rounded or V-shaped, providing greater storage), planing hulls (designed to rise up out of the water and move at higher speeds, often with a flatter geometry), or intermediate semi-displacement hulls that blend the two types. Catamarans with their more widely spaced hulls offer greater stability in the water and convenient locations to mount two motors for a differential propulsion drive that produces larger turning moments. Typically a cross member/bridge connects the two hulls and can be used as a location to store payloads and deploy sensors. Catamaran-SWATH designs have a large portion of the vessel submerged, and use smaller profile strut-like members at the waterline. The smaller profile on the water surface minimizes the adverse effects of waves and provides greater stability. Trimarans are similar to catamarans, but a third hull increases the buoyancy of the system. A discussion of design considerations for different hull types is provided in many classic textbooks on naval architecture. Reference (Vasconcelos et al., 2015) provides a comparison of different design types in a particular application. According to the dataset in this study, see Fig.16, the most common USV design is a monohull, followed by a catamaran, and lastly a trimaran.

Figure 16: Hull designs of USVs. (Left) Monohull (Image Source: CHCNAV, 2024), (Left-Middle) Catamaran (Image Source: Rasal, 2013), (Right-Middle) Catamaran-SWATH (Image Source: YSI, 2024), (Right) Trimaran (Image Source: Triaddrones, 2024).

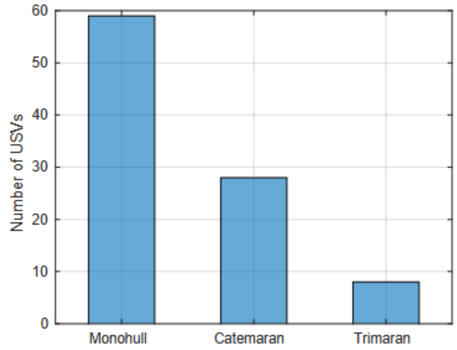
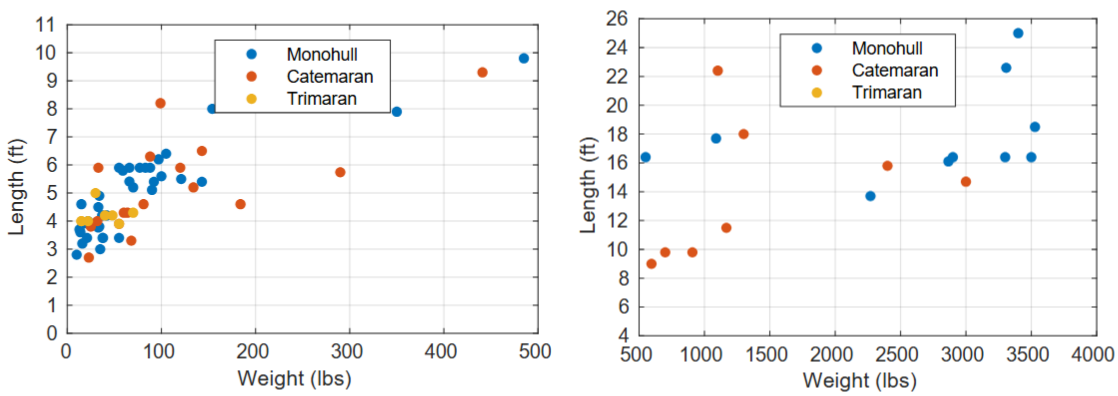


Figure 17: Categorization of USVs by hull type.

Many manufacturers design their own hulls and vehicle structures. Materials include composites such as polyester carbon fiber, Kevlar fiberglass, with gelcoat finish, as well as plastics such as polyethylene, PVC, and various metals such as aluminum or steel as needed. However, it is also common, especially among universities and other smaller-scale productions, to leverage existing small boats (e.g., kayaks, canoes) or elements from these boats, such as outriggers. There are a few examples of USVs designed around inflatable monohulls or rigid inflatables (RIBs). Several companies, such as Milanion Tech, also offer USV conversion kits, that can convert existing manned vessels into USVs (or optionally piloted vessels). Other unique designs include amphibious systems that are capable of operating both on land (wheeled) and as boats in shallow water.

4.6 Typical USV Lengths

The results of the dataset analysis for USV length are shown in Fig. 18. Most USVs that under 100 lbs are less than 6 ft. Group I and II USVs average closer to 4 ft in length. As expected, increasing weight is correlated with lengthier vessels-Group III, IV, and V USVs average about 6, 14, and 18 ft., respectively. It is interesting to note that trimaran hull designs are mostly used in smaller vessels less than 100 lbs. Larger vessels exceeding 3000 lbs are typically monohulls.



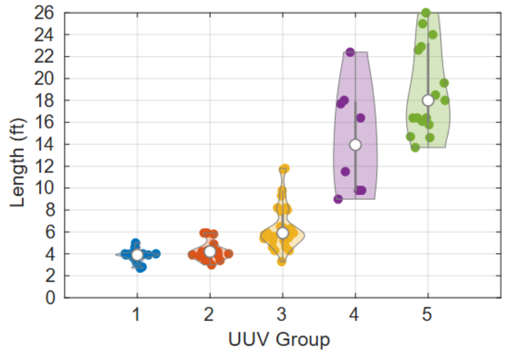
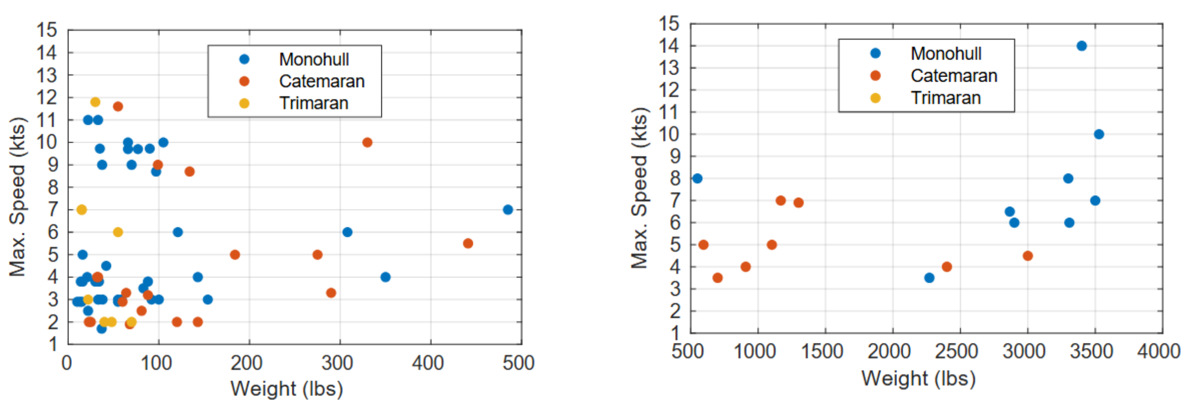


Figure 18: USV lengths reported in dataset. Left: length with weight for Group I-III USVs, Right: lengths with weight for Group IV-V USVs, and Middle: violin plot of length for each UUV Group. The white circular marker indicates the mean.

4.7 Typical USV Propulsion: Speed and Endurance

Propulsion systems commonly used onboard USVs are electric brushless motor thrusters with propellers, water jet propulsion, and diesel motors. Purpose-built electric motors are used. In some custom designs, trolling motors have been adapted for USVs. Various motor/propeller housings are employed, including recessed designs to improve efficiency and mitigate concerns of vegetation fouling the propeller. Some configurations employ more than two thrusters or just one thruster (in which case a rudder is required). When using multiple thrusters, turning motions are achieved by varying thrust output to create a differential thrust and torque. While most of the thrusters are rigidly mounted, there are also servoed designs that rotate the entire thruster relative to the USV body. Larger vessels with greater endurance may use diesel/gas engines in either inboard or outboard configurations.

Some unique propulsion mechanisms include hovercraft for extremely shallow water < 1 lbs (Troup et al.,2023). While not focused on in this report, there are a number of amphibious craft (Rafeeq et al.,2021). These designs include systems that utilize wheels, legged locomotion (biped, quadruped, hexapod, octapod), tracks, spherical rolling motion, spherical, biomimetic (e.g., snake-inspired) locomotion, including hybrid systems (such as wheel or leg paddles).



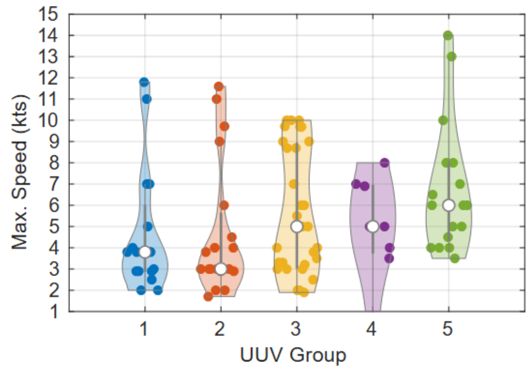
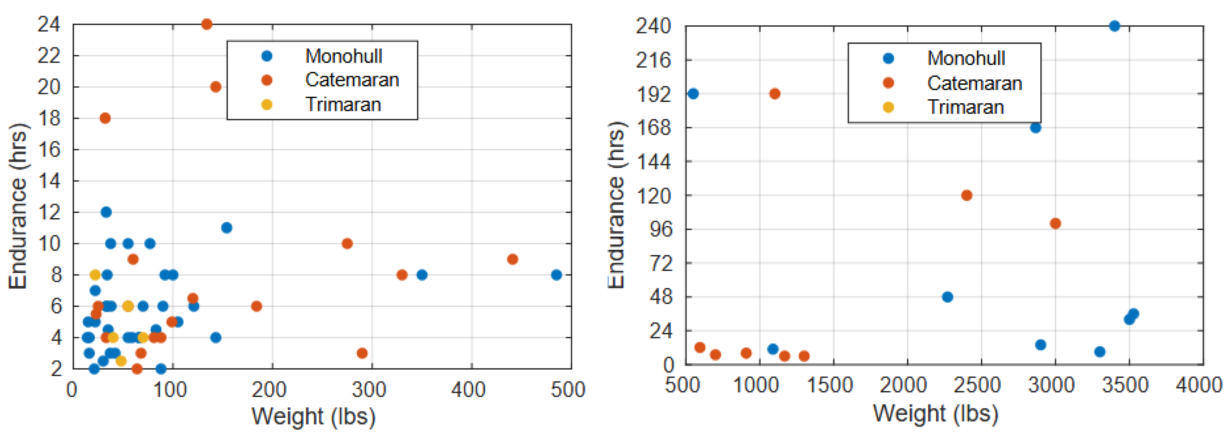


Figure 19: USV maximum speeds reported in the dataset. Left: speed with weight for Group I-III USVs, Right: speed with weight for Group IV-V USVs, and Middle: violin plot of speed for each UUV Group. The white circular marker is the mean.

The results of the dataset analysis for USV speed are shown in Fig.19. Maximum speeds of USVs are generally 12 kts or less and average between 3-6 kts. Typically, the maximum speeds reported are “burst speeds". Survey speeds can be much less (e.g., between 10-30% of the burst speed). Several outliers are observed in Groups I and II and correspond to designs such as the Alpha-Hi (max speed 11.6 kts) that uses high-pressure/power dual pump jet thrusters. The Oceanscience High Speed Riverboat is designed to operate in 11.8 kts water velocities; however, it is a tethered system that is not independently propelled.

The results of the dataset analysis for USV endurance are shown in Fig.20. Most USVs under 100 lbs have an endurance of 10 hours or less (many are limited to 4-6 hours). Typically, these systems utilize lithium polymer batteries. The average endurance across Groups I-III is about 6 hours. Group IV UUVs have an average endurance close to 10 hours. Group V UUVs have an endurance of 100 hours (about 4 days). These large platforms use diesel motors or harvest energy from the environment (e.g., solar, wind, wave).



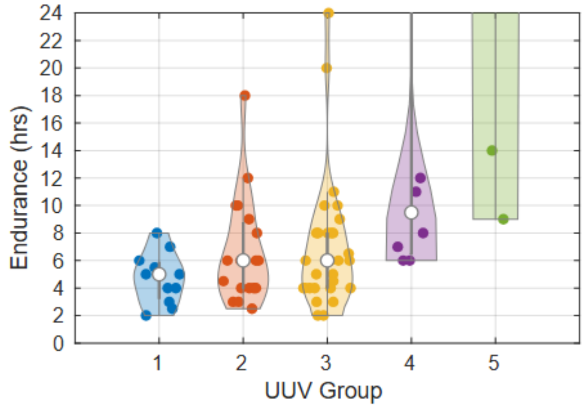


Figure 20: USV endurance reported in the dataset. Left: endurance with weight for Group I-III USVs, Right: endurance with weight for Group IV-V USVs, and Middle: violin plot of endurance for each UUV Group. The white circular marker indicates the mean. Not all data is shown- the axes are truncated for clarity.

4.8 Typical USV Single-beam ECHO-Sounders

A variety of sonar-based technologies exist for bathymetry mapping, including single-beam echo sounder (SBES), multi-beam echo sounder (MBES), and inferometric side-scan sonar systems. An SBES is the easiest to use and interpret; it is also the most affordable of the three types of systems. SBES works by emitting a sound wave at a fixed frequency, usually in the range of 20-500 kHz (or at two frequencies, one low and one high) and recording the resulting Echogram. In simpler models, the Echogram is processed immediately and using an assumed (or measured) depth-averaged speed of sound a depth reading is produced. More advanced SBES systems record the Echogram to allow for later adjustments and post-processing, including various corrections (e.g., tide, draft, sound speed, depth smoothing, outlier rejection). Dual-frequency systems can potentially discern the thickness of a layer of soft mud, sludge, or vegetation. The Echogram data is georeferenced using a GNSS/RTK position or a total station. When SBES systems are mounted on a vessel, they are typically programmed to continuously collect data (e.g., common ping-rates are 10-100 Hz). The result is a nearly continuous profile of a section of the terrain below the path of the vessel (see Fig. 3). Other SBES systems are designed to be used as handheld systems by a surveyor who controls the data collection process. SBES data is processed by professional hydrographic surveying software packages (e.g., HYPACK ECHO) to produce a final product, usually as depth contours of the area of interest.

The factors that influence the quality of data produced from an SBES survey include echo-sounder hardware and data processing, as well as positioning accuracy. Echosounder hardware includes the transducer that is characterized by frequency, beam width, and internal data acquisition electronics, and minimum depth (important for shallow water survey). Generally, lower frequency systems can penetrate greater depths but have larger beam widths that tend to smooth out the terrain. Whereas higher frequency systems have shorter range but narrower beams and more precise measurements. The beam width and the overall depth determine the sensor's footprint and the degree to which the bathymetry is spatially smoothed or blurred (e.g., a 9-deg. beam in 6 ft. of water has a sensor footprint of about 1 ft for which it reports a single Echogram or depth). The transducer itself usually includes some processing of the received Echogram and can be designed from different materials and data acquisition electronics (analog-digital-conversion, filtering, etc.). One popular system, the Sonar Mite v5, is based on the P66 transducer, which was originally designed for commercial fish finders. This technology is widely used in older echo sounder models, but is unable to save Echograms. Many vendors of SBES systems have now moved towards more sophisticated transducer technologies that record the Echogram for processing in software such as HYPACK. Although SBES is relatively simple, it requires some training to use correctly. For example, the operator should appropriately adjust the power gain (dB) to avoid reverberation/multipath issues. Readings may be unreliable in turbulent water with entrained air bubbles and can be more challenging to interpret from the Echogram when there is heavy vegetation. Although SBES technology cannot match the industry standard of multi-beam echo sounders (MBES) it remains very widely used because of its low cost and convenient operation, especially in rivers and shallow sea surveys or in ponds where boat access is limited. MBES is an order of magnitude more expensive and requires complex instrumentation making it more difficult to use. Examples of single-beam echosounder employed on USVs include the following makes/models:

- CEE HydroSystems: CEESCOPE D230/D270
- ECHOlogger: EU400/EU200
- Airmar Technology Corporation: SS510 ECHORange
- Kongsberg: Simrad EK80
- Seafloor Systems: HydroLite-DFX
- Teledyne Marine: ECHOTRAC E20/CV100
- Blue Robotics: Ping2
- KOLIDA: SDE-18s

The typical specifications/considerations for selecting an SBES are described below.

GNSS receiver integration: Sonar systems may be provided as integrated with a GNSS or require the user to perform the integration with their own GNSS receiver.

Ping Rate: The ping rate describes how many measurements are taken per second and can vary from 1-50 Hz. The ping rate should allow sufficient time for sound to travel to the target depth and return between pulses; this setting is determined by the depth in the operating area. Higher ping rates provide more densely spaced measurements.

Clocks: Recording the precise time-stamp with each measurement is important, especially when using GNSS correction software. Time-stamp precision is often achieved using a pulse per second (1PPS) electrical signal.

Frequencies: Common frequencies include a single high frequency band of 200 or 235 kHz, or a dual frequency band with a lower frequency (e.g., 12, 24, or 33 kHz) combined with the higher frequency band. The two channels can potentially be used to distinguish between the hard and soft bottom of a water body, which may be particularly relevant for dredging-related surveys.

Beam width: The beam width depends on the transducer and frequency. A standard 200 kHz beam width is about 5-9 degrees, and a narrow 200 kHz beam width is about 3-4 degrees. Lower frequencies usually have larger beam widths from 19-24 degrees.

Resolution and Accuracy: A common resolution specified is 1 cm. Accuracy is stated as ranging from 1-5 cm at best. The accuracy reduces as a percentage of depth (typically 0.1% of depth). Depth range for SBES operation is typically 0.15 m to 200 m.

4.9 Other USV Bathymetry Mapping, Hydrology, and Inspection Sensors

Other common sensors used onboard USVs include multi-beam echosounders (MBES), side-scan sonar (SS), acoustic doppler current profiler (ADCP), sub-bottom profiler (SBP), above-water LiDAR, and water quality instruments.

Acoustic Doppler Current Profiler: ADCPs are used for measuring the speed of water currents through the water column for discharge calculation. Examples of ADCPs employed by USVs include: the Sontek (S5, M9), Teledyne RD Instruments (StreamPro, RiverRay, RiverPro), LinkQuest Inc. (FlowQuest or FlowScout Models).

Multi-beam Echosounders: MBES have superior coverage rate and are the standard for high-resolution bathymetric surveys; however, MBES require additional sensors (i.e., inertial navigation systems, compass) to achieve accurate processing of the acoustic data. MBES can be deployed as a towfish or mounted on a vessel (e.g., transom or over-the-side) using a specially designed retractable pole that has precise offset measurements between GNSS receiver and transducer. Examples of MBES reported as employed on USVs include: Kongsberg EM2040P, Norbit WBMS/iWBMS series, R2SONIC Series, Teledyne Marine (SeaBat IDH T20/50-R), Teledyne Marine (Odom MB2).

LiDAR: LiDAR units provide point-cloud data when the USV operates in close vicinity to structures. Examples of LiDAR reported as employed on USVs include: Norbit iLiDAR, Velodyne VLP-16, Hesai brand LiDAR, Ouster brand LiDAR.

Side-scan Sonar: Sidescan sonar provides imagery of the lake, river, or sea bottom. Examples of LiDAR reported as employed on USVs include: Blue Print Subsea (Starfish series), Cerulean Sonar (Omniscan 450), Imagenex (YellowFin), Tritech (SeaKing).

4.10 Typical USV GNSS Sensors

SBES measurements obtained from a USV during surveys can be georeferenced using a total station or GNSS with corrections. GNSS-based correction methods include: (a) single-baseline real-time kinematic (RTK) methods wherein a local base station (e.g., tripod mounted base unit) broadcasts corrections over a radio channel to a nearby rover module on the USV, (b) network RTK using virtual reference stations (VRS) that are regional networks (e.g., NC CORS) broadcasting corrections that are received by specialized modems onboard various data collection platforms, or (c) satellite-based correction services (e.g., Trimble RTX) that provide the corrections via an L-band communications satellite available anywhere without additional hardware or infrastructure. The various correction methods can improve standard GNSS accuracy (i.e., more than 1 meter) to within 2 cm horizontal and 3-5 cm vertical, depending on type.

Correctly integrating a GNSS into a USV survey is essential for high-quality data acquisition. However, regardless of correction technology, all GNSS-based systems will degrade or become unusable if there is not a direct line of sight to satellites (e.g., if obscured by heavy vegetation, steeply sloped terrain, or concrete structures). The typical specifications/considerations for selecting a GNSS are described below.

Satellite Constellations: There are numerous constellations of satellites launched by various entities, include GPS, GLONASS, Beidou, Galileo. In general, these constellations are referred to as the GNSS (Global Navigation Satellite System). Different positioning systems may be designed to receive data from one or more of these constellations.

Frequency Bands: Satellites broadcast at multiple frequencies, including the following bands: L1 (1575.42 MHz), L2 (1227.6 MHz), and L5 (1176 MHz). Some receivers are designed to benefit from new civilian GPS signals currently being phased in (L2C, L5, L1C).

Antennas: GNSS receiver antennas are designed to receive one or more frequencies (e.g., commonly L1/L2 dual frequencies). Antennas also can determine how well difficult scenarios, such as operating near buildings or foliage, multipath, and signal-to-noise ratio. Example antennas reported to be used on USVs include the Hemisphere GPS A42 Antenna, NovAtel GPS-702-GGL antenna, and Trimble GA830 Antenna.

GNSS Correction Services: There are many different correction services offered by commercial satellite providers. Examples include the Satellite-Based Augmentation Systems (SBAS), the Atlas correction service (e.g., Atlas Basic L-Band, or Atlas H-10 L-Band Correction), Trimble RTX corrections, NovAtel GPS/GNSS TerraStar correction services, and local RTK base station corrections.

Raw Data Recording: Recording the raw GNSS data can allow surveyors to re-process the data at a later time and include information from other sources, such as a CORS network that was not available during the survey.

Other Factors: The refresh rate describes how many position updates are provided per second; typical values are up to 20 Hz (or even higher 200 Hz).

GPS receivers refer to the physical devices that encompass the antennas, communication, and processing components. Common receiver options include Trimble, Hemisphere, and Novatel brands with options to incorporate into RTK base stations via UHF radio modem. Low-cost receivers include Emlid. Example receivers include: Hemisphere Eclipse L1, Hemisphere Eclipse L1/L2 RTK, NovAtel 729 L1/L2, NovAtel 729 L1/L2 RTK, Trimble BD990 RTK, Trimble GNSS BD982. Some USVs utilize specialized receivers to provide heading information with dual antennas — an example is the Trimble BX992 GNSS heading receiver.

4.11 Typical USV Communication Systems

Common communication systems include standard 2.4 GHz radio systems for manual control within a few hundred feet, as well as other radio systems for telemetry (e.g., 900 MHz radio) or WiFi. ASVs that operate inland can also potentially utilize cellular networks. Offshore systems may rely on satellite systems for communication, such as Iridium.

Chapter 5. NCDOT Use Cases and Platform Rating System

5.1 Potential NCDOT Use Cases of USV and Sonar Technology

Potential use cases of USV and sonar technology by NCDOT applications were generated based on the literature review conducted. NCDOT's Location and Survey Unit is the likely operator/user of USV and sonar technology. NCDOT's Hydraulics Unit (Division of Highways) is a likely consumer of obtained data as well since they provide technical expertise for hydrologic and hydraulic studies managing stormwater, riverine, and coastal aspects of transportation projects (NCDOT Hydraulics, 2024). This includes bridge and culvert recommendations, coastal/riverine modeling, drainage investigations, flood warning tools, scour response support (NCDOT Hydraulics, 2024). Other NCDOT Divisions or specific programs that may benefit from USV technology are mentioned below where applicable. The following eleven (11) use cases were determined:

1. Coastal surveys and monitoring depth/width of ferry channels for dredging assessment. NCDOT Ferry Division is the second largest state-run ferry system in the United States with over 20 ferries on seven regular routes across the Currituck and Pamlico sounds. The ferry division also plays an important role during coastal emergencies. Due to the complex underwater terrain, ferries near ocean inlets often must travel within very narrow channels to avoid collisions (see Fig. 21). USVs can be used to regularly map bathymetry along ferry routes to monitor the need for dredging as well as pre- and post-dredging operations planning and evaluation.

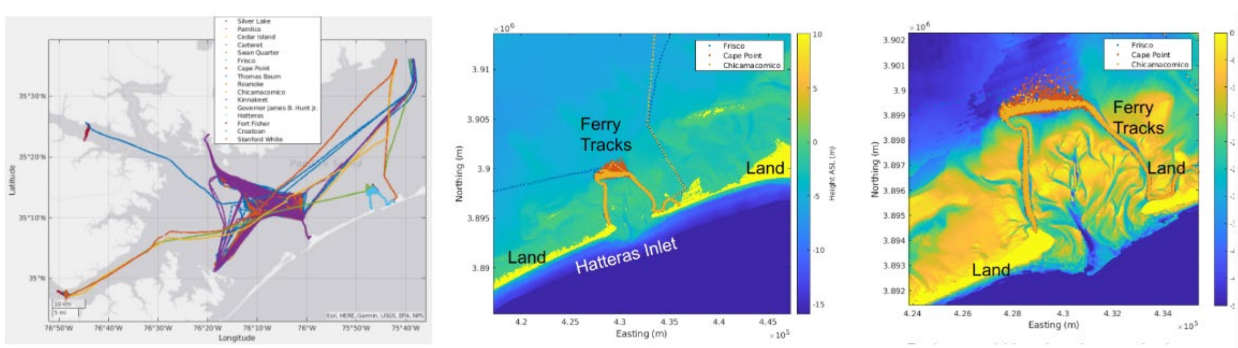


Figure 21: Raw data obtained for dates 3/31/2021-3/31/2022 from marinecadastre.gov using MSSI number for the fleet of NCDOT ferries (includes 5 Sound class, 7 Hatteras Class, and 9 River Class ferries). Middle: Ferry tracks near Hatteras Inlet plotted over the NOAA CUDEM (Continuously Updated Digital Elevation Model). Right: Close-up view of Ferry tracks required to navigate complex channel.

2. Bathymetry measurement in difficult-to-access inland bodies of water. Small portable USVs can be transported in a pickup truck and carried by a two-person team to a more remote testing site that may be difficult to access otherwise (e.g., no boat ramp or vehicle access, steep walls, or vegetation). Moreover, it can be deployed in small areas (e.g., creeks or small retention ponds) where a jon boat would have difficulty maneuvering. NCDOT applications can include data collection in such areas to support hydrologic/hydraulic modeling and drainage investigations near highways and other infrastructure.

3. Bathymetry measurement in strong currents. Small portable USVs can be deployed via a tether to provide bathymetry measurements in strong currents that would be too dangerous and inefficient for a manned vessel. In such cases, the vehicle moves downstream and allows cross-stream control through steering. To adjust the downstream position, the tether is reeled in/out. Examples have included vehicles tethered with operators controlling vehicle movement from an under-bridge inspection unit, from above the bridge, or with a harness while standing mid-stream in waders. NCDOT applications include bridge scour monitoring and data collection for hydraulic modeling in water bodies around bridges with high currents.

4. Bathymetry measurements in easy-to-access lakes with calm water or near bridges with relatively mild currents. USVs are ideally suited for making measurements in small-to-medium-sized lakes, ponds, and rivers that are easily accessible and do not have strong currents. In comparison to manned surveys, the main advantage of USVs is to reduce operator workload, provide repeatable surveys, and enable scaling to multiple vessel surveys simultaneously. For example, once NCDOT performs a survey, the waypoint path can be stored and later reused on subsequent surveys. Data generated can be used to build GIS databases and provide longer-term monitoring of changes in bathymetry.

5. Post-emergency rapid assessment. USVs can be used in the aftermath of coastal emergencies for rapid assessment of bathymetry changes due to hurricanes or other natural disasters. In this context, larger coastal USVs can be used to systematically scan important waterways/routes to ensure sufficient depth for large draft ships to pass and provide support for post-emergency activities (e.g., transporting goods, clearing debris). Smaller USVs can also be used to assess the degree of flooding (e.g., by sampling water level above submerged roads/highways). A major benefit of using USVs in this context is the reduction of risk to personnel since there are many hidden obstacles/hazards in the build environment during floods. Lastly, major weather events can also change underwater terrain around bridges and affect scour conditions. USVs can be used as a rapid assessment tool in this context as well.

6. Bathymetry measurement and/or water quality sampling in toxic or potentially polluted bodies of water. Bodies of water such as coal ash impoundements, agricultural and other wastewater lagoons, and mine tailing ponds can host toxic chemicals. While USVs can be used to monitor water levels, toxicity, or biomass in these water bodies, it is not within the scope of NCDOT activities. However, NCDOT does monitor water quality/pollution from roadways. For example, NCDOT's Highway Stormwater Program helps address pollution in stormwater collection systems and roadside ditches through best management practices, construction of treatment devices, and toxicity testing (NCDOT Stormwater, 2024; NCDOT Centerline, 2020). NCDOT also evaluates the environmental and biological impact of construction projects (e.g., new highway connectors) on wildlife (NCDOT TIP, 2018). NCDOT occasionally handles oil spills on roadways (e.g., via sandtrucks). Most roadside ditches are fairly small and can be accessed/sampled easily by personnel. However, there may be circumstances where pollution or a spill may require sampling a larger adjacent pond or water body that would benefit from rapid assessment offered by a USV so that NCDOT personnel do not need to enter the contaminated water.

NCDOT Ports Authority can potentially also benefit from a water quality monitoring USV. Ships release oil, fuel, waste, and chemicals into the water; monitoring pollution levels in marine ports is an important part of environmental stewardship. While it may be beneficial for NCDOT to maintain an internal capability for water quality monitoring, major environmental concerns would be addressed by the North Carolina Department of Environmental Quality (NCDEQ).

7. Detecting obstructions in drainage/stormwater management systems. Trees, abandoned vehicles or watercraft, and other large debris/items can potentially obstruct water flow in drainage systems and related retention bonds and reservoirs. USVs equipped with imaging sonar (e.g., side-scan) can allow a quick assessment to determine and localize the presence of underwater debris. USV systems outfitted with commercial fishfinder sonars are sufficient for this task and are relatively inexpensive. The UNC Charlotte team hosted a local small business, “Helo & Sub” that recently moved to North Carolina to discuss their uncrewed surface vessel (USV) technology with imaging capability (see Appendix).

8. Other environmental characterization activities (e.g., discharge measurement and sediment characterization).

USVs can be equipped with acoustic Doppler current profiler (ADCP) sensors to measure water velocity profiles and have been specifically designed to operate from a tether in high-speed flow. These devices are routinely used for discharge measurements. An example USV specifically designed for this application is the Teledyne High-Speed Riverboat which is designed to operate in water velocities up to 20 ft/s and typically between 10-16 ft/s (Teledynemarine, 2024). It has also been shown that single-beam echo sounders can be used to characterize sediment type (Hilgert et al., 2016).

9. Ultra-shallow water and/or in culvert/pipe mapping. NCDOT applications can involve measuring water depth in very shallow waters (less than one foot), such as rocky creeks in front of or inside various culverts or other shallow water areas. The main concern for deploying USVs in such environments is the ability to navigate and collect robust measurements. GPS position quality is also a concern for data collection underneath or inside structures.

10. Documenting shipwrecks and underwater historical heritage sites. This application of USV technology is relevant to NCDOT's Division of Highways, Environmental Analysis Unit, and Archaeology. For example, in 2018, NCDOT's Archaeology Unit partnered with the Coastal Studies Institute to study Pappy’s Lane shipwreck (NCDOT Pappy, 2018). USVs equipped with side-scan imaging or multibeam sonar are well-suited for detecting and localizing possible underwater artefacts.

11. Automated cargo vessels. It is recommended that NCDOT Ports Authority closely monitors developments in port automation technology and autonomous commercial vessels. Long-term planning will prepare higher cargo volume NC ports, such as the Port of Wilmington and the Port of Morehead City, to adapt to new technologies. Discussions on potential infrastructure investments with other large neighboring ports, such as the Port of Savannah, the Port of Virginia, and the Port of Charleston, would be beneficial.

5.2 Platform Rating/Categorization

In the following, we establish rating/categorization criteria that are derived from data collected in the USV survey; these include: a logistics rating, environment rating, typical deployment duration, and typical mapping sensor categorization.

Logistics Rating. The logistical requirements to deploy an ASV are related to the number of personnel required to transport, deploy, and recover the vessel, along with the number and type of specialized equipment, instrumentation, or support vessels needed to carry out successful operations. To a large extent, logistics are proportional to the gross weight of the ASV. Smaller ASVs can be deployed by a single person or two-person team, can be disassembled and transported in a personal vehicle or pickup truck, and are easily deployed and recovered from the water. Larger vessels may require a dedicated trailer for the ASV and a boat ramp for deployment. Some ASVs are also deployed from manned ships or research vessels, often with the use of an A-frame and winch system and/or crane to load/offload from the ship at port. This report defines the following categories of transport/deployment logistics:

- Minimal: 1-2 person deployable, transport in personal vehicle/pickup truck, typically Group I and Group II USVs.
- Moderate: Requires a trailer for transport and launch from a boat ramp, typically Group III and Group IV USVs.
- Extensive: Requires trailer for transport and a dedicated research/support vessel with crew, A-frame, crane, or other heavy equipment for deployment/recovery, typically Group V USVs.

Environment Rating. USVs, especially those designed to operate in the coastal ocean, are often rated based on their ability to operate or withstand adverse wave conditions according to the Douglas Sea State Scale (see Table 3).

Table 3: Douglas sea state scale

Degree	Wave Height (m)	Description
0	No wave	Calm (glassy)
1	0.0-0.1	Calm (rippled)
2	0.1-0.5	Smooth
3	0.5-1.25	Slight
4	1.25-2.5	Moderate
5	2.5-4.0	Rough
6	4.0-6.0	Very rough
7	6.0-9.0	High
8	9.0-14.0	Very High
9	>14	Phenomenal

Vessels that can withstand high sea states are designed with higher structural integrity and may feature designs such as a self-righting after being overturned. Under typical conditions, most inland surveys in NC lakes, rivers, and ponds the sea state is 0–1, and wave interference with USV operation is not a concern. It is possible that higher sea states (i.e., greater than or equal to level 2) may arise inland during adverse weather events/strong winds. There are some coastal areas of NC that may be of interest to NCDOT for bathymetry measurement that can potentially experience higher sea states 2–3 on a regular basis. The ASVs that are designed for higher sea states are larger. For example, the 700 lbs vessel "C-CAT 3" by L3Harris is marketed as a robust shallow water ASV and is stated to be capable of operations in up to and including sea state 2. From the same company, the C-Worker 4 is a nearly 14 ft. vessel weighing over 2,200 lbs that is designed for inshore and coastal survey work in shallow and constrained waters that may be inaccessible to standard survey vessels. This system is designed to operate up to and including sea state 4 and survive in sea state 5. An alternative method of evaluating weather conditions is based on wind speed, called the Beufort scale. For example, the Maritime Robotics Mariner is designed for Beufort scale 4 for survey, scale 6 for transit, and 7 for survival.

Water currents in the ocean are typically up to 8 ft/s, whereas water currents in fast-flowing rivers can exceed 20 ft/s. The combination of water currents and sea state is used to define the following rating scale for USV weather operation:

- Calm waters (Sea state 0-1, water currents 0-4 ft/s)
- Coastal waters (Sea state 2-3, regardless of water currents)
- High flow waters (Water currents 4-20 ft/s, regardless of sea state)

Typical Deployment Duration. The required time on-site for a particular survey task depends on the size of the survey area, speed of the vessel, and constraints of the. We define the following deployment durations:

- Single-Day Survey (1-6 hours)
- Multi-Day Survey

Typical Mapping Sensor. USVs typically can accommodate a range of sensors, including standard sensors recommended by the manufacturer or integration of custom sensor payloads requested by the customer. Because of this flexibility, the mapping sensor rating provided here is indicative of a combination of two factors: (1) the payload capacity that a USV can potentially accommodate, and (2) specific advertised usage of a particular USV platform. For example, some USVs are specifically advertised as single-beam echo-sounder platforms, side-scan sonar platforms, or multi-beam platforms. We define the following three ratings:

- SBES: A USV dedicated primarily to single-beam echo-sounder surveys
- SS: A USV dedicated primarily to side-scan (SS) surveys
- Multi-role (MR): A USV capable of accommodating multiple sensors, including SBES, SS, ADCP, sub-bottom profilers, water quality sondes, etc.

Current Usage Rating. This is a subjective application-specific rating that describes how the authors view the current state-of-the-art with respect to each application area. The assessment is based on the frequency with which the application is discussed in existing literature and advertised by manufacturers. The two rating categories are:

- Common: a popular use case for USVs that is widely advertised and employed
- Less Common: a document use case for USVs, but not encountered often or used in more specialized cases

5.3 Requirements for NCDOT Use Cases and Suitable USV Platforms

The following matrix maps the rating criteria defined in the previous section to the NCDOT applications identified.

Table 4: Anticipated characteristics of USVs for NCDOT application cases.

	Current Adoption Level	**Required Logistics / Difficulty**	**Typical Deployment Duration**	**Required Environment Rating of USV**	**Likely Mapping Sensor Required**
A4) Bridge inspection in easy-to-access inland waters / calm rivers	Common	Minimal	Single-Day	Calm	SBES, MBES
A6) Water quality monitoring	Common	Minimal	Single-Day	Clam, High flow	Water quality sonde
A7) Obstruction/ underwater search	Less Common	Minimal	Single-Day	Clam, High flow	Sidescan
A2) Difficult-to-access inland water	Common	Moderate	Single-Day	Clam, High flow	Sidescan, SBERS, MBES
A8) Environment Characterization	Less Common	Moderate	Single-Day	Clam, High flow	Sidescan, SBERS
A5) Emergency assessment	Less Common	Moderate	Single-Day	Clam, High flow	Sidescan, SBES
A9) Ultra shallow water	Less Common	Moderate	Single-Day	Clam, High flow	SBES
A3) Very strong currents	Less Common	Extensive	Single-Day	High flow	SBES, MBES
A1) Coastal survey / ferry channel	Common	Extensive	Single-Day Multi-day	Coastal	SBES, MBES
A10) Archaeology	Less Common	Extensive	Single-Day Multi-day	Coastal	Sidescan, MBES

5.4 Recommendations for NCDOT

The following recommendations are made concerning future use of USVs at NCDOT:

- NCDOT should identify 1-3 key priority areas among those outlined in this report that stand to benefit from incorporating USVs into NCDOT operations (gain efficiency, repeatability, cost/time savings, or access to data previously difficult to obtain).
- The guidance in this report can be used to determine which USV model (or multiple USV models if needed) can support the identified highest priority areas. Vendors should be contacted for quotes and to initiate discussions to further understand cost and capabilities.
- NCDOT should purchase/adopt USV technology, initially through small-scale pilot studies, to gain further experience. This will allow NCDOT to assess the real-world value of the system (data quality and logistical effort given the cost) compared to existing NCDOT assets and capabilities.
- The outcomes of the pilot studies should guide further actions, which may include testing different USV models, sensors, or scaling up NCDOT's fleet of USVs to enable more widespread use.

- USV technology has many similar features to uncrewed aerial vehicles (UAVs). NCDOT should facilitate coordination among various users of uncrewed systems across the Department to share expertise.

Chapter 6. Evaluation of a Small USV for Inland Survey

6.1 Vehicle Selection

Small, unmanned surface vessels have been used for hydrographic survey in inland waters by numerous federal and state agencies for over a decade. For example, Michigan DOT, California DOT, and Florida DOTs, along with NOAA and USGS, have used USVs for bathymetric surveying and other applications, such as bridge scour or environmental monitoring. Several examples of small-scale vehicles with SBES are shown below.

Figure 22: Several USVs with equipped with SBES.

After reviewing platform requirements and discussions with several vendors the HyDrone USV manufactured by Seafloor Systems Inc. (Shingle Springs, California) was selected as an appropriate vehicle for this study.

6.2 HyDrone Overview

The HyDrone is a 1.2-meter catamaran design that can operate in both manually controlled and autonomous mode. The platform is a professional-grade system that balances cost with system robustness and data quality. The USV is equipped with a Hydrolite Plus SBES (also manufactured by Seafloor Systems Inc.) that is an improved version of their previous HydroliteTM/SonarMite SBES. The Hydrolite Plus SBES includes the capability to record georeferenced Echogram information for post-processing and uses a dual-frequency transducer (30/200kHz) with 5 deg. / 26 deg. beamwidth and a fast 100 Hz ping rate. The SBES unit is pole-mounted and can be removed from the USV to be used on a flat-bottom boat for more conventional manned surveys. A commercial platform, such as the HyDrone, will meet the robustness and reliability required for real-world use. Moreover, the vendor can more readily provide long-term support, supply replacement parts, or offer additional units/upgrades if needed by NCDOT in the future.

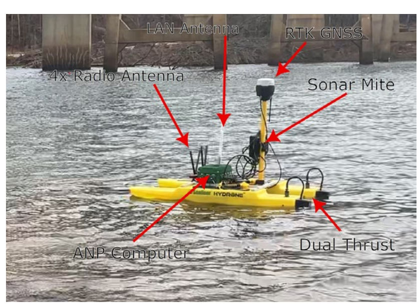


Figure 23. HyDrone deployment in the Catawba river.

Additional HyDrone hardware specifications are listed below.

Table 5: Hydrone specifications

Hydrone Specifications	
Weight:	25 lbs
Length:	3.8 ft
Width:	2.4 ft
Survey Speed:	2 kt
Endurance:	5 hrs
Power:	Two 4S 16000mAh Lipos

HyDrone Computer and Software

The HyDrone unit includes a Windows 11 computer called the AutoNav Plus (ANP) and a Cube Orange flight controller that enables features such as autonomous waypoint following. The ANP is responsible for autonomous operations via Mavlink. Mavlink is a communication protocol that is used in autonomous robotics, and running HYPACK, the bathymetry data collection platform. Mavlink and HYPACK communicate with each other during surveys to record position data and waypoint information during an autonomous survey. Additional ANP specifications are found in Table 6.

Table 6: ANP Specifications

ANP Specifications	
Operating System:	Microsoft Windows 11 Pro
CPU:	Intel(R) Core i3-7100U
RAM:	8.00 GB
Storage:	120.00 GB
Ports:	2 USB-A, 1 HDMI, 1 Ethernet, 1 LAN antenna, 4 Radio Terminals, 4 RS-232

The HyDrone operator can adjust the HyDrones speed settings and Hydro-Lite Dual Frequency echosounder settings from within the HYPACK software. HYPACK is a hydrographic survey data collection and analysis software tool. User interactions within this software will be the main method of adjusting survey parameters, such as the autopilot properties, which can be set up and saved pre-survey. These can be adjusted in Ardupilot (the software for the Pixhawk autopilot), but the HyDrone manufacturer presets them, and they do not need to be changed. A flow chart of the basic data processes of the HyDrone system is shown in Figure 24.

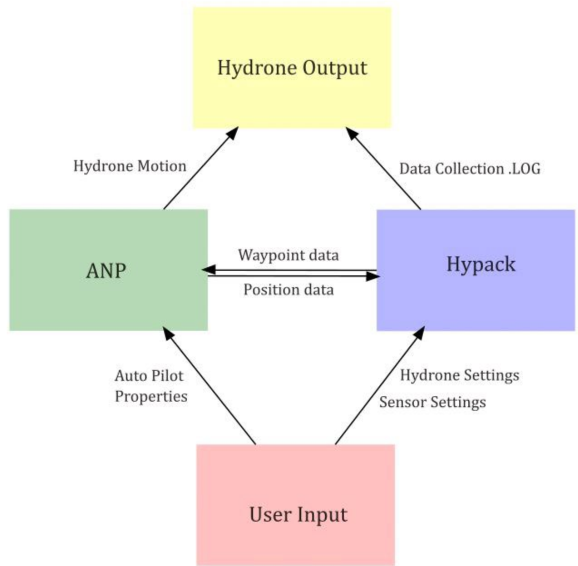


Figure 24: Flowchart of data processes carried out by the HyDrones computer and software components. The user sets up the ANP to control Hydrone motion and HYPACK to control data collection.

The HyDrone requires minimal assembly on-site. Fastening the pontoons to the frame, screwing in telecommunication components, and fitting the thrusters are the only major steps required to assemble the vehicle. To set up software components, the ANP is remotely connected via a shoreside ground station. This is how the ANP receives waypoint, mission plan, and sensor configuration information. The basic configuration seen below requires a portable battery bank to power the router for on-site deployment.

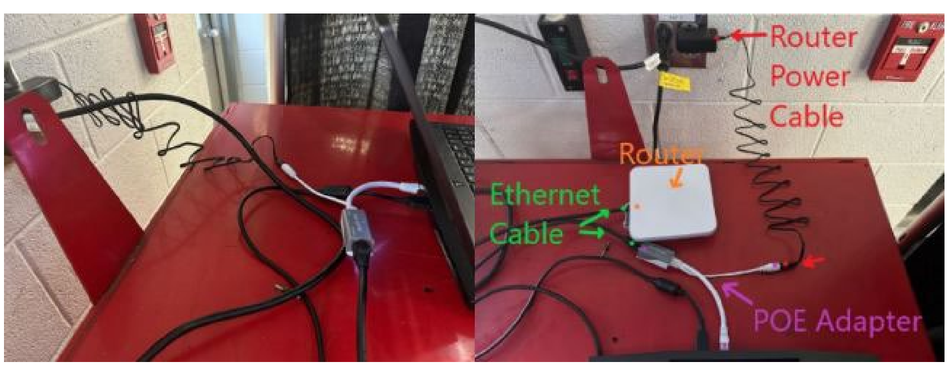


Figure 25: Connections required to remotely connect to ANP. In the field the router can be powered from a power bank.

For this research, the HYPACK ECHO licenses were used, which provided the ANP with project setup files, autonomous survey, data collection, and data export capabilities. Data analysis was conducted in the geostatistical software ArcGIS and MATLAB. The project files include all GUI and vehicle information that a surveyor would need to analyze an environment, including webmaps, border and line plan files, hardware configuration, and sensor correctional properties. The HYPACK GUI with a project setup can be seen in Figure 26.

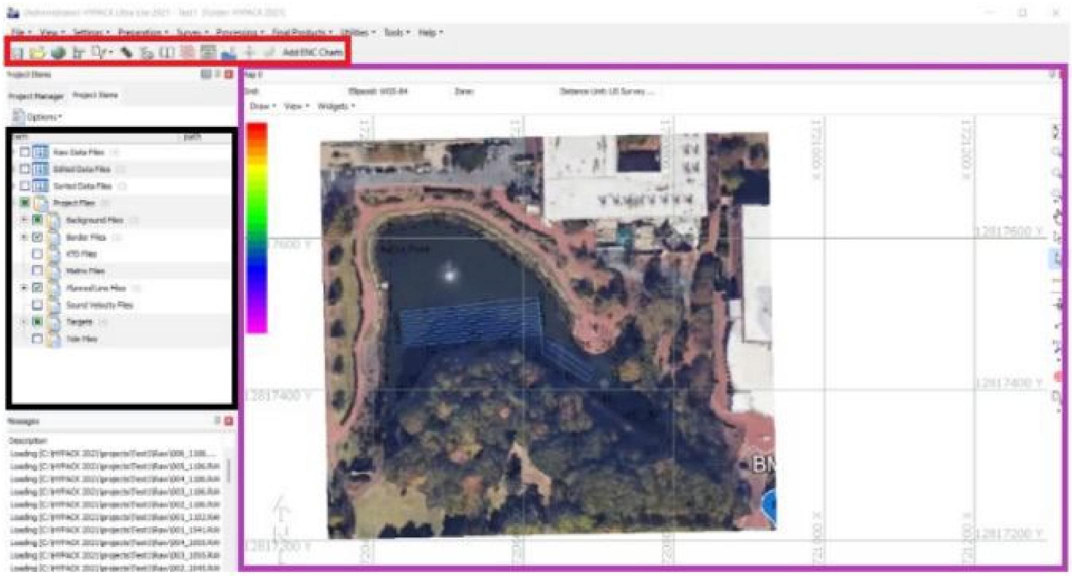


Figure 26: HYPACK user interface.

HYPACK survey is a tool within the HYPACK kernel and allows for live data viewing, survey progress, critical survey information, and allows for sensor configuration changes. The data logging function can be reached from the survey program and will save all survey information within the HYPACK kernel. In the survey program, multiple windows open showing the vessel location against the satellite image and waypoint path plan, echosounder setting, Echogram, and a left-right indicator. The HYPACK survey program is shown in Figure 27.

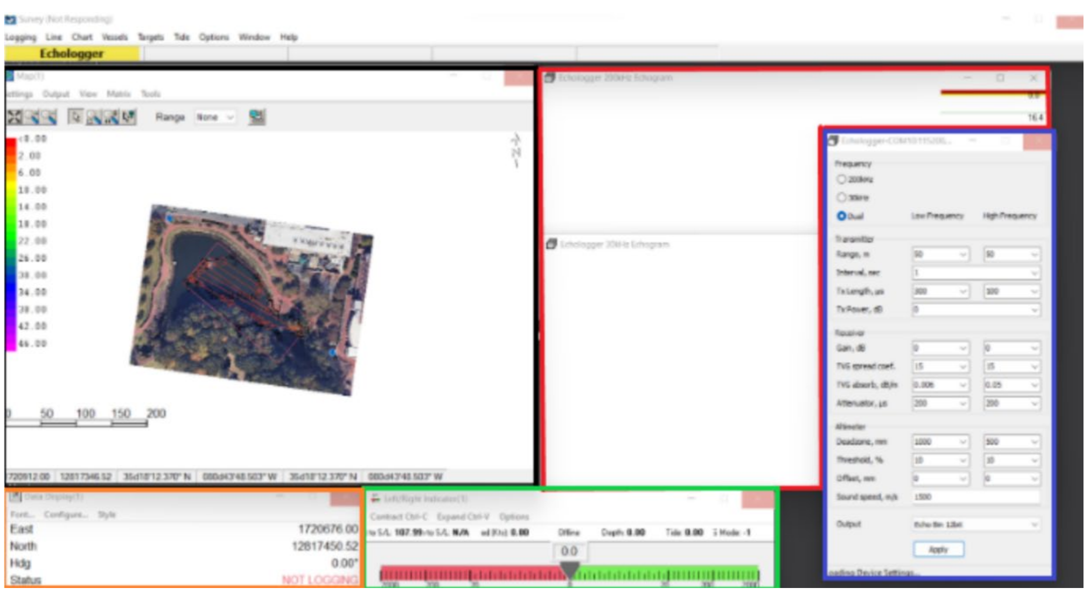


Figure 27: HYPACK survey view.

Once a survey is completed with data collection, survey data can be exported using the single beam editor tool within HYPACK, depicted in Figure 28. The depth values are displayed at the point they were collected from. The analysis tool within the editor shows different characteristics of a survey, this is where the Echogram can be viewed as well as exporting the raw data into a .txt document for further statistical analysis. This data is exported from the HyDrone via a USB drive for on-site data analysis.

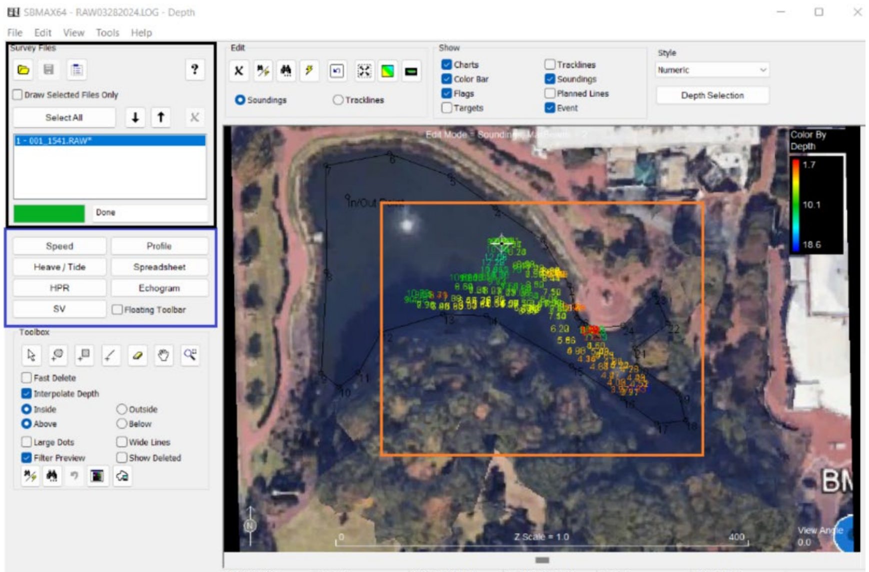


Figure 28: Single beam editor in HYPACK.

On-site data analysis is completed in ArcGIS. The data exported from the HyDrone can be uploaded into geostatistical analysis software for interpolation using kriging, as shown in Figure 29. Once kriged, statistical analysis tools within ArcGIS can be used to make maps, TIN models, contour maps, and geostatistical reports. This ArcGIS analysis can be performed shore-side. This ability allows for a rapid assessment of bathymetric data, which can be used to make on-site conclusions about the survey. In the assessment of bridge scour, disaster relief, and infrastructure inspection, the surveyor can inspect the data and determine if further data collection in a certain area or expanded region should be performed.

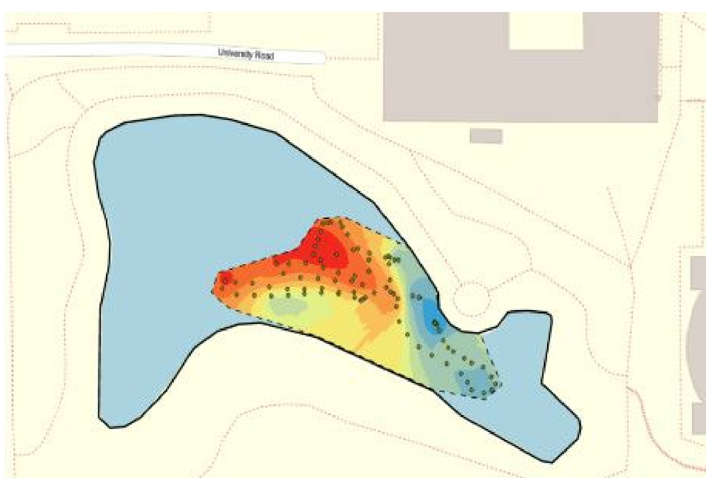


Figure 29: ArcGIS kriged data.

6.3 Initial Setup

UNC Charlotte received the vehicle as shown in Figure 30 and assembled the vehicle. After assembly, the basic capabilities of the vehicle to operate on water in manual and autonomous mode were tested.

Figure 30. Images above show pictures of the Seafloor Systems Hydro-Lite dual frequency echo-sounder on arrival.

As part of the initial setup, the UNC Charlotte team integrated a third-party Emlid RTK GPS unit that is compatible with the NC CORS network. This process involved some troubleshooting to allow Emlid to interface with the HyDrone's autonomy system AutoNav, using the MAVLINK protocol. The issues were determined to be related to the use of a specific "GP" identifier and using the correct series of adapters to convert logic levels for the serial data stream.

6.4 Emlid RTK Differential GNSS

The positioning system integrated with the HyDrone is the Emlid RS2+ GNSS RTK sensor. It is installed on the HyDrone sensor staff using RS-232 to communicate its position to the ANP computer. To obtain RTK corrections, the Emlid M2 GNSS device is used onshore to send positional corrections from the NC CORS network via NTRIP, where it then transmits that correctional data to the Emlid RS2+ on the HyDrone. This differential GNSS setup allows operators to get centimeter-level positional accuracy using inexpensive equipment relative to other RTK solutions. The HyDrones GPS port requires RS-232 at 38400 baud, which the Emlid RS2+ naively supports. Emlid GNSS sensor correctional, differential, and output settings can all be adjusted in the Emlid Flow software. Emlid Flow allows for a user with a computer or mobile device to connect to a Emlid GNSS receiver over a Bluetooth or Wi-Fi connection to adjust system settings.

6.5 Hydrolite Dual Frequency Echosounder

The Hydro-Lite has a complementary software called the ECHOlogger Control Program. This software allows the user to change different settings about device functionality. The same setting can also be changed in the HYPACK survey program. The default baud rate on the Hydro-Lite is 115200 and is connected via an amphenol connector on the front of the ANP, this serial port has a parallel terminal that allows the flight controller and ANP to receive the data. HYPACK is being used to record the GPS and echosounder data, and the control program does not need to be used for data collection. The detailed settings (Table 7) allow the user to change multiple aspects of how the device operates. These settings should be adjusted in different environments to provide the greatest accuracy.

Table 7: Description of several echosounder settings on the Hydrolite DFX.

Hydro-Lite Settings	
Range (m):	Maximum range measurement the sounder can output.
Interval (s):	Time interval in seconds between echosounder pings.
Tx Length (μs):	Transmitting pulse length in microseconds.
Tx Power (dB):	Transmitted pulse power, +48dB (max), -48dB (min).
Gain (dB):	Receiver gain in dB, representing the amplitude of the transducer pulse.
Attenuator (μs):	Time interval to attenuate -20dB analog input.
Deadzone (m):	Minimum distance where reverberations are ignored.
Threshold (%):	Minimum amplitude value for distance measurement.
Offset (m):	Device position offset in mm (also adjustable in Hypack).
Speed of Sound(m/s):	Speed of sound used for distance calculation, adjustable based on water type and temperature.

6.6 Custom First-Person View Camera System

They developed a first-person-view (FPV) camera system to mount on the HyDrone. An enclosure was fabricated with a battery power supply, cooling fans, and DJI 03 Air Unit transmitter. The housing was 3D printed and mounted onto the sensor survey pole that provides a view of both left and right pontoons and clear visibility of the region in front of the HyDrone seen in Figure 31. The operator on shore uses FPV goggles to see the water and the surrounding area from the HyDrone's perspective, and this allows identification of hazards that are difficult to observe from a distance.

Figure 31: DJI air unit housing on the HyDrone sensor pole (left) and view from FPV unit during a field test (right).

6.7 Other Survey Instrumentation and Tools

To provide additional data, environmental properties, or additional survey statistics, several other measurement instruments and surveying aids were included in surveying practice including:

- Global Water Flow Probe for measuring water currents.
- Three-axis Ultrasonic Wind Sensor for measuring wind conditions.
- Exo Multiparameter Sonde for measuring water temperature, turbidity, and other water quality parameters.

Figure 32. Left: Ultrasonic anemometer, Middle and Right: Water current flow probe.

6.8 Basic Functionality Testing (Radio Controlled Manual Data Collection)

The basic functionality of the HyDrone USV was evaluated through a series of GPS tests (dry tests performed outdoors) and in-water tests at our on-campus test site (Lake Hechenbleikner, see Figure 33). The HyDrone recorded bathymetric data in the remote-control configuration. Adjustments to vehicle deployment have also been made to reduce shoreside setup and HyDrone assembly times. The HyPack software was running with Fixed RTK position logging.

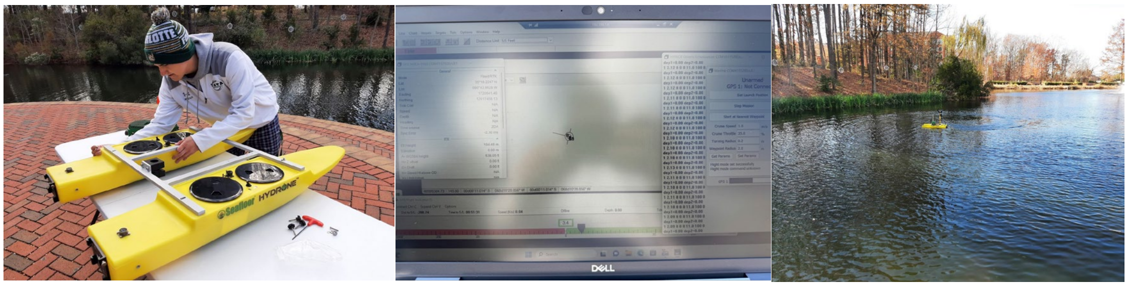


Figure 33: Deployment of HyDrone at Heckenbliekner Lake in December 2023. Left: assembly of the HyDrone pre-deployment, Middle: shore-side computer screen being remote-connected to ANP during the survey, Right: HyDrone surveying Heckenbleikner Lake in remote control mode.

6.9 Basic Functionality Testing (Autonomous Survey)

The HyDrone uses the AutoNav control system to navigate around pre-programmed survey routes with the MAVLINK protocol (a similar protocol as used onboard UAVs). To conduct autonomous surveys, the operator logs into the HyDrone computer via a remote desktop from a laptop and plans a mission in HYPACK (see Figure 34). Following manual remote control testing, the team performed autonomous surveys also on Heckenbliekner Lake.

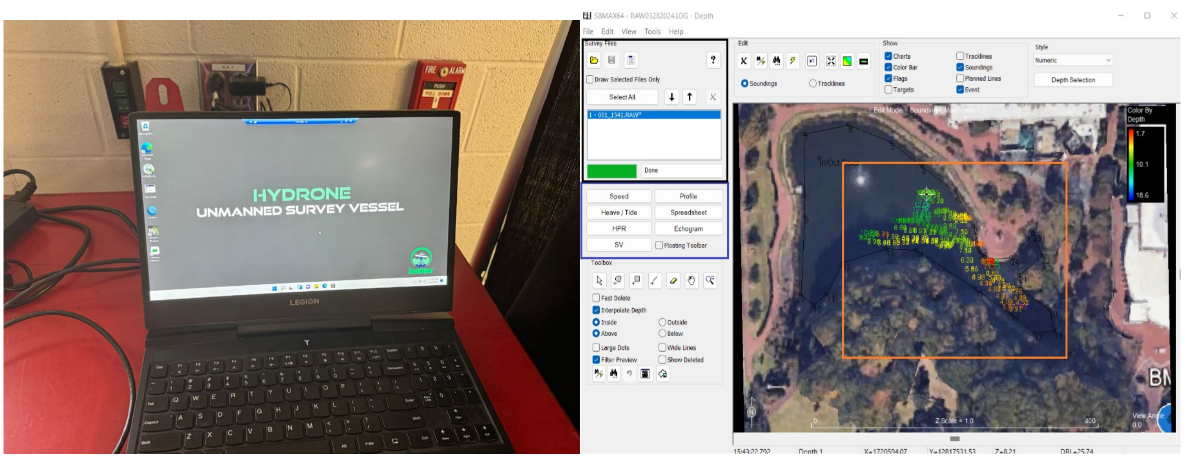


Figure 34. Left: HyDrone onboard computer environment. Right: Post-processing bathymetry data in HYPACK.

6.10 Summary of Field Trials Evaluating USV Data Collection Capabilities

The HyDrone used in data collection for this research was deployed 25 times at 10 unique locations, with a total survey in-water time across all testing being 41 hours. Field experiments were designed to assess survey viability, bathymetric results, and vehicle performance characteristics and statistics. A list and short description of the tests can be seen in the table below. Tests 1 and 2 were excluded, as these tests were used as introductory HyDrone configuration and data workflow tests without data collection.

Tests 1-8 were performed to learn the basics of operating the HyDrone, perform initial troubleshooting, and build survey strategies for off-campus testing. Tests 9-25 are a mixture of on and off-campus tests that have more direct goals. Types of experiments that were performed include GNSS signal strength in constrained areas, swathing widths' effect on geostatistical analysis, vessel speed, cross-track error severity under different conditions, battery drainage comparisons for all surveys, file size against survey time, deployment time, and echosounder tuning affecting statistical output. These experiments have been completed to provide evidence of proper USV deployment practices and draw conclusions about using a USV for rapid inland bathymetry assessment. Each test was accompanied by a detailed test report that is available to NCDOT. As an example, the Appendix includes a test report from testing conducted at Sloan's Ferry Bridge and later compared to prior NCDOT data and plumb line measurements.

Table 8: Summary of field trials.

Test Name	Date	Location	Objective
Test3_Auto	4/5/2024	Hechenbleikner	MavLink test
Test4_EchoOutput	4/5/2024	Hechenbleikner	Echosounder output settings
Test5_Auto$_2$	4/10/2024	Hechenbleikner	MavLink + lawnmower
Test6_BlindDeploy	4/12/2024	Hechenbleikner	Onsite creation of auto test
Test7_BlindDeploy_2	4/26/2024	Hechenbleikner	Onsite creation of auto test (with fix)
Test8_FullLakeTest	5/28/2024	Hechenbleikner	Full test, flow meter, wind, GNSS, full lake test
Test9_Latta	6/12/2024	Latta Nature Preserve	Endurance testing at different speeds
Test10_Cowans	6/12/2024	Cowans Access Point	GPS Health
Test11_Lucia	6/12/2024	Lucia Access Point	Canceled due to low water level
Test12_Latta_2	6/18/2024	Latta Kayak Ramp	RCV range, boat integration
Test13_Hechen	7/03/2024	Hechenbleikner	FPV integration
Test14_Hechen_2	7/26/2024	Hechenbleikner	Test sonde data collection
Test15_Mallard	8/13/2024	Mallard Creek	Collect data in stream
Test16_Hechen_3	9/6/2024	Hechenbleikner	Get info on Hydrone properties
Test17_Riverbend	9/20/2024	Riverbend Ramp	Autonomous bridge inspection
Test18_Latta_3	9/25/2024	Latta Kayak Ramp	Swathing width test
Test19_Dutchman	10/7/2024	Dutchmans Creek	Full bridge inspection
Test20_Hechen_4	12/16/2024	Hechenbleikner	Hydrone re-evaluation
Test21_Cowans_2	12/19/2024	Cowans Access Point	Full bridge inspection
Test22_Gastonia	1/25/2025	Catabwa River	Full bridge inspection
Test23_Norman	3/6/2025	Lake Norman	Echosounder testing
Test24_Gastonia_2	3/28/2025	Catabwa River	Full bridge inspection
Test25_Gastonia_3	4/8/2025	Catabwa River	Full bridge inspection

The deployment strategies across the duration of testing have changed and been refined to maximize data output, quality, cost-effectiveness, and efficiency. The HyDrone itself has several hardware implementations to make deployment faster and simpler.

Figure 35: HyDrone performing a survey under a bridge during Test #10

6.11 HYPACK Workflows and Bathymetry Data Product Generation

The team has become proficient in planning, executing, and analyzing survey data with HYPACK, AutoNAV, and ArcGIS. Surveys are conducted autonomously by following the pre-planned waypoints. The data products can be generated using either the low or high frequency sonar data, corrections are applied, and outliers are removed as part of the "cleaning/thinning" process. Example results include contour maps with a satellite image overlay and three-dimensional TIN mesh models (triangular irregular network). There are many other workflows in HYPACK for analyzing bathymetry, including calculating volumes, cross-sections, areas, etc., that are unavailable with our basic version of HYPACK ECHO. The team has also demonstrated the ability to process survey data on a laptop in the field. This may be useful for NCDOT to improve efficiency during survey projects. It could serve as a decision aid to review data collected on-the-spot and decide whether additional data is needed (e.g., create a new waypoint mission) or if the collected data is sufficient.

We envision that an NCDOT workflow for surveying a new area can involve using the HyDrone in manual/FPV mode to create an outline/perimeter of a survey area of interest and mark any encountered obstacles (e.g., debris in water, heavy vegetation, bridge piers) by recording GPS locations during the encounter or circling them if appropriate. This quick "outline survey" can provide bathymetry on the boundary of the survey area and GPS tracks that are then imported into HYPACK. The GPS tracks are used to define the polygonal regions to avoid when planning the lengthier lawnmower-style survey and reduce risk to collisions (especially a concern for the sensitive sonar unit).

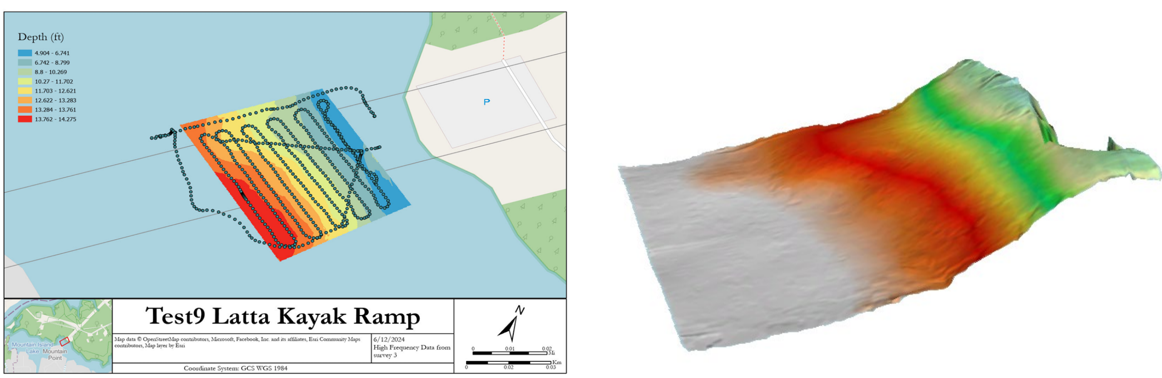


Figure 36. Left: Kriged high-frequency data from a survey conducted by UNC Charlotte with the HyDrone. This data is raw and has not been edited and includes outliers. Right: TIN model generated from the data collected in the experiment.

6.12 GNSS Data

The GNSS data is a critical part of the HyDrone's operation. It is used in geostatistical processing when interpreting bathymetric data and for autonomous waypoint control. Inaccurate GNSS data can cause errors in the measurement locations, leading to inaccurate bathymetry or may cause the vehicle to deviate from its intended path, which can lead to unexpected collisions or running aground. The testing data was analyzed to determine the degree to which GNSS errors affected the HyDrone.

The primary metric used to determine GNSS signal quality in these experiments was the percentage of satellites in sky-view. Sky-view, as it relates to a GNSS receiver, refers to the amount of unobstructed space above the receiver to view GNSS satellites. Error, dilution of precision (DOP), and GPS mode can be difficult to compare in a range of environments, while the number of satellites in sky-view is correlated to sky-view obstructions and time of day during a survey. Normalizing the data set to percent of satellites in sky-view based on the maximum amount of satellites seen during a survey allows for comparison across datasets and can indicate other quality-based GNSS statistics like DOP.

When performing hydrographic surveys with a USV, two main causes of sky-view obstructions are vegetation and infrastructure. Vegetation includes tall trees surrounding the survey region and infrastructure includes bridges and buildings. The environment can also impose an obstruction due to steep banks or various terrain profiles, but for these, this was not a factor. Using data from a survey on the UNCC campus at Hechenbleikner Lake, the satellite percentage can be analyzed while the survey area was partially obstructed with trees and buildings, as shown in Figure 37.

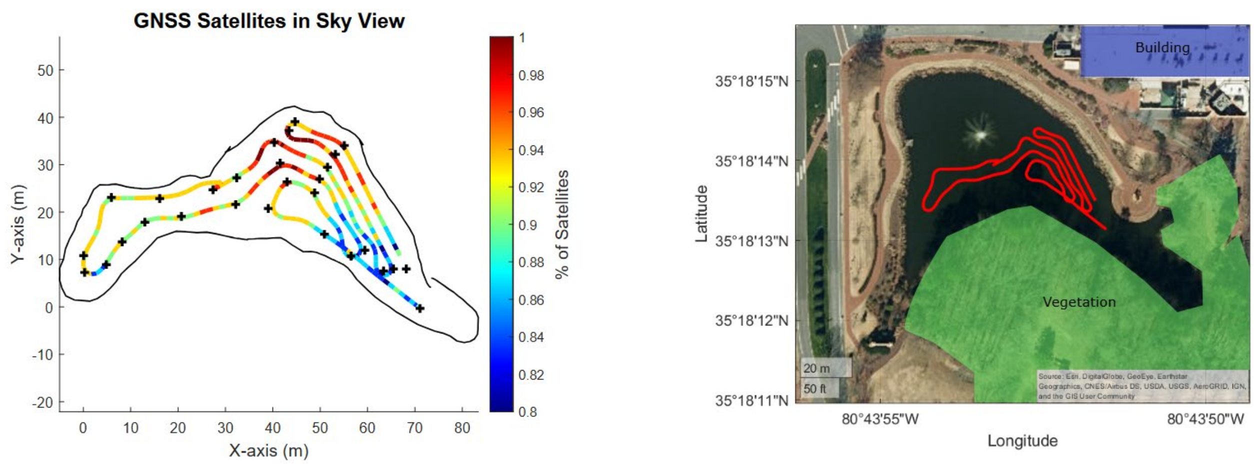


Figure 37: Test #8 GNSS data. Left: Heckenbleikner Lake survey showing satellites in sky-view of GNSS receiver, Right: Satellite image of survey area with plots showing where vegetation and buildings are located

In Figure 37 the satellite in sky-view percentages are shown. The maximum amount of satellites viewed in this survey was 30, with the minimum being 24, which is more than a sufficient amount to collect high-accuracy positional data. However, vegetation on the south side of the Lake does obstruct sky-view by about 20% of the viewable satellites. The building that is present on the north east side of the survey area is present, the building is too short and distant from the survey area to have any significant effect. For comparison, the trees are estimated to stand at about 25 meters tall, while the building is about 12 meters tall. Vegetation can obstruct sky-view, factors such as tree density and height play a significant role in how much of the survey area is restricted. In theory, a GNSS position can be determined with only 4 satellites; however, additional satellites improve quality.

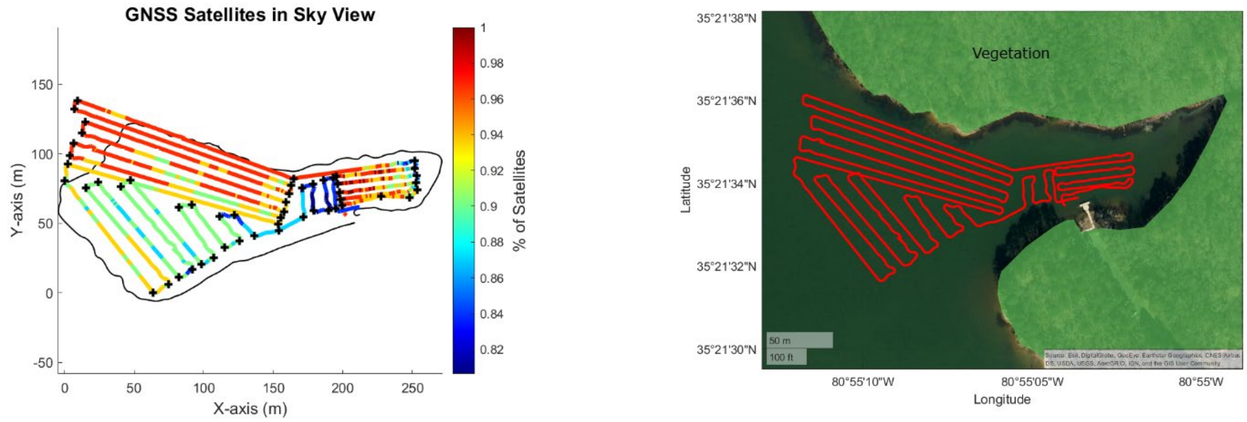


Figure 38: Test #12 GNSS data. Left: Mountain Island Lake survey showing satellites in sky-view of GNSS receiver. Right: Satellite image of the survey area with plots showing where vegetation locations.

Figure 38 shows GNSS satellite view data from a survey at Mountain Island Lake. This survey had dense tree coverage around the inlet survey region and was about 27 meters tall. While satellite degradation is seen on the south side of the survey and within the eastern part of the inlet, more than enough satellites are in view of the receiver to produce accurate GNSS data, with 31 satellites and 25 satellites being the minimum for the survey. While dense tree coverage can restrict the receiver's sky-view, dense tree coverage should not have an effect on high-quality GNSS data.

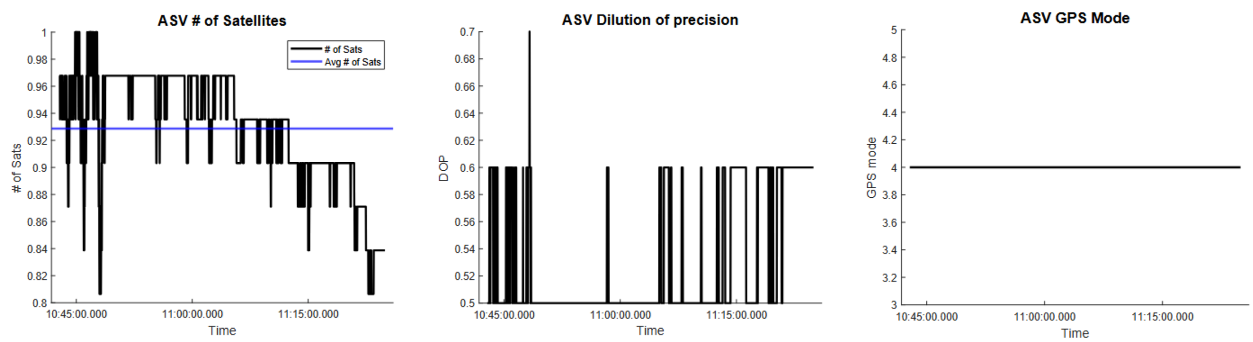


Figure 39: GNSS data quality statistics for Mountain Island Lake survey

As evidence of this Figure 39 shows the DOP and GPS mode data from the Mountain Island Lake survey. While the percentage of satellites viewed decreases across points at the beginning of the survey and consistently at the end of the survey, indicating satellites moved outside the area of the receiver's view at the end survey. The DOP only increases by 0.1 for the duration of the survey, in which GNSS data DOP values below 1 are seen as very accurate. GPS mode for the entire survey remains at 4, indicating the GNSS data is receiving its corrections and no drop-out has occurred.

Bridges spanning the region of interest have more of a direct impact on the receiver’s sky-view as the receiver has to survey directly under the occluded area. Several surveys were conducted in bridge environments; the following survey analysis was conducted in the Catawba River in Gastonia.

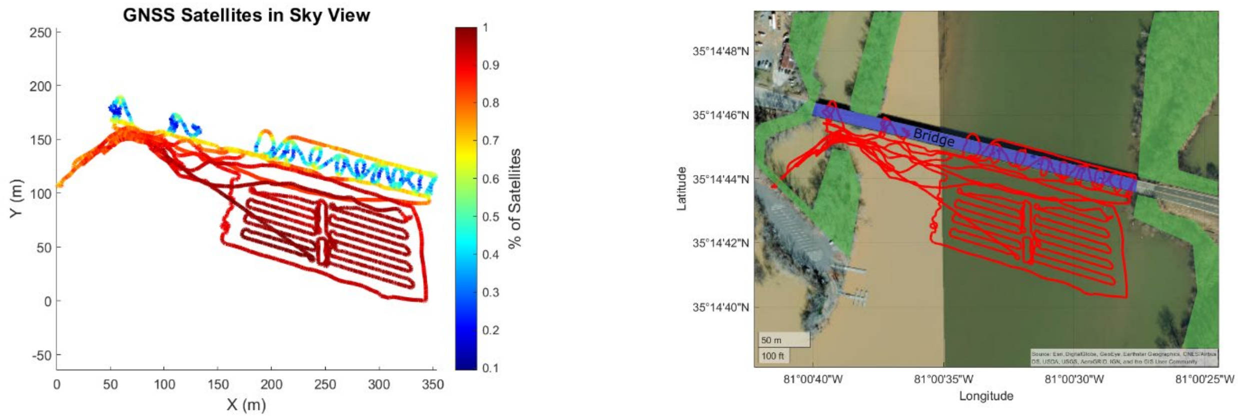


Figure 40: Test #22 GNSS data. Left: Catawba bridge survey showing satellites in sky-view of GNSS receiver. Right: Satellite image of survey area with plots showing bridge and vegetation locations.

Figure 40 shows the satellite percentage data for the entirety of the bridge inspection, where satellite loss is more dominant in this area when compared to surrounding vegetation. In most areas under the bridge, satellites in sky-view drop to 10%-30% from what was visible in the open areas. The dimensions of the bridge are about 12 meters wide and 6 meters above the water level. In this survey, a maximum of 32 satellites were in the view of the receiver, with a minimum of 3. While there are filters and estimation techniques that allow for positional computation, long periods of time under this type of bridge environment, or worse sky-view scenarios, would make these estimations dramatically less accurate. Figure 41 shows the standard deviation of horizontal position error from sensor data being recorded under the bridge.

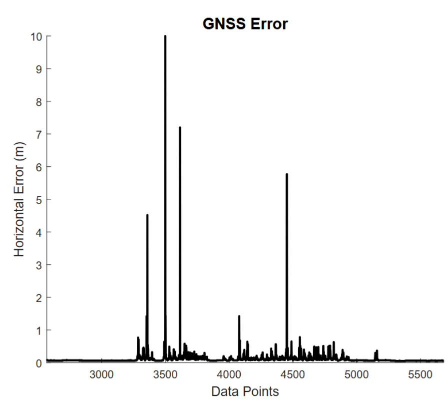


Figure 41: Horizontal position error from the data that was recorded under the bridge.

In some instances, the horizontal error can be as high as 10 meters due to the low number of satellites the receiver must compute its position. While under the bridge, most of the horizontal error measurements are around 0.7 meters, but the error does return to near near-zero value after the USV egresses from under the bridge.

Table 9: Dimensions of each bridge tested.

Test Number	Location	Bridge Height	Bridge Width
Test 17	Cowans Ford	15 m	8 m
Test 21	Mountain Island	11 m	8.5 m
Test 22	Gastonia	6 m	12 m

To visualize the effects that bridges have on GNSS data quality, three bridge surveys are compared with different physical measurements to show the severity of satellite loss. The Gastonia bridge data (Test #22), will be compared to data collected from Cowans Ford (Test #21) and Mountain Island Lake (Test #17) bridge locations. Table 9 shows the physical properties of each of the bridges tested and Figure 42 shows the satellites in sky-view with a polynomial curve fit to the data based on the absolute distance from the center of the bridge.

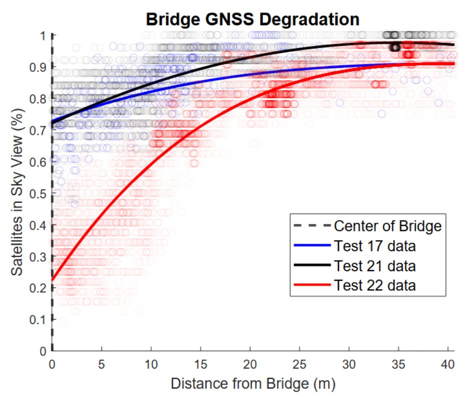


Figure 42: Percent of satellites in sky-view based on absolute distance from the center of the bridge.

Using the satellites in sky-view data from these three tests, it can be determined that the physical properties of a bridge have a great impact on the accuracy of GNSS data. In Tests #17 and #21, the data had about a 30% loss of satellites in sky-view while under the bridge, and in each of the surveys high-accuracy position data was maintained. This contrasts with the data from Test #22, which saw an 80% reduction in viewable satellites and had large variation estimates for the recorded positional data.

GNSS data quality is an important factor for a hydrographic USV. In order to accurately present a geostatistical analysis, the data collected from a USV must have some degree of certainty that it was collected from a certain position, as data corrections, mapping, and autonomous control all rely on an accurate position measurement. The following conclusions are made based on the data and analysis:

- Trees and distant buildings had a lower effect on sky-view compared to bridges directly in the survey area.
- Bridges resulted in up to 90% loss of satellites, including periods with large errors exceeding 10 m and total dropout. The dimensions of the bridge can impact the severity of satellite signal loss.

6.13 Swathing Width

Using SBES technology to collect and analyze depth data requires the USV to survey a region in a way that considers how geospatial interpolation will later be conducted. Because the SBES measures one depth value for every position point, densely sampling the environment to create a high-resolution raster map of the seabed is unrealistic. Geostatistical processes like kriging are used instead to interpolate in unsampled regions. Boustrophedon paths are used to uniformly sample the environment and can be planned with different swathing widths.

To determine the percentage of area covered with a particular swath width, the echosounder footprint is estimated for each data point, and the resulting depth is determined based on the average amplitude of the returning sounding measurements.

An experiment was designed wherein the HyDrone operated autonomously in a predefined area at different swathing widths (100ft, 50ft, 33ft, 20ft, 10ft, 5ft) and the accuracy of geostatistical analysis was characterized as a function of the area covered by the echosounder footprint. The results are shown in Figure 43 and Figure 44.

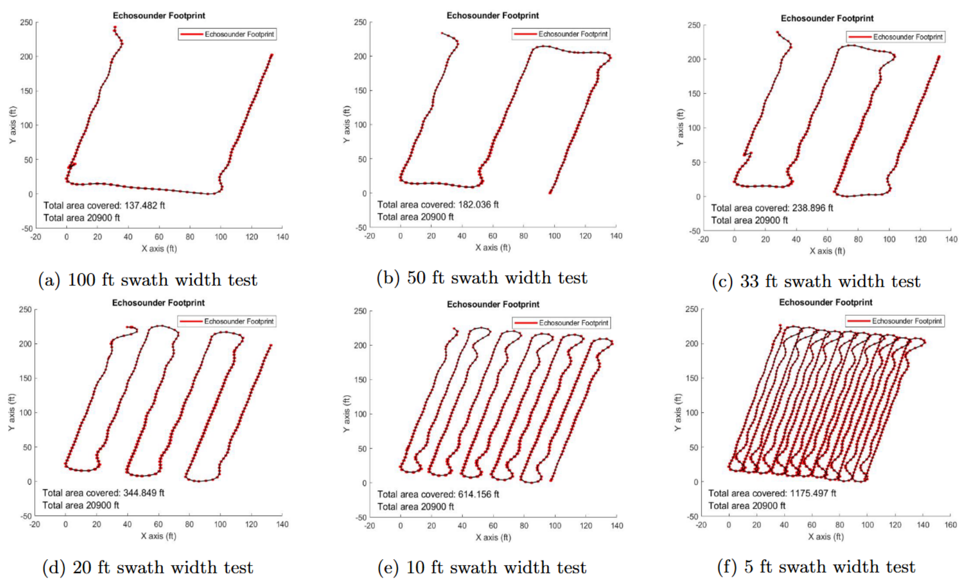


Figure 43: Swath width test echosounder footprint data

In each of the surveys, the total seabed area that each echosounder footprint observed is summed to quantify the total area covered. The footprint is calculated by considering the beam width and the measured depth of the area. The total survey area was the same across all tests.

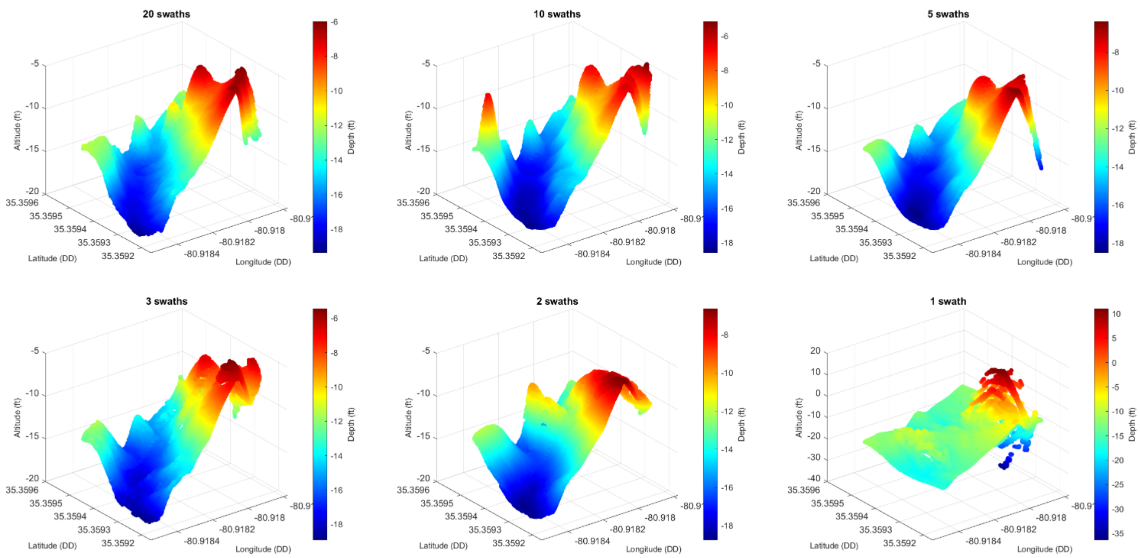


Figure 44: Kriging data pulled from ArcGIS analysis of all swath with tests.

Each of the krigged models in Figure 44 were computed using ArcGIS, and the rasters of each of the spaces were plotted in MATLAB. As expected, more swaths led to a finer level of detail shown in the raster plots. The results for 1 and 2 swath plots are substantially different from the highest resolution plot with 20 swaths. The results for 3, 5, and 10 swath plots are more consistent. To further evaluate the effects of the different swathing widths, the RMS error was calculated assuming the most dense data set (20 swaths) as ground truth. In Figure 45, the relative error as a function of echosounder area coverage shows diminishing returns on data accuracy. A single swath has an average error of 4 ft depth, and 10 swaths have an average error of 0.5 ft with an exponential trend in between. This is expected as overall accuracy will increase with data density, but this experiment shows the RMS error around 0.5 ft when using 3% area coverage.

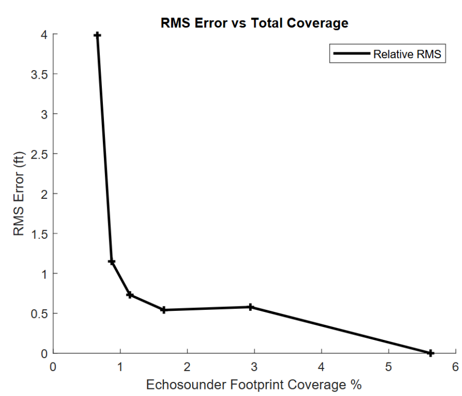


Figure 45: Relative RMS error of each of the swath test where the 20 swath test was used as the baseline.

Using this metric, a recommendation can be given to surveyors that swaths should be placed such that at least 3% - 5% of the total survey area will be covered with soundings. The actual sounding profile is related to the depth of water and a particular echosounders beam width. Calculating this for an unknown region may be difficult, but if needed, multiple surveys can be run with different swathing widths to ensure complete coverage, or prior data/estimates can be used. As high survey times and diminishing returns exists with high area coverage surveys, this methodology provides surveyors a means of producing high-quality geostatistical data in a rapid bathymetric assessment.

6.14 Cross-Track Error

Cross-track error refers to the lateral deviation of a vessel from its planned path and impacts vessel safety and data accuracy. When operating the vessel in its autonomous mode, the surveyor should have an understanding of how accurately the waypoint path is traversed. Excessive overshoot, along with poorly placed waypoints, may cause vessel damage due to collision with in-water obstacles. While performing autonomous surveys with the HyDrone, cross-track error was measured in different scenarios.

In this first analysis, cross-track error is visualized on three similar surveys. Each survey used the same waypoint path. The cross-track error is plotted on the GNSS trace from the recorded survey to analyze where the cross-track error occurs and its severity. Figure 46 shows Tests #9 cross-track error results.

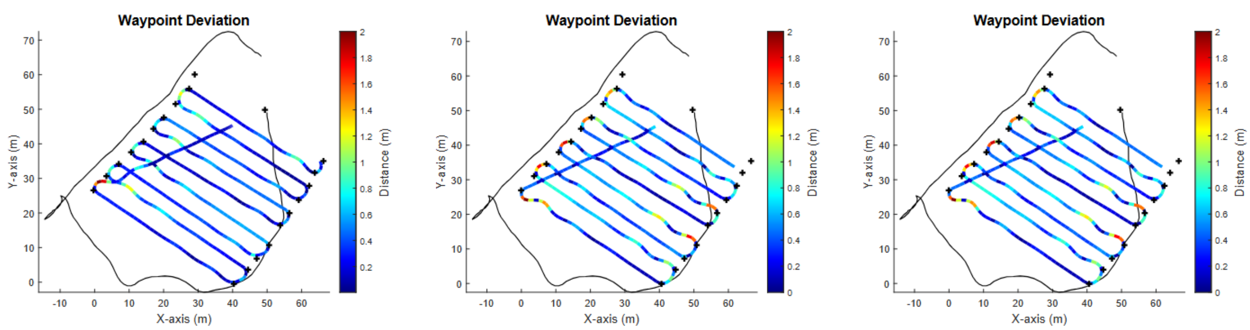


Figure 46: Cross-track error data from Test #9 in Mountain Island Lake.

Analyzing the results of the cross-track error data in the autonomously controlled survey, the vessel tends to stay within 0.3 meters of the planned path waypoint on straight sections. During turns, the vessel exhibits more variability in the amplitude of cross-track error before returning to its straight-line behavior. Large deviations consistently occur at the turning points, albeit with varying amplitudes of about 1 meter. To return to its straight-line behavior, the vessel motion oscillates on the waypoint path to correct for its overshoot. Test #9 also uses a standard boustrophedon path with little variability in the turning angles. Test #12 has a boustrophedon pattern with unique turning angles that provide additional context to the behavior of the HyDrone. Cross-track error data for Test #12 is presented in Figure 47.

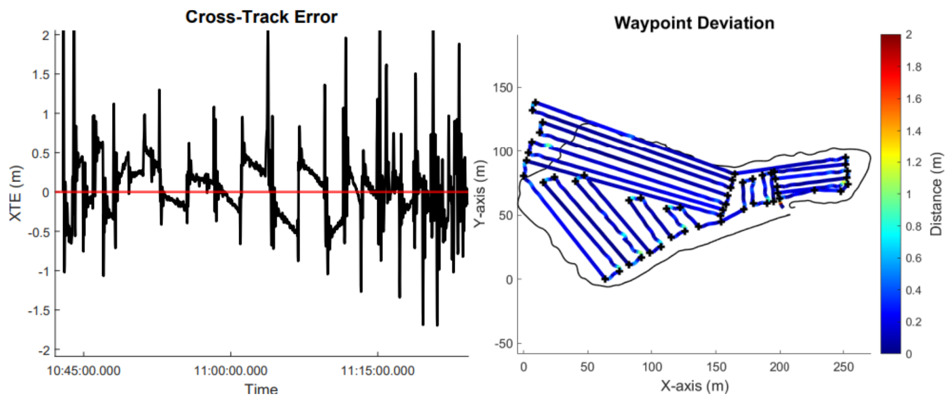


Figure 47: Cross-track error data from Test #12 in Mountain Island Lake (Left: cross-track error with time, Right: cross-track error overlayed on path).

Due to the size of the survey area, the large cross-track error colored in red is mostly absent; however, during tight turns, light blue and green colors appear, denoting that large cross-track error occurred before decaying. The plot of cross-track error versus time shows the large spikes in path deviation before quickly returning to the straight-line variance. For the first half of the survey, right-angle turns are taken, and the maximum amplitude in these areas is around 1 meter of error. In the latter half, tight turns are taken, indicating that these turns induce more cross-track error than slight turns. In the middle of the time plot, after a turn indicated by a large spike in cross-track error, the cross-track error does not return to zero. In some cases, the error trends away from zero at a constant rate. While the magnitude of error is still small, it does indicate that the onboard control system tolerates a deadzone of heading and/or cross-track error. For the vessel to successfully “visit” a waypoint, it must be within 2 meters of the target waypoint. The straight-line error is almost 6 times smaller than this requirement, and this small cross-track error does not impede the vessels waypoint-following ability. Figure 48 shows a histogram of recorded cross-track error across all tests.

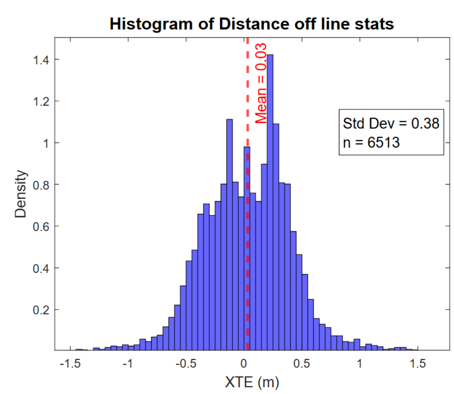


Figure 48: Cross-track error plotted by density across several HyDrone tests.

While these tests have different sizes, shapes, and turning requirements which would change the ratio of high and low errors, it does allow for the visualization of how error is resolved in a survey scenario. When analyzing density, there are three large bins located at 0, -0.2, and 0.2. The area between +/- 0.2 m encompasses nearly 50% of the cross-track error data, and outside of the region, the data density exponentially decreases. This shows that the vessel's ability to correct for turns and large cross-track errors across different surveys is adequate for data collection.

When creating a waypoint path, the operator is under the assumption that the USV will follow that path with a degree of accuracy such that an environment is traversed on the path. If the USV follows that path loosely, duplicated data points could be collected, parts of the survey area could be missed, or the vessel may endure a collision with the shoreline or in-water obstacles. While the USV operator cannot affect how the autonomous controller functions, using this information may allow the operator to place a waypoint to increase unique data point collection and increase vessel safety.

6.15 Geostatistical Analysis

Once data is collected, an on-site analysis of the data can be performed. This can be done using any offline GIS tool like ArcGIS, or HYPACK (given that the analysis tools are included in HYPACK license). Before a spatial analysis is computed, data should be thinned to remove erroneous echosounder data points. This process can be done in HYPACK or using a data analysis/editing tool. Once data is thinned and exported from the USV, the surveyor can upload the data into the GIS software and perform kriging or other forms of spatial interpolation and analysis. This kriged data set can then be turned into a contour map, bathymetry report, or TIN model, and an on-site analysis of the data can be completed. A contour map and TIN model are displayed in Figure 49 and Figure 50, respectively.

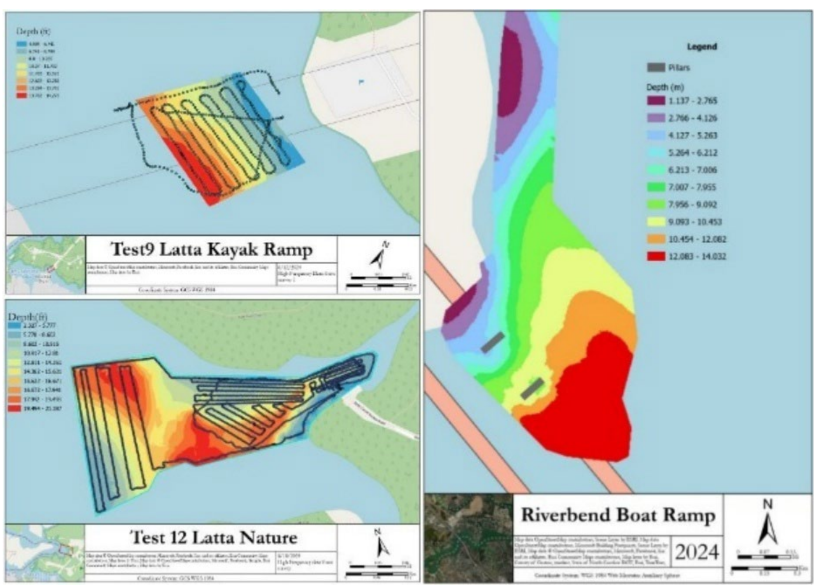


Figure 49: Bathymetric contour map of Mountain Island Lake in the Latta Nature Preserve and the Catawba River under NC Highway 16 developed in ArcGIS.

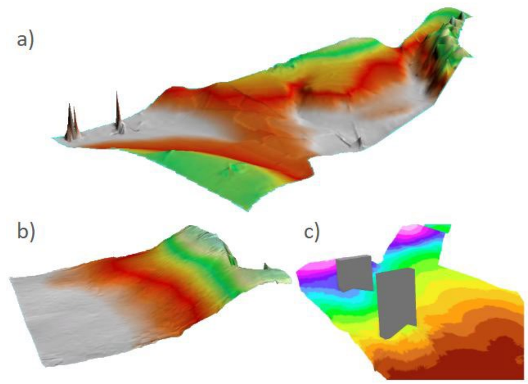


Figure 50: TIN models of (a,b): Mountain Island Lake in the Latta Nature Preserve and (c): the Catawba River under NC Highway 16 developed in ArcGIS. Figure (a) contains the raw data set, resulting in some erroneous peaks in the spatial analysis.

6.16 USV Logistics

To make conclusions about HyDrone deployment metrics, the total survey time, battery drainage, and deployment time were recorded across all the experiments. Statistics like set-up time vary due to location, deployment terrain, number of surveyors, and surveys goals which effect the speed in which the USV can be deployed into the water, but the goal of providing these data points is to give a surveyor who is unfamiliar with a USV integrated bathymetric survey an idea about the time commitment, limiting factors, and typical survey requirements. Figure 51 shows the amount of time it took for the operators to set up and pack away the HyDrone and shore-side equipment.

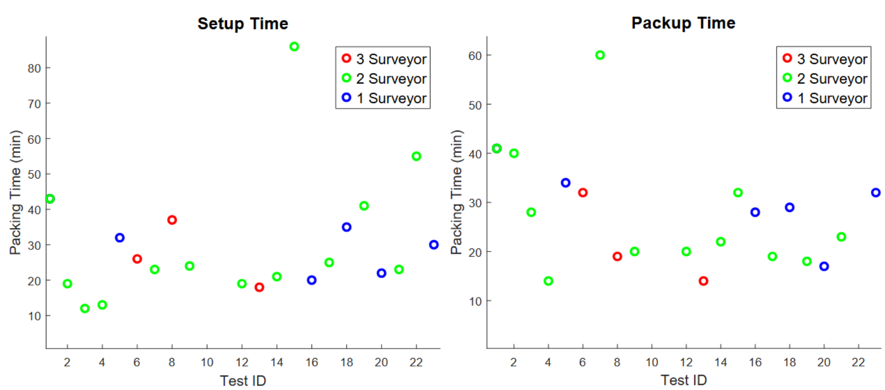


Figure 51: Test data plotted based on time to set up and pack up on site. Depending on team size for a survey, the test ID is colored with red being 3, green being 2, and blue being 1 surveyor.

Over all surveys completed, packing and deployment strategies have been adjusted with a range of equipment selectively brought on-site depending on the mission. In Figure 51 the setup and packup times are plotted against their Test ID. Both setup and packup times average below 30 minutes, with solo deployments taking a little longer on average. A few outliers include the setup for test 15, and packup time for test 7 as onsite troubleshooting, including a defective motor malfunctioning, are included in these recordings. As testing became more involved with additional technology, equipment, and intricate deployment methods, later surveys have longer packing times but are lower than those of the initial tests. Looking at the number of surveyors involved in each survey, there is a small time benefit to having multiple surveyors before and after the post survey in regards to packing. This is mainly due to the linear nature of setting up a USV on site, where things have to be done in a certain order. Every survey will have variability in these times, but as surveyors become practiced with using a USV in a bathymetry collection regimen, these times should be closer to 20 minutes.

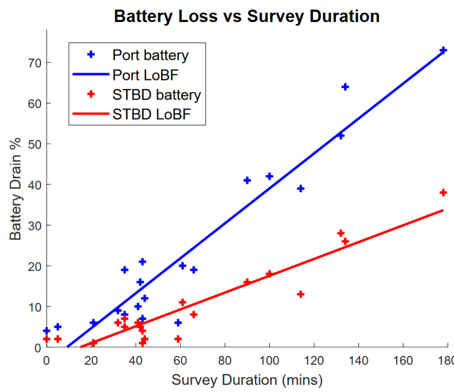


Figure 52: Battery drain percentage plotted against in in-water survey duration.

Throughout testing, the same starboard and port side batteries have been used in their respective housings. This is done so we can analyze the performance of each battery. Shown in Figure 52 are the battery drainage percentages plotted against survey time. Looking at the data, the port side battery drains faster than the starboard side battery at almost double the rate, and causes a bottleneck for total survey endurance. Following the line of best fit, the port side battery limits the total survey time to about 3 hrs. if fully charged.

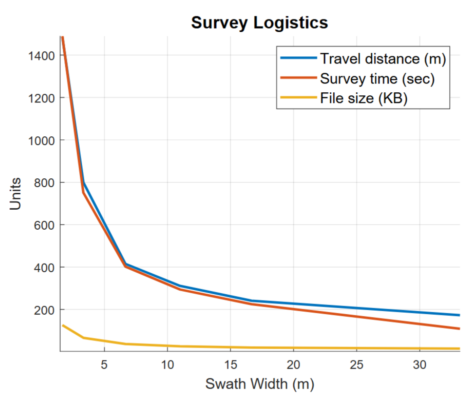


Figure 53: Tracked in survey logistics including file size, time of survey, and travel distance based on a static survey area.

Other logistical data has been tracked like the survey time, length, and file size based on swathing width. Figure 53 shows those metrics as they relate to different swathing widths. This data, taken from Test #18, shows the exponential relationship between increasing the number of swaths in a survey to the amount of time it will take to complete a survey. Given a 1,800 m^2 area, the time to complete the survey and the total distance traveled are exponentially affected given a small swath width. File size also has this characteristic, but given modern-day technology and typical USV hardware, data limits should not be an issue especially if data is loaded off the hardware. However, creating a high-resolution bathymetric dataset does come at the cost of long survey times.

While every survey mission and goal will be different, the data presented in this section can be used to decide the proper survey area, swathing width, or determine the feasibility of multiple surveys given time constraints.

6.17 Echosounder Tuning

Sonar settings can be decided or initially tuned using few rules of thumb that are based on environmental factors and on-site measurements. To come up with a method for tuning these, trials at known locations were completed by implementing different sonar settings and then performing surveys. The results were analyzed across different locations to determine the best tuning method.

The echosounder frequency setting determines the bed type that is measured in a bathymetric survey scenario. Bed type refers to the form of sediment that creates a body of water. When operating the Hydro-Lite echosounder two separate frequencies can be used independently or simultaneously. One frequency operates at 30 khz (low) and the other operates at 200 khz (high). The low-frequency data has the ability to penetrate soft bed types, including sand, mud, and clay. The high frequency sounding data will not be able to penetrate the soft bed types and when performing surveys will allow the operator to collect the two values: a) the depth of the water column to the water beds surface, and b) the depth of the water column to the harder sediment layer including hard materials like gravel and rock. This may help differentiate the locations of solid foundation materials versus the true depth to the surface of the water bed.

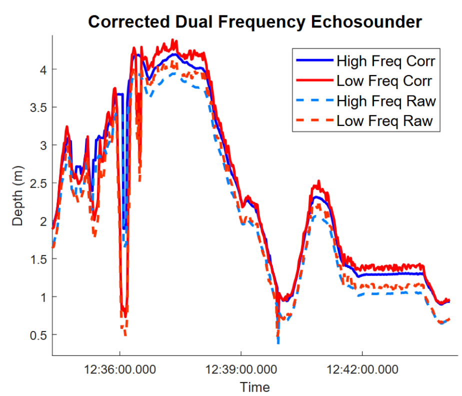


Figure 54: Test #17 showing the difference in low and high frequency data.

Figure 54 shows data from Test #17, where low and high-frequency data were used to record data from under a bridge in Mountain Island Lake. The raw data is corrected by accounting for the offset of the transducer and the orientation of the vessel. This results in the corrected data being deeper than the raw data as the transducer is set around 0.2 meters below the surface of the water. When looking at the trends of both high and low frequency data, the high frequency is about 0.1-0.25 meters shallower than the low frequency data. This indicates that in those areas of the survey, there is a soft bed type in which the thickness of the water bed is the difference between the two depth measurements. The low-frequency data also contains more noise, which can be lessened with tuning but is more susceptible to environmental conditions. This is seen across many soft-bed areas that have been surveyed.

The echosounders gain setting controls the sonar receiver's sensitivity to the measured water columns depth and clarity. Increasing the gain can provide finer detail in the Echogram, which translates to more accurate measurements. However, it may also increase the amount of noise due to water impurities, aquatic life, and bed type changes. The manufacturer's recommendations are for clear water with hard solid bed types to use negative gain values as low amounts of noise should be present and would be considered an ideal scenario for surveying. Positive values of the gain setting are recommended for soft bed types, impure water conditions, and deep sounding survey scenarios as the incoming soundings may need to be amplified to maximize the depth readings. % clean up depth profile tests, show default settings versus tuned

Table 10: Echosounder settings tuned in trial runs.

Trial #	Gain (dB)	Threshold %
1	-6	10
2	0	10
3	+6	10

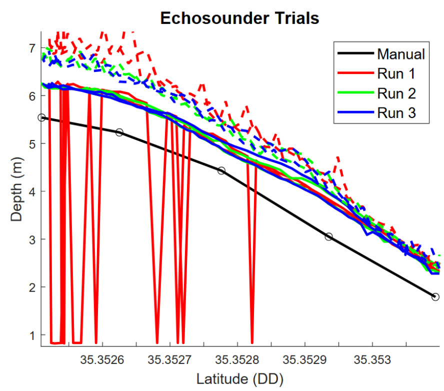


Figure 55: Echosounder gain (dB) true depth measurements from Test #17. Solid lines are high-frequency data, dashed lines are low-frequency data.

Echosounder trials were conducted in Mountain Island Lake in Test #17, the results of which are shown in Figure 55. Using both negative values of gain showed data inaccuracy. It is important to note that the water quality was impure, and it was our hypothesis that increasing the gain would yield clearer depth data. This is true for both low and high-frequency data. In this experiment, the 0 dB and +6 dB data sets are similar, indicating either would be sufficient for surveying in this particular area.

Range and deadzone settings refer to the maximum and minimum values that the echosounder can compute. These settings are important to tune since, even in ideal conditions. erroneous data may result if operating outside of this. For inland surveying, deadzone is a difficult setting to tune since surveys may include the shoreline, creeks, lakes, and other shallow areas where data quality is more sensitive to the accurate selection of the range and deadzone parameters. The operator can take measurements of the shoreline depth and the transducers draft to ensure the best possible estimate for these readings.

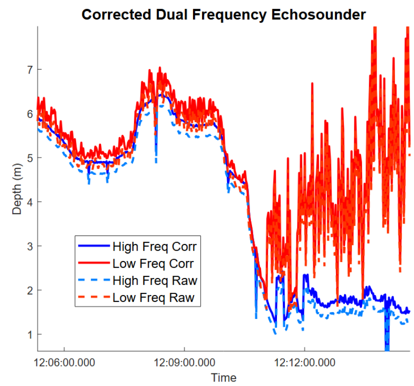


Figure 56: Test #12 data with large amounts of error in shallow water within the deadzone range.

Figure 56 shows data from Test #12 in a shallow area of water. The high frequency data with a deadzone of 1 meter is recording data as expected, while the low frequency data set with a deadzone of 2 meters is providing noisy reading. Because the true depth of the area is around 1-2 meters and the deadzone exceeds that at 2 meters, the recorded depth for this area becomes erratic.

While all these settings may be difficult to infer for an unknown body of water, running the system with default settings and then tuning parameters based on what the Echogram and recorded depth outputs, as well as comparing depth to a measured depth on-site, are ways the echosounder may be tuned. In test 23 at Lake Norman, multiple tests were conducted using the same waypoint path, comparing the default echosounder settings to the tuned settings based on the suggestions proposed in this section. The results of the data are presented in Figure 57.

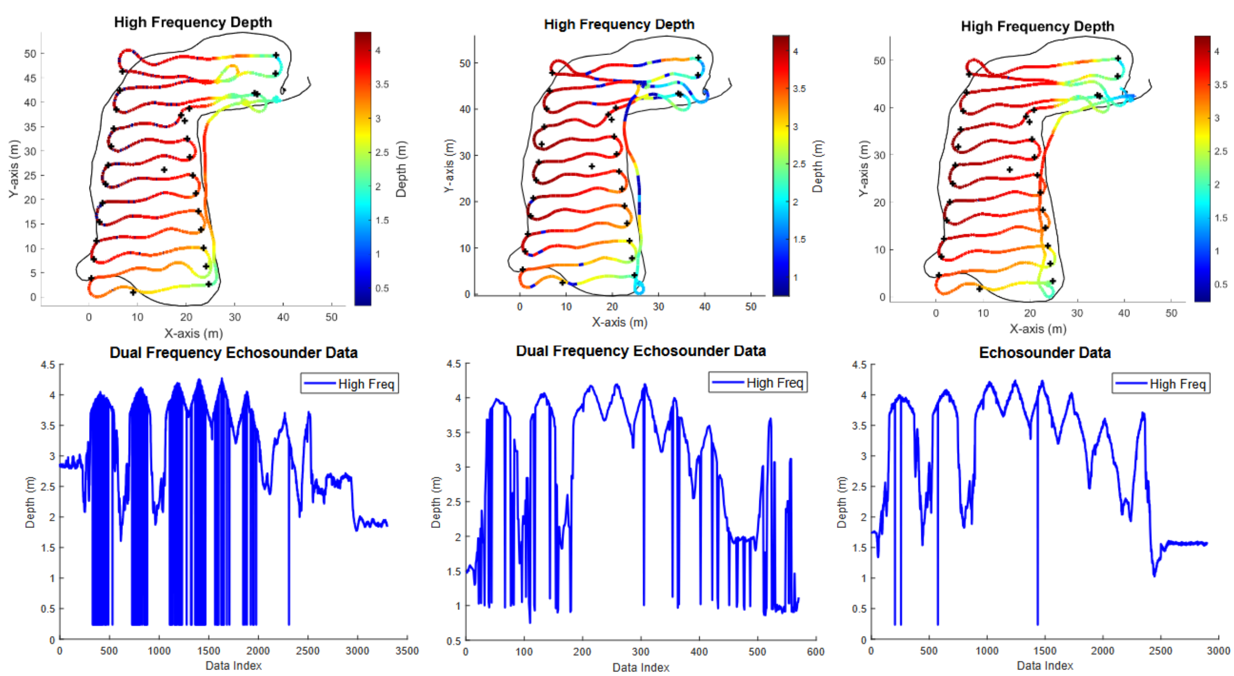


Figure 57. Lake Norman echosounder tuning with three test iterations. The left shows poor tuning, the middle shows the default setting, and the right shows good tuning procedures. The top images show depth plotted with GNSS trace, and the bottom shows depth indexed by each data point collected.

The experimentation in Test #23 also compared data to a known depth on-site to tune each of the experimental trials. The middle data set in Table 11 shows the default settings. Due to the noise seen across the data set, two separate setting combinations were tested, one that used the recommendations provided (right figures), and a semi-tuned configuration illustrating incomplete tuning. Table 11 shows the settings used in each.

Table 11: Settings used for Test #23.

Setting	Semi-Tuned	Default	Fully Tuned
Range (m)	10	30	10
Deadzone (m)	.2	1.5	.2
Interval (sec)	.2	1	.2
Gain (dB)	0	0	6
Threshold (%)	15	10	20
Tx Length (μs)	15	30	15

Range, Tx Length, and threshold were all tuned based on prior knowledge of the environmental area and on-site observations. Tx Length can be tuned by looking at the water quality and bed type, where the threshold can be tuned based on max range assumptions. The interval or sampling frequency was changed from the default 1 Hz to 5 Hz to increase the amount of data collected in experimentation. The range for both semi and fully tuned tests was decreased to 10 as the maximum depth seen was about 5 meters. The main differences between the semi-tuned and fully tuned tests were the deadzone and gain. With a gain set to a low value like 0.2 m, errors can occur if the sounding column detects noise near the face of the transducer. Because the limit is so shallow, noise that does appear in the Echogram may default to the lowest allowable depth output. Along with this, Lake Norman has very cloudy water, making it difficult for a low-gain sounding to properly read the bed type. When looking at the fully tuned data with the same deadzone, but increased gain, the soundings are able to more easily resolve noisy feedback from the lake bed.

Throughout all testing, it was common for erroneous data to occur, and only under ideal conditions was data collected error-free. As a surveyor tuning echosounder parameters is an important part of collecting bathymetry data. Being able to understand what each setting does, how it affects data output, and how to resolve errors in different bodies of water allows for a more accurate dataset and greater confidence in performing a geostatistical analysis.

6.18 Recommended Deployment Flowchart

A USV-integrated bathymetric workflow was created after sufficient experience was gained and analysis was completed to systematically create an efficient workflow that provided sufficient bathymetric data. The proposed seen in Figure 58 follow four main steps being (1) Planning and

Preparation, (2) Deployment, (3) Survey, and (4) Analysis.

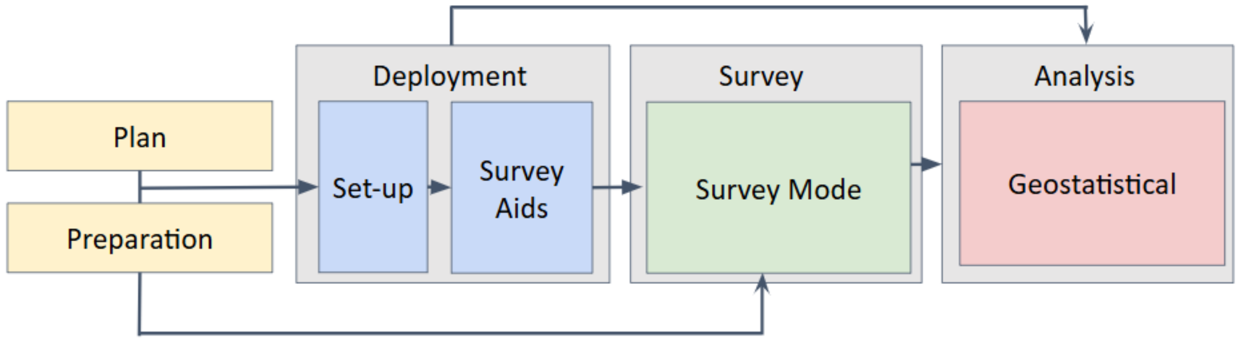


Figure 58: Proposed workflow chart for how to integrate USV into rapid bathymetric survey practices.

This outline provides a methodology for different types of surveys and analyses to be performed with dynamic elemental and time constraints.

6.19 Planning and Preparation

In the planning phases, the surveyor must gather enough information about the survey site to plan a safe and efficient survey. The goal here is to find an unloading location, a ground station location, and a location to deploy the USV in the water. Our practice has included looking at satellite images of survey locations to look for a safe deployment spot. Steep banks, difficult-to-traverse terrain, low water levels relative to boat ramps or docks, and dense vegetation are examples of challenging scenarios to deploy a USV. The HyDrone can be deployed by one person by simply lifting the USV in and out of the water, but doing so safely for the operator and the USV is very important. Depending on the projected difficulty of utilizing a two-person deployment, or a Hybrid survey requiring a manned vessel to traverse waters alongside the USV may be considered. Survey project files should also be created, like background images, geo-location settings, and hardware configurations.

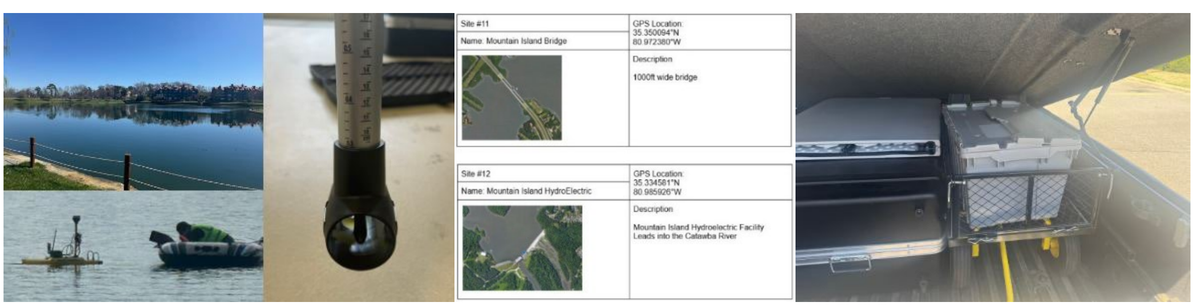


Figure 59: Planning and preparation resources. Left: scouting location including site measurements and pictures, Middle: use of satellite imagery for unloading and ground station setup locations, and Right: all equipment including HyDrone can be put in the back of a truck bed.

In the preparation phase, the surveying team gathers all the equipment, tools, and supplies they will need for a survey. This is when the USV LiPo batteries should be charged, the packing list is checked, and the equipment is loaded. The LiPos take about an hour to charge if using a charger that can support larger amperages, and equipment preparation and loading should take less than 30 minutes.

6.20 Deployment

During the deployment process, the equipment should be unloaded; vessel assembly and software configuration should begin. At the end of the set-up phase, the surveyor should be ready to deploy the vessel with the USV being remotely connected to the ground station, all project files created, and the USV pre-deployment checklist completed. In our experience, the setup takes around 25 minutes after sufficient experience with the HyDrone; setup times for other vessels can vary. Other on-site equipment should be used to check environmental conditions if necessary. If deploying in an environment with dynamic conditions like fast-moving water, the flow rate may need to be checked to ensure the vessel can operate without any additional tools. The water temperature should also be recorded to make adjustments to the echosounder's speed of sound setting.

6.21 Survey Modes

Depending on the environment, different survey strategies should be used, which we summarize as:

- RC Mode (remote controlled survey)
- FPV Mode (first-person view goggles)
- Autonomous Mode
- Hybrid Mode
- Wading Mode
- Tethered Mode

6.21.1 Remote Controlled Survey

Remote-controlled surveys are fully operator-controlled. When controlling the USV by a transmitter, the USV has more maneuverability in the survey area, which can be useful when surveying in constrained spaces or around vegetation. Due to the human factor in controlling the USV, data density may be highly varied throughout the survey region, and the vessel may be difficult to accurately drive past 200 ft. Remote-controlled surveys are most beneficial in small lakes or ponds where the line-of-sight of the vessel in the survey area can be fully maintained by the operator.

Figure 60: Operator controlling the HyDrone via the transmitter.

6.21.2 FPV survey

Similar to a remote-controlled survey, the operator can control the USV from the perspective of the USV. This operational mode uses the custom first-person-view (FPV) housing to provide an advanced perspective of the drone to the surveyor. This survey excels at being able to maneuver more precisely than just an onshore operator and can break the line of sight to the operators, given its new perspective. The operator loses their peripheral vision when operating in this mode, and this should be considered in the case of high water traffic and debris-filled environments.

Figure 61: Operator view of controlling the HyDrone using the custom DJI 03 air unit developed.

6.21.3 Autonomous Survey

An autonomous survey requires a survey area to be defined either from satellite images or previously used surveys, so that a reference can be used to place waypoints. The operator then monitors the USV as it autonomously collects bathymetric data. This provides consistent data density across the environment, given that path planning tools were used, and provides a fast and low-labor method of collecting bathymetric data across large and small survey areas.

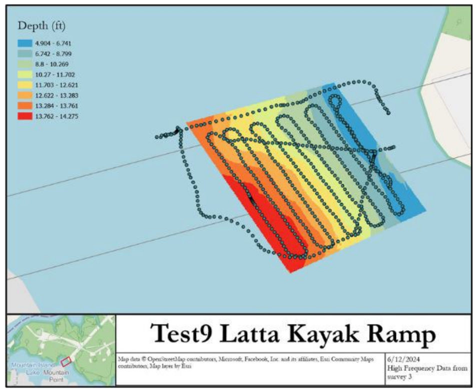


Figure 62: Geostatistical analysis of a survey completed using an autonomous waypoint path.

We found that due to water level changes, background or satellite images may not be accurate when defining a border for an autonomous survey region as the shoreline would change with the water level.

6.21.4 Hybrid Survey

A Hybrid survey utilizes both remote control and autonomous control methods to carry out long-distance surveys. We found this most useful when surveying bridges without a near-bridge deployment location. Using this survey mode, a manned vessel and the USV would be deployed from the nearest boat ramp, to then venture together to the survey location. An operator would drive the USV in remote control mode alongside the manned vessel before sending it to autonomous mode to finish the survey. This hybrid survey allows the USV to reach an otherwise unreachable survey location while being able to autonomously survey a site.

Figure 63: Manned inflatable raft used to transport operators to the survey site (left), and the HyDrone completing an autonomous survey once arrived at the off-site location.

6.21.5 Wading Survey

A surveyor can deploy the USV in a small creek or stream and control it from wading in the stream itself. In difficult-to-traverse terrain, it may be simpler to operate the drone instead of manually collecting the bathymetric data. The operator must be attentive as the USV transmitter is not waterproof, but simply wading within the stream and collecting data using the USV is much faster and safer than collecting it manually. The operator also has an advantageous perspective that is beneficial when maneuvering around a constrained, high-vegetation environment.

Figure 64: Operator wading while in control of the HyDrone in a steep banked creek.

6.21.6 Tethered Survey

In the case that a stream or river flow exceeds the properties of the USV, bathymetric data can still be collected by tethering the USV to a harnessed operator, a bridge, or a fixed point. This tether will act as a pendulum as the operator controls the USV, moving it from side to side and collecting bathymetric data. The tether is lengthened or shortened to change the distance from the operator and swathing width. Examples of the survey mode are provided in Figure 65.

Figure 65: Tethered test in rapidly flowing water.

In our testing, we developed a method to perform this type of survey by retrofitting the HyDrone with rope attachment points and a harness for the safety of the operator. We have attempted performing the tethered survey in the Catabwa River, where the flow rate did not exceed the HyDrones operational limits, but the exercise did prove the ability to perform this type of survey.

These survey modes describe different methods of performing bathymetry data collection that require different workflows from both the surveyor and the USV. In the following section, a number of survey modes and their use cases are outlined.

Table 12: List of survey modes and the environmental factors that would allow for a particular mode of deployment. “X” shows mode validity, and ``-" indicates possible mode validity depending on the environment. Rankings are given from optimal (1) to least optimal (4).

Survey Factors	RC mode	FPV	Autonomous	Hybrid	Wading	Tethered
500 ft + Range		-	X	X		
1000 ft + Range				X		
Reduced line of sight	-	X	X	X		
Constrained Environment	-	X			X	-
Small Region <1000 sqft	X	X	-		X	X
Mid Region <10000 sqft			X	X	-	-
Large Region >10000 sqft			X	X		
Fast water flow						X
Data Density	4	3	1	1	4	2
Labor Intensity	2	2	1	3	4	-

Over the 25 surveys completed, the ability to rapidly deploy a commercial USV and collect bathymetric data to perform on-site bathymetry has been evaluated. Experience with the HyDrone and HYPACK helped define a workflow that allows for efficient and safe operation. Guidance has been provided concerning echosounder tuning, GNSS data quality, optimal swathing practices, and HyDrone path following performance. To provide state DOTs with recommendations about how to integrate a USV into a rapid bathymetric analysis, the workflow shown in Figure 66 outlines the steps to safely prepare for deployment and complete a bathymetric survey.

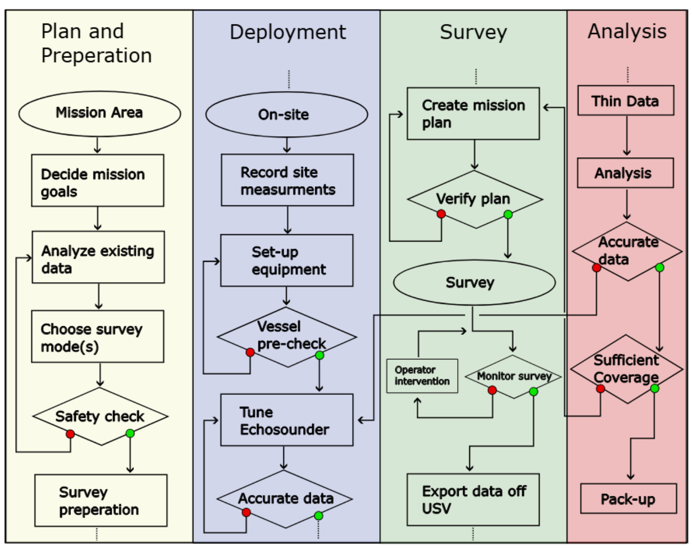


Figure 66: Full survey flow chart, to aid USV operators in survey deployment.

The plan and preparation phase starts with identifying mission goals and parameters and researching the survey area. This will provide information to the operator about how the vessel will be deployed, what settings to use on-site, as well as provide an idea about how the survey will be conducted. While safety should be considered throughout the survey, the initial survey plan in particular should include harnesses, life jackets, safe survey plans, and proper equipment to reduce the risk of equipment damage and keep the operator safe during the survey before more familiarity is gained. To conclude survey preparation, all equipment should be accounted for, batteries for the vessel and other equipment, pre-checks should be completed to ensure operational readiness.

When on-site, measurements such as water temperature should be taken so the echosounder speed of sound settings can be adjusted. All equipment should be set up with a secondary check to ensure all systems are online, with troubleshooting procedures in place if needed. Using existing data and on-site measurements, the echosounder should be tuned. A mission plan can then be executed that satisfies the mission goals. If a generated plan is risky or cannot be completed due to vessel limitations, a mission redesign should be considered. This includes long survey times, losing line-of-sight of the vessel, or operating near obstacles. Once the plan is verified, the survey can commence. The surveyor should have the ability to always take full control of the vessel, as dynamic obstacles like maritime vessels, floating debris, and water waves or currents could impede or damage the vessel. Once data collection is complete, a rapid assessment of the data can be completed to ensure data accuracy and mission goal completion. If needed, adjusting echosounder settings or re-evaluating the mission plan is the next step.

6.22 Recommendations for NCDOT

The following recommendations are made concerning the adoption of the HyDrone at NCDOT:

- The HyDrone has been shown to be a capable platform that can collect high-quality data in relatively calm water, in open areas with no significant obstructions of satellite signals, and in relatively deep water (e.g., 4 feet or more). The HyDrone can be transported and deployed in remote locations without a boat ramp, given a team of two people. Tuning the echosounder and comparing both the high/low frequency data is critical. Using the HyDrone as a rapid assessment tool to quickly generate bathymetry maps and visualize sounding data on-site is feasible. The FPV camera system is very helpful in avoiding in-water debris/obstacles. Such rapid assessments can help inform whether follow-up surveys are needed with the HyDrone or other assets. It is recommended that NCDOT use the HyDrone USV in such circumstances and follow guidance from this report.
- More difficult conditions for the Hydrone include shallower water < 4 feet, low/wide bridges that obstruct GNSS signals, strong currents, and confined spaces with vegetation/debris. While the HyDrone may potentially be a viable option to deploy in such scenarios, it is not certain that it will perform as expected depending on the severity of the challenging environment. It is recommended that NCDOT consider the HyDrone as a secondary/optional tool in such circumstances. If a difficulty is encountered operating the HyDrone, other assets/measurement techniques may be used. After sufficient experience, the NCDOT team will develop intuition on when it is most appropriate to deploy the HyDrone.

Chapter 7. Shallow-Water Coverage Path Planning Algorithm

7.1 Algorithm Objectives

A risk-aware coverage planning algorithm was developed that enables a USV to be deployed in areas with limited prior knowledge regarding the bathymetry that may pose a collision risk. The main risks addressed are the vessel colliding with physical obstacles or striking the waterbed in shallow areas. The algorithm is briefly described in this report. For full details of the mathematical model and algorithm pseudocode, refer to Chapter 5 of the M.S. Thesis (Dept. of Mechanical Engineering, UNC Charlotte, 2025) by Alex Nikonowicz titled “Inland Bathymetric Surveying with Uncrewed Surface Vessels: Performance Characterization and Risk-Aware Path Planning”.

7.2 Overall Methodology

The overall methodology follows three key steps:

1. **Initial Human-in-the-Loop Region-of-Interest (ROI) Survey**: A human operator first steers the vessel to scout the area. This initial survey helps to define the workspace boundaries, identify in-water obstacles, and gather coarse bathymetry (water depth) data. During this phase, a more rugged, less expensive depth sensor is used to prevent damage to the high-precision equipment. The operator guides the vessel around the perimeter of the survey area and known obstacles, and the collected position and noisy depth data are then used to create an approximate bathymetric map. The user then manually outlines the survey region and obstacles using a graphical interface based on the vessel's trace.

2. **Automated Coverage Path Generation**: Once the initial environment information is available, an automated coverage path planning (CPP) algorithm generates a detailed path for the autonomous vessel. This path is designed to efficiently cover the entire survey area using a systematic boustrophedon pattern, which involves sweeping back and forth. The path also accounts for efficient travel between different survey sections, addressing it like a Traveling Salesperson Problem (TSP) to minimize travel costs. The system calculates the optimal spacing between survey lines (swath width) based on the average water depth and the echosounder's coverage area to ensure good data density.

3. **Risk-Aware Adjustment and Iteration**: This is an iterative process where the system evaluates the generated path for safety and adjusts. The goal is to ensure the risk of collision remains below a predefined target level. If the risk is too high, the system modifies the environment model by increasing a "buffer" around obstacles and the survey boundaries, forcing the path planner to generate a new route further away from hazards. This loop continues until the calculated path satisfies the safety criteria.

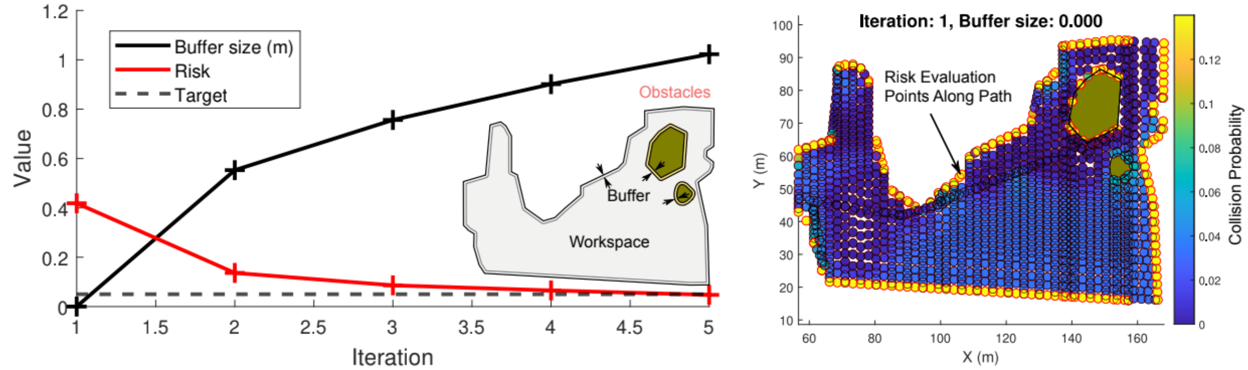


Figure 67: Overview of coverage path planning algorithm. Left: Buffer size and risk variation with each iteration. Right: Set of evaluation points during the first iteration, color-coded by collision probability.

7.3 Detailed Algorithmic Components

Vessel Model. The system incorporates a statistical model to represent the vessel's true position as it follows a planned path. This is important because factors like water disturbances, wind, and GPS errors can cause the vessel to deviate from its intended course. The model accounts for this uncertainty, particularly how it changes during turns:

- The uncertainty (or spread of possible positions) is greater during sharp turns and then gradually decreases as the vessel moves into straight sections of the path.
- This uncertainty is based on experimental data correlating turning angles with how much the vessel typically deviates from its path. This information is used to predict the likelihood of the vessel being at any given point near its intended path.

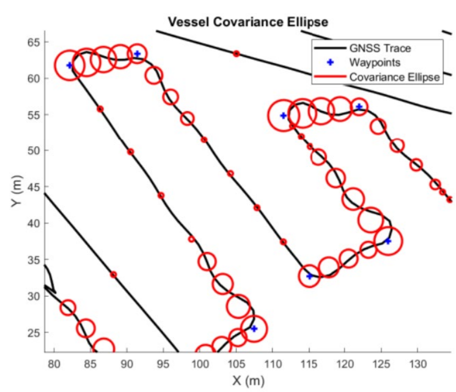


Figure 68: Model of vessel position uncertainty applied to experimental data.

Environment Model. The survey area (workspace) and in-water obstacles are defined as polygons. There are two types of obstacles considered for risk: (i) in-water obstacles and (ii) shallow-water obstacles. In-water obstacles are physical objects like bridge pillars or vegetation, which are identified by the human operator during the ROI survey. Their presence is considered certain when calculating risk. Shallow-water obstacles are areas where the water is too shallow for the vessel or its depth sensor to operate safely. Their presence is uncertain, as it depends on the estimated depth and its variability. To manage risk, a buffer zone parameter is virtually added around these obstacles and the boundary of the survey region. This buffer inflates the perceived size of obstacles, guiding the path planner to keep the vessel away from them. The amount of buffer added is based on the risk calculation as described next.

Risk Calculation. For specific points along the planned path, the system calculates the probability of a collision. This is done by creating a local grid around each point and considering three factors within each grid cell:

1. **Vessel Position Probability**: How likely the vessel is to be in that specific cell, based on its statistical movement model (higher probability near the center of the intended path, lower further away, and influenced by turns).

2. **Shallow-Water Obstacle Probability**: The likelihood of the water being too shallow for safe passage in that cell, derived from the estimated water depth and its uncertainty from the ROI survey.

3. **In-Water Obstacle Certainty**: If a cell contains a physical obstacle (like a bridge pillar), its presence is considered 100% certain. These probabilities are multiplied together cell by cell to create a "collision risk map" for that local area. Summing up all the probabilities in this local map gives the total collision risk for that specific point on the path. The maximum risk value found along the entire survey path then becomes the key measure used to decide if the path is safe or needs adjustment.

Resampling Waypoint Path for Risk Checking. The system doesn't check risk at every step along the path but intelligently selects "risk evaluation points". These points are strategically placed to be more dense in areas where the vessel's position is less and in shallow water areas where the risk of hitting the bottom is higher.

Iteration. The iterative process of adjusting the buffer size based on the calculated maximum risk allows the system to find a path that avoids high-risk areas while still providing maximum survey coverage.

7.4 Real-World Example

To conduct the real-world risk-aware survey, a crucial step was to use a sensitive and expensive echosounder only after a safe operational area had been defined. For the initial Region-of-Interest (ROI) survey, a custom Arduino-based data collection unit equipped with a low-profile, inexpensive Blue Robotics echosounder was utilized. This low-cost setup was intended to collect necessary depth data safely in shallow areas, preventing damage to the primary echosounder. The experiment site chosen was a section of a bridge in the Catawba River, a complex area with bridge pillars and shallow bathymetry.

ROI Survey. The human-in-the-loop ROI survey was performed at this location using the custom data collection unit. A significant observation was that the water level was about 8cm lower than during previous tests, which directly impacted the vessel's traversable workspace. This environmental change, including varying water levels and vegetation, highlighted the critical importance of conducting an ROI survey because operating regions, obstacles, and bathymetry can change over time, rendering previously planned waypoint paths unsafe or inoperable. From the collected GP bathymetry and variance data, combined with operator input (satellite imagery, previous data, field observations, and engineering judgment), the survey workspace and obstacles were defined. Figure 69 illustrates the geometry of the ROI path, the predicted bathymetry from the data collected, and the orange shallow-water obstacle identified. The three encircled regions are pillars of the bridge.

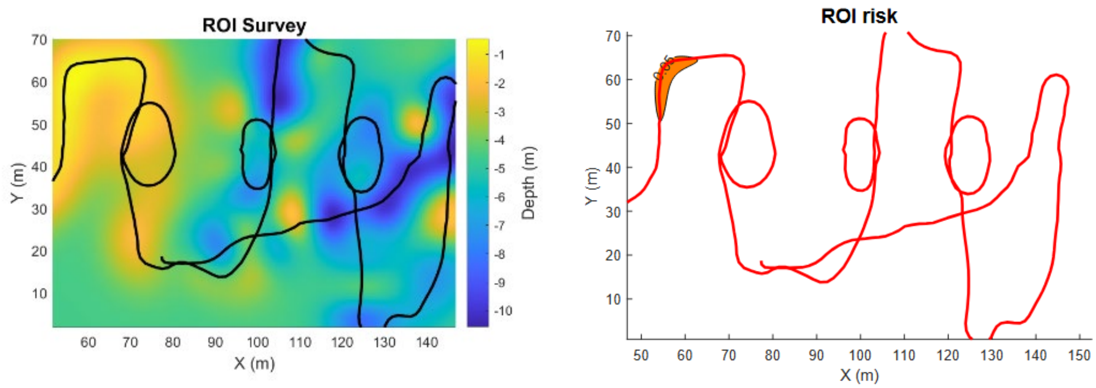


Figure 69: ROI survey with the HyDrone. Left: Path of HyDrone and predicted bathymetry computed by the algorithm. Right: Orange area identified as a shallow water obstacle.

Risk-Aware Survey Execution and Results. After the ROI data analysis, the algorithm computed a path plan for the survey. Over eight iterations, the algorithm progressively increased a "buffer" size around obstacles and shallow regions based on the calculated risk, generating increasingly safe path plans. While only the final path plan was used for the actual survey, previous iterations provided insights into high-risk events. Initially, the risk was about 50% with no buffer, but after eight iterations, it was reduced to 4.86% with a 2.369 m buffer, meeting the target risk threshold of 5%.

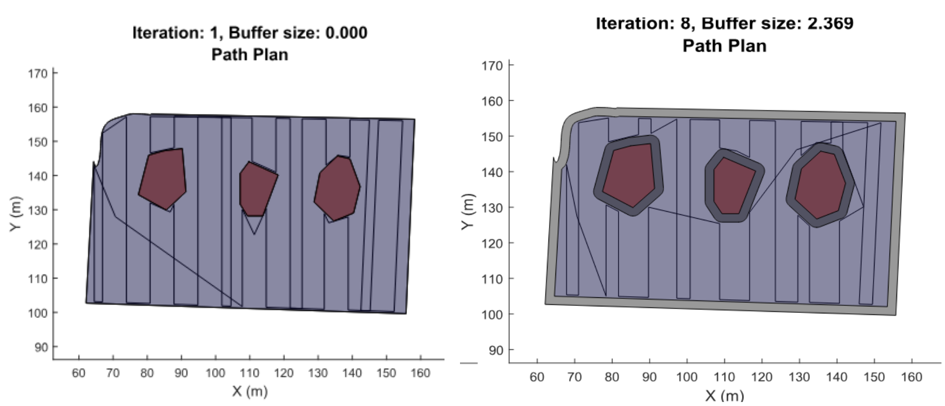


Figure 70: Planned path between first and final iteration.

Final Path Execution. The final version of the path was passed to the HyDrone for execution. The resulting path is shown below in Figure 71.

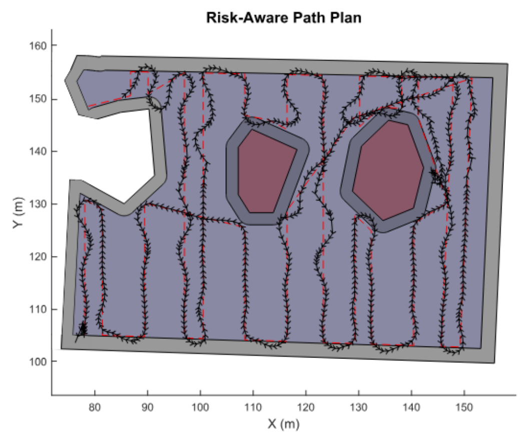


Figure 71: Final Risk-optimized path executed by the HyDrone.

Due to a software error encountered on-site, the first five waypoints were not properly traversed, and the workspace has been truncated to reflect the vessels' path. This was not caused by the algorithm or the coverage path plan; it was an error with the USV path following. Analyzing the vessel's GNSS trace during the survey confirmed that the vessel successfully traversed the workspace without entering obstacle regions or exceeding the defined perimeter while operating autonomously. During turns, the system's buffer effectively restricted vessel movement, demonstrating accurate modeling of vessel dynamics and waypoint placement. Despite some GNSS data errors observed on the right side of the survey region, they did not prevent proper path-following. The vessel's actual path mostly stayed within the 2-sigma bounds and, at times, operated within the 3-sigma bounds of the estimated covariance model, validating the model's accuracy in predicting vessel position. This accurate modeling of vessel movement is crucial because the buffer control directly correlates with the risk calculation, which depends on the probability distribution of the vessel's position.

7.5 Conclusion

A novel coverage path planning (CPP) algorithm was developed utilizing an ROI survey augmented with custom FPV and echosounding hardware to estimate the location of in-water obstacles and shallow water hazards. Using the position of the hazards and their bathymetric uncertainty from a spatial GP, an iterative CPP algorithm determined an appropriate coverage path that reduces the risk of the vessel experiencing a high-risk event by restricting waypoint locations in a workspace by an obstacle buffer. Through simulation, it is found that by iterating on resampled risk evaluation points, an obstacle buffer can effectively be controlled to minimize obstacle collision or traversal through shallow water while accounting for vessel dynamics and crosstrack error that exists in a PID-controlled waypoint following USV. In experimentation, it is shown that the CPP can be developed with a coarse ROI survey performed on-site and the resulting coverage path successfully avoids obstacles, while delivering a high-resolution bathymetric dataset that can be used for further geostatistical analysis.

Chapter 8. Implementation and Technology Transfer Plan

<table>
<tr><th colspan="2">Research Product 1: Literature review and platform rating system for Uncrewed Surface Vessels (USVs) for NCDOT-relevant applications.</th></tr>
<tr><td>Suggested User</td><td>NCDOT Division of Highways, Location & Surveys Unit
NCDOT Office of Strategic Initiatives & Program Support</td></tr>
<tr><td>Recommended Use</td><td>Chapters 3-5 of this report contain an overview of USV technology, its potential applications in NCDOT applications, associated regulations, a survey of 91 market-ready platforms, and a platform rating system. The information can be used by NCDOT personnel considering the acquisition of USV platforms to:
Gain familiarity with a wide spectrum of USV technology
Identify high-value applications for NCDOT
Initiate additional focused follow-on research and pilot studies using USVs and related technology
Shortlist candidate USV platforms to consider for acquisition/integration into NCDOT operations</td></tr>
<tr><td>Recommended Training</td><td>None at this time.</td></tr>
</table>

<table>
<tr><th colspan="2">Research Product 2: HyDrone USV platform with custom FPV camera system and related documentation/guidance for operation by NCDOT.</th></tr>
<tr><td>Suggested User</td><td>NCDOT Division of Highways, Location & Surveys Unit</td></tr>
<tr><td>Recommended Use</td><td>Chapter 6 of this report provides an overview of the HyDrone’s capabilities and experience gained through extensive testing. This includes a proposed deployment workflow that describes the best survey mode to use given conditions, guidance on the effect of bridge occlusion on GNSS signal strength, guidance on the selection of swathing width, guidance on echosounder tuning, potential use of auxiliary survey equipment, and a procedure for using related software (HYPACK Echo or ArcGIS). The HyDrone itself and related equipment will be transferred to NCDOT. The information can be used by NCDOT personnel to:
Gain familiarity with the HyDrone platform and integrate any NCDOT-owned equipment (e.g., GNSS receiver)
Initiate testing with the HyDrone in select/relevant scenarios to save time and improve efficiency
Successful initial testing may lead to procurement of additional HyDrone units or other variants with differing capabilities</td></tr>
<tr><td>Recommended Training</td><td>Basic familiarization is being provided by UNC Charlotte. NCDOT may also consider training from Seafloor Systems or other operators.</td></tr>
</table>

Research Product 3: Data folder, field reports, and related MATLAB code for visualization.	
Suggested User	NCDOT Division of Highways, Location & Surveys Unit
Recommended Use	A digital folder is being provided alongside this report that contains testing reports, raw data, vehicle telemetry logs, field notes, media, and MATLAB code to process past experiments to visualize data and perform analysis. The digital folder can be used by NCDOT using the HyDrone to: • Gain familiarity with the HyDrone platform by reviewing past data/deployments. • Use the MATLAB code to visualize/analyze future HyDrone data to be collected.
Recommended Training	None at this time.

Research Product 4: Shallow-water, risk-aware, coverage path-planning algorithm.	
Suggested User	NCDOT Division of Highways, Location & Surveys Unit
Recommended Use	Chapter 7 of this report describes a novel path-planning algorithm that is designed to maximize survey performance (in terms of area covered) while avoiding shallow water regions, given prior information and uncertainty in the operating region. The output of the software tool is a set of optimized waypoints that can be loaded onto the HyDrone. This is an advanced tool that was developed to illustrate the potential use of the HyDrone in areas where there may be shallow water and a risk of colliding with bridge structures or running aground. The tool has shown promising results but is still in a research phase and is not ready for real-world deployment. NCDOT may use the outcomes of this research to: • Potentially support follow-on research to mature the tool, or related tools that optimize paths for improved data collection using autonomous platforms (USVs, UAVs, etc.)
Recommended Training	None at this time.

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Appendix A. Demonstration of a Low-Cost Side-Scan USV

The UNC Charlotte team hosted a local small business “Helo & Sub” that recently moved to North Carolina to discuss their uncrewed surface vessel (USV) technology. Helo & Sub visited campus on June 20, 2024 and provided an overview of their USV and sonar technology along with a live demonstration at Hechenbleikner Lake on campus. The figure below shows the system they have developed. The system is designed for rapid deployment to search small bodies of water such as retention ponds, canals, creeks, small lakes, rivers, and along the shores of larger lakes such as around boat ramps, possible accident locations, and recreation areas. To date the company has located over 75 vehicles/watercraft leading to discovery of remains of 4 missing persons by law enforcement. This type of system may be of interest to NCDOT to visualize underwater terrain and observe if there are any debris, blockages, or other unexpected objects in or around transportation infrastructure. The USV also collects basic bathymetry data along its track via the fishfinder sonar system it employs.

The boat uses fairly large pontoons on each side that are connected by PVC tubing with a sealed electronics box in the center of the vehicle. Switches on the vehicle are used to power on the system and sonar. Voltage is displayed on an LCD. The sonar unit is a commercial fishing sonar: Garmin Ultra High-Definition with ClearVü (down scan), SideVü (side scan), and LiveScope (multibeam). The different transducer heads are all mounted on a PVC pipe with an adjustable in-water angle (each mode requires manual adjustment), which can be stowed for transport. Motors (blue rings with red propellers) are stowed in an upright position and are swung down when deployed. The design of the motors was purported to assist with removing vegetation (i.e., the absence of additional housing/fins in the motor area makes it easier to “clear” the motor by running it in forward and reverse when it is clogged with vegetation).

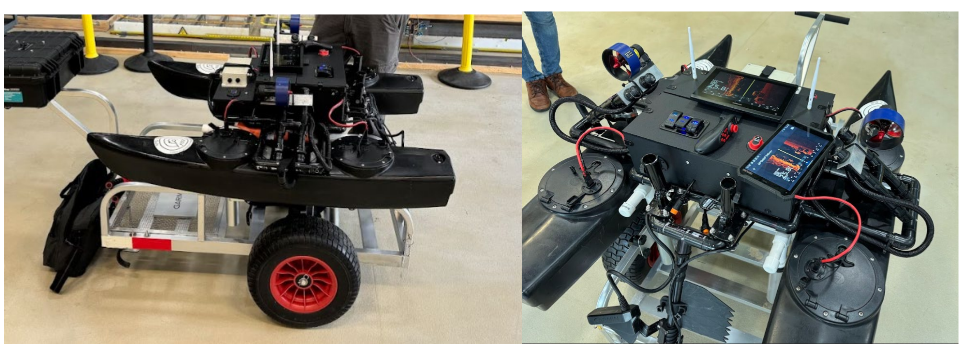

Figure 72: Images of Halo & Sub USV on a modified offshore angler beach cart. Right: Two of the touchscreen displays showing sonar data. The screen mounted on the middle box is rigidly attached to the vessel. The screen on the right is a tablet that can be viewed from shore.

The system also has a separate monitor for displaying the sonar data (see Fig. 2), and all the monitors are repeating the same display using the ActiveCaptain® App by Garmin. This is a WiFi application that allows controlling the sonar system remotely. The WiFi signal originates from the sonar unit itself and has been boosted on the vehicle to allow a longer range (see white antennas visible in Fig. 1).

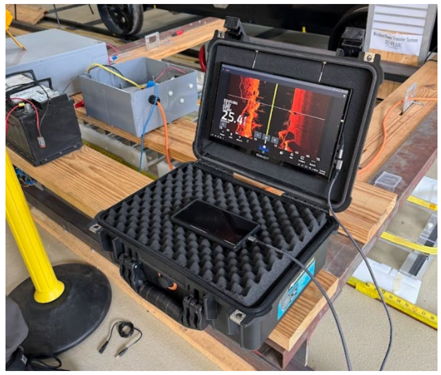

Figure 73: Monitor displaying sonar data in benchtop demo/test mode. The screen can be used to mark GPS locations of objects encountered during the mission as well as to record imagery for later review.

Helo & Sub provided a demonstration of how the sonar data can be stitched together to create a mosaic. This was done in the lab using prior collected data in Florida, where a number of abandoned cars were discovered (Fig. 3). The Garmin unit records the sonar data (presumably RSD files) that are then imported into SonarTRX (https://www.sonartrx.com/). Georeferenced tiles are then imported into Google Earth Pro and saved as KML files.

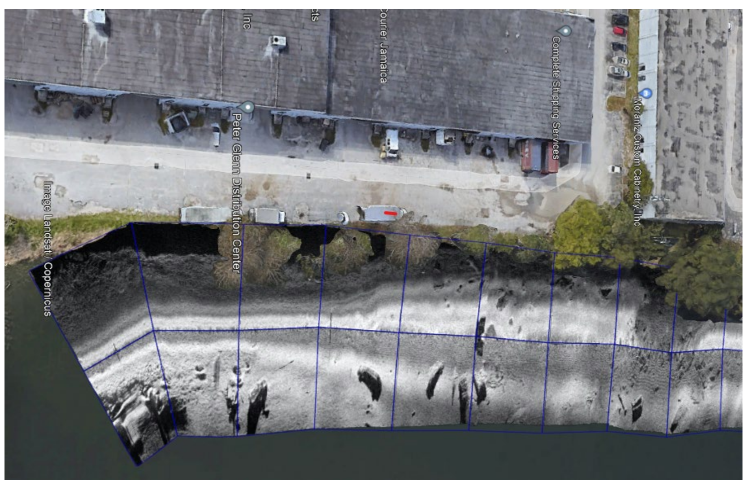

Figure 74: Example side-scan mosaic from Helo & Sub data collected in Florida.

The USV can be operated by a single operator, but it is best to deploy with a team of two. The image below shows how the vehicle is transported from a beach cart to a pickup truck. The Halo & Sub team mentioned that a typical deployment from a bank involves clearing a small area of vegetation with a rake. In this case, the hooks were used to lower the vehicle into the water (note: the transducers are below the water line, and care must be taken to avoid hitting them on the ground).

Figure 75: Transportation and deployment of the USV

The boat was easily controlled in the water with just a brief overview of how to use the handheld joystick. The vehicle has a “cruise control” feature and was capable of moving in forward and reverse directions. The maximum speed was about 1-2 m/s (estimated). The placement of the motors along the boat centerline allows it to rotate in place without translating. This is useful in the LiveScope view since it allows the operator to pivot in place while panning through the water. The control range is about 200-300 meters (estimated). Helo & Sub described the use of a DJI Drone with vision tracking to hover over the vehicle in cases where there is no line of sight.

Figure 76: Left: The vehicle is controlled with a one-handed joystick controller by a student, similar to used for remote-control hobby boats. Right: USV deployed on Hechenbleikner Lake on UNC Charlotte’s campus.

Example of data collected (visible live to the team on shore) in the three sonar modes is shown below. The LiveScope Perspective Mode provides a top-down view of the area below the USV, similar to shining a flashlight with shadows behind objects visible. It consists of multiple beams stitched together, and the edges of these beams are visible in the display (as a narrow blurred/distorted region). The angle is a 150-degree field of view. The ClearVu mode provides a vertical-plane cross-sectional view of the terrain below the USV. The SideVu provides a side-scan style view to the left and right of the vehicle, with a nadir gap visible directly below (black area with absent data).

Figure 77: Examples of three modes of the sonar data collection from left to right: LiveScope, ClearVu, and SideVu as observed during the on-campus test.

The images in Fig. 6 are challenging to view due to the glare when being photographed. An example of the same type of data presented in the Garmin Transducer Selection Guide manual is shown in Fig. 7 below.

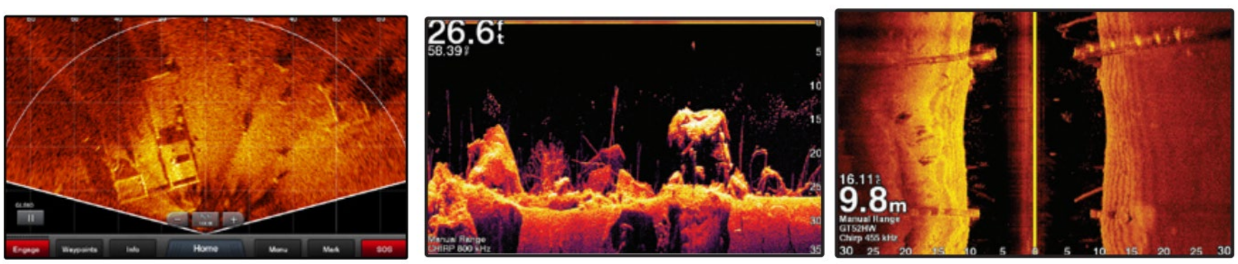

Figure 78: Examples of three modes of the sonar data collection from left to right: LiveScope, ClearVu, and SideVu as advertised by Garmin (Image Source: Garmin Transducer Selection Guide, 2022. URL: https://static.garmincdn.com/shared/nordic/catalogs/ Transducer-Selection-Guide-2022-all-LR.pdf).

Appendix B. Example Deployment: Sloan's Ferry Bridge

B.1. Summary

The UNC Charlotte team (Artur Wolek and student Alex Nikonowicz) visited Sloan's Ferry Bridge (Bridge #350091, Latitude: 35.245739, Longitude: -81.009163) on the boundary of Gaston County and Mecklenburg County on January 24th, 2025 to collect sounding measurements. The HyDrone uncrewed surface vessel (USV) equipped with a Hydrolite single-beam echosounder (dual frequency 20/300 kHz) was deployed for data collection. Three sets of data were collected:

1. Depth measurements using the HyDrone USV in manual (human operated) mode that allowed close navigation around bridge bents, avoiding very shallow water and large fallen trees near the bridge. Sections of the upstream and downstream parts of the bridge were measured.
2. Depth measurements using the HyDrone USV in automated survey mode. This survey was conducted further away from the bridge on the downstream side following a lawnmower-type pattern.
3. Measurements made by the team using a plumb line from an inflatable raft near each bent.

The total time on site for setup, measurements, and recovery/packup was approximately 4 hours (from 11 AM to 3 PM). The GNSS measurements from the HyDrone used corrections from NC CORS Network that were received over the internet (NTRIP) using a mobile phone hotspot. In addition to the above measurements, the GNSS position and altitude of the waterline were recorded, and the GNSS position and altitude of the wing wall used as a reference point in prior NCDOT reports. The testing location is shown Figure 79 and the path of the HyDrone during testing is shown in Figure 80.

Figure 79: Sloan's Ferry Bridge testing location.

During the manual survey (green in Figure 2), an attempt was made to encircle each bent. The operator had a live video feed into first-person view (FPV) goggles from a camera onboard the HyDrone. Due to shallow water and debris (trees), some bents were not encircled. A long track alongside the bridge was followed to approximate the location where prior measurements were made from the bridge railing.

Figure 80: Two data collection runs were executed using the Hydrone USV. The first run (green markers) consisted of a remotely piloted survey in the vicinity of the bridge and an outline of a "box" in which to conduct the second automated survey (orange markers).

B.2. Raw Soundings Recorded by HyDrone ASV

The raw soundings of the HyDrone were collected (measured from transducer to river bottom) as shown in Figure 81. The precision of the sounder measurement is 4 decimal places in units of meters. For ease of visualization, the initial plots shown here are color-coded to display intervals in 1-meter increments.

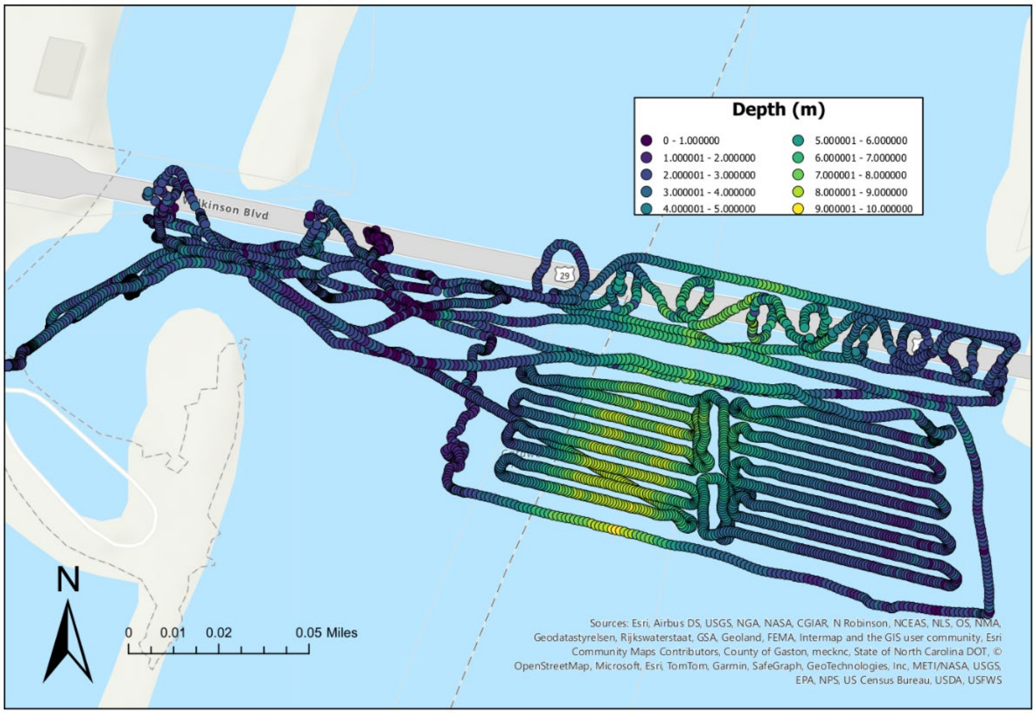

Figure 81: Depth measurements recorded by the HyDrone USV.

The raw measurements were processed to remove a small number of outliers and to add the offset of the waterline to the transducer. Vehicle pitch and roll deviations have not been corrected at this time. Other sources of error may include the assumed speed of sound. Results are shown for the low-frequency data (30 kHz). The low-frequency data can penetrate deeper into the riverbed and may result in larger depth readings, but generally has lower noise characteristics than the high-frequency echosounder setting.

ArcGIS Interpolation

The raw measurements shown above were geostatistically processed using ArcGIS. Standard Co-Kriging interpolation was used, and the area of interpolation was limited to the region containing measured points and around the bridge area of interest.

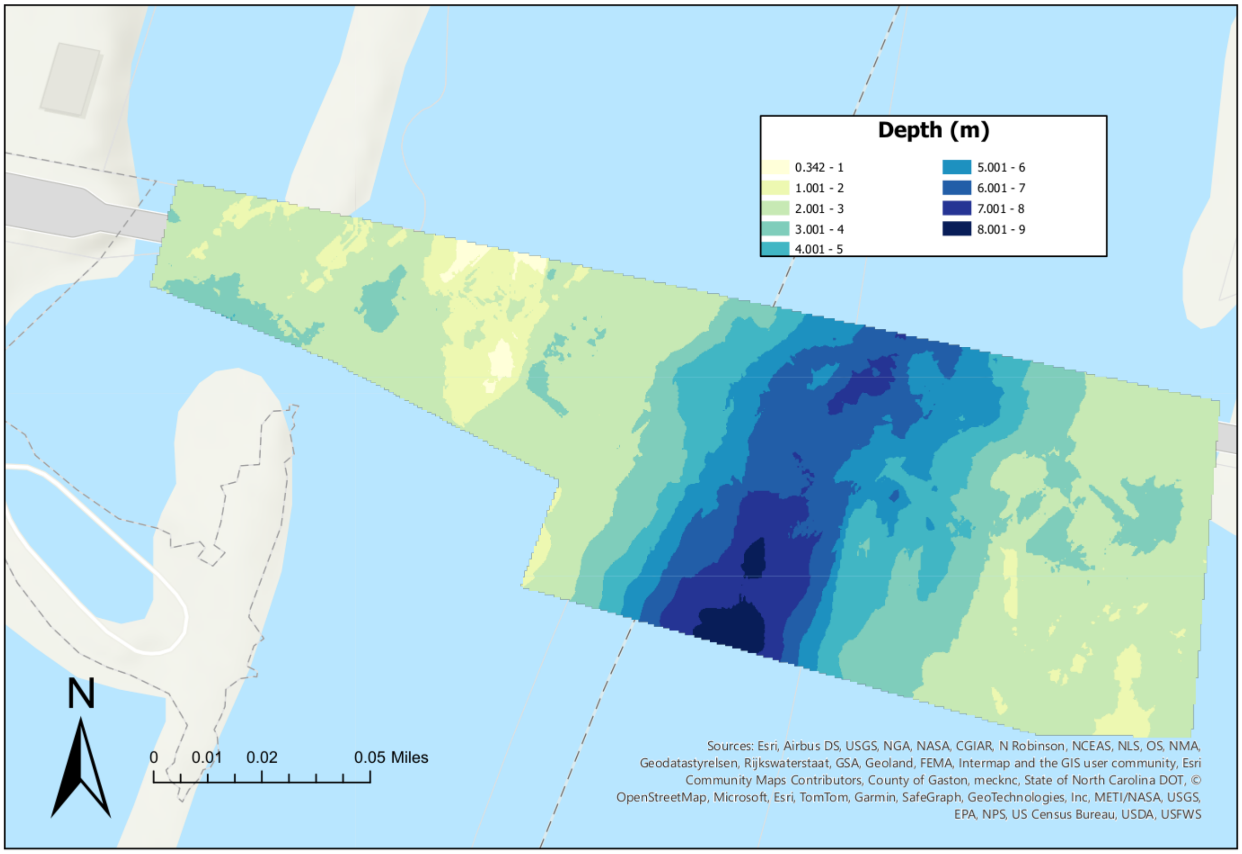

Figure 82: Depth measurements interpolated and smoothed.

Plumb Line Measurements

To collect additional data for comparison, Bents 1-16 were visited using a small inflatable raft with a trolling motor. A plumb line (an oil gauging Derrick tape) was used to measure water depth on the downstream side of the bridge, approximately in the middle of each bent. Due to wind and small currents, the inflatable raft was difficult to keep stationary for long periods. Some inherent measurement errors include sag and/or an angle between the contact point on the riverbed and the tape on the surface, as well as rocking of the boat and small wave action, causing an oscillating measurement. The accuracy of the measurements below is likely depth-dependent, with larger errors for greater depths. The measurements were recorded in feet and inches. Equivalent (converted) depth in decimal ft and meters is shown in the Table below.

Bent Number	**Depth Relative to Waterline (ft and in)**	**Depth Relative to Waterline (decimal ft)**	**Depth Relative to Waterline (meters)**
1	3 ft. 0 in.	3.00 ft	0.91 m
2	2 ft. 0 in.	2.00 ft	0.61 m

3	0 ft. 8.5 in.	0.71 ft	0.22 m
4	3 ft. 0 in.	3.00 ft	0.91 m
5	3 ft. 3 in.	3.25 ft	0.99 m
6	2 ft. 9 in	2.75 ft	0.84 m
7	4 ft. 1 in.	4.08 ft	1.25 m
8	8 ft. 2 in.	8.17 ft	2.49 m
9	18 ft. 9 in.	18.75 ft	5.72 m
10	19 ft. 6 in.	19.5 ft	5.94 m
11	24 ft. 1 in.	24.08 ft	7.34 m
12	19 ft. 9 in.	19.75 ft	6.02 m
13	17 ft. 3 in.	17.25 ft	5.26 m
14	8 ft. 9 in.	8.75 ft	2.67 m
15	5 ft. 4 in.	5.33 ft	1.63 m
16	1 ft. 8 in.	1.67 ft	0.51 m

Table 1. Measurements obtained via Derrick tape (plumb line).

Downstream Streambed Profile Comparison

The origin point used to plot streambed profile measurements is shown below and was measured using RTK GNSS to be located at (35.24610042,-81.01114885) with an altitude (relative to GNSS reference ellipsoid) of 147.553 meters.

Figure 83: Location of origin point used for streambed profile measurements.

The water line near the testing location (-81.01148520,35.24554618) was measured with RTK GNSS to be at an altitude of 141.543 meters. Therefore, we assume the waterline was about 6.01 meters (19.71 ft) below the origin point during the day of the test. The streambed profile has the abcissa defined parallel to the bridge. To properly align and rotate the HyDrone measurements to be consistent with this direction, two points along the bridge centerline were selected based on satellite imagery (see below). From these points, the orientation of the bridge was found to be -13.469 deg. South of East.

Figure 84: HyDrone path parallel to bridge and other key points used to rotate the path into the same coordinate system as the streambed profile measurements.

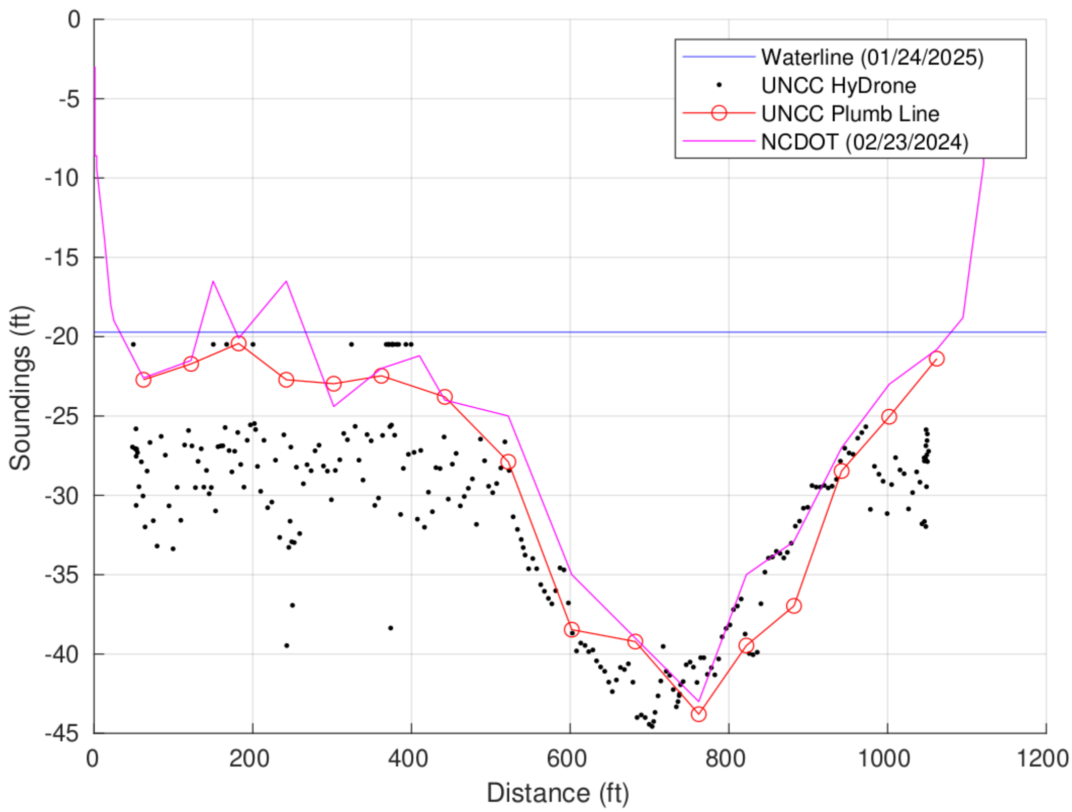

Figure 85: Comparison of soundings at 30 kHz.

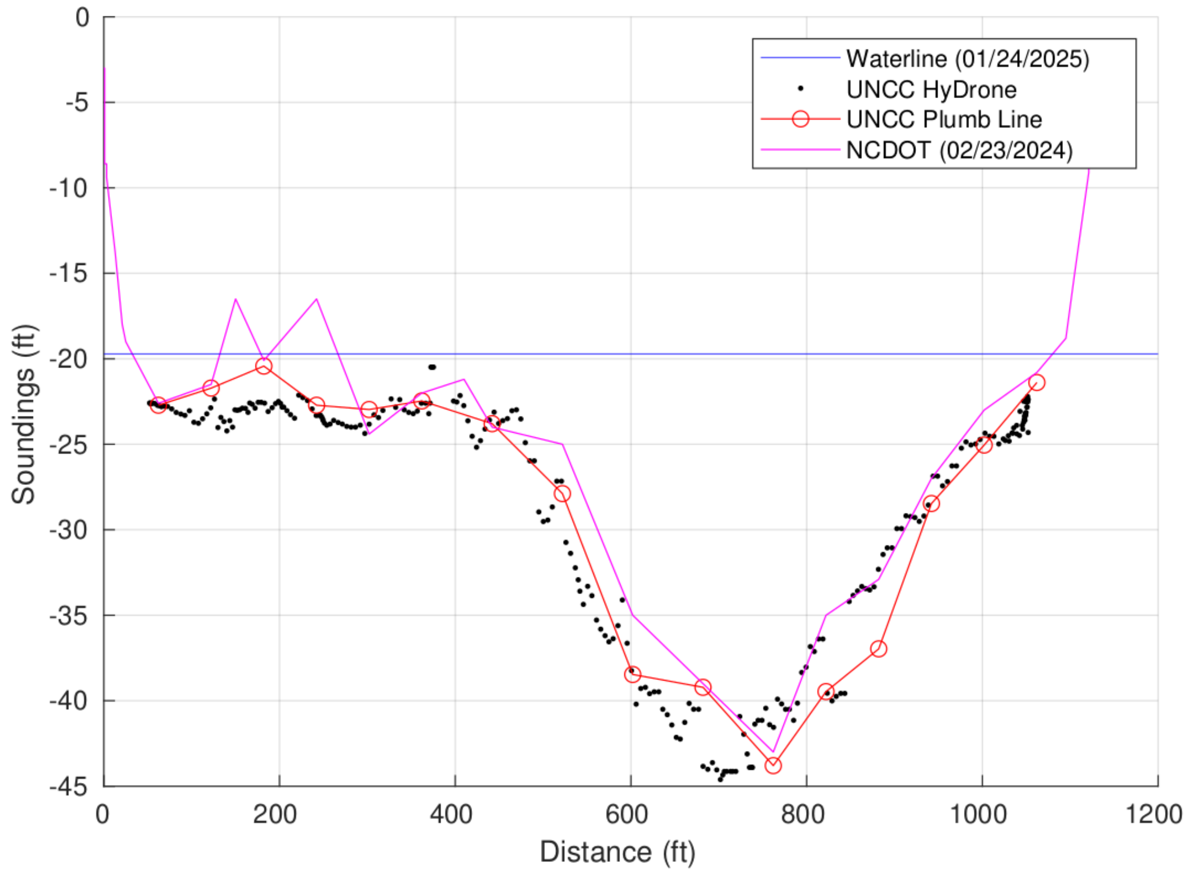

Figure 86: Comparison of soundings at 250 kHz.

Figure 85 compares the prior NCDOT measurements (02/23/2024) to the plumb line measurements and the low-frequency (33 kHz) HyDrone measurements (limited to the first line of the test that was parallel to the bridge). Both the plumb line and HyDrone measurements are plotted by offsetting them from the origin by the amount determined as the waterline (19.71 ft) above. The plumb line measurements appear to be similar to the prior NCDOT measurements with the deepest point of the channel occurring at about 760 ft. near Bent 11. The Hydrone was deployed parallel to the bridge but offset by about 12 ft. during this manually piloted run. Measurements near the deepest point of the channel are similar, although they are shifted to the left with the deepest point at about 700 feet. This appears to be consistent with Figure 4 which shows the overall geometry of the channel skewing towards the center of the river downstream of the bridge. The HyDrone measurements exhibited low noise when operating in deeper water. However, high noise and unreliable measurements were observed in the shallow sections of the river that had a depth of less than < 5 ft (at distances between 0-500 ft seen in Figure 85 and later on the East bank of the river near distances of 1000 ft). The HyDrone transducer is mounted 0.77 feet below the waterline, and at depths of a few feet is susceptible to reverberations and other acoustic and signal processing limitations.

Figure 86 also compares the prior NCDOT measurements (02/23/2024) to the plumb line measurements and the high-frequency (250 kHz) HyDrone measurements. In this case we see much better agreement with higher frequency data.

Media (Photos)

Figure 87: Left: Setup location prior to deployment near the west side of the bridge. Right: HyDrone transiting towards survey area (Bent 1 and 2 in view).

Figure 88: Left: Student piloting drone using first-person-view (FPV) goggles. Right HyDrone on the east side of the bridge near Bent 16.