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PREPRINT

Development of Low-Cost, Open-Source Unmanned Surface Vehicle for Water System Monitoring

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Abstract

Commercially available Unmanned Surface Vehicles (USVs) in the market are expensive, and the software used for automating navigation and bathymetry mapping are typically proprietary. Large-scale collection of water quantity and quality data requires dynamic in-situ sensing approaches with open-source software for user flexibility. This manuscript presents an open-source, economic, and efficient USV platform for in-situ depth sensing to perform hydrographic surveys in freshwater bodies with capabilities to explore inaccessible shallow regions by humans. The USV components cost less than $3,000. The application of the USV for a bathymetric survey was performed at Horse Creek Cove at Grand Lake O' the Cherokees. These results find that an estimated 43,000 m^3 of sediment accumulated in this cove over a time span of eleven years between a 2009 manual survey and our 2020 analysis with the USV. This USV platform provides an advantageous method for widescale adoption and use manual methods of mapping of bathymetry and potentially other water quality parameters.

Keywords

Unmanned Surface Vehicle (USV), Hydrographic survey, bathymetry mapping, Open-source software

Introduction

Continuous monitoring of water quantity/quality in freshwater bodies is a priority because of increased water demands and uncertainty in extreme weather events due to climate change (Duran-Encalada et al., 2017; Omar et al., 2021; Sun and Caldwell, 2015). Bathymetry refers to the underwater topography of surface water bodies in both saltwater and freshwater environments. Collecting bathymetric data helps study sediment deposition and habitat conditions of benthic organisms in both fluvial and marine/coastal systems (Kostylev et al., 2001). Historically, echo sounders were used to measure depths and map the bathymetry of surface waterbodies (Blondel, 2012; Dierssen et al., 2014; Vincent et al., 2012). The constant influx of sediment into shallow regions of surface water bodies creates water quantity issues, such as a reduction in surface water storage and navigational capacity of lakes/reservoirs. Sediment pollution in water bodies also results in $16 billion dollars of environmental damage annually and likely contributes to Harmful Algal blooms (HABs) (Bloesch, 1995; Elliott, 2012; Gao, 2009).

Remote sensing methods have been used to measure the depth of lakes and reservoirs, but they are constrained by factors including sun glint (reflection of light from waterbodies), atmospheric conditions (cloud cover), turbidity, and disruptions due to turbulence in the water [10]. Technological advances with echosounders attached to manned vessels, Unmanned Surface Vehicles (USVs), and Unmanned Underwater Vehicles (UUVs) provide efficient bathymetry monitoring opportunities for surface water bodies compared to remote sensing in turbid and turbulent waters (Bertram, 2008). Manned surface vessels equipped with LiDAR or echosounders can map the marine seabed with high precision. However, their deep draught limits access to shallow water regions, making them ineffective for surveying such areas. . Additionally, these vessels require significant operational resources, including fuel, maintenance, and skilled personnel, making them costly and less efficient for extensive survey operations, particularly in shallow or complex coastal environments. A hydrographic survey using a manned boat costs around $250 to $400 per square kilometer depending on boat ownership and rental costs (de Araújo et al., 2015). USVs enable in-situ access to shallow turbid regions in water bodies that are inaccessible by larger, manned vessels for high spatial and temporal bathymetry data collection (Wang et al., 2009). Commercially available USVs designed for hydrographic surveying collect bathymetric data with endurance ranging from hours to days (Orthmann and Ziegwied, 2017; Zwolak et al., 2017). However, these commercial USVs are expensive, and their proprietary navigation software prohibits user preferences to calibrate innovative autonomous vehicles. Besides economic considerations, automated approaches monitoring sediment deposition help prevent humans getting into contact with contaminated aquatic environments including HAB events and oil spills (Li et al., 2022). Therefore, a reliable, inexpensive, and efficient surface water monitoring system is necessary to improve water quantity monitoring. This article presents the design, development, and application of a low-cost, reliable, and open-source USV (also known as Mobile Autonomously Navigable USV for Evaluation of Lakes (MANUEL)) platform to perform hydrographic surveys in freshwater bodies.

Hardware description

The kayak that is used in MANUEL is a 6ft long and 2ft wide vehicle with dual underwater propulsion system. The LiPo batteries that power MANUEL are placed in a pelican case (Figure 1) for waterproofing while providing some air circulation. The endurance of the MANUEL is 3.5 hours with a cruising speed of 1.4 m/s. The maximum speed at which MANUEL can perform autonomous missions is 3 m/s. The integration approach for engineering MANUEL is to keep it simple and functional. A summary of the materials and links to suppliers for parts needed to build MANUEL is provided in Table S1. The parts cost under $3,000.

MANUEL has a ping sonar (shown in Figure 1) installed at the bottom of hull between the thrusters to measure depth. The ping sonar is a single beam echosounder that can be used to perform hydrographic surveying. MANUEL contains a lightweight single hull kayak that can carry up to 130 lbs. Observations of water depth are currently stored locally on a Secure Digital (SD) card. The data are later retrieved and analyzed using a Python script that can be used to visualize interpolated bathymetry maps.

Application, Validation, and characterization

An autonomous mission collecting bathymetry data was conducted using MANUEL in the study area of Grand Lake, Oklahoma in the summer of 2020, as shown in Figure S2. The time resolution of the depth measurements collected are at 2 Hz and a lawn mower pattern was used as shown in subplot (a) of Figure 2. The interpolated bathymetry map is plotted to visualize the bottom elevation of the Grand Lake as shown in Figure 2. The depth measurements collected by MANUEL during the bathymetry survey of Horse Creek Cove in 2020 were compared with the bathymetry survey data collected by Oklahoma Water Resources Board (OWRB) in 2009 that resulted in a similar heat map as shown in subplots (b) and (d) as shown in Figure 2. Differences between the two surveys are attributed to the single beam echosounder, environmental factors, and scour and deposition between the two events. The supplemental documentation contains a more detailed description of the initial testing under different environmental conditions and performance metrics of MANUEL and recent similar studies.

Application for sedimentation and reservoir volume analysis

Sedimentation is a major issue that negatively affects the storage capacity of 51% reservoirs along the plains in the central USA (Krogman and Miranda, 2016). The estimated reservoir capacity of Grand Lake based on the 1940 and the 2009 surveys of OWRB were 2,387,400 acre-ft 2,183,200 acre-ft respectively (Hunter and Labriola, 2019). Thus, the capacity of Grand Lake has decreased by about 204,200 acre-ft between these years. After 2009, extreme rainfall events in 2013, 2015 and 2019 transported large amounts of sediments into the Grand Lake (Mignogna et al., 2012; Schooley et al., 2022). The bathymetry survey of Horse Creek Cove conducted by MANUEL presented the capability of the USV to estimate the reservoir volume and assess the storage capacity. As shown in Figure 3, the Horse Creek Cove has sediment deposition with volume of 42,958 m^3 in the period of eleven years from 2009 to 2020. In addition to bathymetry mapping MANUEL has been tested with YSI-EXO3 sonde as payload to measure water quality parameters in freshwater bodies (Jdiobe, 2020). The in-situ data collected by MANUEL is currently used to monitor HABs in freshwater reservoirs of Oklahoma and Kansas (Pamula et al., 2025). The supplemental documentation describes other potential applications for hydrologic monitoring using this technology in more detail.

Summary and conclusions

This paper presents a low-cost, and open-source USV (also known as MANUEL) that performs hydrographic surveys of freshwater bodies. Using the low-cost materials available in the market MANUEL can be built easily to conduct hydrographic surveys with a range of 1 mile from launch. The bathymetry survey performed by MANUEL in the Horse Creek Cove of Grand Lake resulted in the finding that the reservoir storage is decreased by the volume of 42,958 m^3 due to sedimentation from 2009 to 2020. The assessment of sediment deposition improves the decision-making process of dredging to restore reservoir storage. Finally, this paper presents that autonomous vehicles reduce the hydrographic survey time and provide smart engineering solutions to develop bathymetry maps that facilitate lake managers and other important stakeholders to manage quantity of surface water resources.

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that influenced the work reported in this paper.

Supplemental Materials

A companion document is available for this article containing additional details including Figures S1-S6 and Tables S1-S3. The statistical analysis data and code can be found in the Mendeley repository at https://data.mendeley.com/datasets/t8cncxrfh2/1. Detailed evaluations of error metrics and durability over extended periods of MANUEL's operation are presented in the referenced thesis (Jdiobe, 2020).

Acknowledgments

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Figure Caption List

Figure 1. (a) Placement of Ping sonar, (b) Mounting location of Ping sonar between thrusters, (c) water resistant battery box.

Figure 2. Hydrographic survey of MANUEL compared with Manual survey of Grand Lake, Oklahoma. (a) Autonomous survey path of MANUEL; (b) Lake bottom elevation mapped using linear interpolation; (c) Manual survey performed by USGS in 2009; (d) Lake bottom elevation mapped using linear interpolation.

Figure 3. Bottom elevation difference of Horse Creek Cove showing the sedimentation in the eleven years from 2009 to 2020.

Figure1

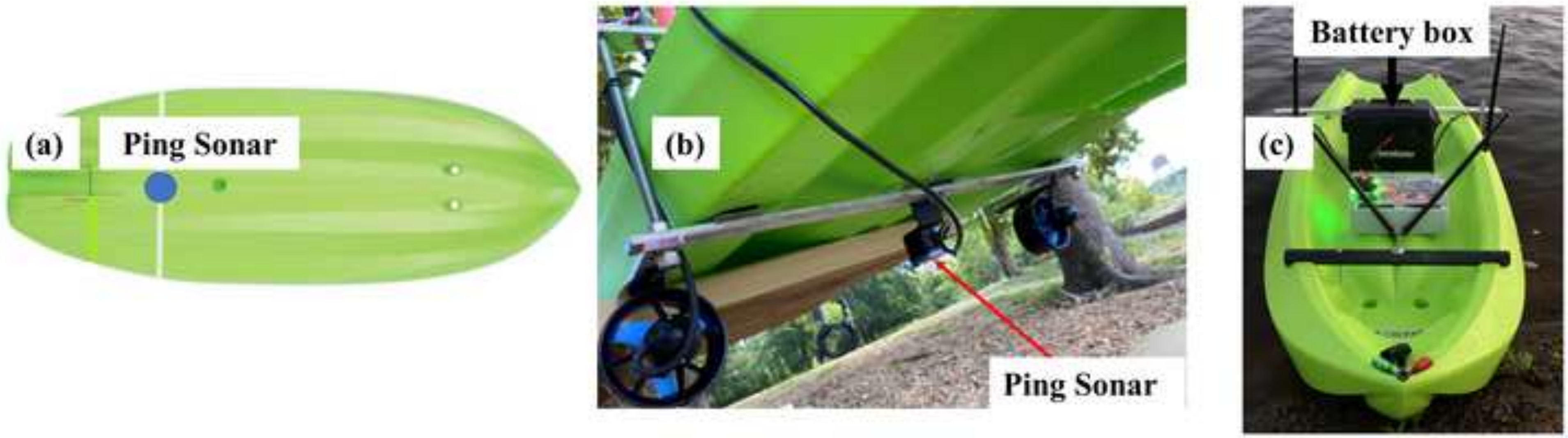

Figure2

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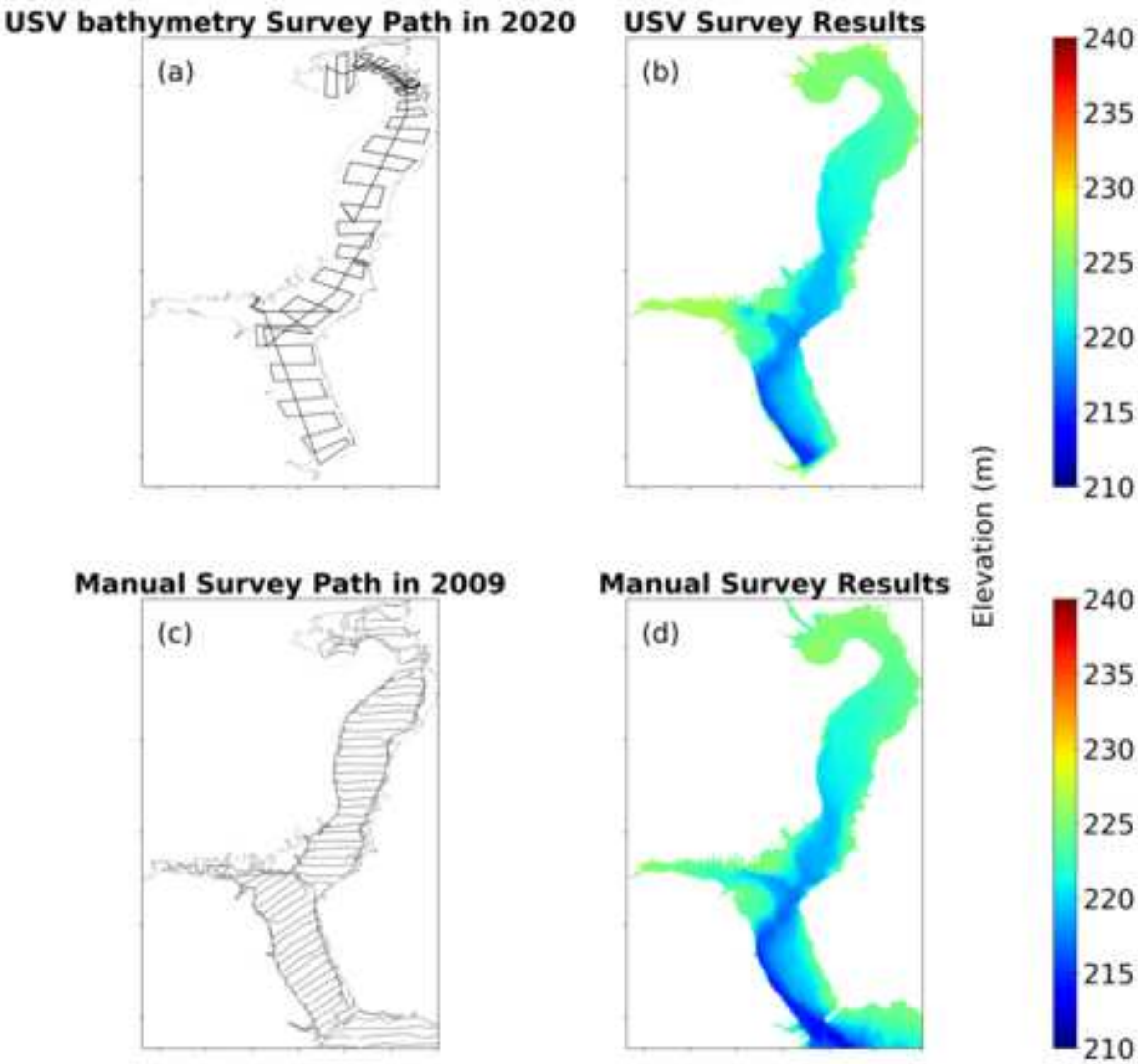

Figure3

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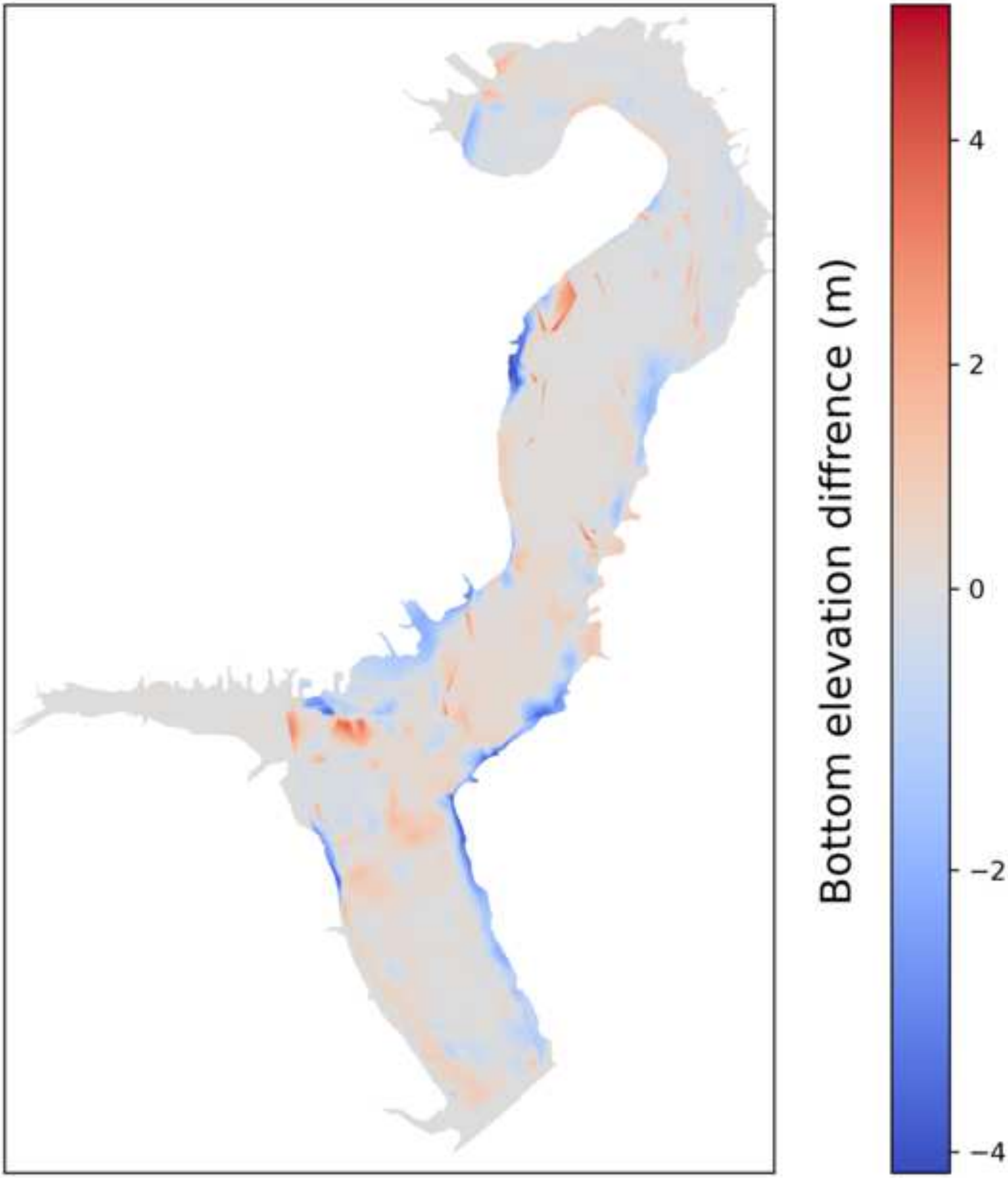

Supplemental Information for "Development of low-cost USV operated with open-source software for bathymetry mapping"

Hardware setup

The avionics on Mobile Autonomously Navigable USV for Evaluation of Lakes (MANUEL) used to perform autonomous hydrographic surveying are shown in Figure S1. The Electronic Speed Controllers (ESCs) on MANUEL provide differential thrust to move forward, backward, and turn while being connected to the Futaba T8J 2.4 GHz S-FHSS (Radio transmitter) for connections to approximately one mile. The telemetry in MANUEL includes RFD 900X for encrypted long-range operations with an operating frequency between 902 and 928 MHz at a transmission power of 1 watt. The electronic devices, including the Pixhawk, ESCs, and RFD are enclosed in the waterproof avionics casing to prevent water damage. A humidity remover is installed in the avionics casing to remove any incidental moisture.

While the Orange cube Pixhawk works as an autopilot to perform autonomous missions, the bathymetry data is collected using the EnviroDIY Mayfly board. The ping sonar is connected to the Mayfly board to measure depths up to 30 m. The beam produced by the sonar is 30 degrees and operates between 0 °C to 30 °C. The Mayfly board has 20-pin I/O headers for both analog and digital pins to connect sensors integrating with IoT networks. The ping sonar stores depth measurements in an SD card at a logging frequency of 2 Hz. The depth data collected by the ping sonar are geo-tagged with GPS coordinates from Pixhawk. The Mayfly board has a Bee module socket that integrates with cellular or Wi-Fi communications, to transmit the bathymetry data to the Cloud.

MANUEL's stability and endurance were tested in Boomer Lake, Oklahoma under wind speeds ranging from 15 to 20 kilometers per hour and waves up to 1 meter high. During the initial testing, pontoons considered were flat-bottomed, round-bottomed, and V-shape. Both the flat-bottomed and V-shaped bottom pontoons are not stable in turbulent waters and strong winds. The round-bottom is stable in calm water environments but tends to roll and bank in sharp turns. Therefore, considering turbulence and unexpected wind speeds in open water, a mixed hull design was selected for MANUEL as shown in Figure S2.

MANUEL is powered by two underwater T200 thrusters that are placed at the back of the kayak which are 0.6 meters apart from each other. The T200 thrusters consist of a brushless motor and 3-bladed propellers to provide the propulsion and maneuverability of MANUEL. Each thruster efficiently produces a maximum forward thrust of approximately 53 Newtons with a maximum power consumption of 390 watts. An aluminum bar that is resistant to corrosion is used to secure the thrusters which provide maneuverability and steering capabilities to MANUEL. To maintain forward and reverse mobility, MANUEL thrusters rotate at the same rate as shown in Figure S3. MANUEL turns using differential thrusting, where the thrusters rotate at different speeds and in the opposite directions as shown in Figure S3. Differential thrusting enables MANUEL to perform smooth, tight, and rapid maneuvers bathymetry surveys. MANUEL's avionics consist of an Orange Cube Pixhawk 2.0 (Autopilot), a GPS module, two Electronic Speed Controllers (ESCs), a receiver, a radio transmitter, and a radio frequency telemetry device. The autopilot used to control MANUEL navigates using the MAVLink satellite navigation system and operates between -10 °C and 55 °C (Ahmed et al., 2022; Meier et al., 2011). The Autopilot is connected to the GPS module, ESCs, and radio Telemetry device as shown in Figure S1. The speed of the thrusters and direction to maneuver the thrusters are performed by the ESCs. While the avionics and batteries of the MANUEL are waterproofed, the receiver and GPS module are not enclosed inside the waterproof casing to avoid electromagnetic interference between the electronics such as the Telemetry device and ESCs. All the electronics on board MANUEL are powered by four-cell Lithium polymer (LiPo) batteries each 314 watts with 22voltage and 14,000 milliamps.

Design files

Parts for MANUEL are available in the online market. The parameters used in the ARDUPILOT to run the autonomous missions, open-source scripts for geotagging the data collected by the ping sonar, and scripts for interpolation plots are available on the online repository at Mendeley Data.

(https://data.mendeley.com/datasets/t8cncxrfh2/draft?a=8ec5a947-bc00-450c-b963-4b14fe556ebf)

Calibration of compass

A compass calibration of MANUEL is performed using onboard calibration or heavy vehicle calibration settings. The onboard compass calibration requires the Futaba radio calibration first. After the radio calibration, the vehicle can be calibrated either using onboard calibration or the heavy vehicle magnetic calibration settings (Audronis, 2017). MANUEL is calibrated using an onboard calibration method when there is no GPS lock of the vehicle. The large or heavy vehicle calibration feature provides an accurate calibration if there is a GPS lock with vehicles actual heading based on a reference landmark in Mission Planner.

Testing of the USV

The testing of MANUEL was conducted in three phases. Phase 1 involved testing the propulsion system to steer and move in liquid medium including addressing and resolving the basic functioning of the thrusters in water. Phase 2 involved testing the autonomous capabilities of MANUEL to conduct a hydrographic survey. During this phase, the communication between MANUEL and ground control station was tested through several missions in Boomer Lake. One of these missions is shown in Figure S4. In Phase 2, the endurance of the batteries, maximum cruising speed, the range of operation before losing communication, and the sampling rate for bathymetry data acquisition were tested. In Phase 3, the limits of the telemetry while performing autonomous missions were tested and it was found that MANUEL had a successful telemetry connection with ground control station up to one mile. Loss of telemetry during the autonomous missions resulted from vegetation around the water body.

Outdoor testing for all phases was conducted at Boomer Lake and Grand Lake, Oklahoma in the testing area shown in Figure S5. Field tests at Boomer Lake and Grand Lake, conducted in windy, turbulent, and adverse weather conditions, evaluated the system's robustness and adaptability, confirming its reliability and demonstrating MANUEL's durability and effectiveness in real-world scenarios.

The selection of Boomer Lake and Grand Lake for field testing was strategic, as both reservoirs exhibit unique hydrological characteristics that make them ideal for evaluating water monitoring systems. Boomer Lake is an artificial reservoir created by the damming of Stillwater Creek. The lake was designed and constructed to store 3600 acre-feet of water but based on the

Oklahoma Water Resources Board (OWRB) survey of 2015, the capacity has dropped to 1484 acre-feet (OWRB, n.d.). The Grand Lake o' the Cherokees (Grand Lake), located in Northeast Oklahoma as shown in Figure S5 was formed by damming of the Neosho River. It serves multiple critical functions, including recreation, water supply, and hydroelectric power generation, providing electricity to numerous households in Oklahoma.Given its economic and environmental significance, monitoring changes in these reservoir storages are crucial. The gradual loss of capacity, often due to sediment deposition and other hydrological changes, underscores the need for continuous water quantity monitoring to ensure sustainable management of these vital water resources.

Operation mode

The available operation modes for MANUEL include MANUAL, AUTO, and SmartRTL as described above. The Futaba radio has a flip switch available to take MANUAL control or return MANUEL home using SmartRTL during emergency scenarios. For instance, MANUEL lost communication with the transmitter after one mile during phase 3 testing in Boomer Lake but MANUEL returned to the home point using SmartRTL operation mode. These features are also important if there is a possibility of interacting with other autonomous vessels that can cause electromagnetic interference with the avionics on MANUEL.

Operation instructions

The software application used to operate MANUEL via wireless telemetry is Mission planner. There are several open-source ground control station software options available for unmanned vehicles, as mentioned in Table S2. Although there are several options available, the mission planner was selected due to its compatibility with the components in MANUEL. Mission

Planner is compatible with the autopilot using three modes of operation, including Auto, Manual, and SmartRTL. Open-source rover firmware from the Ardupilot was uploaded to the Autopilot through mission planner and the vehicle configuration was changed and tuned to a boat by setting the frame-class parameter to 2. Manual operation mode enables MANUEL to be controlled using the Futaba radio. Auto operation mode enables MANUAL to perform autonomous missions based on predetermined GPS coordinates given to Mission Planner. SmartRTL operation mode is a failsafe that is triggered when MANUEL loses communication with the Futaba radio. Every time the MANUEL gets connected to the Futaba radio and GPS module; a home point is set by the missions which is considered as a safe return point when the failsafe is triggered. The information regarding the calibration of MANUEL's compass and testing is explained in detail in the supplemental information.

Validation

The data validation presented as a scatter plot with the linear fit is shown in Figure S6. A linear fit shows a strong correlation between the bathymetry data of both the surveys with an R^2 of 0.96. However, there is a time gap of eleven years between the two surveys and therefore we investigated further the deposition of sediment in the next section.

Limitations

MANUEL is currently equipped with a single beam echosounder (Ping Sonar) for bathymetric surveys and mapping. In addition to sonar, it can also carry YSI-EXO sensor bundles to measure various water quality parameters. However, the point-based nature of the

Ping Sonar limits spatial coverage to approximately 1 mile from the launch point. The sonar has a maximum depth range of 30 meters (98 feet) under ideal conditions, but its accuracy decreases in very shallow waters (<30 cm or 1 foot) due to signal interference and reflections from the water surface and bottom, which can lead to data loss or inaccuracies.

The acoustic signal is also vulnerable to environmental factors, including distortions caused by high turbidity, suspended particles, and dense biological activity, which can further affect depth readings. Additionally, the Ping Sonar lacks the ability to provide detailed seabed characterization (e.g., sediment type differentiation), limiting its effectiveness for applications such as marine habitat mapping or sediment analysis.

While the Ping Sonar integrates well with MANUEL's open-source system, processing and interpolating depth data requires technical expertise, potentially introducing variability in data interpretation. Although MANUEL's design allows it to withstand wave heights of up to 4 feet, the sonar's accuracy is highly dependent on stable deployment. Excessive movement or tilt due to turbulence can compromise depth readings. Despite having a depth rating of 300 meters, its single-beam functionality makes it more suitable for shallow to mid-depth applications rather than deep-sea exploration.

To overcome these limitations, ongoing efforts are focused on improving MANUEL's capabilities by integrating more advanced sonar technology, enhancing data processing algorithms, and optimizing its stability for more reliable depth measurements. These improvements aim to enhance spatial coverage, reduce environmental interferences, and improve seabed characterization, making MANUEL a more robust platform for autonomous bathymetric surveys.

Future directions

Scalability for larger and complex water systems

A promising avenue for scalability is the implementation of multi-USV deployments, where multiple autonomous surface vehicles operate collaboratively to monitor large reservoirs, rivers, or coastal areas. This approach improves spatial coverage, enhances data resolution, and optimizes resource allocation, making it ideal for large-scale hydrographic surveying and environmental monitoring. Coordinated USV fleets could be particularly beneficial for tracking sediment deposition, detecting pollutant dispersion, and assessing habitat conditions in real time.

To further expand MANUEL's capabilities, larger USV platforms with increased payload capacity could be developed, allowing for the integration of more advanced sensors and extended operational durations. This would be particularly useful for long-term monitoring programs in dynamic water systems, such as estuaries and flood-prone regions. For highly dynamic or expansive water bodies, networked USV fleets could enable real-time communication and coordinated navigation. Adaptive sampling strategies, where autonomous vehicles dynamically adjust their paths based on environmental data, would significantly enhance monitoring efficiency and responsiveness to changing conditions. This would allow MANUEL to autonomously adjust its survey route in response to sediment accumulation, changing flow patterns, or pollution events.

Integration with other technologies

MANUEL can significantly enhance water monitoring by integrating complementary technologies. These integrations improve data collection, efficiency, and adaptability in complex aquatic environments, allowing for a more comprehensive understanding of water quality and ecosystem dynamics. Pairing MANUEL with aerial drones enables multi-dimensional environmental monitoring by combining surface and subsurface data collection. Drones can capture high-resolution imagery of surface conditions, identifying pollutant dispersion, sedimentation zones, and algal blooms (Popescu et al., 2024). These insights can guide MANUEL for targeted in-situ sampling, improving efficiency in monitoring remote or inaccessible areas where traditional methods are limited. Combining MANUEL with autonomous underwater vehicles (AUVs) enhances subsurface monitoring, significantly improving water quality assessments. AUVs can conduct water column profiling, habitat mapping, and contaminant detection, complementing MANUEL's surface-level observations. This integration provides a holistic view of aquatic ecosystems, capturing crucial data on hydrodynamics, sediment transport, and biological activity across different depths. Besides integrating with other vehicles, adding sensors that collect water quality data that measures pollutant concentrations (including heavy metals, nitrates), dissolved oxygen levels, turbidity, algal pigment concentrations (Chlorophyll-a, Phycocyanin), and temperature helps in monitoring freshwater environments effectively. Also, integrating MANUEL with Internet of Things allows real-time data sharing across autonomous platforms, including USVs, AUVs, and UAVs. Cloud based integration facilitates large-scale environmental assessments, where AI-driven analytics improve water quantity/quality models.

Besides integrating with cloud and other autonomous systems, we are planning to develop a graphical user interface for data processing and visualization, reducing reliance on programming expertise. Also, for non-technical users, information on pre-assembled kits and components will be provided with the design and development of MANUEL 2.0.

Table S1. Bill of materials for MANUEL

Designator	Component	Number	Unit Cost ($)	Total cost ($)	Material link
Remote controller	Futaba 8J 8-Channels 2.4 GHZ S-FHSS Radio System	1	370	370	https://www.aeroflyhobbies.com/radio-transmitters/44-futaba-8j-8-channels-24ghz-s-fhss-radio-system.html
Microcontroller	EnviroDIY Mayfly	1	120	120	https://www.envirodiy.org/product/envirodiy-mayfly-data-logger/
Battery	Long cycle life SEFU battery 14000mAh 18C 4S|6S|12S 22.2V 6S1P UAV lithium battery	4	128	512	https://www.alibaba.com/product-detail/Long-cycle-life-SEFU-battery-14000mAh_1600226721698.html
Propeller	T200 thrusters from Blue Robotics	2	210	420	https://www.robotshop.com/products/t200-thruster-bluerov2-spare-ccw-propeller-w-penetrator-cable?gad_source=1&gclid=CjwKCAjwodC2BhAHEiwAE67hJIVmzskXiW4cPxY-bbwf0HF_zw1G7G5l6FTe7GTrAB9fhQJCH6hKCxoCg-YQAvD_BwE
GPS module	Here2 GNSS GPS Module	1	150	150	https://www.getfpv.com/here2-gnss-gps-module.html
Autopilot	Orange Cube Pixhawk	1	500	500	https://www.getfpv.com/hex-pixhawk-2-1-the-cube-orange-standard-set-ads-b.html

Designator	Component	Number	Unit Cost ($)	Total cost ($)	Material link
Communication module to remote controller	R7008SB S.Bus2 FASSTest Receiver 14SG 18MZ 18SZ	1	170	170	https://www.towerhobbies.com/product/r7008sb-s.bus2-fasstest-receiver-14sg-18mz-18sz/FUTL7675.html?gclid=CjwKCAiA7vWcBhBUEiwAXieItk156fsmwm5QvKJz9iDUhUrZZql1a7cHfXKb6NBF8dQEQP0g616cXRoCsEwQAvD_BwE
Telemetry	RFD-900X	1	160	160	https://store.rfdesign.com.au/rfd-900x-modem/
Single beam echo sounder	Ping Sonar from Blue Robotics	1	410	410	https://bluerobotics.com/store/sensors-sonars-cameras/sonar/ping-sonar-r2-rp/
Miscellaneous parts (nuts, bolts, adhesive, etc.)				100	
Total				**2912**	

Table S2. Open-source ground control station (GCS) software for unmanned vehicles for autonomous missions

Software name	User Interface	Operating system	Web link
Mission Planner	Graphical User Interface	Windows, Linux, and Android	https://ardupilot.org/planner/
APM Planner 2	Graphical User Interface	Windows, Mac, and Linux	https://ardupilot.org/planner2/
MAVProxy	Command Line, basic Graphical User Interface	Linux, Mac, and Windows	https://ardupilot.org/mavproxy/
QGroundControl	Graphical User Interface, Command Line	Windows, Mac, Linux, Android, and iOS	http://qgroundcontrol.com/

Table S3. Performance comparisons of USVs capable of bathymetry surveys in terms of accuracy, reliability, and speed.

USV name	Cost ($)	Positional accuracy	Reliability	Depth capability (m)	Survey Speed (m/s)	Survey Purpose	References
MANUEL Shallow Water Autonomous Multipurpose Platform (SWAMP)	N/A	N/A	N/A	< 1.5	2 - 3	Remote and shallow water monitoring	This study (Odetti, 2019)
Proto-Type USV	N/A	N/A	N/A	< 2	2 - 3	Hydrographic surveys	(Constantinou et al., 2023)
HARLE USV	N/A	N/A	N/A	0.5 - 3	N/A	Freshwater fish monitoring	(Goulon et al., 2021)
ROAZ USV	N/A	N/A	N/A	1 - 2.5	N/A	Disaster risk assessment	(Ferreira et al., 2009)
INNOBAT USV	N/A	N/A	N/A	< 2	N/A	Bathymetric surveys	(Specht et al., 2021)
Autonomous Hydrographic Survey USV	N/A	0.877 m to 0.941 m (RTK mode, R95(2D))	N/A	< 2.5	1 - 3	Nearshore and river surveys	(Lubczonek et al., 2022)
Autonomous Surface Vehicle (ASV) for Reservoir Surveys	N/A	N/A	N/A	1 - 3	1.5 – 2.5	Water quality and sediment mapping	(Lee et al., 2023)

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