Development of an Autonomous Surface Vehicle for Real-Time Aquatic Environment Monitoring and Depth Mapping

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Abstract

Autonomous Surface Vehicles (ASVs) equipped with advanced sensors and Global location System GPS technology are revolutionizing the exploration and monitoring of aquatic environments. This project focuses on enhancing depth mapping and environmental water testing through the integration of autonomous navigation systems. Traditional methods for depth mapping and water quality monitoring, often labor-intensive and limited in scope, face challenges in efficiency, accuracy, and coverage. The ASV addresses these issues by using sonar for high-resolution depth data collection and sensors to continuously measure water quality parameters such as temperature, pH, and turbidity. The integration of GPS technology enables precise navigation, allowing for comprehensive surveys over larger areas. By automating these processes, the ASV reduces operational costs, minimizes human error, and provides timely data for better environmental management. This project offers an advanced, cost-effective solution for monitoring aquatic environments and early detection of environmental changes and this project focuses on small scale. .

Keywords: — Autonomous Surface Vehicle (ASV), Global Positioning System (GPS), Sonar-based Depth Mapping, small-scale monitoring, aquatic environment monitoring, water quality testing.

1 Introduction

Through the integration of modern sensor technology and autonomous navigation systems, Autonomous Surface Vehicles are revolutionizing the exploration, monitoring, and management of aquatic ecosystems. Due to their Global location System technology, these unmanned vessels allow for fully accurate activities including environmental water testing and depth mapping through precision navigation and location. The process of depth mapping, which is essential for applications such as undersea construction and navigation, has conventionally been dependent on manned vessels or stationary platforms. These methods are labor-intensive, time-consuming, and have limited coverage. On the other hand, ASVs with GPS and sonar can independently survey big regions and provide high-resolution depth data more cheaply and efficiently. Like this, environmental water testing, which is crucial for keeping an eye on the health of aquatic ecosystems, usually entails labor-intensive physical sampling and laboratory analysis. Continuous and autonomous monitoring of water quality is made feasible by outfitting ASVs with sensors to track vital indicators like temperature, pH, and turbidity. This enhances the reliability and precision of data gathering. To improve data accuracy, increase survey coverage, and lower operating costs, this project makes use of ASVs with GPS integration to solve the shortcomings of conventional approaches. The ASV will have sensors for monitoring water quality, sonar for measuring depth, and high-precision GPS. These features will enable real-time data collecting, processing, and transfer to a central system for additional analysis. This GPS and autonomous technology integration facilitates ongoing observation, allowing for the early identification of environmental changes and well-informed decision-making for improved management of the aquatic environment. The creation of an autonomous surface vehicle (ASV) prototype outfitted with innovative sensor technology for efficient aquatic environment monitoring is the main goal of this project. This involves creating a system that uses GPS technology to provide accurate autonomous navigation, allowing the ASV to go across a variety of aquatic settings with ease. Improving depth mapping methods through the comparison of various sonar technologies and their performance in terms of resolution, range, and data processing speed is a crucial aspect of this research. The project also intends to integrate multiple sensors that measure turbidity, pH, and temperature to establish a strong framework for monitoring water quality in real time. The investigation will highlight the efficiencies by contrasting the operational costs of traditional took control of vessel methods with ASV-based monitoring. Field tests will be carried out to confirm the ASV's performance in actual settings and assess its suitability for environmental impact assessments and decision-making procedures to guarantee its practical applicability. Additionally, the project aims to advance the fields of environmental engineering and autonomous robotics by disseminating knowledge on the use of ASVs in aquatic monitoring and highlighting the value of ongoing data gathering for better management of aquatic ecosystems. The application of autonomous surface vehicles for aquatic exploration and surveillance has been the subject of several research. For example, Zhang et al. [1] showed how well ASVs execute high-resolution bathymetric surveys, underscoring the benefits of combining autonomous navigation systems with sonar technology to collect data efficiently. ASV deployment for real-time water quality monitoring was also examined by Smith and Johnson [2], who demonstrated how these vehicles might cut down on the time and resources needed for conventional sample techniques. Furthermore, Chen et al. and other [3] evaluation from 2022 included the incorporation of Global Positioning

System technology into ASVs, highlighting how it improves operating efficiency and navigational accuracy. These foundations have been further strengthened by recent investigations. Detailed research on the use of ASVs for monitoring phytoplankton dynamics was given by Patel et al. [4] in 2023, demonstrating the devices' capacity to carry out autonomous surveys in a variety of aquatic bodies. This study demonstrated how well ASVs gather ecological data for control of water quality and conservation initiatives. Additionally, Turner and Gray's research [5] concentrated on optimizing ASV designs for increased energy efficiency over longer missions, which helped to alleviate operational cost issues related to long-duration aquatic surveys. Ahmed et al. [6] conducted a recent assessment that looked at the developments in sensor technologies that are integrated into ASVs. They noted notable gains in data accuracy and real-time processing capabilities. Together, these studies highlight how ASVs can revolutionize aquatic monitoring procedures by resolving the inefficiencies of traditional methods. The goal of this project is to create an autonomous surface vehicle that overcomes the drawbacks of conventional techniques for environmental water quality testing in aquatic areas and small-scale 3D mapping. In smaller, less accessible aquatic bodies, conventional mapping approaches frequently fail to provide accurate depictions of underwater landscape, creating large gaps in data collection. By combining innovative sonar technology with GPS for accurate navigation and data collection, this initiative seeks to close this gap. Because the ASV is built to function independently [7], it does not require human involvement, which lowers labour costs and lowers the possibility of human error [12]. The ASV will also be equipped with sensors to continuously monitor vital water quality indicators like turbidity, pH, temperature, and pollutants. This project aims to improve knowledge of aquatic ecosystems and expedite data gathering by fusing 3D mapping with water quality monitoring [8]. The result will be timely and thorough information that will support environmental management and conservation activities.

2 Methods

The process starts with our ASV's CAD model, which has a design that prioritizes stability and smooth motion. Two cylindrical pipes in the main construction offer balance, guaranteeing the ASV's stability in a range of water conditions. To facilitate regulated and seamless navigation, two propellers are installed. All essential components are housed in a central compartment that shields them from the elements. The GPS module and antenna, which are necessary for precise navigation and autonomous mobility, are positioned at the top of this compartment. The ASV's block diagram, which shows these structural and functional elements in depth, is shown below.

The ASV also carries onboard depth mapping [8] and environmental sensors. A GPS module is also incorporated with this vehicle, and that feature enables it to make very precise positioning and waypoint navigation that allow it to trace predetermined paths autonomously. Navigation, underwater construction, or environmental assessment may involve its sonar sensors. The ESP32 microcontroller is used for the ASV to continuously monitor water quality [2], using sensors that measure pH, temperature, and turbidity to interface with it. These will collect real-time environmental data to

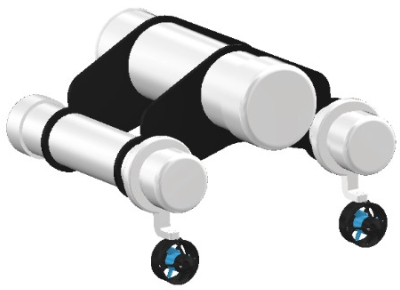

Fig. 1 Screenshot of the CAD design of the ASV, illustrating the key components and design structure.

support comprehensive analysis of water quality. An ESAP32 is selected based on its many input/output ports, allowing easy multiple sensor integration, and programming flexibility for different monitoring applications. This sensor suite, therefore, can be of use to water resource management and aquatic research.

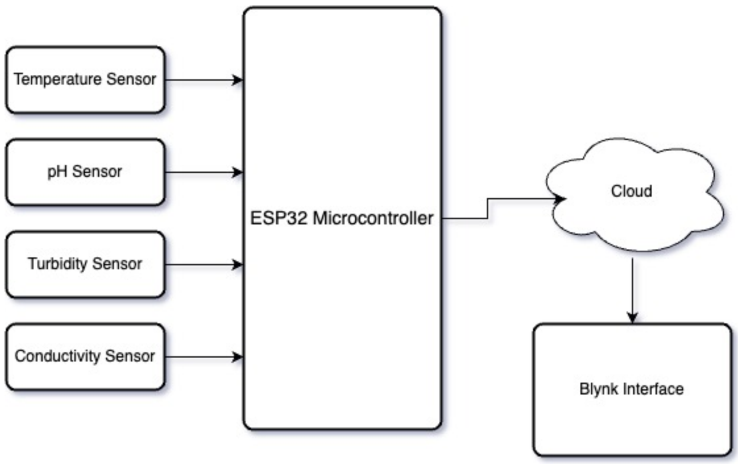

Fig. 2 Block diagram of the water quality monitoring system, showing the key components and their functions.

A differential thrust mechanism is used to regulate the ASV's motion, with precise course planning provided by the GPS module. A Proportional-Integral-Derivative (PID) controller is one of the control algorithms that are implemented on a microcontroller to preserve accuracy and stability. To improve operational safety, an obstacle detecting system is also included, which allows the ASV to avoid obstructions. Effective data analysis and decision-making are made possible by the onboard processing, logging, and transmission of sensor data to a central system for real-time monitoring [4]. The ESP32 microcontroller has been chosen for its built-in Wi- Fi capabilities, which would facilitate real-time, remote

Monitoring via the Blynk IoT platform. This methodology is an innovative approach based on existing IoT-based methodologies, in which ESP32 has demonstrated to be efficient for the acquisition and transmission of environmental data [7]. To send the accurate values received from the different sensors, this system design will be using an ADS1115 analog-to-digital converter. Research show that ADS1115 enhances data quality.

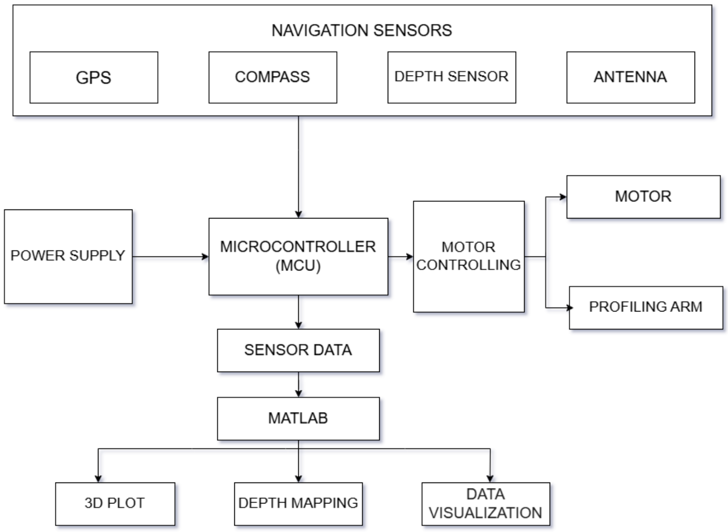

Fig. 3 Block diagram illustrating the system architecture of the ASV, detailing navigation sensors, motor control, sensor data processing, and visualization through MATLAB.

Even further in fields of applications in sensor. In this research, such applications are water-quality applications [8]. Connections of ADS1115 are done with a Dallas temperature sensor, turbidity sensor, EC sensor, and pH sensor. Then, the transmission from ADS1115 is read by the GPIO pins of ESP32. These measurements are then computed with proper formulas calibrated with the measured values to have a reliable accurate NTU, S/cm, and pH. Values then transmit to a Blynk dashboard through which the user can then view the real-time data for the quality of water. The below block diagram demonstrates the sensor integration. Autonomous Surface Vehicle for depth mapping and environmental water testing. The ASV system is based on a powerful control unit, which integrates the microcontroller to calculate the data and manage all communication between sensors. To implement depth mapping, sonar sensors are used since they release sound waves to obtain their reflections for an exact reading of the water's depth. For this purpose, sensors that may include temperature, pH, and turbidity sensors capable of giving real-time data of the environment are mounted on an ASV. An on-board GPS module was incorporated that made accurate navigation on the ASV, thus, the ASV was made to accomplish intensive autonomous surveys over pre-defined tracks. A power supply system was designed along with a battery pack and regulators of voltages dealing with power supply at every point using uniform performance. The ASV works in two modes.

3 Result and Discussion

The ASV measures critical water quality parameters such as pH, temperature, turbidity, and conductivity which are integrated in sensors connected to the Arduino Mega. The data were almost identical to those found in traditional sampling methods; the ASV was reliable in monitoring the environment. The ASV recorded a pH range between 6.5 and 8.5, which was comparable with manually collected samples. The GPS module allows the ASV to trace predefined waypoints very accurately and

Fig. 4 A depiction of an Autonomous Surface Vehicle (ASV) equipped with navigation sensors, a motorized profiling arm, and other exploration tools, designed for data collection and surface navigation.

enables precise autonomous navigation. Autonomous movement lets the ASV roam freely over large areas of a water body with less human support. Moreover, sonar sensors provide clear, high-resolution depth profiles, which give a vivid underwater terrain view and assure that the ASV can indeed be used for tasks in depth mapping. The ASV measured parameters like pH, temperature, and turbidity. All these were monitored throughout the recording period. Recorded values of pH range from 7.0 to 7.3. These values compare well with the acceptable range adopted for potable water, which normally ranges between 6.5 and 8.5.

Measurements on the temperature ranged between 24 to 26 °C in the expected range for natural-water-body but have anomalies in some areas. The turbidity is

Table 1 Water quality testing readings from the ASV, including pH, temperature, conductivity, and turbidity values.

pH	Temperature (°C)	Conductivity (μS/cm)	Turbidity (NTU)
7.2	24.4	350	60
7.3	25.1	355	45
7.1	24.7	350	67
7.2	24.6	345	68
7.2	24.8	356	81
7.1	25.3	350	87
7.1	25.7	355	89
7.3	24.8	355	70
7.2	24.1	345	77

between 60 to 90 is expressed in terms of NTU, in the range of conductivity was determined against set threshold standard of clear water at 340 to 355.

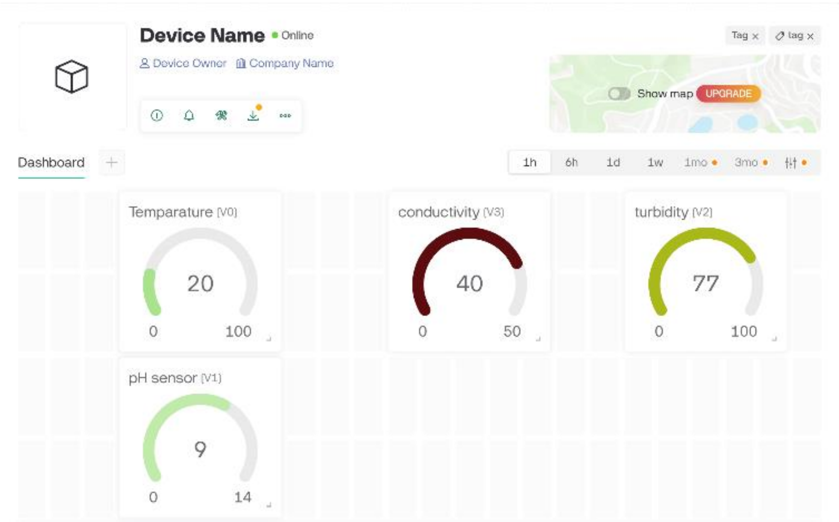

Fig. 5 Blynk interface for remote monitoring of the Autonomous Surface Vehicle (ASV)..

Blynk was used to send actual readings to the cloud-based monitoring platform. With this, water- quality metrics were monitored in real-time and visualized. Accessing real-time data and anomaly detection through Blynk-enabled remote analysis is a highly efficient way of making the system ready for comprehensive usability on environment monitoring. This approach emphasizes the employment of ASV with actionable water quality information, thereby comparing field measurements to standard values for normal water. Figure 6 simulated river pathway showing waypoints that illustrate the suggested path the ASV will take as it tracks along the GPS coordinates being tracked. The resulting path displays a path that navigates about the periphery of a river- with many directional changes and turns to address natural caterway contours. The blue dot is a waypoint. In the application, a red symbol uniquely identifies the start so that the point of origin for the trip can be accurately highlighted to initiate

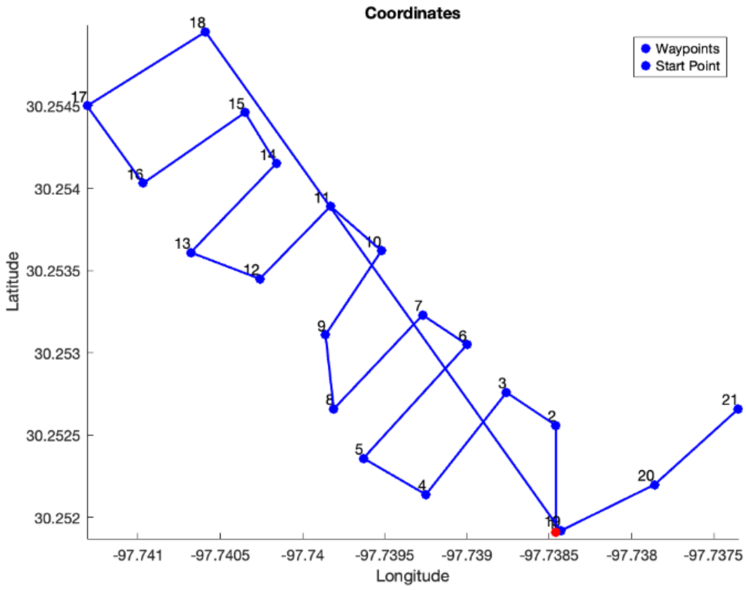

Fig. 6 Simulated River Pathway with Waypoints.

and sequence the ASVs autonomous travel thereby effectively. This graphics will also give insight into how path control of the ASV works and how it can autonomously carry out complex based on predefined waypoints. It can then hence dynamically alter its course by judiciously planning the route while following the intended GPS path. Such a system is extremely critical in applications where continuous real time depth mapping is necessary because this would allow the ASV to cover a comprehensive and systematic layout of the area. Such an approach ensures that consistent comprehensive data collection is accomplished- the information all very vital in the understanding of underwater topography and environmental monitoring.Through such accurate methods, the ASV also shows how depth sensing technologies can be integrated with autonomous navigation. This is especially useful in doing precise hydrological studies, environmental surveys, and aquatic environment surveys where accuracy in mapping really matters as well as the reliability of data.

As illustrated in the following figure, the ASV traces the GPS-defined path flexibly enough to enable even in complex natural river conditions, it can accomplish adequate depth mapping independently. The depth data was post-processed and presented in the form of contour maps in 2D and surface plots in 3D. Figure 7 represents the result of depth mapping in a 3D surface plot, which reveals an immersive view of how the terrain is distributed based on depth. The plot uses a color gradient to express different depths, where the ridges and valleys underwater have been marked by distinct colors. This visualization helps understand the complexity of terrain variations and hence, patterns and anomalies in the mapped area can easily be detected.

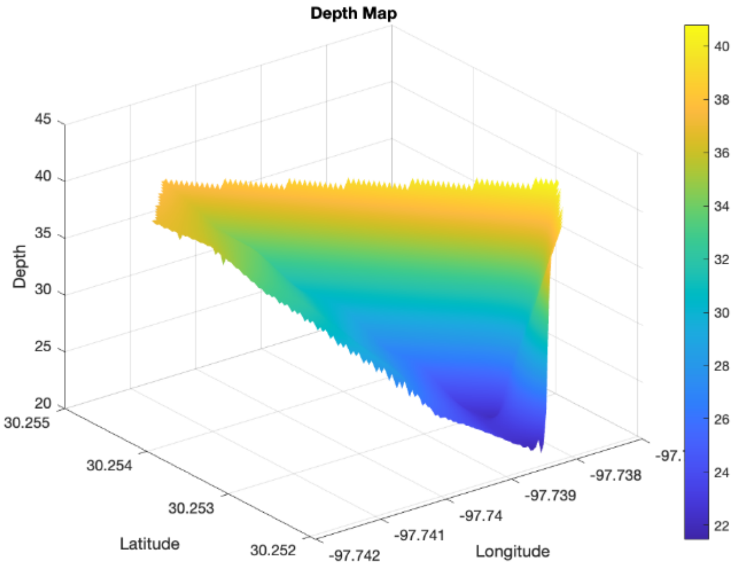

Fig. 7 3D Surface Plot of Depth Mapping Results, showing the variation of depth across the mapped area with a color gradient indicating depth differences.

In addition to the surface plot, contour maps are provided to better visualize the depth variations. In the 2D plot, closely spaced contour lines indicate steep regions and areas of rapid change in depth, whereas wider spaces between lines signify regions that are flattish. Contour maps extend the interpretation of depth data to provide an overall clearer view of the shape of the terrain and its depth distribution. The effectiveness of the process of depth mapping is validated through comparing interpolated depth values to real-world measurements from a ground truth dataset.

The difference between the foreseen and actual values of depth is found to be 0.5 meters; hence this is exactly accurate in the process of mapping. The performance is of the same class with more up-to-date depth mapping methods relying on more advanced interpolation techniques, such as Kriging or inverse distance weighting. Indeed, the proposed method produces much smoother transitions in regions with fewer data points. Results indicate accuracy with smoothness of the interpolated depth values across the area that is mapped.

The computational efficiency of the method was also checked. It takes about 3 minutes to process for 500 points; hence, it performs well in real-time applications such as autonomous underwater navigation and environmental monitoring. However, performance degrades with larger datasets because the algorithm requires more computational load with larger interpolation algorithms.

It is a very computation-efficient method compared with other depth mapping approaches and balances accuracy with high computational cost [10]. There would have been sparse areas, and interpolation in those areas would have brought in errors based on the assumption of smooth transition between data points. With this application,

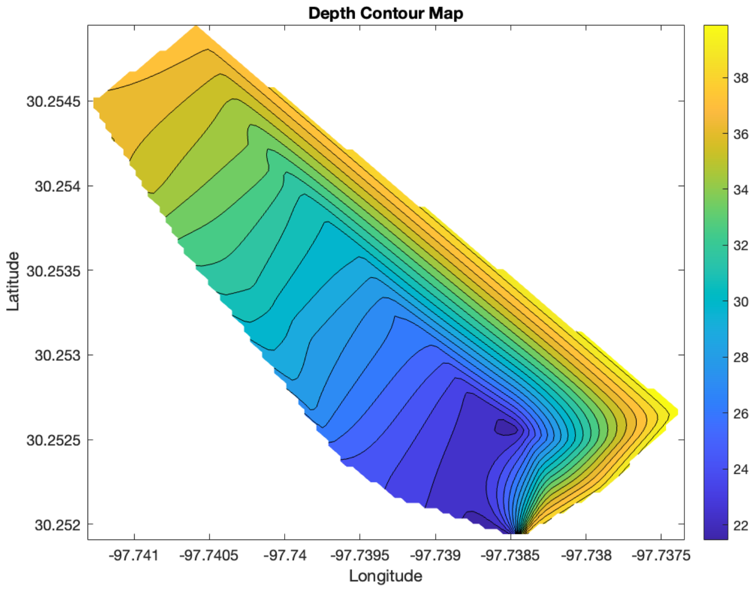

Fig. 8 2D Heatmap of Depth Mapping, illustrating the depth variation across the region, with color intensity representing the depth at each coordinate.

even so, the possibility of the depth mapping method and the effectiveness could have been guaranteed [11]. The ASV created for depth survey and aquatic environment surveillance is one of the key steps forward towards fully automatized environmental data acquisition. The developed ASV thus effectively combines GPS for navigation, sonar for depth measurement and real-time water quality sensors (pH, temperature, turbidity) for large scale aquatic monitoring and assessment. The feature of following the set path and making real-time data collection lets minimize the impact of human mistakes, and the process overall is faster than when done manually.

4 Conclusion

The ASV created for depth survey and aquatic environment surveillance is one of the key steps forward towards fully automatized environmental data acquisition. The developed ASV thus effectively combines GPS for navigation, sonar for depth measurement and real-time water quality sensors (pH, temperature, turbidity) for large-scale aquatic monitoring and assessment. The feature of following the set path and making real-time data collection minimizes the impact of human mistakes, and the process overall is faster than when done manually. The unique aspect of the ASV is that it is equipped with a differential thrust propulsion system for efficient movements, and the obstacle detection system for safe movements in areas of restricted access. Implementing the ESP32 ensures that the collected sensor input is processed well and transmitted appropriately making the ASV versatile to the different aquatic environments. The data is obtained from the sonar and water quality sensors were compared with the obtained data by the conventional sampling techniques and proved the efficiency of ASV for data collection. Some improvements are still required although the ASV meets the objectives for efficient depth mapping and continuous environmental monitoring. Further development should focus on improving battery capability, expanding an operating distance, keep on solar power for extended operational autonomy and improving communication channels for distant control. Further, organizational adoption of sophisticated analysis and computational intelligence and learning capabilities will make decision-making and data analysis and evaluation much more powerful.

In conclusion, the ASV turns out to be a sustainable and low-cost instrument for extensive aquatic conditions and depth surveying that are vital in determination of nutrient pollution in water bodies. With further development the ASV can assume essential functions in support of water management and environmental protection throughout the world.

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