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Non-contact capacitive-based water wave sensing system for reservoir surveillance

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Abstract: Water quality is a major environmental concern and one of humanity's grand challenges. Many countries face water pollution from oil spills, plastic waste, and illegal activities. Vision cameras are commonly used to monitor reservoirs and dams, but their performance declines between day and night, and they remain fixed in position. Installing numerous cameras to cover every area is costly. Environmental monitoring in remote water sources is further limited by time, cost, and labor. Conventional water monitoring systems often lack intelligence, are bulky, and provide poor real-time results. This research introduces a novel approach using capacitive-based water level sensing to detect patterns and predict types of water activities around an Unmanned Surface Vehicle (USV). The USV operates in real time to monitor illegal activities such as swimming, boating, chemical disposal, and logging in reservoirs and lakes. The system's innovation lies in a circular array of capacitive sensors that measure water displacement and interpret wave direction and strength. By analyzing these wave patterns, the USV can detect and classify surrounding water activities, providing a cost-effective and intelligent solution for remote water surveillance and pollution prevention.
Keywords: *Capacitive sensing, Unmanned surface vehicle, Water activities, Water wave detector, Water wave patterns.*

1. Introduction

Most actions that induce water surface variation produce water waves in the process. These activities can be caused by nature, such as gravity quakes beneath the water, or by individuals, such as swimming, chemical disposal, drowning, and other activities. Water waves produced by various activities will differ in amplitude, frequency, direction, and duration. As a result, numerous activities may be determined by recording and studying the water surface wave. An immediate reaction may also be provided to avoid future hazards and injury if abnormal actions occur in the regions under monitoring [1]. Gas leakage in underwater pipelines can also be detected via the changes in water wave patterns because gas fountains will be created on the water's surface due to the high pressure of gas leakage [2].

Furthermore, underwater information can be analyzed and obtained using water surface waves [3]. A wider application and longer durability can be achieved by developing water wave monitoring devices that do not require a static platform and direct contact with water. Contactless sensing techniques that apply visual and light methods require a static platform and a specific distance from the water surface to perform the detection actions [4]. Cameras and light reflection water wave detection usually must be fixed in a static position, and pre-calibration must be done for accurate measurement [5-8]. Although simple to set up and offering spatial measurements over large areas, the method can require manual processing and is historically computationally challenging [9, 10]. Recent advances in computational power and advanced processing methodologies have overcome many of these issues [11]. Of particular

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note is the open-source Wave Acquisition Stereo System (WASS) [5, 12] which autonomously processes images to provide high quality processed surface elevations.

Besides, the weather condition is also a major constraint for the light reflection detection method [13]. Other optical techniques have been developed based on exploiting light refracting through, and reflecting from, the water surface. Refraction-based methods effectively indirectly measure the surface slope [14]. Recent refraction-based approaches offer good measurement performance. The methods presented in Moisy, et al. [15] and Kiefhaber, et al. [16] are able to reconstruct complex wave fields with very high spatio-temporal resolution. There are some inherent limitations in terms of surface deformations/slope. However, the obvious shortcoming of refraction-based techniques is the requirement to submerge components, which offers installation challenges as well as resulting in a (potentially) intrusive measurement approach which itself is subject to wave loading. Conversely, reflection-based methods excel in being non-intrusive and a number of experiments have been conducted using different optical systems. LIDAR has proven to be effective at measuring the water surface in both laboratory and ocean settings [17, 18].

Water wave detection methods, such as the Kinect sensing method [19] and CCD camera sensing method [20] rely on altering the properties of the liquid to improve detection accuracy. Specifically, these methods require adding dyes or particles to the water to reduce its transparency, allowing changes in surface waves to be more easily captured. While effective in certain conditions, this approach may not be suitable for all applications due to the need to modify the liquid's composition. Radar-based detection methods [13, 21, 22] offer a contactless alternative, but they also present limitations. These systems require static positioning and are sensitive to constructive and destructive scattering, as they rely on the backscattering of radar signals. This scattering can distort the accuracy of wave detection, particularly in environments with complex surface interactions.

Pressure sensing methods Witze [23] and Zhang, et al. [6] provide a more direct approach but require physical contact with the water. A single pressure sensor can detect changes in water level at one specific point, necessitating the deployment of multiple sensors to track wave direction across a broader area [24]. Additionally, the performance of pressure sensors can be affected by changes in the electrolyte concentration within the water. Sensors that operate based on chemical properties may experience interference, potentially compromising their accuracy in environments where water composition fluctuates [25]. Thus, while each method offers unique advantages, they also face specific challenges, especially in terms of scalability and environmental suitability.

Static platform methods offer limited flexibility. Once the system is set up, any change in the monitoring area requires the dismantling and reinstallation of the system, which is time-consuming and inefficient. Furthermore, expanding the monitoring area increases the need for additional devices and platforms to ensure comprehensive coverage, which can be both costly and complex to manage [20, 26, 27]. In particular, static platforms face significant challenges in environments where installation is difficult, such as on oceans, dams, or lakes. In contrast, non-static monitoring devices provide a more adaptable solution, allowing for easy adjustments to the monitoring area without the need for significant restructuring. This flexibility makes non-static systems more suitable for dynamic or hard-to-access environments.

2. Prototype Development

An Unmanned Surface Vehicle (USV) is a fully automated device designed to operate autonomously on the surface of water bodies. USVs are equipped with advanced satellite positioning systems and self-sensing technologies, allowing them to navigate intelligently based on pre-programmed tasks without the need for human intervention [28, 29]. These devices represent a sophisticated form of water-based robotics, integrating a range of technologies, including communication systems, automation, robot control, remote monitoring, and networked systems [30, 31].

One of the key capabilities of USVs is their ability to be programmed for a variety of autonomous functions. These include intelligent navigation, where the vehicle can move along a specified path;

obstacle avoidance, allowing it to detect and bypass objects in its path; and long-distance communication, enabling the transmission of data over vast distances. USVs are also capable of real-time video transmission, providing a live feed from the water surface, and networked monitoring, allowing for remote oversight and control of the vehicle's operations [32].

The versatility and reliability of USVs have made them valuable tools in a range of applications. They are widely used in environmental monitoring, where they can collect data on water quality, temperature, and other ecological parameters. Additionally, USVs play a significant role in scientific research and exploration, enabling the study of marine environments, water bodies, and underwater ecosystems without the need for human-operated vessels [33, 34]. These capabilities make USVs indispensable in fields requiring continuous and precise data collection over large or hard-to-reach aquatic areas [29, 35, 36].

2.1. Hardware Structure

In this study, a cylindrical Unmanned Surface Vehicle (USV) prototype was developed as a surveillance system, and its functionalities were tested in controlled environments, including a swimming pool, as well as larger water bodies like lakes and reservoirs. The decision to adopt a cylindrical structure for the USV is based on the hydrodynamic advantages of its edgeless, circular cross-section. This design minimizes resistance and interaction with water waves, allowing them to propagate through the USV without causing strong reflections or exerting excessive force on the structure. The edgeless circular shape significantly reduces the impact of water waves, unlike flat-edged or angular designs, which tend to reflect waves back toward their origin. Such reflections can lead to the constructive and destructive interference of water waves, which not only disrupts the surrounding wave patterns but also diminishes the accuracy of data collection from sensors designed to monitor wave activity. Additionally, the flat surfaces of non-cylindrical designs make these structures more susceptible to being swept by strong water waves, causing the USV to drift uncontrollably toward the shore. The cylindrical shape, with its smooth contours, provides greater stability by allowing waves to pass around the vehicle with minimal disturbance.

The material used for the outer structure of the USV is an insulating material that houses an array of circular capacitive sensors, designed to capture real-time data without interference from external environmental factors. These sensors are strategically placed inside the cylindrical body to ensure accurate and uninterrupted wave monitoring. Figure 1 illustrates the internal layout of the USV prototype, highlighting the arrangement of the capacitive sensors within the insulated cylindrical shell.

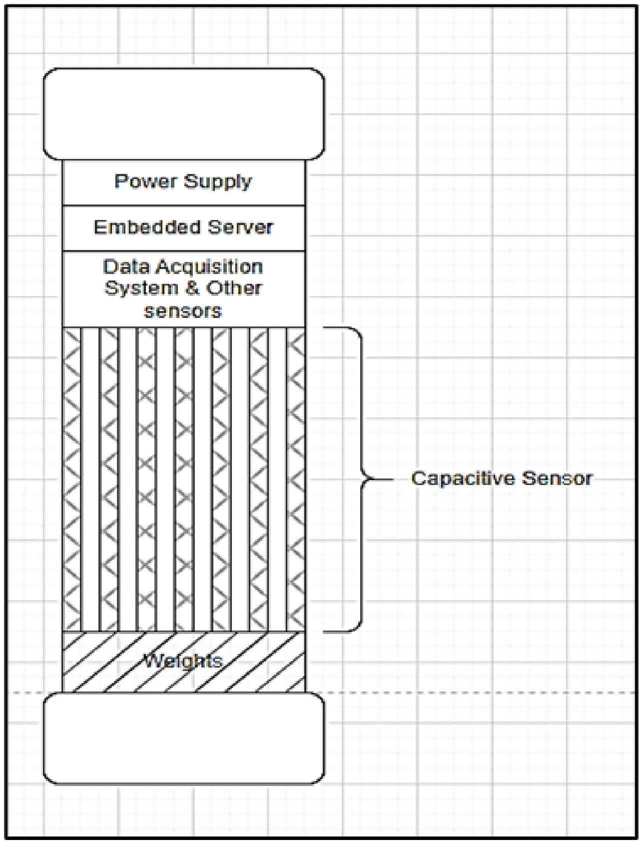

Figure 1.
USV internal components.

This design ensures that the USV remains stable in the water while optimizing sensor performance, making it well-suited for its role in surveillance and environmental monitoring in diverse aquatic environments. The cylindrical body of the USV prototype measures 100 cm in height and 25 cm in diameter, designed to optimize both stability and functionality in water. The structure is divided into three distinct sections, each serving a specific purpose: the electronics circuitry compartment (30 cm), the sensing region (40 cm), and the weight platform (30 cm). This segmentation allows for the efficient arrangement of components while maintaining the integrity and performance of the system in aquatic environments.

The electronics circuitry compartment, located at the top, houses the essential control systems and circuitry that manage the USV's operations. This compartment is kept separate from the rest of the structure to protect sensitive electronics from water exposure and to maintain their operational efficiency. It also ensures easy access for maintenance and upgrades.

In the middle section is the sensing region, which spans 40 cm of the body. This is the core functional area of the USV, where the capacitive sensors are embedded. The choice of UPVC (unplasticized polyvinyl chloride) for the cylindrical structure is key to enhancing the performance of these sensors. UPVC provides the advantage of thinner walls, which reduces the physical distance between the capacitive sensors and the water surface, thereby increasing the sensitivity of water level detection. The proximity of the sensors to the water allows for more precise measurements of wave activity, water level fluctuations, and other aquatic conditions, critical for surveillance and monitoring tasks.

The weight platform at the bottom of the structure plays an important role in the USV's stability. Weights are carefully placed and adjusted in this section to ensure that the USV remains partially submerged, with the appropriate portion of the body below the waterline. This partial submersion is crucial for the optimal functioning of the capacitive sensors, as they require direct interaction with the water to detect changes in water level and movement. By distributing the weight evenly at the base, the USV maintains a low center of gravity, which helps prevent tipping and ensures that the vehicle remains upright and stable, even in turbulent water conditions.

Overall, this carefully designed cylindrical structure ensures the USV is both functional and resilient, with the UPVC material contributing to enhanced sensor accuracy and the weight distribution providing necessary stability. This design makes the USV highly effective for water level detection, wave monitoring, and other surveillance tasks in various aquatic environments. Due to its low cost and minimal maintenance requirements, the USV presents a highly scalable solution for water level monitoring. Its affordability allows for multiple units to be deployed without incurring significant financial burden, making it an efficient option for large-scale applications.

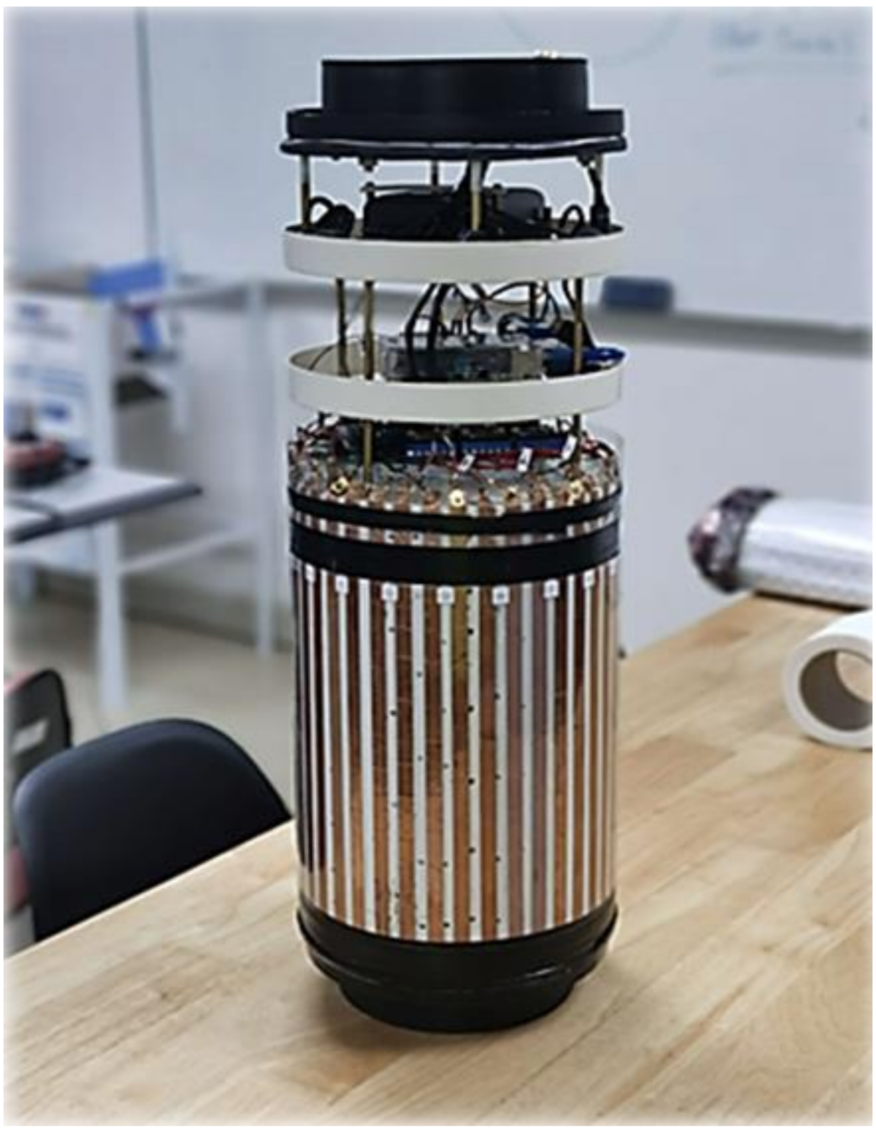

Figure 2.
Actual USV prototype with capacitive plates around the circumference.

Figure 2 provides a detailed illustration of the internal design and electronic circuitry of the USV. One of the key aspects of this design is the strategic positioning of the capacitive sensor strips around the entire circumference of the cylindrical body. This 360-degree arrangement ensures that the USV can detect water wave patterns from all directions, providing comprehensive coverage for real-time monitoring. By surrounding the body with these sensor strips, the system gains the ability to capture a full range of water surface data, which is critical for applications such as environmental monitoring, wave detection, and surface pattern analysis. This thorough coverage enhances the USV's accuracy and responsiveness in varying water conditions.

The capacitive sensors play a pivotal role in the USV's functionality, as they are responsible for measuring subtle changes in water levels and wave activity. These sensors detect variations in the capacitance, which changes based on the proximity of water. By monitoring these fluctuations, the USV can generate precise data on water wave patterns and behavior. The capacitive sensing technology is particularly well-suited for aquatic environments because of its non-invasive nature and ability to operate without direct physical contact with the water surface, enhancing the durability and reliability of the system. Additionally, Figure 2 highlights the integration of various internal circuitry components that support the overall operation of the USV. These circuits handle tasks such as data processing, power management, and communication between the sensors and the onboard control systems. The circuitry is meticulously organized within the internal structure of the USV to optimize space and ensure efficient performance. The close integration of these components allows the USV to operate seamlessly, collecting, processing, and transmitting real-time data while minimizing power consumption and maintaining system stability.

Figure 3 emphasizes the protective measures incorporated into the USV's design to safeguard its internal components from environmental exposure. The outer enclosure, made from UPVC material, acts as a robust barrier that shields the electronic circuitry from water, preventing potential damage that could compromise the system's performance. The enclosure also contributes to the overall durability and longevity of the USV, ensuring that it can withstand prolonged use in challenging aquatic conditions. This protection is crucial for maintaining the reliability of the capacitive sensors and other sensitive electronics, especially during long-term deployments in environments such as lakes, reservoirs, or coastal waters.

Figure 3.
USV external UPVC casing to enclose the capacitive sensors.

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Figure 4 offers a detailed top-down view of the capacitive wave detector used in the USV showcasing its innovative design. The perimeter of the detector is carefully divided into four distinct positions, each strategically placed to enhance the system's ability to detect the direction and intensity of water waves. This configuration allows the capacitive sensors to capture a comprehensive understanding of wave dynamics from multiple angles, improving the accuracy of wave direction detection. The division into four quadrants provides a balanced distribution of sensing capabilities, ensuring that wave activity can be monitored regardless of the direction of the water's motion [33].

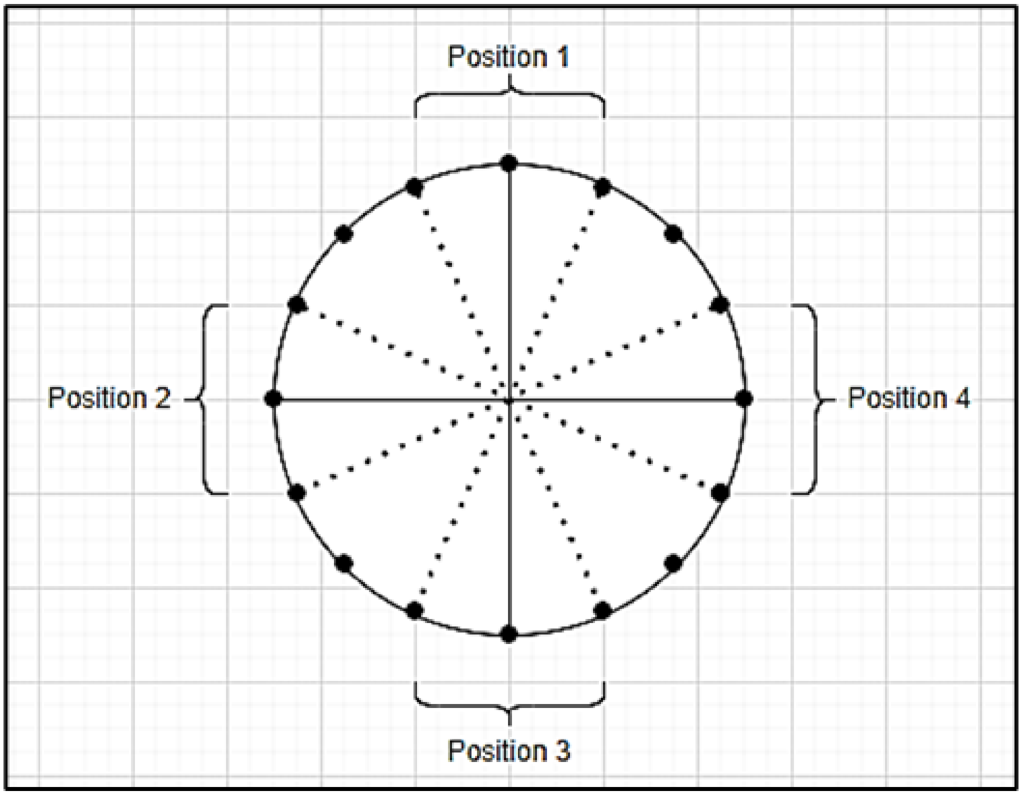

Figure 4.
Top-view of capacitive sensors distributed along the perimeter.

One of the most significant benefits of this capacitive wave detection design is that the sensors are not directly exposed to the water. This contactless sensing approach leverages changes in the electric field to detect wave activity, offering a non-invasive solution that eliminates the need for sensors to be submerged or in direct contact with the water surface. This design feature reduces the potential for sensor degradation, as it minimizes the risk of corrosion, fouling, or physical damage that could occur in harsh aquatic environments. The sensors can thus remain functional for extended periods without requiring frequent cleaning or maintenance.

Another major advantage of this system is the absence of any movable parts in the capacitive sensors. Traditional mechanical wave detection methods often rely on components such as floats, levers, or other moving mechanisms that are in direct contact with water. While these mechanical systems can effectively detect waves, they are inherently prone to wear and tear due to continuous motion, friction, and exposure to water. Over time, this can lead to a decline in performance, reduced sensitivity, and an increased likelihood of mechanical failure. Furthermore, these systems typically require frequent maintenance to ensure that their moving parts remain functional, which can be both time-consuming and costly, especially in remote or challenging environments.

3. Simulation and Data Processing

In general, water waves can approach the body of the USV from any direction. The direction of these waves is measured by analyzing the angles at which they impact the array of capacitive sensors, acting as water level indicators, and subsequently deviate from them. Under calm water conditions, all sensors detect the same water level, resulting in uniform signal amplitudes. When these signal amplitudes are plotted on a polar coordinate system, they form a consistent, uniform circle graph, indicating an undisturbed water surface.

However, when water waves propagate across the array of sensors, this uniformity is disrupted. As the wave interacts with the sensors, the shape of the plotted graph changes from a circle to various oval or ellipse-like shapes, as depicted in Figure 5. These alterations in shape occur because the signal amplitudes vary depending on the wave's interaction with each sensor. The direction in which the graph deviates correspond directly to the wave's direction of propagation. Thus, by examining these deviations, one can determine the precise direction from which the waves are approaching. Once the wave passes and no longer affects the sensors, the system returns to detecting a uniform water level, and the graph reverts to its original circular shape. This cyclical change in the graph's shape, from uniform circle to ellipse-like and back to uniform circle, provides a clear visual representation of wave activity and direction, thereby enhancing the USV's ability to monitor and respond to wave dynamics effectively.

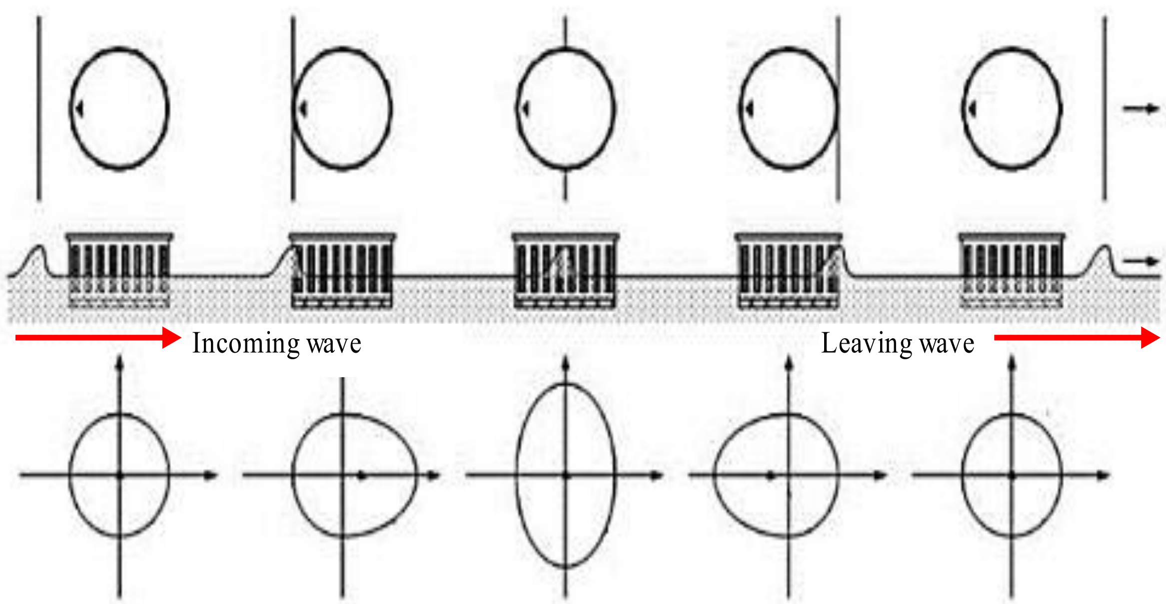

Figure 5.
Conceptual diagram of water wave propagation approaching and leaving the USV body.

Figure 6 presents the results of the simulation test designed to visualize the polar graphs of waves approaching from four distinct directions. The simulation aimed to assess the effectiveness of the capacitive wave sensors in accurately determining wave direction. The resulting patterns from the test have been consistent across all four directions, providing clear and reliable indicators of wave movement. For each of the four directions tested, the polar graphs displayed characteristic shapes that corresponded precisely to the direction of the incoming waves. These consistent patterns effectively demonstrate the detector's ability to identify not only the original direction from which the waves are approaching but also the direction in which they are propagating as they pass the sensors. This dual

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capability is crucial for comprehensive wave monitoring, as it provides both real-time and predictive insights into wave behavior.

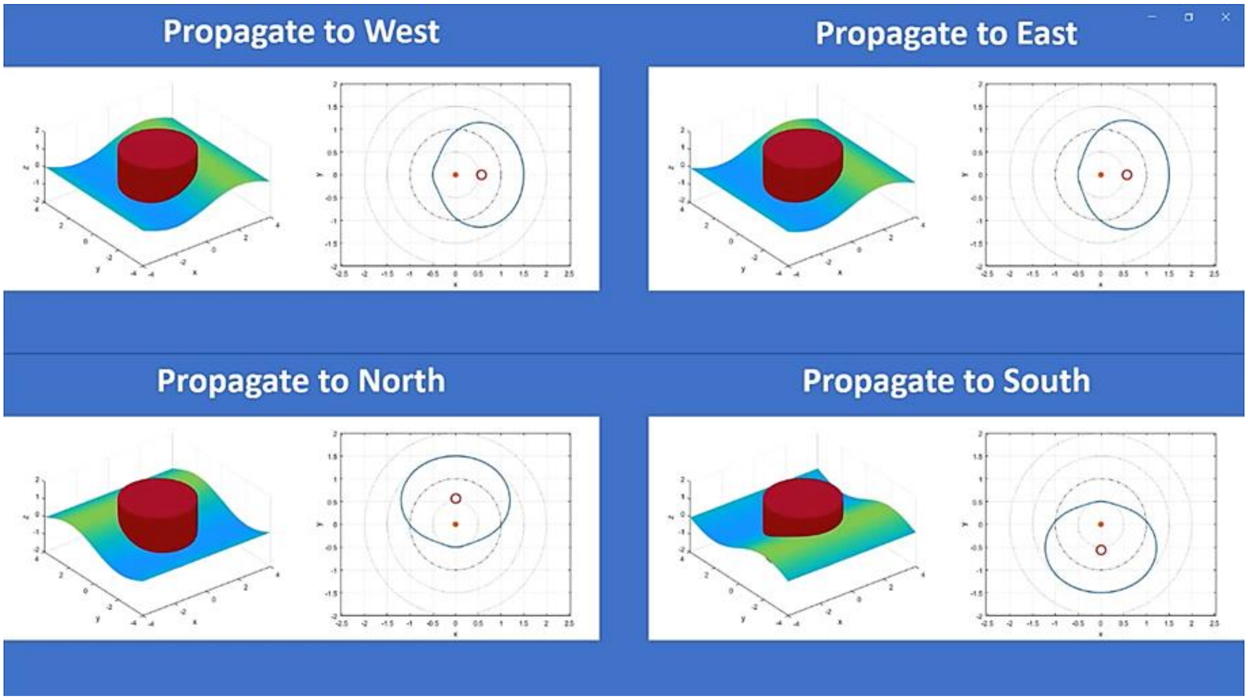

Figure 6.
Simulation test verifying water wave from the four distinctive directions.

The simulation results reinforce the effectiveness of the capacitive wave detector's design. By maintaining consistent patterns across multiple directions, the detector proves its reliability and accuracy in real-world applications. This consistency ensures that, regardless of the wave's approach direction, the system can provide clear and actionable data, enabling the USV to respond to wave conditions effectively.

4. Experiment and Results

In the final stage of testing, the USV is evaluated with three different types of water activities: swimming, drowning, and dumping (disposal) of an object into the water. These activities are selected to simulate a range of real-world scenarios that the USV might encounter. During each activity, the water wave patterns are collected and analyzed to evaluate the performance and reliability of the capacitive wave detector under diverse conditions.

Two different types of environments were selected to conduct the testing of the USV under calm weather condition. These environments included a controlled setting at a swimming pool and a more dynamic natural setting in a lake. The swimming pool provided a stable and predictable environment, allowing for precise evaluation of the USV's fundamental functions, maneuverability, and basic operational capabilities. In contrast, the lake environment introduced real-world variables such as water currents, wind effects, and varying depths, enabling the assessment of the USV's performance under more complex and unpredictable conditions. Figure 7 illustrates the two types of conditions in which the USV was deployed for testing, highlighting the differences between the controlled and natural settings.

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Figure 7.
Two different environments deployed for the USV testing (swimming pool and open lake).

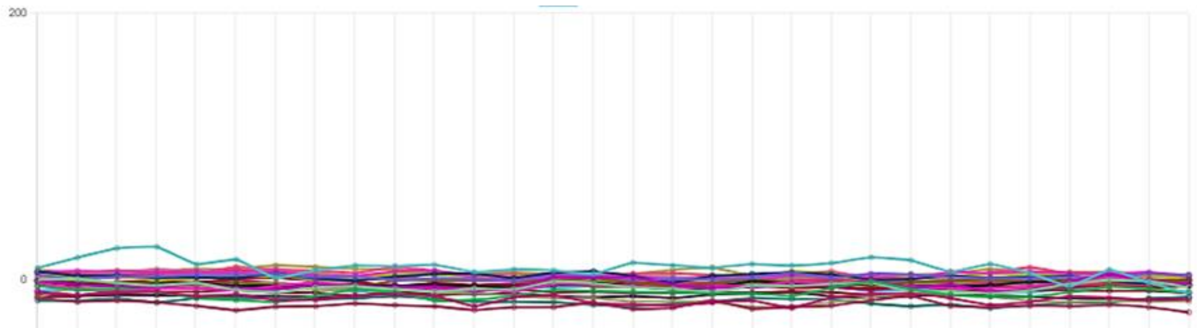
For the swimming activity, the USV monitors wave patterns generated by a swimmer moving through the water. This test aims to assess the detector's sensitivity to relatively small and rhythmic wave disturbances typical of human movement. The data collected from various directions provide insights into how well the system can track and interpret waves caused by swimming action.

In the drowning scenario, the USV detects wave patterns associated with more erratic and potentially urgent movements. This test is crucial for evaluating the detector's ability to identify and respond to irregular wave patterns, which are indicative of distress situations. By analyzing wave data from multiple directions, the effectiveness of the detector in recognizing and differentiating these critical wave patterns is assessed.

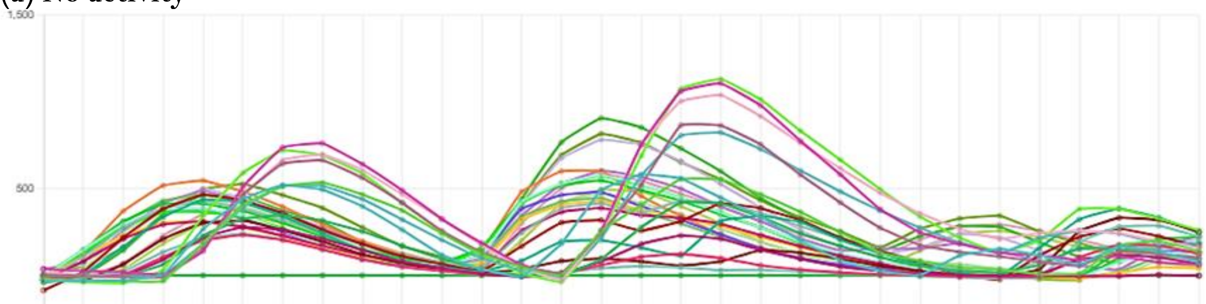
Lastly, the dumping (disposal) of an object into the water generates a different type of wave disturbance, characterized by a sudden and localized impact. This activity tests the detector's responsiveness to abrupt changes in water surface conditions. The collected wave patterns from various angles help determine the system's capability to accurately detect and analyze the immediate effects of objects entering the water.

The data collected from both test environments, namely the controlled swimming pool and the open lake, were systematically compared and analyzed to assess the performance of the USV. Given the differences in environmental conditions, signal filters were applied to process the generated waveforms, particularly to mitigate unwanted noise. This filtering was crucial for data obtained from the lake environment, where external factors such as wind, water currents, and surface disturbances could introduce significant noise and fluctuations. Following the application of signal filters, normalization technique was used to standardize the waveforms from both test environments, ensuring a fair comparison. After normalization, the results demonstrated that the waveform patterns from the two environments closely resembled each other. This finding indicates that despite differences in testing conditions, the USV consistently detected water level changes with high accuracy. Therefore, the experiment successfully validated the USV's capability to generalize water level detection under normal weather conditions, reinforcing its operational effectiveness in both controlled and real-world aquatic environments.

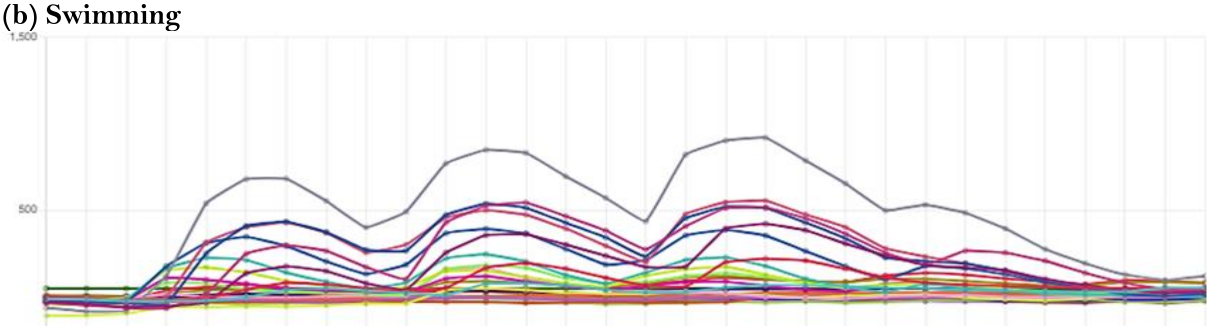
Figure 8 displays the waveforms produced by the each capacitive sensor in response to three selected water activities during the test, including the scenario of calm water (no activity). The y-axis is scaled to milli-unit for wave amplitude comparison purpose and the time interval in the x-axis is one second.



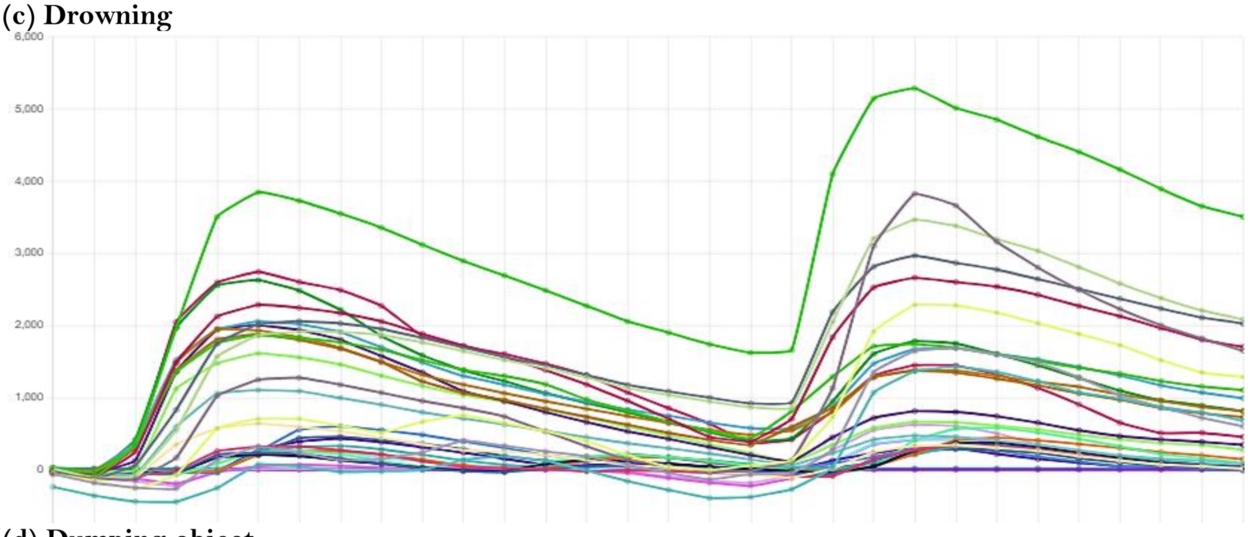
(a) No activity



(b) Swimming



(c) Drowning



(d) Dumping object

Figure 8.
Waveforms produced by the three selected water activities (a) No activity: calm water (b) Swimming (c) Drowning (d) Dumping object.

Each water activity generates unique waveforms which are efficiently characterized by distinct amplitude and frequency profiles. This clear differentiation among the waveforms for swimming, drowning, and object dumping underscores the capacitive wave detector's capability to accurately capture and analyze various types of water activities. This ability enhances its utility in diverse water surveillance scenarios, making it a valuable tool for monitoring and ensuring water safety in reservoir.

5. Conclusion

Water wave detection is extensively employed in oceanography, early warning systems in remote areas, and weather monitoring. Earlier research on contactless water wave detection methods has shown limited flexibility in application. This research develops a capacitive-based sensing system to capture water wave patterns and an algorithm to detect the direction of surface water waves. The water wave patterns captured are then translated into distinguishable water activities namely swimming, drowning and disposing object into the water. The hardware development includes the outer and inner structures, with the outer structure serving as an enclosed container to protect the internal electronics from water exposure. On the other hand, many other contact-based methods suffer from lower durability due to sensor corrosion caused by prolonged water exposure. The proposed solution has been tested in a swimming pool and in an open lake, proving its effectiveness in detecting water activities as shown in the analysis waveforms.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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