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UNMANNED SURFACE VEHICLES USED FOR WATER QUALITY MONITORING

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Abstract: Water is an essential element for sustaining life, making the continuous monitoring of aquatic resources a critical task. Advances in technology have paved the way for modern systems that enable water quality monitoring with lower labor requirements and reduced operational time. Unmanned Surface Vehicles (USVs), whether remotely operated or fully autonomous, serve as mobile platforms capable of collecting data from various locations within lakes, rivers, seas, and other water bodies. Their mobility and flexibility provide significant benefits, especially in large-scale or inaccessible regions. This paper reviews USV-based water quality monitoring systems and analyzes the hardware and software components used in their development. The study focuses on microcontrollers, storage units, propulsion and navigation techniques, sensor configurations, positioning systems, and energy management strategies. Furthermore, it examines the design and functionality of control station interfaces utilized for operating USVs and visualizing real-time environmental data.

Keywords: Autonomous surface vehicles, Remote control, Water quality, Real time monitoring, Sensors.

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1. INTRODUCTION

Water is vital for life, and the survival of all living organisms on Earth depends on its state. It is used to satisfying essential needs, life quality, industrial production, and personal consumption. Most of the Earth's surface water exists seas, lakes, and rivers, which are extensively used for activities such as tourism, manufacturing, agriculture, and transportation. The quality of water, which is present in all of life, directly impact the efficiency in this area. The quality of water bodies can be evaluated through chemical, physical, and biological parameters. Standardized values help in effective decision making for sustainable water management. It is also a critical indicator in determining the cleaning, storage and maintenance of water bodies (SWQR, 2015).

Measurements in water bodies are conducted using portable sensors or by collecting samples, which are subsequently analyzed in the laboratory. However, these approaches involve significant labor and time costs. With advancements in technology, various innovative techniques have in water monitoring systems to enhance efficiency. One of method is the wireless collection of sensor data, which enables real-time monitoring and reduces the need for manual intervention. (Mukta et al., 2019). These remote monitoring methods are classified into two categories based on sensor module configurations: mobile and stationary systems. In stationary systems, one or more fixed sensor nodes are positioned on the water surface to continuously collect data from a specific location. (Duran and Yucel., 2021). In mobile systems, sensor modules can operate either on the water surface (Jo et al., 2019) or underwater (de Lima et al., 2021). Additionally, these systems can be categorized as either remotely controlled (Jo et al., 2019) or fully autonomous (Bayusari et al., 2021), depending on their operational mode. Both systems include a control and monitoring station. While sensor data in stationary systems is continuously collected from a single fixed location, mobile systems enable data acquisition from multiple points, providing a more comprehensive spatial assessment of water quality.

USVs can be defined as vessels designed to operate without a man operator. These vehicles can either be remotely controlled or function autonomously. If a USV is capable of autonomous navigation, it is referred to as an Autonomous Surface Vehicle (ASV). The usage of USVs for water quality monitoring has become increasingly widespread in recent years. A typical monitoring system consists of a USV and a control station, as showed in Figure 1 (Stateczny and Burdziakowski, 2019).

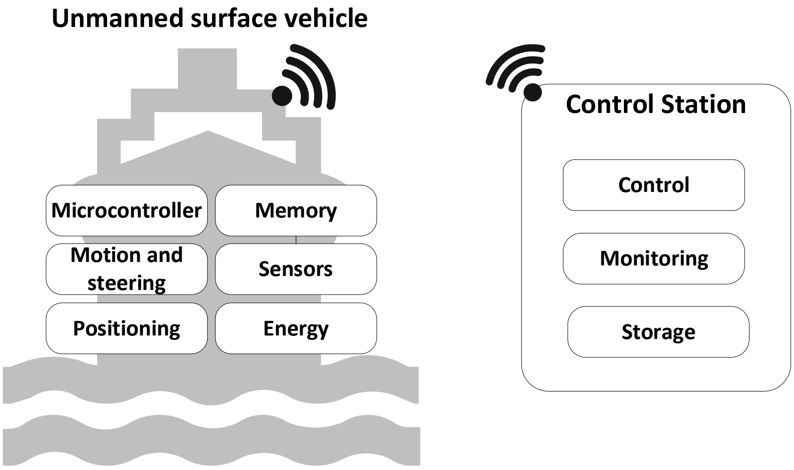

Figure 1: A typical water quality monitoring system developed using USV

1. UNMANNED SURFACE VEHICLE

USVs developed for water quality monitoring consist of including sensors, memory units, communication modules, positioning systems, motion and navigation mechanisms, power sources, and processors. This study examines USVs of varying dimensions, ranging from 50 to 150 cm in length and 30 to 100 cm in width. The research provides an overview of the system components, sensor modules, hull designs, power sources, microcontrollers, motion and navigation systems, communication modules, and control stations used in these platforms.

2.1. Sensor module

The assessment of water quality involves the evaluation of chemical, physical, and biological parameters. Sensors are utilized to detect physical and chemical properties and convert these measurements into electrical or digital signals. In USVs, sensor modules enabled the measurement of both water and atmospheric parameters. Commonly monitored parameters include pH (potential hydrogen), temperature, turbidity, oxidation-reduction potential (ORP), electrical conductivity (EC), and dissolved oxygen (DO). The functions of the modules used in water quality monitoring systems are briefly described below.

The pH value indicates the concentration of hydrogen ions in water, representing its acidity or alkalinity. pH sensors measure the balance between acidic and alkaline components in water and express it as a pH value. The World Health Organization (WHO) recommends that water should not be excessively acidic or alkaline, with an optimal pH range for drinking water typically between 6.5 and 8.5. Additionally, it is suggested that the pH value for aquatic life should remain within the range of 5 to 9 to ensure a suitable environment for biological sustainability.

Temperature is a critical parameter for aquatic ecosystems such as rivers, lakes, and seas. Variations in water temperature directly impact the quality of life for aquatic organisms, their migration ways and, in extreme cases, led to death. Temperature plays a significant role in biological activity and growth, as it affects metabolic rates and processes. Additionally, it determines the diversity of organisms that is inhabit rivers and lakes. Fish, insects, zooplankton, phytoplankton, and other aquatic species each require specific temperature ranges for survival. When temperatures exceed or fall below these optimal ranges, population sizes decline, and species may ultimately face extinction (WSS, 2018).

Turbidity is a measure of the clarity of a liquid and is an important optical property of water. It is quantified by assessing the amount of light scattered by suspended particles in a water sample when a light source is applied. The higher the intensity of scattered light, the greater the turbidity. Various materials are increased turbidity such as clay, silt, inorganic and organic matter, algae, dissolved colored organic compounds, microscopic organisms, and plankton (WSS, 2018).

The oxidative power of a solution is measured by its ORP, which also represents its self-purification capacity. Higher ORP values indicate a greater number of oxidizing agents, while lower ORP values suggest a higher concentration of reducing agents. For aquatic life, the optimal ORP range is typically between 100 mV and 200 mV. Values outside this range may indicate hazardous conditions, potentially threat the survival of aquatic organisms (Prasad et al., 2015). The ORP level of tap water is typically high, around 600 mV, due to the use of disinfectants such as chlorine. This elevated ORP value indicates strong oxidative properties, which help in eliminating harmful microorganisms and ensuring the microbiological safety of drinking water.

EC varies depending on several parameters, including temperature, pH, alkalinity, total hardness, calcium concentration, total solids, total dissolved solids, chemical oxygen demand, chloride levels, and iron concentration in water. In rivers and streams, conductivity is influenced by the geological characteristics of the surrounding area. Streams flowing through regions with granite bedrock tend to have lower conductivity, whereas those passing through clay-rich soils exhibit higher conductivity. Additionally, discharges into water bodies can alter conductivity depending on their composition. For instance, a malfunctioning sewage system increases conductivity due to chloride, phosphate, and nitrate, while an oil spill reduces conductivity by introducing hydrophobic compounds that limit ion mobility (Bhateria and Jain 2016).

DO refers to the amount of oxygen present in water. Water bodies obtain oxygen from aquatic plants and atmospheric change. Flowing water, such as rivers and streams, typically contains higher oxygen levels compared to stagnant water bodies like ponds or lakes. Aquatic organisms need dissolved oxygen for respiration, making it a critical factor for sustaining life. Oxygen levels in water bodies can change periodically due to various environmental and biological processes. As DO directly influences aquatic ecosystems, it is considered one of the key parameters that are measured and monitored to assess water quality.

In addition to commonly used sensors for monitoring water parameters, water quality can be evaluated using sensors that measure light, color, salinity, and other related properties. These additional parameters provide valuable insights into the overall condition of aquatic environments, enabling a more comprehensive evaluation of water quality (Setiawan et al., 2022). In the developed systems, in addition to water parameters, sensors measuring temperature and humidity are also utilized to monitor atmospheric conditions. These environmental factors play a crucial role in understanding the interactions between water quality and weather conditions, providing a more comprehensive assessment of aquatic ecosystems (Xing et al., 2020). The water parameter sensors used in the sensor modules of the developed USVs are presented in Table 1.

Table 1**.** Sensors used on USVs to measure water parameters.

Ref.	**pH**	**Temperature**	**Turbidity**	**ORP**	**EC**	**Chlorophyll-a**	**TDS**	**Light**	**Color**	**Salinity**	**DO**
(Melo, et al., 2019)	X	X		X							X
(Kaizu, et al., 2011)	X	X	X		X	X					X
(Arko, et al., 2020)	X	X	X								
(Ansari, et al., 2022)	X	X	X				X				
(Shuo, et al., 2017)	X	X		X	X			X			X
(Setiawan, et al., 2022)		X						X			
(Balbuena, et al., 2017)	X	X	X		X				X		X
(Chang, et al., 2021)	X										
(Madeo, et al., 2020)	X	X		X						X	X
(Cao, et al., 2018)	X						X				
(Dsouza, et al., 2021)	X	X			X						
(Xing, et al., 2020)	X	X	X								
(Siyang and Kerdcharoen, 2016)	X	X		X	X						X

In a USV developed for water quality monitoring, the selection and quantity of sensors for the monitored parameters is determined based on the size of the USV, the scale of the study area, and the available energy capacity. This is because each additional sensor contributes to increased energy consumption and spatial constraints within the system. Fundamental sensors such as temperature, pH, turbidity, DO, and EC are commonly used to obtain a general assessment of water quality. However, the technical specifications of these sensors vary across different studies depending on the research objectives and environmental conditions.

2.2. Hull design and material

Surface vehicles are designed to remain partially submerged while ensuring they do not fully sink. To achieve this, various hull designs are utilized, including flat-bottomed boats (Fig. 2a), V-bottomed boats (Fig. 2b), round-bottomed boats (Fig. 2c), and catamarans (Fig. 2d). Each design offers distinct advantages depending on the operational environment, stability requirements, and intended application of the USV (Riley, 2021).

In addition to these standard designs, customized hull structures can be developed based on specific operational requirements. Catamaran hulls offer advantages such as stability, better water contact, reduced submersion, and increased deck space; however, they are generally not optimized for high-speed operation. Among monohull designs, V-bottom hulls provide higher speed and enhanced maneuverability, making them suitable for dynamic environments. Flat-bottom hulls good in shallow waters, allowing for efficient maneuver in narrow areas. Round-bottom hulls can design to minimize wave impact and enhancing stability in rough water conditions.

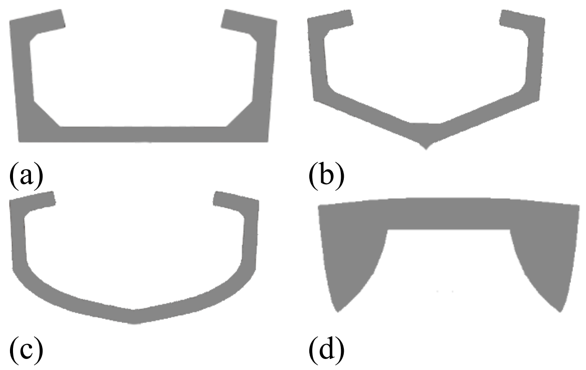

Figure 2. (a) Flat bottom, (b) V-bottom, (c) Round bottom, (d) Catamaran

Dsouza et al. (2021) developed a remotely controlled boat for monitoring water parameters. The boat is designed with a flat-bottomed hull to enhance stability on the water surface. It is reported that the square-shaped flat hull contributes to improved stability, reducing the external effects. The square hull structure is constructed using Polyvinyl Chloride (PVC) material. This is providing durability, stable buoyancy and lightweight design.

In the study by Siyang and Kerdcharoen (2016), a USV is designed in a catamaran form. The catamaran structure consisted of two V-bottomed hulls made of fiberglass, which are positioned parallel to each other. To house electronic equipment and ensure protection, a waterproof enclosure is placed in the central section between the two connected hulls. This design allowed for balanced weight distribution, with the center of gravity positioned at the midpoint, enhancing stability and structural integrity in aquatic environments. Although this design offers advantages such as enhanced stability, the alignment of the motors, propellers, and shafts positioned in both hulls are precisely adjusted to optimize their interaction with the water.

While various hull designs have been developed for surface vehicles used in water quality monitoring systems, the catamaran form is the most preferred due to its stability and spacious platform for sensor integration. Table 2 show hull types used in the literature.

Table 2. USV forms developed to measure water parameters.

Ref.	Hull Design
(Melo, et al., 2019)	Flat bottom
(Kaizu, et al., 2011)	Catamaran
(Arko, et al., 2020)	Catamaran
(Ansari, et al., 2022)	Catamaran
(Shuo, et al., 2017)	Catamaran
(Setiawan, et al., 2022)	V-bottom
(Balbuena, et al., 2017)	Catamaran
(Chang, et al., 2021)	V-bottom
(Madeo, et al., 2020)	Catamaran
(Cao, et al., 2018)	Catamaran
(Dsouza, et al., 2021)	Flat bottom
(Idris, et al., 2016)	Catamaran
(Xing, et al., 2020)	V-bottom
(Siyang and Kerdcharoen, 2016)	Catamaran

The hull material used in the development of a USV is an important factor. The material is necessary highly resistant to external environmental conditions and impermeable to water to ensure durability and long-term functionality. Additionally, it is strong enough to withstand the pressure exerted by water while the vehicle moves on the surface. Among the most used materials are iron, wood, and epoxy resin-based fiberglass composites. Epoxy resin-based fiberglass offers several advantages in terms of weight reduction, structural rigidity, ease of manufacturing, and water resistance, making it a preferred choice for USV hull construction (Mohan et al., 2016).

Different types of materials are used in the construction of USVs developed, primarily due to cost considerations. Additionally, the choice of material varies depending on the operating environment. In calm water bodies such as pools and ponds, where wave action is minimal, lighter and less rigid materials may be sufficient. However, in more dynamic environments such as lakes, rivers, and seas, where water turbulence and wave impact are higher, stronger and more durable materials are required to ensure structural integrity and long-term performance.

In a study, a plastic material is used for the hull of an USV developed for water quality monitoring. The boat is designed in the form of a flat-bottomed plastic box to increase stability. The developed USV is tested in a laboratory setting, where it is successfully floated in calm water conditions, demonstrating its buoyancy and functionality (Ansari et al., 2022). According to researchers, the system tested in calm water is not suitable for turbulent water conditions and may pose a risk, compromising the protection of electronic components.

In another study, USV is designed using polyvinyl chloride (PVC) material. The V-bottom hull is constructed to house electronic components and other onboard equipment. Additionally, polystyrene extensions are attached to the edges of the hull to prevent potential capsizing. The developed USV is tested in five different lakes, demonstrating its functionality in various aquatic environments. The study suggested that the hull design can further improved and made waterproof through the integration of advanced sealing technologies and high-tech materials (Arko et al., 2020).

In the USV developed by İdris et al., a catamaran design is constructed using PVC pipes. The use of pipes in the catamaran structure allowed the USV to achieve the required speed, while the dual-hull configuration provided a spacious platform for integrating sensors and other onboard equipment. This design enhanced both stability and functional capacity, making it suitable for water quality monitoring applications (Idris et al., 2016).

The MicroUSV, an USV proposed for use in robotic research, is manufactured using polylactic acid (PLA) material via 3D printing technology. The vehicle is assembled by combining small modular components, resulting in a structure with dimensions of 230 mm in length, 89.2 mm in width, and 125.5 mm in height. Designed as a monohull, the vehicle incorporates a stabilizing at the central to enhance stability and prevent capsizing. Developed specifically for laboratory, the MicroUSV is characterized as a low-cost, rapidly produce, and easily modify platform, offering flexibility for experimental applications in water quality monitoring. (Gregory and Vardy, 2020).

In studies in large water bodies, fiberglass and plastic materials are more commonly preferred for USVs. These materials enhance the structural durability of the USV, making it safe against potential hazards encountered in open water environments. Additionally, they provide resistance to challenging terrain conditions, such as rocks, sand, and gravel. USVs developed using plastic and polystyrene materials is tested in small water bodies and pools. In these studies, the focus is primarily on electronics and software development, rather than hull design, as the controlled environment minimizes external physical challenges.

In a study conducted with a USV designed for operation in large water bodies, fiberglass material is used for the hull, and a catamaran structure is formed by connecting two separate hulls with aluminum strips. This design allowed for the placement of a waterproof casing between the hulls, ensuring the protection of electronic components. During field tests, researchers reported that the USV maintained its structural integrity despite multiple collisions with rocks near the lake shore and exposure to 5 mm diameter hailstones. These results highlight the durability and resilience of the fiberglass-based catamaran design in challenging environmental conditions (Balbuena et al., 2017). The hull designs of surface vehicles developed for water quality monitoring are shown in Figure 3.

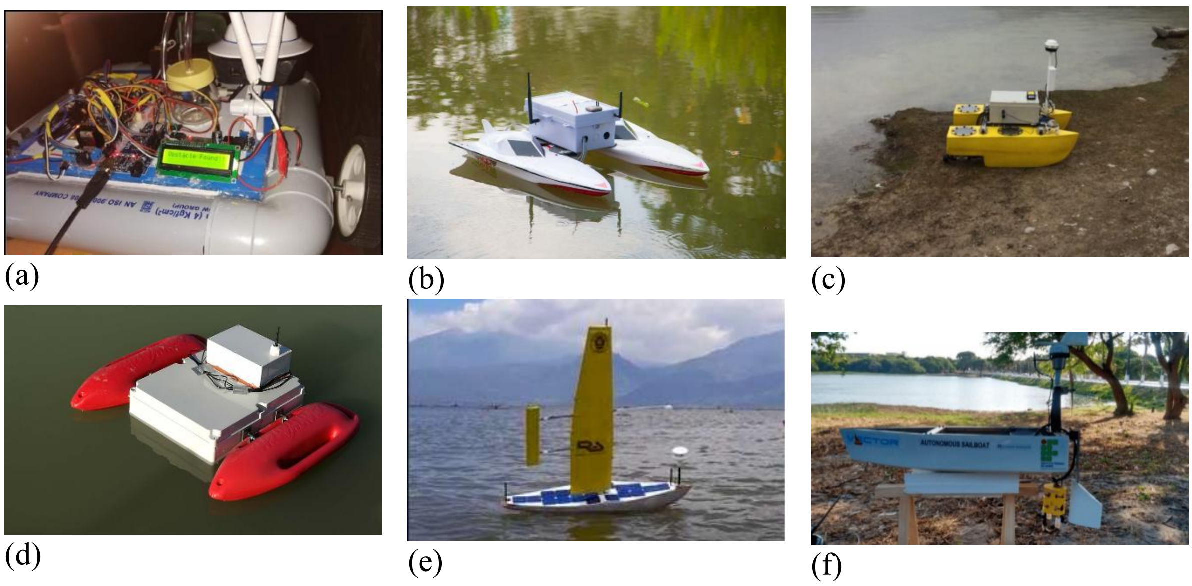

Figure 3. a) PVC material, square form (Dsouza et al., 2021), b) Fiberglass material, two v-bottom form (Siyang et al., 2016), c) Fiberglass material, catamaran form (Balbuena et al.,

2017) d) Plastic material, catamaran form (Madeo et al., 2020), e) Fiberglas material, v-bottom form (Setiawan et al., 2022), f) Fiberglass material, mono hull (Melo et al., 2019)

2.3. Power supply

In USVs developed for water quality monitoring, energy management is critical to ensuring system continuity. Power requirements are met through various sources, including wind, fuel, and electricity. Energy is primarily used to support both the navigation system and the monitoring equipment. In some studies, a shared energy source is used for both subsystems, while in others, separate power sources are used for propulsion and monitoring equipment. Batteries are commonly employed as the primary energy source for the monitoring system, as shown in Table 3.

Table 3. Energy sources used in USVs developed for water quality monitoring.

Ref.	Propulsion			System Energy	
	Electric	**Gasoline**	**Wing**	**Battery**	**Solar Panel**
(Melo, *et al.,* 2019)	X			X	
(Kaizu, *et al.,* 2011)		X		X	
(Arko, *et al.,* 2020)	X			X	
(Ansari, *et al.,* 2022)	X			X	
(Bautista, *et al.,* 2022)	X			X	
(Shuo, *et al.,* 2017)	X			X	
(Setiawan, *et al.,* 2022)			X	X	X
(Balbuena, *et al.,* 2017)	X			X	
(Chang, *et al.,* 2021)	X			X	
(Madeo, *et al.,* 2020)	X			X	
(Cao, *et al.,* 2018)	X			X	
(Dsouza, *et al.,* 2021)	X			X	
(Idris, *et al.,* 2016)	X			X	
(Xing, *et al.,* 2020)	X			X	
(Siyang and Kerdcharoen, 2016)	X			X	

In the Jetyak USV, developed for oceanographic studies, separate energy sources are utilized for the propulsion system and the monitoring system. The propulsion system is powered by a 5.2 kW gasoline engine, equipped with an 11.4 L fuel tank. This engine, weighing 135 kg, enabled the vehicle to reach a speed of 5.5 m/s. For the monitoring system, two 12 V batteries are used to supply the necessary power, ensuring the continuous operation of onboard sensors and data collection. This dual-power system enhances efficiency by optimizing fuel consumption for movement while ensuring a stable and independent power source for data collection (Kimball et al., 2014).

Energy provision in USVs is constrained by the need to maximize operational duration (autonomy) while minimizing vehicle weight and size. A commonly chosen solution involves high-capacity Lithium batteries; for example, one USV utilizes a high-capacity 12V 10000mAh Lithium battery supplemented by two separate solar panels to ensure energy maintenance during extended voyages (Tran vd. 2024).

In another system, solar and wind energy are integrated into the battery system to provide a renewable power source for the USV. The propulsion batteries are recharged using energy from renewable sources through relay-controlled charging mechanisms. The system is generated 200 Watts of electrical power from solar panels and 400 Watts from wind turbines. It provides extending operational hours and the duration the USV could remain at sea. Hybrid system also includes a control unit to prevent overcharging, ensuring stable and efficient power management (Khaled et al., 2021).

In the ROAZ II surface vehicle, batteries are used as the primary energy source. The power supply system consists of 12 V/50 Ah LiPo battery providing power for the motors. To ensure system reliability, 12 V 3700 mAh battery packs independently power critical systems in case of failure. Additionally, an internal 12 V distribution and protection board is integrated within the hull to manage power delivery to the motors and other electronic components. The vehicle's power system is safeguarded against overvoltage and overcurrent failures (Ferreira et al., 2009). To monitor Indonesia's seawater conditions, a USV named POPTAN is developed. POPTAN utilizes wind energy to power its motors, while solar panels supply energy for system operation. This hybrid energy allowing for extended operation periods in marine environments without reliance on conventional fuel sources (Setiawan et al., 2022).

In another study, a custom-built, solar-powered USV with a catamaran design is developed to collect various water parameter data. It is stated that in the developed system, 300W of energy is produced by solar panels. This situation resulted in a maximum speed of 4 knots, which is insufficient to reach the vehicle's potential speed of 5.5 knots. Despite operating at lower speeds, the system is successfully tested over hundreds of kilometers, demonstrating its efficiency and reliability in long-duration missions (Dunbabin et al., 2009).

The boat with a 150 kg carrying capacity is developed for water sampling in a swamp environment. The boat is found two four-stroke gasoline engines, each with a maximum power output of 1.2 kW. Propulsion is provided by two 350 mm diameter fans, ensuring efficient movement through the swamp terrain. With a 5 liter fuel capacity, the boat can operate at maximum engine power for up to 6 hours. The boat is allowed for extended field operations in challenging environments (Kaizu et al., 2011).

USV propulsion and navigation systems play a critical role in determining the suitable energy source. Additionally, factors such as the size of the USV and its operational environment significantly influence energy source selection. Liquid fuel-powered USVs offer high power output, making them suitable for demanding applications. However, their environmental impact is a major disadvantage. Wind energy, which is minimal environmental impact, is a viable alternative but is limited to specific operational conditions. Batteries are among the most used energy sources in USVs today, yet their capacity remains limited compared. Increasing the number of batteries can extend operational time but also adds weight, which can negatively affect performance and maneuverability. To mitigate these limitations, renewable energy sources such as solar panels and wind turbines can be integrated into battery-powered systems. This approach enhances the sustainability and efficiency of the energy supply, ensuring longer operational durations while minimizing environmental impact.

2.4. Microcontroller

Microcontrollers are responsible for managing the entire electronic system in USVs developed for water quality monitoring. In most cases, both the water monitoring system and the USV's are controlled by a single microcontroller. However, in some studies, a separate control architecture is implemented, where one microcontroller manages the monitoring system, while another controls the USV's movement and operation. The microcontrollers used in the developed USVs are listed in Table 4.

Table 4. Microcontrollers used in USVs developed for water quality monitoring.
X: *Vehicle microcontroller,* Y: *Monitoring system microcontroller*

Ref.	Raspberry Pi	myRIO	Ardunio	STM
(Melo, et al., 2019)	X		Y	
(Arko, et al., 2020)			XY	
(Ansari, et al., 2022)			XY	
(Bautista, et al., 2022)			XY	
(Shuo, et al., 2017)		XY		
(Setiawan, et al., 2022)			Y	X
(Balbuena, et al., 2017)	X		Y	
(Chang, et al., 2021)			XY	
(Madeo, et al., 2020)			XY	
(Cao, et al., 2018)	XY			
(Dsouza, et al., 2021)			XY	
(Idris, et al., 2016)			XY	
(Xing, et al., 2020)			XY	
(Siyang and Kerdcharoen, 2016)			XY	

The capability, speed, operational efficiency, and overall performance of a USV are largely determined by the microcontroller. Since different applications have varying requirements, a single microcontroller cannot be universally applied to all USV designs. Instead, the selection of a microcontroller should be based on the specific capabilities and operational needs of the system. Several technical factors are considered in this selection process, including bit architecture (8 bit, 16 bit, or 32 bit), power efficiency, input and output interfaces, package size, RAM and ROM capacity, temperature tolerance, processor speed, and software compatibility. Choosing a microcontroller that aligns with these specifications ensures optimal system performance, reliability, and energy efficiency, enabling the USV to operate effectively in diverse environmental conditions.

In the robotic airboat "Vektor", two different microcontrollers are used to manage various subsystems. An Arduino is employed for the water parameter measurement system, while a Raspberry Pi controlled the USV's movement, navigation, and communication functions. The system utilized the Arduino Mega 1280, which is chosen for its enough I/O pins and adequate memory capacity to support sensor connections and data processing. Water parameter data collected by the Arduino is transmitted to the Raspberry Pi, which acted as the central processing unit for higher-level functions. The study specified that the Raspberry Pi B+ model is selected due to its USB interfaces, general-purpose I/O pins, Micro SD storage capability, and low power consumption, making it well-suited for efficient system operation and real-time data processing (Melo et al., 2019).

In another study, two microcontrollers are used to manage water parameter monitoring and USV navigation and control. The system incorporated two Arduino Mega 2560 microcontrollers, each assigned to a specific function. One microcontroller is responsible for surface cleaning, obstacle avoidance, and propulsion control, while the other managed position tracking and water parameter monitoring. This dual-microcontroller architecture enabled efficient task distribution, ensuring improved performance and reliability in autonomous operations. (Chang et al., 2021). In a smaller-scale USV, a single microcontroller is used to manage both the control and monitoring systems (Arko et al., 2020). This highlights the importance of microcontroller selection based on the size and functional requirements of the developed USV. The choice of a single or multiple microcontrollers directly impacts the system’s efficiency.

Although microcontrollers are widely preferred due to their lower power consumption and compact size, Kaizu et al. utilized a computer for both the USV's control system and water parameter monitoring. In their study, the computer continuously transmitted navigation and heading data to the electronic control unit, which managed the motors. Additionally, the system is designed to enable continuous data recording through a custom-developed program, allowing for real-time monitoring and long-term data storage (Kaizu et al., 2011).

In another study, the Raspberry Pi B is utilized in the development of a small-scale USV based on stereo vision. The Raspberry Pi is used to with two cameras and ultrasonic sensors for navigation and environmental perception. The system is developed on a Linux-based platform, where algorithms are executed directly on the Raspberry Pi. OpenCV is employed for image processing, while the Video4Linux2 API enabled parallel image acquisition (Neves and Matos, 2013).

2.5. Propulsion and steering

The propulsion and steering systems of a USV are responsible for navigating the vehicle to its designated coordinates. Sails and propellers are commonly used for movement, while propellers and rudders are employed for steering. In dual-propeller systems, the difference in rotation speed and direction between the two propellers acts as a rudder mechanism, enabling directional control without a separate rudder. Propellers generate thrust by use water or air, facilitating movement. The ability of propellers to generate thrust through airflow in water environments makes USVs adaptable for use in reed beds, marshes, and other challenging terrains. Additionally, the hull design of a USV directly influences the selection of propulsion and steering components. Various studies are employed different propulsion and steering systems, and Table 5 shown.

Table 5**.** Equipment used for propulsion and steering in USVs developed for water quality monitoring

Ref.	Propeller position		Steering hardware	
	Contact water	**Noncontact water**	**Rudder**	**Propeller**
(Melo, et al., 2019)		X		X
(Arko, et al., 2020)		X		X
(Ansari, et al., 2022)	X		X	
(Bautista, et al., 2022)	X		X	
(Shuo, et al., 2017)	X		X	
(Setiawan, et al., 2022)		X		
(Balbuena, et al., 2017)	X			X
(Chang, et al., 2021)	X			X
(Madeo, et al., 2020)	X			X
(Cao, et al., 2018)	X		-	-
(Dsouza, et al., 2021)	X		X	
(Idris, et al., 2016)	X		X	
(Xing, et al., 2020)	X		-	-
(Siyang and Kerdcharoen, 2016)	X		-	-

- *unspecified*

Motors are essential for propeller and rudder movement in USVs. While propellers require continuous movement, rudders operate effectively with intermittent adjustments. Due to these differing requirements, brushed or brushless motors are typically used for propellers, whereas servo motors are preferred for rudder control. Navigating to a target location is achieved through the precise control of the propellers and rudders. Motor operation is managed using

Electronic Speed Controllers (ESCs), which regulate motor movement based on commands received from the microcontroller. The ESC ensures speed control, enabling responsive maneuverability of the USV (Harrington and Kroninger, 2013; Kusko and Peeran, 1988; Sakama et al., 2022).

The processing core of a USV often involves a multi-tiered control architecture, where microcontrollers manage either low-level or high-level tasks to ensure efficient operation. In the case of the ROWENA prototype, the Arduino Mega 2560 was selected as the main microcontroller due to its availability and sufficient connectivity to integrate navigation sensors (GPS, compass) and a dedicated SD Card module for data storage. Conversely, more complex platforms, such as the EDSON-J USV, implement a hybrid control architecture. This design employs a main computer, running the Robot Operating System (ROS) for deliberative control and a secondary computer running a Finite State Machine (FSM) for hierarchical control (executing low-level tasks such as navigation algorithms and propeller control). The Jetson TX2 was chosen for its flexibility, native Linux/Python compatibility, computational power (NVIDIA Pascal GPU), and energy efficiency (Mendoza-Chok vd. 2022).

In USVs which used dual-propeller systems, the difference in rotation speed and direction between the two motors is used to control the vehicle's heading. In contrast, rudder-based systems determine the direction of movement based on the angular position of the rudder relative to the hull. The distance, direction, and angular difference between the current position and the target location are calculated by the microcontroller. Based on these calculations, appropriate commands are sent to the motors and steering system, ensuring that the USV adjusts its trajectory and moves toward the target (Wang et al., 2009).

In single-propeller USVs, a rudder is essential for changing the vehicle’s direction. A stern-mounted rudder helps maintain a minimal angular offset between the USV’s heading and the target direction. However, rudders are less effective for large directional changes and have several limitations, including speed reduction and the need for a larger turning radius. As a result, rudders are typically more suitable for larger, slower-moving vessels that do not require rapid maneuvers. In some USVs, propeller-based steering systems are used instead of rudders. Propeller-driven control improves the maneuverability of the vehicle, allowing for faster and sharper turns. This makes propeller-based systems ideal for sensitive and rapid maneuvers, enabling the USV to navigate efficiently in complex environments where agility is required.

2.6. Communication

Communication between the USV and the control station is established wirelessly, enabling real-time data exchange and remote operation. However, there is no universal connectivity solution that suits all physical environments and operating conditions. Various wireless communication protocols are employed depending on the range, data transmission requirements, and environmental factors. Commonly used standards include Wi-Fi, ZigBee, Bluetooth, LoRa, and GSM, each offering different advantages in terms of range, power consumption, and data transfer speed. Table 6 shows the communication technologies used in USV systems.

Wi-Fi is a widely used, low-cost communication solution with an outdoor range of up to 100 meters. It operates using IEEE 802.11x radio technologies, which transmit and receive wireless data over the 2.4 GHz and 5 GHz frequency bands. Bluetooth is a short-range, low-power, and cost-effective digital radio communication technology. Depending on the power class, its range typically varies between 1 to 10 meters. While Bluetooth requires significantly less power than Wi-Fi, its coverage area and data transmission rates are also much lower. Bluetooth transceivers operate in the 2.4 GHz frequency band with a 1 MHz bandwidth per channel. ZigBee is a wireless personal area network technology based on IEEE 802.15.4, capable of communicating over distances of up to 2500 meters. It offers advantages such as low cost, low power consumption, and extended coverage, making it suitable for long-range, energy-efficient applications in USV communication systems (Singh et al., 2014).

In the ECOSAIL system, ZigBee is used for communication between the control station and the USV. Sensor data collected from the USV is transmitted to the control station via ZigBee at 10 second intervals. The ZigBee modules are configured to operate on similar frequency channels for efficient data transfer. The study highlights that ZigBee, instead of LoRa, is chosen due to its mesh networking capability and high-speed data transmission, which enable real-time monitoring and reliable communication between the USV and the control station (Ang et al., 2022).

In another study, the water quality monitoring system and the main control unit on the USV are designed as separate components, with communication between them established via Wi-Fi. Sensor data collected from the monitoring system is first recorded and then transmitted to the main control unit over Wi-Fi. Subsequently, the data is sent to a cloud-based control station using GPRS. The transmission to the control station is carried out in JSON format, where the data is parsed and stored in the cloud for further analysis and monitoring (Cao et al., 2020).

GSM technology enables remote data communication by utilizing cellular network infrastructure. The communication range depends on the coverage area provided by the service provider. Various GSM-based communication technologies include General Packet Radio Service (GPRS), Universal Mobile Telecommunications System (UMTS), and Long-Term Evolution (LTE), each offering different data transfer speeds and capacities. These technologies provide varying levels of performance, presenting distinct advantages and disadvantages depending on the application requirements. When compared to other wireless communication methods, GSM-based systems are more costly due to service provider fees. However, their global coverage makes them a solution for applications requiring data transmission over large geographical areas. Despite this advantage, GSM infrastructure dependency can vary based on local service provider policies and network investments, potentially affecting availability and performance in certain regions. The selection of a communication standard is entirely dependent on the specific communication requirements and the scope of the application. Factors such as range, data transfer speed, power consumption, environmental conditions, and infrastructure availability are considered to determine the most suitable wireless communication technology for a given USV system.

Tablo 6. Communication methods used in USVs developed for water quality monitoring.

Ref.	Wi-Fi	ZigBee	Lora	GSM	Bluetooth	3DR Radio
(Melo, et al., 2019)	X					
(Arko, et al., 2020)	X					
(Ansari, et al., 2022)	X			X	X	
(Bautista, et al., 2022)				X		
(Shuo, et al., 2017)		X				
(Setiawan, et al., 2022)			X			X
(Balbuena, et al., 2017)	X					
(Chang, et al., 2021)					X	
(Madeo, et al., 2020)		X				
(Cao, et al., 2018)				X		
(Dsouza, et al., 2021)					X	
(Idris, et al., 2016)						X
(Xing, et al., 2020)	X					
(Siyang and Kerdcharoen, 2016)		X				X

In a study, LoRa and 3D Radio Telemetry Module are compared for communication performance. The evaluation is conducted by transmitting 20 data packets, and parameters such as transmission distance, data quality, and power consumption are analyzed. The results indicated that the 3DR Radio Telemetry Module is efficient up to 300 meters, whereas the LoRa module maintained effective communication up to 10,500 meters. Additionally, LoRa exhibited lower power consumption in idle mode, but during data transmission, its power consumption is observed to be nearly twice as high as that of the 3D Radio Telemetry Module (Setiawan et al., 2022).

2. CONTROL STATION

The control station is responsible for operating the USV, monitoring incoming data, and storing collected information. USV control can be categorized into two main approaches: manual remote operation and autonomous navigation. In remotely operated USVs, the vehicle is controlled manually by commands sent from the control station, allowing the user to navigate forward, backward, left, or right. The thrust system's speed and direction, as well as the rudder angle, are adjusted according to the received instructions, enabling precise movement control. For USVs, coordinate data can be transmitted either in real-time from the control station or predefined before deployment. The system calculates the optimal route between the current position and the target destination, adjusting motor speed and rudder movements accordingly. During navigation, external environmental factors such as wind and waves are considered. To handle these challenges, various path-planning algorithms can be implemented, including linear, nonlinear, adaptive, and intelligent routing methods, depending on the complexity of the operational environment.

A study discusses the use of various methods for developing a route control system in an USV. Several control strategies, including Proportional-Integral-Derivative (PID) control, optimal control, adaptive control, intelligent control, robust control, and sliding mode control, have been evaluated for their suitability in USV navigation. Due to environmental disturbances such as wind, waves, and currents, fuzzy logic control has been proposed as an alternative approach for handling uncertain and nonlinear dynamics in complex systems. This method enhances the USV’s ability to adapt to unpredictable conditions, making it particularly useful for real-world applications where precise modeling of environmental influences is challenging (Azzeri et al., 2015).

In a study conducted using a USV developed for water quality monitoring, a grid-based path-planning method is implemented. Water parameter values are measured at grid points spaced 10 meters and 40 meters apart. The USV completed its journey across 45 points with 10 meters spacing in 20 minutes, while the journey across 130 points with 40-meter spacing took 144 minutes, requiring an additional battery to sustain operation. The collected data is transmitted to the control station, where it is processed and utilized for mapping purposes using the ArcGIS software (Kaizu et al., 2011).

In a study conducted by Cao et al., a mobile application is developed as a control station for USV operations. The application is designed to integrate mapping, remote control, and data query functionalities, enabling real-time monitoring of the USV's position directly from the mobile interface. The system allowed for instant task assignment, enabling the USV to navigate dynamically based on operational needs. Upon reaching the target coordinates, the USV measured water parameter values and transmitted the data to a server for further analysis. The study concluded that the system is suitable for real-world experimental applications, demonstrating its potential for practical deployment in field operations (Cao et al., 2018).

The control station is used for both monitoring and controlling the USV. Data visualization plays a crucial role in understanding and analyzing collected information, making the system more effective for users. A well-designed control station should be user-friendly, support multiple platforms, and provide real-time tracking of the USV on a map. Additionally, the control station should feature an interface for manual remote control, allowing for immediate intervention when necessary. To ensure uninterrupted operation, the connection between the control station and the USV always remains stable. A comparison of the devices and software used in various control stations, including whether they support remote manual control and how target coordinate data is uploaded, is presented in Table 7. Additionally, the different control units implemented with various devices and software are illustrated in Figure 4.

Table 7. Control station features in USVs developed for water quality monitoring

Ref.	Target Coordinate Information	Manual Remote Direction	Monitoring Device/Software
(Melo, et al., 2019)	Saved at first	No	PC / Google Maps
(Kaizu, et al., 2011)	Saved at first	No	-/-
(Arko, et al., 2020)	Saved at first	Yes	-/-
(Ansari, et al., 2022)	-	No	PC / -
(Bautista, et al., 2022)	Saved at first	No	-/-
(Shuo, et al., 2017)	Send instantly	Yes	PC / Lab View
(Chang, et al., 2021)	Saved at first	Yes	PC / Lab View
(Madeo, et al., 2020)	-	Yes	-/-
(Cao, et al., 2018)	Send instantly	No	Smart Phone / Mobile App
(Dsouza, et al., 2021)	-	Yes	Smart Phone /-
(Idris, et al., 2016)	Send instantly	Yes	PC /-
(Siyang and Kerdcharoen, 2016)	-	Yes	PC / Smart Phone

- unspecified

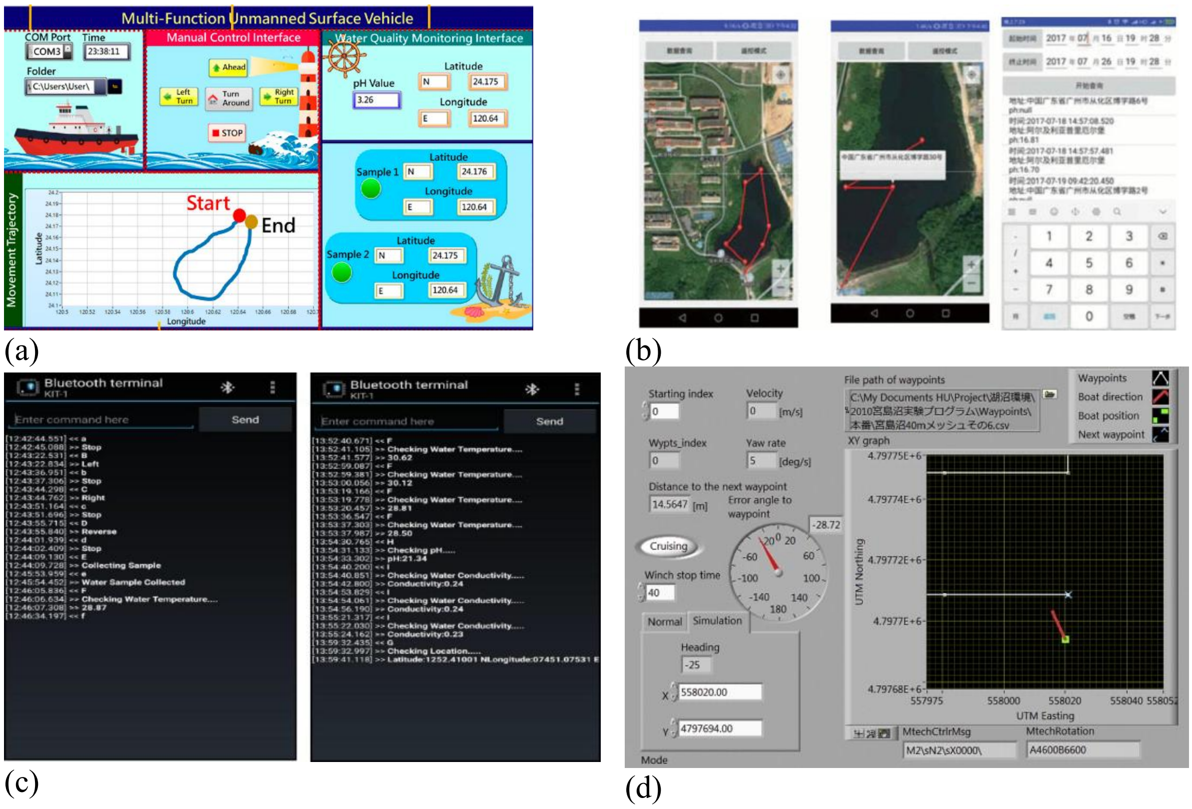

Figure 4. (a) Control unit developed using LabVIEW (Chang et al., 2021), (b) Control unit developed with a mobile application (Cao et al., 2018), (c) Mobile application with text-based command input (Dsouza et al., 2021), (d) Computer-based control unit (Kaizu et al., 2011)

3. CONCLUSIONS

This study demonstrates the potential of USV-based systems for effective water quality monitoring through the integration of multiple sensors and wireless communication technologies. The catamaran hull design, with its modular and detachable structure, ensures stability, increased payload capacity, and ease of transport, making the system adaptable for diverse operational scenarios. By reducing cost, time, and labor requirements, while simultaneously enhancing safety, USVs represent a practical and scalable solution for environmental monitoring. The findings highlight that flexible communication alternatives, such as Wi-Fi, 4G/5G, and LoRa, can be tailored to different mission requirements, improving system reliability and independence. Moreover, the use of portable control stations and custom-developed software strengthens operational flexibility. In conclusion, USV-based monitoring systems offer a promising approach to real-time water quality assessment. Future studies should focus on long-term field validation, integration of additional water quality and biological sensors, and the development of advanced autonomous navigation and data-processing algorithms to further improve system performance and applicability.

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