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https://ieeexplore.ieee.org/abstract/document/9829573

An Autonomous Sailboat for Environment Monitoring

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Abstract**—** The marine environment is constantly at risk from coastal urbanization. The deterioration of coastal and marine environments is evidenced by the decline of mangroves and the biodiversity of such environments and increasing recurrences of algal and jellyfish blooms. There is a lack of environmental data especially in developing countries such as Malaysia to determine the sustainability and impact of the current development on coastal resources. We developed an autonomous sailboat that utilizes the Internet of things technology to collect and analyze ocean water quality data for local authorities to obtain insights into the sustainable development of coastal resources. The USV is equipped with sensors, microcontrollers, and a wireless communication module based on ZigBee standards to allow sending water quality data to a gateway located at the shore. The data collected by the USV will be processed by a cloud server and visualized through user applications.

Keywords—Internet of Things, Autonomous sailboat, Remote sensing, Environment Monitoring

I. INTRODUCTION

Water is an important natural resource for human life and activities. The ocean occupies 71% of the surface area of the Earth, and 97% of the total water on the Earth originates from the ocean. Many of the major problems that humanity is facing in the 21st century are related to water quantity and/or water quality [1]. Modern human activities have aggravated the pollution of the sea, severely affected marine lives, and damaged the integrity of the marine food chain, food security, tourism, and all the other provisioning, regulating, cultural, and supporting services the marine and coastal ecosystems provide. These activities also have a significant impact on the marine water quality and the stability of the natural environment. Because of the close link between the ocean and human life, extensive marine hydrological observations to detect pollution sources are necessary. In addition, climate change and extreme weather events such as hurricanes and climate patterns such as El Nino and La Nina events [2] induce instability in the marine environment. Early detection of such events can help to reduce economic property losses and safeguard life in the planet.

Conventional field measurements for evaluating water quality are based on time-consuming and labor-intensive on-site sampling and data collection [3]. Water quality measurements are performed using special research vessels with expert personnel on board. Water is sampled from a fixed position identified in advance. The collected water samples are sent to laboratories for further analysis. These traditional methods have major limitations. For example, the coverage of the area is not extensive. Moreover, it is labor intensive and incurs high cost (labor, operation, and equipment costs). Furthermore, since water quality is analyzed in a laboratory, real-time data that enable swift decision-making for public health protection are not obtained [4]. In addition, weather and other uncertain factors can affect the deployment of the measuring equipment, and excessively complicated lab analysis greatly reduce the efficiency of obtaining measurements and results. Therefore, there is a need for a more efficient method ofmonitoring water quality.

This paper proposes a system for efficient and real-time water quality monitoring in the ocean. It combines USV technologies with sensors to measure water quality and wireless communication and Internet to transmit the measured data to an online platform. The relevant authorities can access and check the real-time water quality data via this online platform. The rest of this paper is organized as follows. Section 2 presents the related works on water quality monitoring. Section 3 describes the proposal of this study, including the hardware, software, and integrated communication. The prototype and its performance results are analyzed in Section 4. Finally, the conclusion and future works are provided in Section 5.

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II. RELATED WORKS

Water quality monitoring has been extensively studied. Mamun et al. [5] proposed a monitoring system based on the IoT and remote sensing to quantify the key performance indicators of water quality, such as temperature, pH, oxidation reduction potential, and conductivity. These indicators are important to maintain a suitable environment for marine life. The system was used to study the quality of water from various sources such asa creek, sea, river, and tap. Pasika [6] proposed a low-cost water quality monitoring method using commercial microcontroller ESP8266. The system sends data through WiFi to ThingSpeak mobile application for monitoring. Silva Junior et al. [7] proposed an architecture based on Raspberry Pi for a water quality monitoring system that can be installed in either fixed buoys or robotic systems to acquire water quality data. However, the system uses power-intensive WiFi or 3G wireless technology to send data to a cloud server. Deploying such water-monitoring systems in fixed buoys has numerous limitations such as a lack of mobility and high cost required to cover a large area.

To realize a mobile monitoring system, Jo [8] proposed an open-source, low-cost, and small USV for water quality monitoring. The proposed USV can be controlled by a mobile phone via Bluetooth. However, it is limited by the range of BLE 4.0 connectivity (approximately 10 m) [9], making it unsuitable to cover a wide area. Ferri et al. [10] developed HydroNet USV that can monitor coastal water quality. This USV measures the hydrocarbon and heavy-metal concentrations using custom-made miniaturized sensors. The USV navigation is based on VFH+ algorithm. Cao et al. [11] presented a USV-based water quality monitoring and analysis system that sends the measured data to a cloud server via WiFi or General Packet Radio Service technology. Water quality sensors such as modules for total dissolved solids (TDS), pH, and turbidity are attached to the side of the USV. The USV is directly connected to an automatic-positioning cruise system. Automatic positioning is achieved by processing data from a nine-axis sensor and global positioning system (GPS) module. These sensors are used to identify the position and determine the movement of the USV. Madeo et al. [12] developed a customized USV that utilizes LoRa technology to send the data from USV to cloud server. The USV had been used to collect and monitor water quality in lake. Li et al. [13] proposed a hexagonal grid-based survey planner and online quality index that were implemented in a customized USV to monitor water quality. The algorithm implemented in the control system assumes that the power for the USV is limited.

Sauze et al. [14] designed an autonomous sailing robot as USV for ocean observation and monitoring. The USV comprises a hull constructed from ABS plastic, a 1.3m high single aluminum wing sail, a 55cm deep keel with 3.5kg of lead ballast at its base and a single rudder. The sail is controlled via an electric motor and the rudder via a servo. A CMPS03 magnetic compass provides a mechanism for basic navigation and a GPS receiver was placed onboard during testing to log the boat's position. The second one features a hull constructed from plywood, dual acrylic wing sails and dual rudders. The sail and rubber control mechanism has been changed to a stepper motor to control easily and reduce power consumption.

Besides USV, other technologies such as Unmanned Aerial Vehicles (UAVs) and Autonomous Underwater Vehicles (AUVs) have been used for ocean monitoring. Yan et al. [15] designed a UAV that can be used to sample water quality. The dynamic model of the hexacopter is derived based on Newton-Eulerian's law. Dynamic inversion control (DIC) based on nonlinear feedback is proposed to control the altitude of the UAV so that it can sample the water quality. Autosub Long Range (AutosubLR) [16] is a slow speed AUVs that is designed for ocean monitoring. A major factor in the size of the AUV is the 6000m depth rating and requirement for 6000km range. The vehicle is maneuvered using three all moveable control planes, while the top rudder is fixed and contains antenna for GPS, Wi-Fi, and Iridium as well as an optional strobe. The movable control planes are controlled using custom actuators, similar in structure to the propulsion motor, which are installed along the fore-aft axis of the vehicle to simplify installation and removal.

Despite extensive research on the use of technologies to monitor water quality, several challenges persist. First, a low-cost and scalable platform should be developed. The cost of UAVs and AUVs are expensive, thus may not be suitable for developing countries. In addition, the technologies used should have low power consumption so that it can operate for longer duration. Moreover, the system should allow real-time data transfer with a high throughput. Further, the system should automatically sense data, transmit it to a cloud server for analytic, and provide notification if an abnormality is detected to enable the relevant authorities to take prompt actions. These requirements motivated the design of the autonomous sailboat in this paper. Unlike other USVs, the autonomous sailboat is controlled based on the environment condition. Not only it will capture water quality data, but it will also measure the environment conditions such as wind and water movement. Instead of using batter, wind energy is used to maneuver the sailboat.

The autonomous sailboat combines the idea of the existing autonomous sailboat with a water quality monitoring system. Sailboat USV is selected as it allows harness of wind power which is a sustainable green energy and reduce the power consumption needed for control system. The sailboat can navigate autonomously after the user inputs thedestination and does not require any operator while collecting data. It provides functions such as notifying the client about thewater quality condition if the set conditions are satisfied and providing past water quality data to the user. The autonomous sailboat technology allows the vessel to navigate to the set destination and back while simultaneously collecting data and uploading it to the cloud. Once the destination is defined, the user does not have to intervene during the process of collectingwater quality data from marine environments. Thus, the user canmonitor the sailboat via a user application while performing other tasks. The water quality analysis system gathers andanalyzes the data in the cloud server. If the water quality is unhealthy, the user is alerted via a notification from the applications. Furthermore, users can view the historical water quality data and course path of the sailboat through theseapplications.

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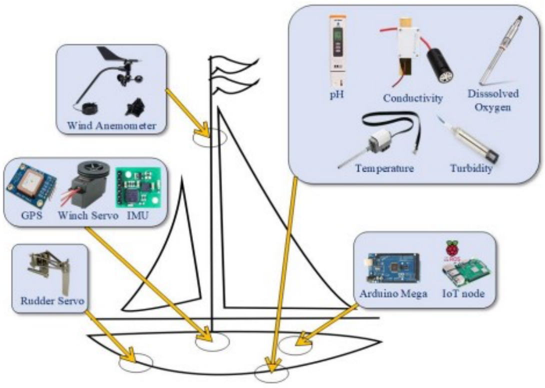

Fig. 1: Sailboat hardware architecture

III. System Design

The proposed autonomous sailboat, or in short ECOSAIL, weights 4 kg and its dimension is 1.0 m (length) x 0.22 m (width) x 1.7m (height). It includes ballast that is attached to the keel for stability and to resist the lateral forces on the hull. This can avoid tipping of the sailboat in high wind conditions. The water quality monitoring subsystem collects the pH, electrical conductivity (EC), dissolved oxygen (DO), temperature, and turbidity data.

ECOSAIL architecture is divided into two subsystems, namely, the USV control sub-system and water quality monitoring subsystem as shown in Fig. 1. The USV control subsystem comprises an anemometer, GPS, and inertial measurement unit (IMU) sensors to gather the data from surrounding waters. around the boat. The heading of the boat will be detected by the IMU sensor against the current location and destination. At the bottom of the boat, the actuator will change the rudder angle upon receiving instructions until it faces the correct direction toward the destination. The anemometer data consist of wind speed and direction. These data will be sent to the main computer for calculating and altering the sail angle. The winch servo will open and close depending on the calculation results.

A. USV Control Subsystem

To realize autonomous navigation, the IMU and GPS sensors and wind anemometer will provide data on the heading angle and body angle of the boat, its current location, and the wind speed and direction. The sensors are connected to Arduino Mega that collects the data and sends it to Raspberry Pi, which processes the data and determines whether the angle of the winch and rudder need to be changed. The USV control system was designed based on a robotic operating system framework for easy and rapid integration with the USV. The IoT node (Raspberry Pi) runs the complex control algorithms using the data sent by Arduino and uses the method proposed by Vautier [17] to maintain the position of the USV as desired. The optimized rudder and sail control is based on different wind orientations (such as apparent wind or true wind as shown in Fig. 2). The rudder control uses course angle to compensate the perturbations as shown in (1) and (2).

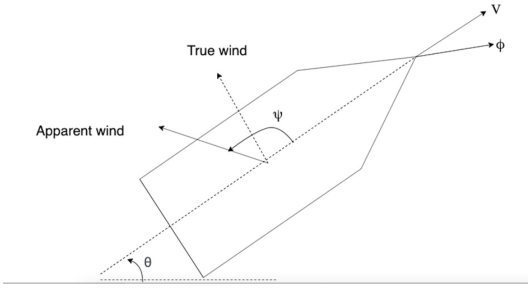

Fig. 2: Sailboat vector and wind orientation

$$\delta_r = \delta_{r,max}\ \sin(\Theta - \theta) \text{ if } \cos(\Theta - \theta) \geq 0, \tag{1}$$

$$\delta_r = \delta_{r,max}\ \text{sign}\,(\sin(\Theta - \theta)) \text{ else} \tag{2}$$

where θ is the desired orientation, $\Theta = \varphi$ if $\cos(\theta - \varphi) - \cos(\varepsilon) \geq 0$, with $\varepsilon \in [0,\pi/2]$.

The fastest path to reach destination is to choose the direct angle between sailboat and its destination. Nevertheless, wind orientation and waves can force the sailboat to navigate in different direction. As such, the USV control subsystem implemented strategy that comprises four (4) steps to help the sailboat to come closer to the target so that it will arrive at the destination with a low velocity, and small corrections should be performed to compensate for the action of the wind and waves. Below are the steps of sailboat orientation:

- Step 1: The control subsystem directs the shortest path to the destination.
- Step 2: When the sailboat approaches its destination, the sail angle will change to go round the destination. Since the sailboat is far to the destination, it will follow small the angle to reduce the distance to the destination.
- Step 3: To help the sailboat slow down and maintain its position, it will need to arrive upwind (against the wind) and maintain its orientation after reaching the target.
- Step 4: When the sailboat approaches its target, the sail angle should be changed to slow down to the smallest velocity required to reach the target.

The stepwise adjustments required to achieve the desired orientation are shown in Fig. 3. The control system directs the path of the sailboat toward the pre-arrival area (red circle). If the sailboat is upwind, it should continue with the current angle to slow down and reduce the distance to the target. Otherwise, the sail and rudder angle should be changed to go around the target. Subsequently, to get the sailboat to move upwind, it will need to make one tack. A tack variable is increased to take the boat closer to the target when it is far from the target (blue circle); otherwise, it is maintained to keep the sailboat close to the target area. Finally, when the sailboat is within the target area, the movement will be minimal to ensure that the orientation the front of the boat is towards the wind.

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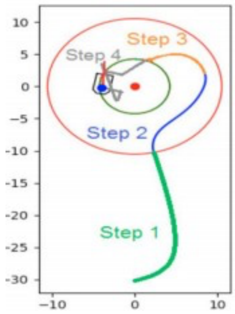

Fig. 3: Steps of sailboat orientation

B. Water Quality Monitoring Subsystem

As shown in Fig. 4, the water quality monitoring subsystem consists of industrial grade sensors for pH, EC, DO, temperature, and turbidity by DFRobot Gravity. These sensors support 5V voltage input and are connected to Arduino, which willprocess the data. The excitation source of these sensors is AC signal; thus, it can effectively reduce the polarization effect, improve the precision, and prolong the life of the probe. Since there are several sensors connected to the same microcontroller, each sensor is connected to Gravity's Analog electrical isolator to prevent electrical interference between sensors and ensure the stability and reliability of the sensor reading.

To ensure the accuracy of the sensors, the pH and EC meters need to be calibrated before use. For the pH meter, the microcontroller is programmed to use two-point calibration and therefore requires two (2) standard buffer solutions namely 4.0 and 7.0. When the microcontroller enters the calibration mode, the program will automatically identify which standard buffer solutions is present and save the relevant parameters in Arduino's electrically erasable programmable read-only memory (EEPROM). For the EC meter, a single-point calibration method is used. A standard buffer solution of 12.88 ms/cm and temperature sensor are used for calibration and measurement. A temperature sensor will be used for automatic temperature compensation. The microcontroller is programmed to automatically identify the standard buffer solutions when calibrating the EC meter and store the parameters in EEPROM.

All the sensors are mounted at the back of the sailboat so that it will not affect the movement of the sailboat. These sensors will detect the quality of the water every 10 seconds during sailing and then send to the Raspberry Pi, which will store the data in a local database and send the data to IoT gateway. This information can be used to understand the water quality of the ocean and the impact to the aquatic life. If contamination is present, it can be detected immediately, and deductions can be made on its effects towards marine life and human well-being. At the same time, the coordinate of the measurement is collected so that local authorities can trace the contamination point. Both IoT node and gateway are connected to Xbee module that are configured with the same frequency for data transmission. Xbee is selected instead of LoRa as it supports mesh communication and high-speed data transmission which allow the real-time monitoring and control. TheIoT gateway is installed near the shore site to receive the data and transmits the merged data to the cloud server via a Python script that utilizes the Mosquitto library with the MessageQueuing Telemetry Transport (MQTT) protocol.

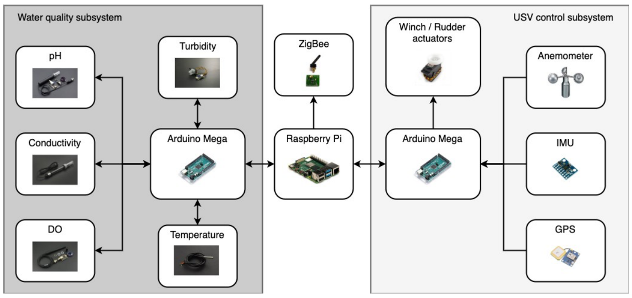

Fig. 4: Autonomous sailboat control subsystem

Fig. 5: System evaluation

IV. SYSTEM EVALUATION AND VALIDATION

In this section, the performance evaluation of the proposed system, ECOSAIL, is presented based on a real-scale experiment use case. The first step in the experiment was to validate the overall control system of ECOSAIL. Fig. 5 shows the testing of the sailboat in coastal area. The actuators of the sailboat managed to control the sail so that it moves based on the physics of a sailboat movement. Water quality monitoring sensors are attached to the back of the sailboat as illustrated in Fig. 5.

The geolocation information was transmitted to the IoT gateway and accessed through a mobile application as illustrated in Fig. 6. The real-time communication of sensed data to the IoT gateway was tested within 40 meters and able to maintain an effective data transmission rate required for real-time monitoring and control. Through ECOSAIL mobile application, the user can input the destination. Accordingly, the sail moved to the specified location via rudder and sail control. The automated navigation function was tested to ensure that it reaches the destination point set by the user from the application without anyhuman intervention.

The second part of the experiment involved validating the water quality sensor. Real-time monitoring dashboard is developed to show the status of the sensors and real-time reading of the sensor data as illustrated in Fig. 7. The sensor was tested and calibrated to ensure accurate results. After calibration, the USV was deployed in the coastal area, and the mobile application was used to monitor real-time data from the USV. Table I shows the functional testing of the autonomous sailboat system.

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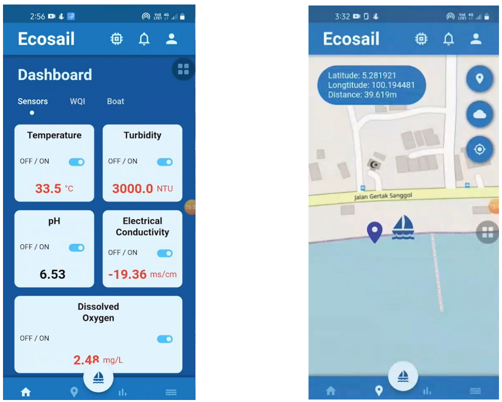

Temperature OFF / ON 33.5 °C

Turbidity OFF / ON 3000.0 NTU

pH OFF / ON 6.53

Electrical Conductivity OFF / ON -19.36 ms/cm

Dissolved Oxygen OFF / ON 2.48 mg/L

Latitude: 5.281921
Longtitude: 100.194481
Distance: 39.619m

(a) Sensor (b) Sailboat monitoring

Fig. 6: Mobile application

TABLE I. FUNCTIONAL TESTING

Functional Test	Results
Users managing sailboat	Passed
Obtain data from sensor nodes	Passed
Calibrate sensors	Passed
Set the destination of the sailboat	Passed
Send notification to users if contamination is detected	Passed

V. CONCLUSION

In this study, we built a prototype of an autonomous sailboat based on an easy-to-use Arduino microcontroller board and Raspberry Pi and Xbee modules. We considered a water quality monitoring application to demonstrate the proof-of-concept of our system. The collected data can be stored into the MongoDB database and retrieved later for analysis. This innovative approach provides insight into the use of IoT technologies with the sailboat for data collection and water quality analysis. The motivation of this project was to identify the problems related to marine environments and the challenges faced in traditional water quality monitoring process. This work was motivated by the autonomous sailboat navigation system.

In future work, the system developed for water quality monitoring will be enhanced by adding deep learning features to learn and provide useful insights into the water quality. In addition, higher efficiency with lower cost will be emphasized in the case of a fleet of USVs to cover a wider area in the ocean.

ACKNOWLEDGMENT

This research was funded in part of the USM-University of Plymouth collaboration, Grant 304/PNAV/6501023/U157.

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