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DEVELOPMENT OF IOT-BASED MONITORING FOR UNMANNED SURFACE VESSELS (USV)

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Abstract

The increasing need for real-time, autonomous marine monitoring-particularly in archipelagic nations like Indonesia-demands robust, scalable technological solutions. This study presents the development and evaluation of a web-integrated, Internet of Things (IoT)-based monitoring and control system for Unmanned Surface Vehicles (USVs), implemented on the Sea Autonomous Observer (SEANO) platform. The system was designed with a modular architecture to integrate multiple environmental and navigational sensors, including DHT22 (temperature and humidity), MPU6000 (motion and orientation), and SE100 (GPS and compass). A Raspberry Pi 3 Model B served as the main controller, communicating with a Pixhawk PX4 autopilot and an Ubiquiti Rocket M5 for wireless data transmission. The web-based interface enables real-time sensor visualization and bidirectional control via a standard browser. Experimental testing was conducted in a nearshore environment to evaluate sensor accuracy, communication latency, and system reliability. Results showed high data accuracy-98.09% for temperature, 98.95% for humidity-and an average GPS error of 3.66 meters. System responsiveness was low-latency, with data fetch and transmission times of 199 ms and 165 ms, respectively. The platform maintained stable performance during continuous operation and supported hot-swapping of sensor modules. The findings demonstrate that the proposed system provides an effective, extensible, and reliable solution for autonomous marine monitoring and control. It contributes to advancing sovereign maritime observation technologies and supports future integration with advanced sensors and AI-based navigation systems.

Keywords: IoT, Marine observation, Modular architecture, USV, Web-based system.

1. Introduction

Marine observation systems are crucial for collecting environmental data to support navigation safety, climate research, and maritime resource management [1, 2]. In Indonesia, the world's largest archipelagic nation, the development of autonomous marine observation systems is particularly strategic [3, 4]. Given its geographic configuration and exposure to complex marine phenomena such as monsoons, upwelling systems, and tectonic activity, Indonesia requires sophisticated technologies to monitor its coastal and offshore environments consistently and independently. The integration of autonomous platforms such as Unmanned Surface Vehicles (USVs) offers a promising solution by enabling persistent, wide-area data collection with minimal human intervention. Figure 1 illustrates the extent of Indonesia’s maritime domain, underscoring the geographic and geopolitical rationale for developing indigenous, real-time marine observation systems capable of supporting both national security and scientific inquiry. Figure 1 illustrates the vast maritime territory of Indonesia, highlighting the strategic importance of autonomous marine observation systems.

Fig. 1. Map of Indonesia’s maritime territory, highlighting the strategic importance of autonomous marine observation systems in the nation’s archipelagic and EEZ regions.

Despite its vast ocean territory, Indonesia currently relies heavily on foreign technologies and platforms for oceanographic data collection, raising concerns over national data sovereignty and operational independence [5-7]. Existing observation infrastructures, such as stationary buoys and coastal monitoring stations, offer limited coverage and operational flexibility [8-10].

Moreover, dependence on external servers for data processing poses potential security vulnerabilities [11]. These challenges underline the urgent need for domestically developed, autonomous, and real-time marine observation solutions [12, 13]. Unmanned Surface Vehicles (USVs) provide a promising alternative by enabling long-duration missions with reduced human involvement [14, 15]. The application of unmanned vehicles has also expanded to solve complex routing and operational problems across various domains [16-18]. However, most existing USV systems are designed for either monitoring or control, lacking integrated frameworks capable of combining both functions seamlessly.

Advances in Internet of Things (IoT) and web technologies have opened new possibilities for enhancing USV capabilities [11, 19]. IoT facilitates real-time sensor data acquisition and remote-control operations [20], while web integration ensures accessible and centralized monitoring [21]. Figure 2 presents the conceptual architecture of the IoT-based monitoring and control system for USVs.

This study presents the development of a web-integrated IoT-based monitoring and control system for USVs, with implementation on the Sea Autonomous Observer (SEANO) platform. The system employs a modular, sensor-agnostic architecture, initially validated with DHT22, MPU6000, and SE100 sensors, but adaptable to a wide range of oceanographic instruments such as ADCPs, CTDs, side-scan sonar, and MBES devices [6, 18, 22]. System performance is evaluated based on data accuracy, response time, and communication efficiency to support autonomous marine operations and contribute to strengthening Indonesia's sovereign capability in maritime observation [3, 4].

Despite growing interest in USVs and IoT applications in marine contexts, most existing platforms remain limited in two critical aspects. First, there is a clear divide between monitoring and control functionalities, with many systems offering only one-directional data acquisition or limited remote command capabilities. Second, few systems adopt a truly modular architecture that supports seamless integration of diverse and advanced oceanographic instruments. These limitations hinder the adaptability, responsiveness, and long-term sustainability of marine observation operations-especially in complex maritime geographies like Indonesia, where real-time responsiveness and technological independence are essential.

This limitation is especially problematic for developing nations like Indonesia, which require sovereign, adaptable, and cost-effective solutions to monitor their vast maritime territories. While previous studies have explored either sensor networks for environmental data collection or vehicle autonomy in isolation, there remains a lack of comprehensive systems that combine real-time monitoring, bidirectional control, modular sensor integration, and web accessibility in one coherent design.

Furthermore, few studies have addressed these challenges using locally developed, open-source platforms tailored to the specific operational and infrastructural conditions of Southeast Asian marine environments. The novelty of this study lies in the development and field implementation of a fully integrated, modular IoT-based system for USVs that unifies environmental sensing, remote command execution, and real-time web-based visualization. Unlike prior work, this system is designed with scalability and openness in mind, enabling rapid customization and future enhancements. The research contributes both a functional prototype and an operational framework that can serve as a reference for developing sovereign marine observation technologies in Indonesia and similar regions.

Moreover, there is a notable lack of literature addressing the simultaneous implementation of sensor-rich monitoring, web-based visualization, and bidirectional control within a unified, open-source platform tailored to the Indonesian marine context. Existing studies either focus on prototype-level hardware without scalable communication frameworks or emphasize data acquisition without interactive control mechanisms. This study aims to address these gaps by designing, developing, and evaluating a web-integrated IoT-based system for real-time monitoring and control of an Unmanned Surface Vehicle (USV), implemented on the Sea Autonomous Observer (SEANO) platform. The system is built with a modular architecture that facilitates sensor extensibility, wireless communication, and browser-based control interfaces. The goal is to create a robust and scalable solution capable of supporting Indonesia's sovereign marine observation efforts through autonomous, real-time, and user-accessible technologies.

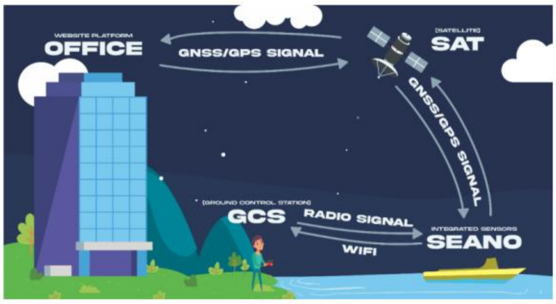

Fig. 2. System architecture of the IoT-based USV monitoring platform.

2. State of the Arts

2.1. Related works

Research on Unmanned Surface Vehicles (USVs) has grown significantly in the last decade due to their potential in hydrographic mapping [23-25], environmental monitoring [3, 26, 27], and maritime surveillance [1, 2, 28-30]. Early studies mostly focused on the vehicle design, autonomy algorithms, and low-level control systems [6, 14-15]. Wu et al. [14] and Gu et al. [6] provided overviews of hardware and software development in autonomous marine vehicles, including navigation, propulsion, and path planning. However, these works largely lacked emphasis on web-based control or scalable data integration.

In parallel, the integration of the Internet of Things (IoT) in ocean monitoring platforms has gained attention. Albaladejo et al. [19] and Ullo and Sinha [20] developed distributed sensor networks for ocean data collection and cloud storage, while Albaladejo et al. [11] and Majumder et al. [10] built web interfaces for environmental data access from fixed buoys. Chen et al. [22] introduced a multi-sensor USV platform for environmental surveys, yet without integrating interactive web-based control features.

Work combining USVs and IoT is still limited. Dallolio et al. [17] proposed lightweight communication modules for marine data transmission, and Arifin et al. [18] emphasized the importance of web-enabled data flow in coastal surveillance systems. Vo et al. [12] recommended modular software-hardware design to ensure long-term scalability in IoT-based maritime platforms.

2.2. Literature review

In the Indonesian context, sovereign marine monitoring remains a pressing issue due to heavy reliance on foreign platforms [3, 4]. Chowdury et al. [13] proposed a simple USV for surface observation, while Lewicka et al. [3] designed a buoy-based prototype with cloud-connected data features. However, both projects lacked integration of real-time control, extensible sensor systems, and web-based interfaces.

Sukarno and Ridwan [8] developed an onboard datalogger system using IoT for heading and position tracking on a USV. Though effective for localized monitoring, the system did not support remote command execution or real-time web visualization. These efforts provide a foundation but have yet to offer a comprehensive USV management framework that merges real-time sensor feedback and bidirectional control via web infrastructure.

Manley [5] and Xu et al. [7] underscored the need for autonomous systems that can operate independently and continuously in marine environments, especially across complex geographies such as Indonesia's Exclusive Economic Zone (EEZ) [1].

2.3. Key challenges and strategic role

Despite increasing interest in integrating Unmanned Surface Vehicles (USVs) with Internet of Things (IoT) technologies, most existing systems are still limited in functionality. A significant challenge lies in the separation between monitoring and control subsystems-many platforms offer data acquisition or vehicle actuation, but rarely both within a unified, interactive framework [6, 11, 14]. This limitation reduces operational responsiveness, especially in marine environments that require real-time decision-making and dynamic control.

Another key challenge is the lack of modular and extensible architectures. As observed by Vo et al. [12] and Arifin et al. [18], only a few systems support scalable integration of advanced marine sensors such as ADCP, CTD, or multibeam sonar [22]. Additionally, in the Indonesian context, limited infrastructure and reliance on foreign technologies hinder the implementation of sovereign, long-range monitoring systems [3, 4, 13].

This study addresses those challenges through the development of a web-integrated, IoT-based USV monitoring and control system. Implemented on the Sea Autonomous Observer (SEANO) platform, the system unifies sensor acquisition, bidirectional control, and web-based visualization in a modular and scalable architecture. Its strategic contribution lies in enabling real-time marine observation that is accessible, extensible, and aligned with the goal of building sovereign maritime technology infrastructure.

3. Materials and Methods

This study employs an experimental systems engineering method to develop, implement, and assess an IoT-enabled monitoring and control system for an Unmanned Surface Vehicle (USV). The process unfolds through four key stages: system design, prototype development, experimental testing, and performance evaluation.

3.1. System overview

The developed system enables real-time monitoring and control of an Unmanned Surface Vehicle (USV) through an Internet of Things (IoT)-based platform integrated with a web interface. Core components of the system include environmental and navigational sensors (DHT22, MPU6000, SE100), a Raspberry Pi 3 as the central controller, a Pixhawk PX4 for autopilot functions, and an Ubiquiti Rocket M5 module for wireless communication. These components are integrated onboard the Sea Autonomous Observer (SEANO) prototype, designed for nearshore marine observation tasks.

Sensor data is collected, processed, and transmitted to a remote server, where it is visualized through a web dashboard built with PHP and JavaScript. Users can monitor live data, access historical logs, and issue control commands such as mode switching via the interface. The system architecture is modular, allowing for future integration of additional oceanographic sensors, making it suitable for environmental monitoring, research missions, and educational deployments.

3.2. Architectural design

The system architecture is structured into three functional layers: the onboard layer, the communication layer, and the web-based interface layer. This layered design ensures modularity, scalability, and reliability, allowing for seamless interaction between sensing, data transmission, and user control. The onboard layer is centered around a Raspberry Pi 3 Model B, which serves as the main processing unit. It collects data from several sensors:

- DHT22 for measuring air temperature and humidity,
- MPU6000 for motion tracking (pitch, roll, and yaw),
- SE100 for GPS coordinates and compass heading.

The Raspberry Pi communicates with the Pixhawk PX4 autopilot via MAVLink to send control commands such as Hold and Auto mode. All components are powered using a regulated battery system supporting both 5 V and 3.3 V. An Ubiquiti Rocket M5 module operating at 5 GHz provides long-range, low-latency wireless communication between the USV and a remote server. The web-based dashboard, developed with PHP, JavaScript, and MySQL, offers real-time monitoring, historical data access, and remote control. It receives data from the Raspberry Pi through HTTP and sends user commands back to the Pixhawk in real-time. Figure 3 illustrates the overall system architecture, showing the interaction between sensors, controller, communication modules, and the web interface.

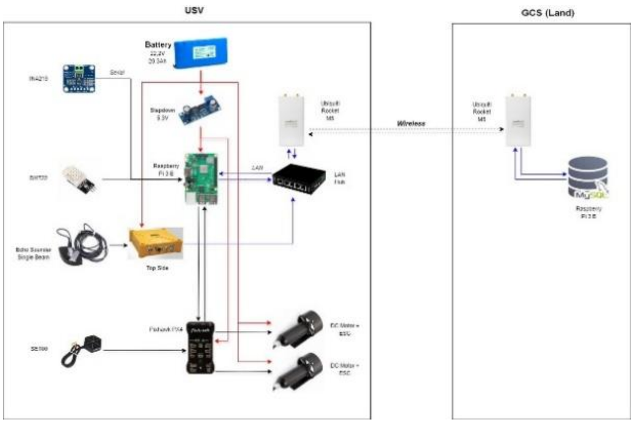

Fig. 3. Conceptual architecture of the IoT-based monitoring and control system for USVs.

4. Results and Discussion

A series of tests were conducted to evaluate the performance of the developed system in terms of sensor accuracy, response time, and data transmission reliability. The experimental setup involved controlled testing of the SEANO USV in a nearshore environment, with all system modules integrated and operational.

4.1. Sensor data accuracy

To evaluate sensor performance, measurements from the DHT22, MPU6000, and SE100 were compared with commercial reference devices under controlled conditions. The DHT22 showed accuracies of 98.09% for temperature and 98.95% for humidity, while the MPU6000 achieved 94.94% accuracy in estimating velocity. The SE100 GPS module recorded an average positional error of 3.66 meters, with pitch, roll, and yaw measurements exceeding 99% accuracy. These results demonstrate that the system delivers reliable real-time environmental and navigational data, sufficient for general marine observation tasks.

4.2. System reliability and integration

The integrated system was tested continuously for up to two hours and demonstrated stable performance without overheating or communication failure. Sensor modules functioned reliably, and the modular design allowed for easy component replacement without major reconfiguration. The system maintained consistent data flow and control responsiveness throughout the test, confirming its robustness for marine observation scenarios. A web-based dashboard was also developed to visualize real-time sensor data, display GPS location, and enable remote control through a browser interface. This dashboard served as the primary user interface during testing and is shown in Fig. 4.

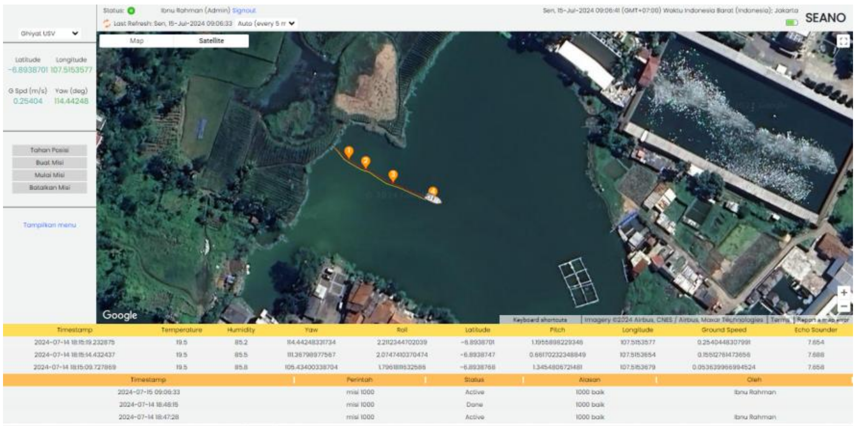

Fig. 4. Web-based monitoring dashboard showing real-time data visualization and remote-control interface for the SEANO platform.

4.3. Future direction

While the system has proven effective in real-time monitoring and control of a USV, several directions remain for future research. These include integrating more advanced marine sensors such as CTD, ADCP, or sonar devices; enabling autonomous navigation through AI-based decision-making; and expanding communication infrastructure for long-range deployment using satellite or hybrid networks. Such enhancements would strengthen the system's applicability for national-scale marine observation and position it as a scalable solution for sovereign maritime operations.

5. Conclusion

This study has successfully developed and implemented a web-integrated IoT-based monitoring and control system for Unmanned Surface Vehicles (USVs), tested on the Sea Autonomous Observer (SEANO) platform. The system integrates environmental and navigational sensors, a Raspberry Pi controller, wireless communication, and a browser-accessible dashboard to enable real-time data acquisition and bidirectional control. Experimental results demonstrate reliable sensor accuracy, low-latency responsiveness, and stable performance in nearshore conditions. The modular architecture allows for future expansion to support more advanced sensors and autonomous navigation features, making the system a practical foundation for scalable, sovereign marine observation technologies.

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