

Optimization of Portable Floating Net Cages Based on the Internet of Things and Robot Operating System for Smart Navigation and Water Quality Monitoring

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Keywords	Abstract
Floating Net Cage; IoT; Robot Operating System	Traditional floating net cages (<i>Keramba Jaring Apung/KJA</i>) face significant challenges, including mass fish mortality due to upwelling phenomena, the inability to monitor water quality in real time, and the lack of mobility to avoid polluted areas. This study develops a portable floating net cage system integrating the Internet of Things (IoT) for water quality monitoring and the Robot Operating System (ROS) for autonomous navigation. The prototype was constructed using a PVC frame (75 × 75 cm) with jerry can buoyancy. Sensors for pH, water temperature (DS18B20), and turbidity were connected to an ESP32 microcontroller via the MQTT protocol. Navigation was managed by a Pixhawk flight controller equipped with a GPS module, controlled via Mission Planner and QGroundControl software. A Kalman filter was applied to enhance measurement stability. The system was powered by solar energy using a 20 Wp photovoltaic panel and a 12V 7.5Ah lithium-ion (Li-ion) battery. Field testing was conducted at Wadaslintang Reservoir, Wonosobo, Central Java, with data collected at 3-hour intervals over a 24-hour monitoring period. Sensor accuracy reached 98.2%, with a pH measurement error of 0.2–5%, a temperature measurement error of 0.25–0.50°C, and a turbidity measurement error of 2–3.5%. The autonomous navigation system achieved a mean positional error of 1.52 metres across five test runs. The prototype successfully monitored water quality in real time and navigated autonomously to locations with more favourable water conditions when measured parameters fell outside the predetermined normal ranges. This IoT- and ROS-based portable floating net cage system demonstrated effectiveness in supporting smart aquaculture operations by enabling real-time monitoring and autonomous navigation without human intervention, with considerable potential to enhance the operational efficiency and sustainability of Indonesia's fisheries sector.

INTRODUCTION

Indonesia as a maritime country has great potential in the fisheries sector, especially fish farming in open waters. One of the methods that is widely used in fish farming is the Karamba Floating Net (KJA). However, conventional KJA used by many fishermen in Indonesia has a number of limitations, such as difficulties in monitoring water quality in real-time and the inability to adapt to rapidly changing water conditions, such as the upwelling phenomenon (Utama, 2024; Wahyono et al., n.d.). Drastic changes in water quality, such as a drop in temperature, a pH that is too high or too low, and an increase in water turbidity, often lead to mass fish deaths and harm fishermen. For this reason, innovation is needed in the development of the Portable Floating Net Karamba that can monitor water quality and automatically change locations based on data obtained from sensors and intelligent navigation systems (Caluag et al., 2025; Omar, 2022; Pramana & Alajuri, 2025).

According to (Wijaya *et al.*, 2019), the use of the Internet of Things (IoT) in the fisheries sector can facilitate real-time monitoring of water conditions and increase operational efficiency in fish farming. With IoT technology, water conditions such as pH, temperature, and water turbidity can be monitored directly through mobile and web-based applications, allowing fishermen to more quickly respond to changes that occur in the aquatic environment.

The development of Karamba Portable Floating Nets Based on the Internet of Things (IoT) and Robot Operating System (ROS) aims to overcome these problems by incorporating renewable technologies that can increase efficiency and sustainability in fish farming. Through pH, temperature, and turbidity sensors linked to IoT-based, the system is intended to monitor water quality in real-time (Abu Bakar *et al.*, 2025; Syafrudin *et al.*, 2024). In addition, by using an ROS-based automated navigation system, the karamba can move independently according to better water conditions, thereby reducing the risk of fish deaths caused by sudden changes in water quality (Boyd, 2017; Mramba & Kahindi, 2023; Wanja *et al.*, 2020). By utilizing solar energy as the main power source, the system is also more environmentally friendly and does not depend on external electricity supply.

(Santoso *et al.* 2021) in their research on the application of automated navigation systems in fishing devices, showed that Robot Operating System (ROS)-based systems can improve precision and flexibility in the movement of devices such as the Portable Floating Net Karamba. By using an integrated ROS system with controllers such as Pixhawk, the karamba can move automatically according to changing water conditions, moving the position to a place with better water quality (Ashrafi *et al.*, 2022; Jdiobe, 2020; Mamani *et al.*, 2025).

The novelty of this research lies in several aspects. First, it integrates IoT-based water quality monitoring (pH, temperature, turbidity) with ROS 2-based autonomous navigation in a single portable floating net cage system. Second, the system uses a Kalman Filter to reduce sensor noise and enhance measurement stability a technique not commonly applied in low-cost aquaculture sensors. Third, the system operates on solar renewable energy (20 Wp panel, 12V 7.5Ah Li-ion battery) with a Solar Charge Controller, enabling independent operation in open waters without external power infrastructure. Fourth, the prototype was field-tested under actual reservoir conditions at Wadaslintang (water depth 8-12 meters, wind speed 1.1-1.8 m/s, temperatures 24-30°C), providing real-world validation. Fifth, the system provides two operational modes automatic (autonomous relocation based on sensor triggers) and manual (direct user control) offering flexibility for different farming scenarios. Unlike conventional KJA that uses wooden or bamboo frames, this prototype uses a PVC pipe frame with jerry can buoyancy, making it more durable and portable (Brose, 2018; McLean & Silver, 2021).

The benefits of developing this system are to increase operational efficiency in fish farming, reduce losses due to fish deaths, and save time and labor for fishermen who have had to move the karamba manually. In addition, a real-time water quality monitoring system through web-based and mobile applications provides fishermen with the ability to monitor water conditions anytime and anywhere. This device can help fisherman ensure the survival of cultured fish and control karamba.

The creation of this transportable floating net cage has the potential to lower adverse environmental effects and increase aquaculture productivity. As an innovative solution that encourages more efficient and ecologically friendly aquaculture practices, this technology

might be used more extensively in the fishing industry. This method is an improvement in smart fisheries technology in addition to being a helpful tool for fish growers.

METHOD

The following were the stages carried out in the implementation, which include several steps ranging from system design to evaluation of test results.

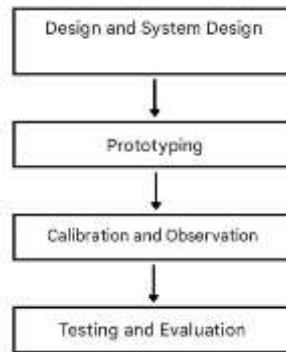


Figure 1. Implementation Stage

1. Prototype Design

The design of the Portable Floating Net Karamba Based on the Internet of Things (IoT) and Robot Operating System (ROS) began with a deep understanding of the challenges faced by fishermen in managing conventional floating net karamba. In this case, the two main aspects that are of concern are real-time monitoring of water quality and the ability of the karamba to change locations according to water conditions. Based on the analysis, the system design is designed to take into account the integration of the latest technologies that can improve operational efficiency and sustainability of fishery aquaculture.

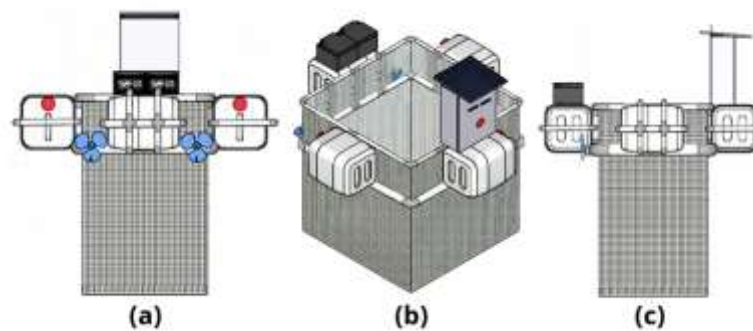


Figure 2. Design (a). Rear view, (b). Appearance Isometry, (c). Side view.

The karamba frame is designed using PVC pipe, which was chosen for its lightweight, waterproof, and easy to assemble. PVC pipes provide enough strength to support the sensor devices and navigation system without adding unnecessary weight. The karamba frame is designed with dimensions of 75 cm × 75 cm, which helps maintain stability while floating and provides sufficient space to place all required components. Jerry cans are attached to each side of the frame to allow the cage stable on rough water surfaces.

2. System Design

In the first part, the design of water quality monitoring sensors involves the use of pH, temperature, turbidity, and GPS sensors to monitor environmental conditions in real-time. pH

sensors are used to measure the acidity or alkaline level of water that greatly affects the survival of fish, while temperature sensors DS18B20 monitor water temperature which is also important for fish health. Turbidity sensors are used to measure the level of turbidity of the water, which can affect dissolved oxygen and the survival of fish. Data from these sensors is sent to the ESP32 microcontroller, which is then processed and forwarded to a web-based or mobile application, allowing fishermen to monitor water conditions remotely.

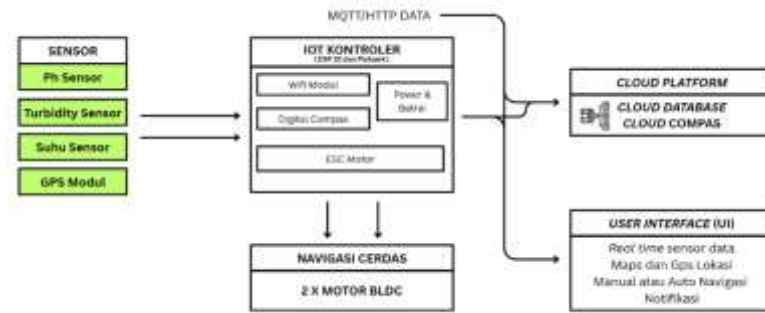


Figure 3. System Diagram

The design of the automatic navigation system uses Pixhawk, which is connected to a GPS module to monitor the position of the karamba in the waters. Pixhawk functions to automatically control the movement of the karamba based on the data received from sensors and GPS. Using the Robot Operating System (ROS 2), this system allows for more precise regulation of the movement of the karamba, and can move automatically to a location with better water quality if a change in water conditions is detected. The karamba is propelled above the water's surface by two brushless DC (BLDC) motors that are controlled by an Electronic Speed Controller (ESC).

The energy system is designed using a 20 Wp solar panel installed on top of the karamba frame to convert sunlight into electrical power. The solar panel charges a 12V 7.5Ah Li-ion battery, which stores the energy and supplies power to the control and navigation systems. The system employs a solar charge controller (SCC) to regulate the transfer of energy from the solar panel to the battery. This component ensures that the battery is protected from overcharging while maintaining stable and reliable battery performance.

In the final stage, a user interface (UI) was developed to enable monitoring of water conditions and control of the karamba system. The interface presents sensor data such as temperature, pH, turbidity, and an overall water quality status categorized as good, fair, or poor. Through this interface, fishermen can also track the position of the karamba using a GPS-based map. The system provides two operational modes: automatic and manual navigation. In automatic mode, the karamba moves autonomously toward suitable locations based on environmental conditions, whereas in manual mode fishermen can directly control its movement.

3. Prototyping

a. Prototype Frame Assembly

Initially, a structural frame measuring 75 cm × 75 cm was constructed using PVC pipes to accommodate the electronic and mechanical components. Jerry cans were installed on both sides of the structure to provide sufficient buoyancy and stability on shifting water surfaces.



Figure 4. (a). PVC pipe, (b). Pipe Fittings

Clamp joints and T-shaped connectors on the PVC pipes are used to assemble the frame. This keeps the construction sturdy and makes it simple to remove when repairs are required. The solar panel and water quality sensors are installed on the upper portion of the frame.

b. Installation of Sensors, Navigation Systems and Energy Systems

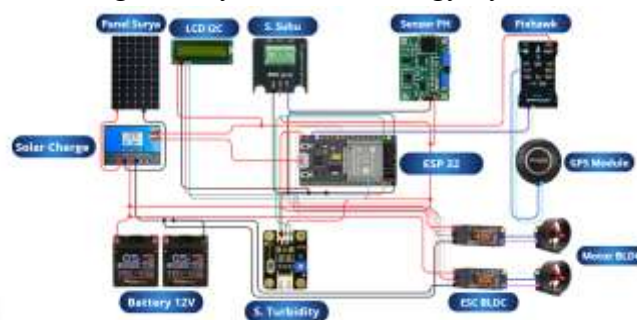


Figure 5. Electrical Diagram

Installing sensors and modules to track cage movement and water quality was the first step in the prototype installation. The underside of the cage frame was equipped with a pH sensor, a DS18B20 temperature sensor, and a turbidity sensor. To interpret the collected data and transmit it to a web-based and mobile application platform for real-time monitoring, these sensors were linked to an ESP32 microcontroller. Don't forget to install a GPS module on the top of the cage frame to monitor the position accurately. The data from this GPS is used by the automatic navigation system to direct the caravan to move to a location with better water quality, if the water conditions at the current location are not optimal.

The installation of the automatic navigation system is carried out by integrating Pixhawk, which serves as the main controller in the movement of the karamba. The Pixhawk is connected to two brushless DC (BLDC) motors controlled by the Electronic Speed Controller (ESC), which function to move the karamba above the surface of the water. The Robot Operating System (ROS 2) is installed on the ESP32 to manage communication between devices and facilitate high-precision control of the movement of the caramba.

The installation of the energy system is carried out by installing a 20 Wp solar panel on the top of the frame. These solar panels convert sunlight into electrical energy which is used to

charge a 12V 7.5Ah Li-ion battery. A solar charge controller (SCC) is fitted to regulate the power flow from the solar panel to the battery and ensure safe charging.

c. Software used

The development of this system involves several software tools, each serving a specific function within the system architecture. These tools are described below:

1. Arduino IDE: is used to program the ESP32 microcontroller and to manage communication between the hardware components integrated into the system.
2. Mission Planner and QGroundControl: These applications are utilized to operate and manage the Pixhawk controller responsible for directing the cage movement. Mission Planner is mainly used for route planning and waypoint configuration, while QGroundControl functions as a monitoring platform to observe the movement and status of the cage.
3. Visual Studio Code (VSCode) with Laravel: VSCode serves as the development environment for building the web-based and mobile monitoring applications. On the backend, the Laravel framework handles database management, application logic, and real-time communication between the ESP32 device and the monitoring platforms.
4. MQTT (Message Queuing Telemetry Transport): acts as the communication protocol that transfers sensor data from the ESP32 to the monitoring system through an MQTT broker. Its lightweight and efficient design supports real-time data transmission, making it suitable for environments with limited network capacity. Through this protocol, water quality data can be sent directly to the server for further analysis and for generating alerts when water conditions reach critical levels that require immediate action.

4. Sensor Calibration and Navigation Testing

After all components have been installed, the system undergoes testing and calibration to verify measurement accuracy. The pH and turbidity sensors are calibrated using standard reference solutions to ensure reliable readings.

We use the Welford Method and the Kalman Filter to increase accuracy. Even when there is noise or interference in the data, the Kalman Filter technique uses sensor data and prediction models to produce more accurate estimations. In this instance, the pH and turbidity of the water are predicted and corrected using the Kalman Filter. According to Brown et al. (1997), this method enhances the estimation based on the most recent measurements.

Meanwhile, the Welford Method is used to calculate the average and standard deviation. This method allows for real-time data updates, without the need for recalculation of the entire dataset. (Welford, 1962) states that this method is effective for continuous monitoring applications, such as in water quality systems.

Navigation system testing was carried out to ensure that Pixhawk could steer the karamba based on GPS data and water quality. All tests are conducted in automatic mode to ensure the movement of the karamba towards a location with better water quality.

5. Observational Data Collection

The data collection process was carried out through direct observation at the Wadaslintang Reservoir, Wonosobo Regency, Central Java. This location was chosen because it is one of the freshwater fish farming areas with calm water characteristics and is suitable for testing portable floating net karamba systems. The reservoir has a depth of 8 to 12 meters and the water flow is relatively slow.

Data collection was conducted under cloudy to overcast conditions, with temperatures ranging from 24 to 30°C during the day and 22 to 24°C at night. Surface wind speeds were recorded at around 1.1 to 1.8 m/s.

Water quality data, including temperature, pH, and water turbidity (NTU), were collected using sensors connected to an ESP32 microcontroller. Measurements were taken every 3 hours for 1 day both day and night to monitor changes in water parameters periodically.

In addition, an automatic navigation system was tested to ensure the ability of the karamba to change positions based on the predetermined GPS coordinates. The trial was carried out 5 times, consisting of 3 times in the middle area of the reservoir with a depth of about 10 - 12 meters, and 2 times in the reservoir edge area with a depth of ± 4 meters. During the test, the water conditions were relatively calm with low waves, allowing the evaluation of the performance of the Pixhawk - ROS 2 system in regulating the direction and speed of the karamba's motion, as well as verifying the stability of IoT data communication over the wireless network.

6. Evaluation and Testing of Prototype Feasibility

Feasibility testing is conducted to ensure that the Karamba IoT and ROS Based Portable Floating Nets meet performance standards and can operate in open water environments. Field experiments were carried out to assess the performance of the system's primary components, including the automated navigation mechanism, water quality sensing units, and the energy supply system. During these tests, important water parameters such as temperature, pH, and turbidity were recorded.

To ensure reliable measurements, the sensors were calibrated using standard reference solutions, and data stability was enhanced through the application of the Kalman Filter method. In addition, the navigation functionality was evaluated using Mission Planner and QGroundControl to confirm that the karamba moved accurately according to the GPS coordinates and sensor inputs.

The test results data are then analyzed to evaluate the accuracy of the sensors, the suitability of the navigation route between the automatic and manual modes. The results of the analysis are used to make adjustments and refinements to the prototype so that it can function optimally in the field.

RESULT AND DISCUSSION

1. Resulting Prototypes

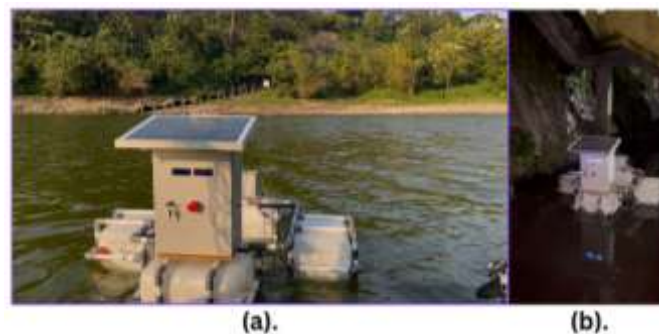


Figure 6. Prototype on condition (a). Open waters during the day, (b). Open waters at night

The Karamba IoT and ROS-Based Portable Floating Net is a prototype that incorporates a water quality sensor, an ESP32 microcontroller, a Pixhawk for automatic navigation, a solar panel for controller energy independence, and a GPS module for position monitoring. The product is assembled using a PVC frame and jerry can buoy, which allows stability in open water. Installation involves installing sensors on the karamba to monitor water quality, as well as setting up the navigation system with Mission Planner and QGroundControl.



Figure 7. Displaying Display (a). Website-based (b). Mobile devices

In addition, for real-time water quality monitoring, the system is integrated with an IoT-based monitoring website, which allows users to view sensor data, karamba movement status, and energy conditions directly through a web-based interface or mobile application. This monitoring website sends data through the MQTT protocol to ensure fast and accurate information updates.

2. Product Testing and Qualification

a. Sensor Performance Analysis

Tests are carried out to verify the accuracy of the sensor using standard solutions and the Kalman Filter, with the aim of ensuring that the sensor reading results are within a valid range of values and have a high level of stability against environmental disturbances.

Table 1. Temperature, pH, and Turbidity Sensor Test

No.	Date	Hours	pH	Temperature (°C)	Turbidity (NTU)	Standard Solution (Acid/Base)
1.	15 - 10 - 2024	00:00	7.4	24.5	3.0	Asam
2.	15 - 10 - 2024	03:00	7.5	24.6	2.8	Asam
3.	15 - 10 - 2024	06:00	7.6	24.8	3.1	Asam
4.	15 - 10 - 2024	09:00	7.7	25.1	3.4	Basa
5.	15 - 10 - 2024	12:00	7.5	25.3	2.9	Basa
6.	15 - 10 - 2024	15:00	7.4	25.0	3.0	Basa
7.	15 - 10 - 2024	18:00	7.3	24.8	3.3	Asam
8.	15 - 10 - 2024	21:00	7.4	24.7	3.1	Asam
9.	16 - 10 - 2024	00:00	7.5	24.6	2.9	Asam

The sensor is tested by comparing the measurement results with standard solutions to ensure data accuracy. Kalman Filters are used to reduce noise, improve stability and measurement accuracy despite external interference. Calibration with standard solutions and the use of Kalman Filters improve the reliability of measuring water quality parameters such as pH, temperature, and turbidity.

Table 2. Error Calculation Results

No.	Date	Jam	pH Error (%)	Temperature Error (%)	Turbidity Error (%)
1.	15 – 10 2024	00:00	0.50	0.25	2.00
2.	15 – 10 2024	06:00	0.20	0.30	2.50
3.	15 – 10 2024	12:00	2.70	0.50	3.00
4.	15 – 10 2024	18:00	4.50	0.40	3.50
5.	16 – 10 2024	00:00	3.20	0.35	2.80

Good water quality in reservoirs for fisheries has a pH range between 6.5 to 8.5, according to studies that state that lower or higher pH can interfere with fish life (Makori et al., 2017). Water temperatures should ideally be in the range of 22°C to 30°C to support fish metabolism, which is explained by various studies that show this temperature range is optimal for many freshwater fish species (Makori et al., 2017). Meanwhile, good water turbidity is in the range of 2 to 10 NTU, which indicates water conditions that are clear enough to support fish growth and algae photosynthesis (Arnold, 2019).

From the test results, it can be concluded that the sensor shows good accuracy, despite the increase in errors in pH measurements at night, especially at 18:00 and 23:59, with errors of 4.5% and 3.2%, respectively. Temperature measurements showed a smaller error of 0.35% at 23:59 (0.35%) and turbidity measurements had a higher error of 3.50% at 18:00.

b. Navigation System Performance Analysis

The navigation system is tested with Mission Planner and QGroundControl to ensure the movement of the karamba according to GPS data and water quality instructions.

Table 3. Navigation System Test

No.	Date	GPS Starting Point	GPS Destination Point	System Status	Error (Meter)	Tolerance
1.	1 – 11 - 2024	110.3504562, -7.0418431	110.3496087, -7.0411191	Successful	1.4	
2.	1 – 11 – 2024	110.3496087, -7.0411191	110.3488684, -7.0407996	Successful	1.7	
3.	1 – 11 – 2024	110.3488684, -7.0407996	110.3479028, -7.0404270	Successful	1.5	
4.	1 – 11 – 2024	110.3479028, -7.0404270	110.3470016, -7.0402034	Successful	1.6	
5.	1 – 11 – 2024	110.3470016, 7.0402034	- 110.3462076, 7.0400330	- Successful	1.3	

The navigation system is tested by comparing the movement of the karamba based on the planned route and the position achieved. This test was conducted to evaluate the ability of the Pixhawk to steer the karamba according to the instructions received from the GPS module and water quality data. The test results showed good performance in calm and slightly disturbed waters, but there were limitations in more turbulent waters, where the accuracy of the navigation system decreased slightly due to interference from more dynamic water conditions.

3. How it works

The prototype works through three main stages:

- Monitoring: The pH, temperature, and turbidity sensors read the water conditions and send data to the controller.
- Data Processing and Transmission: Data is sent to a web-based IoT application for real-time visualization.
- Auto Navigation: If the water parameters are outside the normal limits, the system activates navigation to move the karamba to a better location.

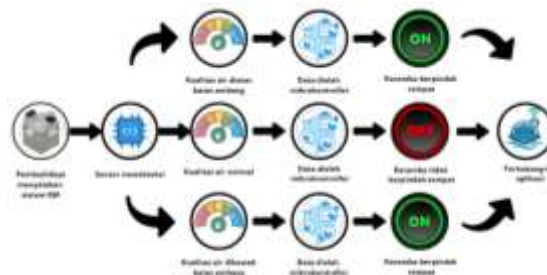


Figure 8. How Karamba Portable Floating Net Works

With this mechanism, this system functions as an intelligent tool that is able to assess, adjust, and maintain ideal conditions for farmed fish.

4. Advantages and Disadvantages of Prototypes

This prototype of the Karamba Portable Floating Net is designed as a modern solution for fish farming in open waters. This tool combines Internet of Things (IoT) technology and Robot Operating System (ROS) to create a smart, efficient, and environmentally friendly cultivation system. Its main function is to automatically monitor water quality (pH, temperature, turbidity) and perform self-guided navigation if water conditions deteriorate. The advantages of this product include:

- Portable and Self-Contained: The Karamba can switch locations automatically without human intervention.
- Real-time monitoring: The app allows for constant monitoring of water quality data.
- Eco-friendly: The system's primary power source is solar energy.
- ROS 2 integration: Enables accurate self-navigating.
- Future expansion: By including cloud-based control features and artificial intelligence (AI), the system can be improved.

Disadvantages: The system relies on network connectivity for data transmission, and severe water conditions, like intense rain, may reduce the karamba's movement precision, which could have an impact on the system's overall effectiveness.

5. Future Benefits and Development

There is potential for extensive development and use of the Portable Floating Net Karamba. This device may be able to assist fishermen in effectively raising fish. It also has the potential to serve as an example of smart aquaculture technology based on IoT and autonomous systems. The social and economic benefits of this development include:

- a. Supporting fish farmers: The system allows fish farmers to monitor karamba conditions remotely in real time. Reducing the need to be on site and helping them manage their time more efficiently.
- b. Saves Operational Costs: With an integrated automated system, fishermen don't need a lot of additional labor to manage and monitor karamba.
- c. Opportunity to Become a Commercial Product: If further developed, this Portable Floating Net Karamba has the potential to be mass-produced and sold to fish farmers in various regions. In addition, there is a great opportunity to collaborate with the private sector or the government in the development and distribution of these products, which can expand its impact in the global fisheries sector.

The future development of Karamba IoT-Based Portable Floating Nets and ROS 2 can be directed towards a more intelligent, adaptive, and predictive system through the integration of several technologies. Integrating Artificial Intelligence (AI) would allow the system to automatically predict changes in water quality and weather conditions. Adding dissolved oxygen (DO) sensors is important because oxygen levels directly affect fish health and growth. In addition, the development of a centralized and multi-karamba control system can be used to control multiple karamba units in one cultivation area automatically and efficiently.

6. Comparison with Similar Products



Figure 9. Karamba Conventional Floating Net

Conventional Floating Net Karamba generally uses a wooden or bamboo frame as the base material, which makes it more affordable in terms of initial cost. The water quality monitoring system in conventional KJA does not use sensors to monitor parameters such as temperature, turbidity, or pH. In addition, the navigation system on a conventional KJA is not equipped with automated technology, so the movement of the cage is highly dependent on manual intervention by the operator. The costs incurred for conventional KJA are relatively lower, making them a more cost-effective option for small-scale fishermen or fish farmers.

Table 4. Comparison of Karamba Floating Net (KJA)

Aspects	Conventional KJA	KJA Portable
Construction and Materials	Wooden or bamboo frame	PVC Pipe Frame
Water Quality Monitoring System	None	Using Temperature, Turbidity, and pH Sensors
Navigation System	None	Using GPS
Technology	Human intervention	Integrated with IoT
Cost	Relatively low initial cost	Relatively high initial cost

In contrast, Portable KJA uses a PVC pipe frame that is more durable and stable compared to wood or bamboo. The water quality monitoring system on KJA Portable is more advanced, equipped with sensors to measure temperature, turbidity, and pH, which allows real-time monitoring of water quality. The Portable KJA is also equipped with an automated navigation system that utilizes GPS and Internet of Things (IoT) technology, allowing for the movement of the cage independently without the need for human intervention. Although the Portable KJA offers a wide range of technological advantages, the initial cost required to build it is higher compared to conventional KJA, given the use of integrated components and technology.

CONCLUSION

The Karamba IoT and ROS-Based Portable Floating Nets developed in this study successfully achieved the main goal, which is to provide an automation solution for water quality monitoring and autonomous navigation in aquaculture fisheries. The prototype uses water quality sensors, an ESP32 microcontroller, a Pixhawk navigation system and solar panels, which allow the karamba to operate independently in open waters with minimal reliance on external resources. This prototype facilitates autonomous karamba movement based on environmental circumstances, lessens the need for manual checks, and enhances real-time water quality monitoring. These characteristics facilitate more effective and ecologically responsible fisheries management. In order to improve the system's ability to adjust to shifting environmental conditions, future development may concentrate on boosting energy capacity, enhancing navigation accuracy, and incorporating artificial intelligence algorithms. With these improvements, the prototype has strong potential for wider use in the aquaculture industry and other related sectors.

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