ISSN–2278-5655

Aarhat Multidisciplinary International Education Research Journal

Volume–XV, Special Issues– I(a) Jan – Feb, 2026

OPEN ACCESS

Original Research Article

AN AUTOMATIC BOAT GUARD SYSTEM USING SENSOR-BASED MONITORING AND AI-ASSISTED SENSOR FAULT DETECTION

*** Needhumol Madhusoodanan Pillai**

* IT/CS Department & Mumbai University, India.

Abstract:

Marine transportation continues to face significant safety challenges due to boat overloading, unexpected sinking, fire accidents, and delayed emergency response, particularly in small and medium-sized vessels. Many existing safety measures rely heavily on manual monitoring and periodic inspection for such ferry or water taxi and workboats, which may not be sufficient in dynamic and unpredictable marine environments. With increasing dependence on electronic sensing systems for safety monitoring, sensor reliability has also become a critical concern, as unnoticed sensor failures can lead to incorrect safety decisions. This paper addresses the need for a reliable and real-time boat safety solution that can continuously monitor hazardous conditions while ensuring the dependability of the sensing infrastructure itself. By emphasizing automated monitoring, timely alerting, and early identification of sensor malfunctions, the proposed approach aims to reduce accident risks, improve response time, and support preventive maintenance. The work highlights the importance of intelligent and dependable safety systems in modern marine applications to enhance passenger safety and minimize loss of life and property.

Keywords: *Marine safety monitoring; Boat safety system; Sensor fault detection; Real-time monitoring; Intelligent alerting*

Introduction:

A. Background

Small passenger boats play a crucial role in inland waterways, coastal transportation, and short-distance maritime travel due to their affordability and operational simplicity. However, these vessels typically operate with minimal safety infrastructure because of constraints related to size, power availability, and cost. As a result, safety incidents such as passenger overloading, vessel imbalance, uncontrolled drifting, and onboard fire accidents remain prevalent, often leading to severe human and economic consequences.

Among these risks, boat instability caused by overloading and uneven weight distribution is one of the most critical safety challenges for small passenger boats. Even minor lateral imbalance or sudden passenger movement can cause significant tilting, increasing the risk of capsizing, especially in narrow or crowded vessels. Conventional safety practices largely rely on manual passenger counting, visual inspection, or passive alarm systems, which are insufficient to prevent instability once unsafe conditions arise.

To improve maritime safety, recent research has explored embedded multi-sensor systems that integrate force sensors, inertial or motion sensors, fire detectors, and wireless communication modules to monitor vessel conditions in real time [1]–[3]. These systems primarily focus on detecting hazardous situations and issuing alerts to boat operators or authorities using GSM and GPS technologies. While such approaches enhance situational awareness, they remain largely.

In parallel, advancements in embedded intelligence and machine learning have enabled the development of more reliable safety systems through sensor fault detection and anomaly identification. AI-based techniques, such as Isolation Forest algorithms, have demonstrated effectiveness in identifying abnormal sensor behavior caused by noise, degradation, or intermittent failure, particularly in harsh marine environments. However, the integration of intelligent sensor validation with mechanical stabilization mechanisms in small passenger boats remains largely unexplored.

B. Problem Definition

Despite the availability of sensor-based monitoring solutions, several limitations persist in ensuring the safety of small passenger boats. First, existing systems predominantly emphasize hazard detection and alert generation, with no provision for automated mechanical stabilization when dangerous conditions such as excessive tilt or imbalance occur. In current practice, even if a hazardous tilt is detected, the system can only warn the operator, leaving corrective action dependent on human response, which may be delayed or ineffective.

Second, pre-departure overloading is often inadequately addressed. Manual checks are prone to error, and existing electronic load monitoring systems rarely communicate overload conditions to authorities before the journey begins, reducing preventive enforcement and increasing operational risk.

Third, embedded decision-making frameworks commonly rely on static threshold-based logic, making them highly vulnerable to sensor noise, drift, and failure in marine environments characterized by vibration, humidity, and corrosion. Faulty sensor readings may result in false alarms or incorrect actuation decisions, undermining system reliability and user trust.

To overcome these challenges, this research proposes an automatic boat guard system featuring a motor-driven, direction-aware anchor stabilization mechanism. The system continuously monitors vessel tilt and load conditions; when excessive lateral tilt is detected, a motorized anchor is automatically deployed from the opposite side of the tilt to counteract imbalance and stabilize the boat. Force sensors are used to detect passenger overloading prior to departure, with overload alerts transmitted to authorities via GSM communication. Fire sensors enable early detection of onboard fire incidents, while GPS-supported messaging provides precise location information during emergencies. To enhance robustness and decision reliability, an AI-based sensor fault detection framework using the Isolation Forest algorithm is incorporated to identify abnormal sensor behaviour and prevent false alarms or unsafe actuation

Literature Review :

A.Isolation Forest and Explainable Anomaly Detection in Maritime Sensors

Sensor fault detection and anomaly identification have become critical research areas in safety-critical embedded systems. Unsupervised machine learning methods such as Isolation Forest and explainable AI models have been successfully applied to marine sensor streams to identify abnormal behavior without labeled fault data. For instance, Kim *et al.* proposed an explainable anomaly detection framework for maritime main engine sensor data using Isolation Forest enhanced with Shapley Additive Explanations (SHAP) to interpret detected anomalies and attribute them to specific sensor variables [4]. This approach demonstrated how unsupervised algorithms can identify sensor outliers in a complex marine environment and provide interpretable insights into sensor health and abnormal operations.

B.Fault-Tolerant Control and Sensor Fault Diagnosis in Marine / Underwater Vehicles

Fault diagnosis and fault-tolerant control structures have also been explored in marine and underwater vehicle domains, where robust detection and control are required under sensor uncertainty and harsh environments. Surveys on fault-tolerant control for unmanned underwater vehicles review techniques for detecting, isolating, and mitigating sensor and actuator faults using model-based and data-driven strategies, underscoring the need for resilient control strategies in marine embedded systems.[5].

C. Sensor-Based Safety Monitoring in Small Marine Vessels

Embedded multi-sensor systems have been widely investigated for monitoring operational and environmental conditions of marine vessels. Sensors such as load cells, inertial sensors, temperature sensors, and smoke detectors are commonly employed to detect overloading, excessive motion, and onboard fire incidents [6], [7]. These systems provide early warnings and improve situational awareness; however, they are largely limited to passive alert generation. Studies on safety monitoring for fishing and small passenger vessels highlight that, while sensor integration improves detection capability, corrective actions are still dependent on human intervention [7].

D. GSM and GPS-Based Maritime Communication Systems

Wireless communication technologies such as GSM and GPS have been extensively used in maritime safety applications for emergency alerting and vessel tracking. GSM-based systems enable automatic transmission of hazard notifications, while GPS modules provide precise vessel location information to support rescue operations [8]. Research has shown that integrating communication modules significantly improves response time during emergencies. However, many low-cost systems designed for small boats lack a unified framework that combines hazard type, severity, and location, limiting their effectiveness in real-world scenarios.

E. Fire Detection in Embedded Marine Systems

Fire detection remains a critical aspect of marine safety due to the confined nature of small vessels and the rapid spread of fire onboard. Embedded fire detection systems typically use temperature, smoke, or gas sensors to identify early fire conditions and trigger alarms or notifications [9]. While effective in detection, these systems are often implemented as standalone modules and do not incorporate mechanisms to verify sensor reliability.

SYSTEM MODEL

The system architecture is designed as a layered embedded framework that integrates real-time sensing, intelligent data validation, decision-making, and physical safety actuation. Multiple onboard sensors continuously monitor critical parameters such as fire conditions, passenger load, vessel motion, AI-based sensor fault detection module operates in parallel to assess the reliability of sensor data and suppress faulty or inconsistent readings, as shown in Fig 1.

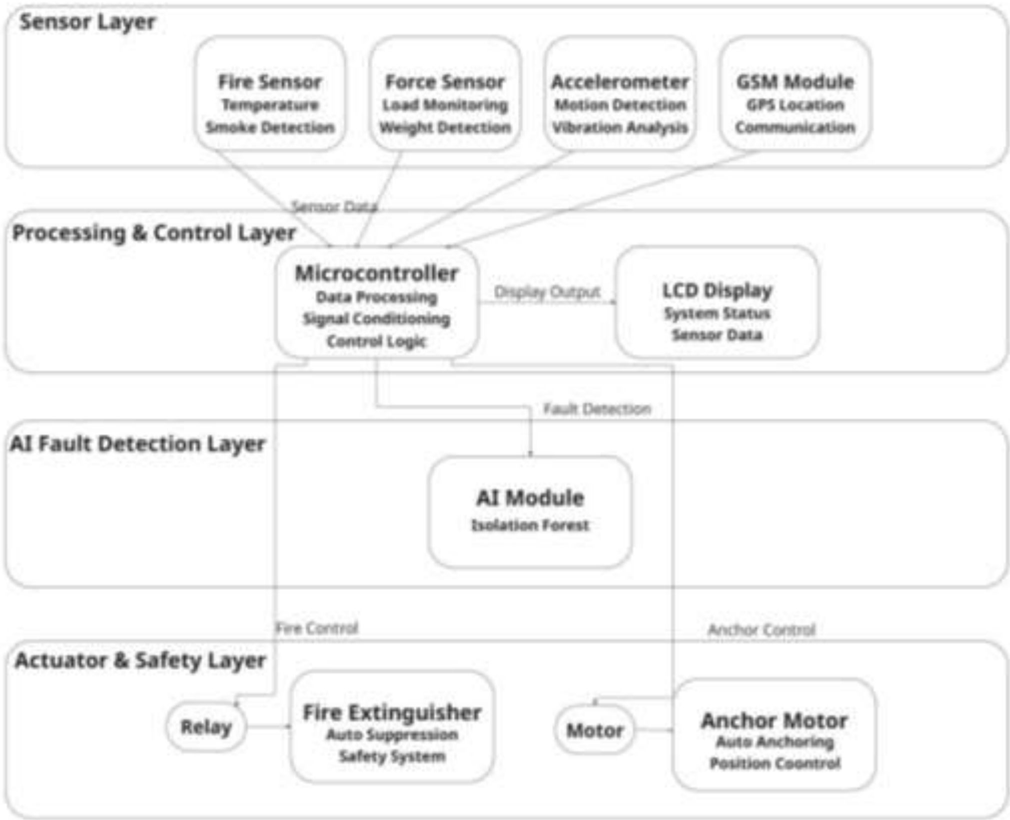
ISSN–2278-5655

Aarhat Multidisciplinary International Education Research Journal

Volume–XV, Special Issues– I(a) Jan – Feb, 2026

OPEN ACCESS

Original Research Article



A. *Sensor-Based Boat Safety System*

The proposed sensor-based boat safety system is designed as a layered embedded architecture that integrates real-time sensing, intelligent processing, wireless communication, and active mechanical intervention to enhance safety in small passenger boats.

1) Sensor Layer

The sensor layer continuously monitors critical parameters related to vessel safety and stability. It consists of the following sensing modules:

- Force (Load) Sensor: Measures the total onboard load to detect passenger overloading conditions. This sensor enables verification of safe loading limits prior to vessel departure and during operation.
- Accelerometer: Monitors vessel motion, tilt, and vibration to identify instability, excessive lateral inclination, or uncontrolled drifting caused by uneven load distribution or environmental disturbances.
- Fire Sensor: Detects abnormal temperature rise and smoke concentration to identify potential onboard fire incidents at an early stage.
- GSM Module with GPS: Facilitates wireless transmission of emergency alerts and provides real-time vessel location information to authorities during hazardous situations.

All sensor data are continuously sampled and transmitted to the processing layer for analysis and decision-making.

2) Processing and Control Layer

A microcontroller serves as the central processing and control unit of the system. Its key functions include:

- Signal conditioning and preprocessing of sensor data from the force sensor, accelerometer, and fire sensor
- Evaluation of sensor data using predefined safety thresholds
- Execution of control logic for safety-related actions
- Transmission of system status, sensor readings, and hazard alerts to the LCD display and GSM communication module

The LCD display provides real-time visualization of onboard load status, vessel motion, fire alerts, and system health, enabling situational awareness for the boat operator. Hazard notifications are simultaneously communicated to authorities via GSM, along with GPS-based location information.

3) Anchor-Based Stabilization and Safety Actions

Based on the processed sensor inputs, the system initiates appropriate automated safety actions:

- Overload Alerting: When the force sensor detects an overload condition exceeding permissible limits, the system generates an alert and transmits overload information to authorities before the ride begins, preventing unsafe vessel operation.
- Automatic Fire Suppression: Upon detection of fire-related parameters beyond safe thresholds, a relay-controlled fire extinguisher system is activated to suppress the fire.
- Anchor-Based Stabilization: If excessive tilt or instability is detected by the accelerometer, a motor-driven anchor is automatically deployed to stabilize or halt the boat, reducing the risk of capsizing or uncontrolled drifting.

While this rule-based safety framework enables rapid hazard response, it assumes reliable sensor operation. In real marine environments, sensor faults or noise may lead to false alarms or incorrect actuation. Therefore, this system model is further enhanced by incorporating an AI-based sensor fault detection mechanism using the Isolation Forest algorithm, which improves decision reliability and prevents erroneous safety actions.

B. AI-Based Sensor Fault Detection

1) AI Fault Detection Layer

The AI module analyses incoming sensor data for anomalies using unsupervised learning. Data preprocessing (e.g., normalization, time-window aggregation) prepares the dataset for the model. If a sensor reports measurement outside normal behavior patterns, the system classifies it as anomalous and can:

- Ignore data from the faulty sensor
- Trigger maintenance alerts
- Bias decisions using redundant sensor data
- This layer significantly improves the dependability of automated decision-making.

2) Isolation Forest Algorithm

Isolation Forest isolates anomalies by recursively partitioning data using random splits. Anomalies, being fewer and different, require fewer splits to isolate [10][11]. This characteristic is the basis for the anomaly score.

<u>**Mathematical Insight**</u>

$$s(x,n) = 2 - \frac{E(h(x))}{c(n)}$$

where,

- E(h(x)) is the average path length over all trees
- c(n) is the normalisation factor
- Scores close to 1 represent anomalies

This formula is widely used to compute anomaly scores in the literature [10].

C. Comparative Analysis

TABLE I

Features	**Sensor-Based Boat Safety System**	**AI-Enhanced Model**
Fault Detection	No	Yes
Dependence on Thresholds	High	Lower
False Alarm Reduction	No	Yes
Maintenance Prediction	No	Yes
Computation Cost	Low	Moderate

Conclusion:

This paper presented a conceptual design of an intelligent embedded Boat Guard System aimed at enhancing the safety of small passenger boats. The proposed system integrates multiple sensors for real-time monitoring of critical parameters, including fire hazards, passenger load, and vessel motion. Unlike conventional alarm-based solutions, the system introduces automatic anchor deployment for active stabilization, relay-controlled fire suppression, and GSM-based emergency communication with GPS location reporting. To improve reliability in harsh marine environments, an AI-based sensor fault detection layer using the Isolation Forest algorithm was incorporated, ensuring that faulty or noisy sensor data does not trigger false alarms or unsafe actuations. Overall, the proposed architecture demonstrates a holistic approach to maritime safety by combining monitoring, intelligent decision-making, and physical intervention, specifically tailored for resource-constrained small passenger boats.

Future Scope:

While the current work is conceptual, it opens several avenues for future research and development:

Hardware Implementation and Field Testing: Building a prototype of the Boat Guard System and deploying it in real-world maritime conditions will allow validation of sensor performance, anchor actuation, and AI fault detection under dynamic and harsh environmental factors.

Integration of Advanced AI Models: Lightweight neural network architectures or ensemble learning methods could be explored to enhance fault detection accuracy, handle sensor drift, and adapt to varying operational conditions in real time.

Energy Optimization for Embedded Systems: Investigating low-power sensor networks and microcontroller-based computation will ensure the system is sustainable for long-duration boat operations.

Multi-Vessel Communication and IoT Integration: Extending the system to support communication among multiple vessels or shore-based monitoring centers could facilitate coordinated emergency response and fleet-level safety analytics.

Enhanced Hazard Prediction: Incorporating predictive analytics to forecast potential hazards, such as overloading or drift-prone conditions before they occur, could further improve passenger safety and operational reliability.

ISSN–2278-5655

AMIERJ Aarhat Multidisciplinary International Education Research Journal

Volume–XV, Special Issues– I(a) Jan – Feb, 2026

OPEN ACCESS Original Research Article

Regulatory and Standardization Studies: Future work could focus on aligning the system design with maritime safety standards and certifications, ensuring adoption in commercial or public transport vessels.

By pursuing these directions, the Boat Guard System could evolve from a conceptual framework to a practical, scalable, and intelligent maritime safety solution, potentially reducing accidents and saving lives in inland and coastal water transport.

References:

1. *G. B. and V. C., "Review on Sensors for Sustainable and Safe Maritime Mobility," J. Mar. Sci. Eng., vol. 12, no. 2, 2024.*
2. *K. Yang, J. Lin, J. Ding, B. Zheng, and L. Qin, "An Integrated Safety Monitoring and Pre-Warning System for Fishing Vessels," J. Mar. Sci. Eng., vol. 13, no. 6, 2025.*
3. *Z. Zhang, L. Tan, and R. L. Kong Tiong, "Ship-Fire Net: An Improved YOLOv8 Algorithm for Ship Fire Detection," Sensors, vol. 24, no. 3, 2024.*
4. *J. Kim, S. Park, and Y. Kim, "Explainable anomaly detection for maritime main engine sensor data using isolation forest and SHAP," IEEE Access, vol. 9, pp. 135094–135107, 2021.*
5. *M. Baldauf, K. Benedict, and S. Fischer, "Maritime safety and security through integrated navigation systems," IEEE Intelligent Transportation Systems Magazine, vol. 3, no. 1, pp. 22–30, 2011.*
6. *S. K. Singh and R. Sharma, "Design of GSM and GPS based vessel tracking and monitoring system," International Journal of Engineering Research & Technology (IJERT), vol. 4, no. 5, pp. 1050–1054, 2015.*

a. *K. Jain and R. Kumar, "IoT-based passenger boat safety and monitoring system," International Journal of Advanced Research in Computer Engineering & Technology, vol. 6, no. 4, pp. 421–426, 2017.*

7. *R. Prasad, A. Kumar, and S. Verma, "GPS–GSM based emergency alert system for marine applications," International Journal of Electronics and Communication Engineering, vol. 10, no. 2, pp. 89–95, 2016.*

a. *K. Jain and R. Kumar, "Embedded fire detection and alert system using wireless sensor networks," Procedia Computer Science, vol. 79, pp. 935–942, 2016.*

8. *T. Liu, K. M. Ting, and Z.-H. Zhou, "Isolation Forest," ICDM, 2008.*
9. *T. Ahmed et al., "Anomaly detection algorithms for sensor data streams: A survey," ACM Computing Surveys, vol. 53, no. 2, 2021.*
10. *X. Wang and Z. Lu, "Recent Advances in Sensor Fault Diagnosis," Sensors Actuators A, 2020.*
11. *N. Abdeladhim, "Machine Learning–Based Anomaly Detection in Ship Behavior," Eng. Appl. AI, 2026.*
12. *C. Gamage et al., "Machine Learning in Maritime Surveillance," WMU J. Marit. Aff., 2023.*
13. *R. Wang et al., "Marine Engine Fault Monitoring Using Isolation Forest," Appl. Ocean Res., 2021.*
14. *D. Kim et al., "Explainable Anomaly Detection for Maritime Sensors," Sensors, 2021.*
15. *H. Kim and I. Joe, "Transformer-Based Anomaly Detection for Maritime IoT," Electronics, 2024.*
16. *S. Raj et al., "Survey on Fault-Tolerant Control of Marine Vehicles," Springer, 2023.*
17. *M. Stopford, Maritime Economics, 3rd ed. London: Routledge, 2009.*
18. *S. K. Singh et al., "Advances in marine sensor networks," J. Marine Systems, vol. 183, pp. 75–86, 2018.*

a. *Sha et al., "Embedded sensor reliability challenges in marine environments," IEEE*

Sensors Journal, vol. 17, no. 23, pp. 7704–7712, 2017.

19. *M. Björkman et al., "Fire sensor failures: detection and mitigation," Safety Science, vol. 107, pp. 203–212, 2018.*
20. *J. Ye et al., "Fault detection in dynamic systems using unsupervised methods," Control Systems Magazine, vol. 39, no. 2, pp. 32–45, 2019.*
21. *T. Liu, K. M. Ting, and Z.-H. Zhou, "Isolation Forest," ICDM, 2008.*
22. *T. Ahmed et al., "Anomaly detection algorithms for sensor data streams: A survey," ACM Computing Surveys, vol. 53, no. 2, 2021.*
23. *Y. Wang et al., "Real-time maritime fire detection using wireless sensor networks," Sensors, vol. 17, no. 5, 2017.*
24. *P. Mavromoustakis, "Multi-sensor fusion for maritime environments," IEEE Communications Surveys, vol. 18, no. 3, 2015.*
25. *R. Isermann, Fault-Diagnosis Systems, Springer, 2006.*
26. *P. Frank, "Fault diagnosis in dynamic systems using analytical and knowledge-based redundancy," Expert Systems with Applications, 2019.*

Cite This Article:

Pillai N.M. (2026). *An Automatic Boat Guard System Using Sensor-Based Monitoring and AI-Assisted Sensor Fault Detection.* **In Aarhat Multidisciplinary International Education Research Journal**: Vol. XV (Number I, pp. 69–76) **Doi:** https://doi.org/10.5281/zenodo.18608632