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Developing Ubiquitous Computing Architectures for Real-Time Ship Navigation and Control Systems

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Abstract

Modern automated systems are paramount for ships' effective and safe operation in today's complex and dynamic environment. This research focuses on the development of pervasive computing architectures for real-time navigation and control systems. Incorporation of ubiquitous computing into marine systems has the potential to automate ordinary activities such as decision making, data gathering, processing, and awareness of one's surroundings. Using distributed sensor networks, cloud and edge computing, AI, and other components, our architectural framework enables continuous monitoring, adaptive routing, and autonomous control tasks. Designed to support various types of vessels and operations, the framework emphasizes interoperability, fault tolerance, and scalability. Simulations conducted in marine environments with the integrated prototype demonstrated improved navigational accuracy, reaction time, and system resilience. This study provides further development of advanced smart marine systems while highlighting the disruptive impact of pervasive computing toward enhanced efficiency and safety in maritime operations.

Keywords: Ubiquitous Computing, Real Time Control, Maritime Systems, Edge Computing, Sensor Networks, Intelligent Transportation, Autonomous Vessels.

1 Introduction

The maritime industry plays a crucial role in international trade and offers a variety of services as ships navigate vast and unpredictable oceans. The safe, quick, and timely operation of vessels is becoming increasingly difficult due to the rising level of sea traffic, changing weather patterns, and complex navigational ways (Huy, 2018). While basic navigation and control systems of vessels somewhat fulfill their purpose, they usually heavily rely on human input and outdated technology that stands little chance of coping with the modern marine industry's advanced demands (Park et al., 2020). Ubiquitous computing, where intelligent processing is seamlessly embedded into everyday objects and the surroundings, is one appealing strategy which may aid in solving these problems (Uvarajan, 2024). General data collection, exchange, and processing in real Autonomic systems form the basis of unparalleled advancements within a domain, enabling significant improvement of aircraft situational awareness and decision-making pertaining to aircraft navigation (Tasnimi, 2014). The military governing body can also apply this method in macro cognition for adaptive route planning, autonomous

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control, maintenance forecasting, and the fusion of a multitude of technologies situated both on the vessel and on land (Kumar, 2024). The core focus of this article is on a real-time ship control and navigation computer architecture (Jain & Babu, 2024). To achieve a responsive and cognitive marine ecosystem, the system integrates AI with sensor networks, edge and cloud computing. Enhancing the precision of navigation, mitigating human errors, maximizing safety, and optimally enhancing vessel operations are the primary objectives (Sharma & Gupta, 2022). Multiple marine scenarios were evaluated using analyses and simulations and were found to demonstrate the system's ability to transform traditional navigation systems into autonomous smart navigation systems (Zhang & Wang, 2019).

Key Contribution

- The study compares edge, cloud, and hybrid computing architectures using key performance metrics (e.g., latency, accuracy, fault detection, energy usage), clearly understanding their suitability for real-time maritime applications.
- The proposed architecture supports high system availability (99.95%) and strong fault tolerance, enabling autonomous ship navigation and control even during network disruptions (98% uptime during network loss).
- The architecture facilitates rapid and accurate decision-making for navigation, collision avoidance, and environmental adaptation by ensuring low latency (85 ms) and high predictive accuracy (98.10%).
- It identifies hybrid computing as the most balanced and effective architecture, combining the real-time responsiveness of edge systems with the processing power and analytics capabilities of the cloud.

The following sections include Section I, the Introduction, which describes the main key findings of this research. Section II describes the Literature review, in which we compare the work related to previous research. Section III proposes the architecture and explains the data flow diagram for the ship navigation and control system. Section IV describes the results and discussion, representing the performance comparison for various computing methods. Section V summarizes the main findings of this research.

2 Literature Review

Ref No	Focused Area	Methodology	Key Findings
(Hansen et al., 2023)	IoT based navigation (Ship)	Testing followed by simulation	To demonstrate the route optimization followed by decision making with cloud-based data.
(Kim & Choi, 2021)	Edge computing with ship control	Prototype and real time processing	Improved latency and system responsiveness
(Kigarura et al., 2023)	Autonomous architecture	Case study analysis	Pervasive computing technologies
(Sreevidya & Supriya, 2024)	Sensor network related to Maritime CPS	Sensor network followed by maritime CPS	Real time monitoring for to improved the navigation safety.
(Lee et al., 2018)	AI integrated with maritime navigation	AI modeling and simulation	More accurate predictions for collision avoidance with route planning.
(Li & Tan, 2024)	Maritime safety with ubiquitous computing	Architecture design and risk assessment	Reduction of human error with intelligent control systems.
(Pushpavalli et al., 2024)	Hybrid cloud edge framework related to maritime navigation	Framework development and evaluation	Hybrid approach for to provides the balance between latency and computational power.

To interpret Table, the available literature indicates that computing technologies should be incorporated into control, navigation, and ship management systems (Vaishnav, 2024). There have been numerous attempts to enhance maritime operations using intelligent architectures. For instance, IoT-based navigation systems illustrate how much better route planning and decision-making can be accomplished with cloud-integrated data (Hansen et al., 2023). Furthermore, edge computing techniques enhance the responsiveness of ship control systems due to lowered latency from real-time data processing proximity (Kim & Choi, 2021). Research on autonomous vessel designs (Kigarura et al., 2023) explores the potential self-navigating ships hold for pervasive computing technologies, showcasing how far these computing technologies can go with context-sensitive and adaptive decision-making frameworks (Martelli et al., 2021). Real-time monitoring sensor networks in marine cyber-physical systems have advanced the development of cyber-physical systems, contributing toward improved navigational safety situation awareness and increased situational awareness featured in and aiding monitored oscillation cycle gauge system (MOCGS) (Sreevidya & Supriya, 2024). The domain of maritime navigation has served as the basis of AI development and is bound to facilitate future advancements in AI (Ghate & Roy, 2024). Elements of collision avoidance and route optimization have shown a significant AI predictive capability (Lee et al., 2018). Studies on maritime safety systems (Li & Tan, 2024) noted the role of pervasive computing intelligence in mitigating human error through risk-based system design and intelligent control architectures. Incorporated frameworks such as hybrid cloud-edge (Pushpavalli et al., 2024) facilitate balanced, scalable architecture applicable to diverse vessel operations while managing computing load and latency trade-offs. The literature strongly tends towards fully automated adaptive intelligence systems that function in real time. However, there is a gap when it comes to integrated frameworks for comprehensive real-time microscale marine navigation and control systems that merge IoT, AI, edge/cloud computing, and sensor networks (Nayak & Raghatate, 2024). Some additional research on system interoperability, scalability, and standardization is necessary to support the viability of such architectures in maritime contexts (Rahman & Begum, 2024).

3 Proposed Model

3.1 Architecture of Real-Time Ship Navigation and Control Systems

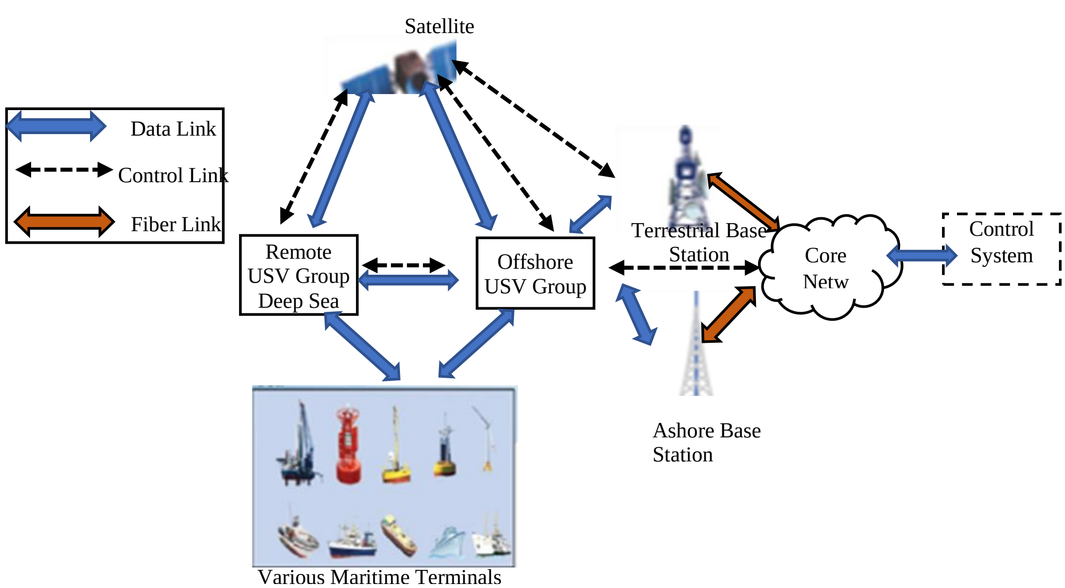

Figure 1: Architecture of Real-Time Ship Navigation and Control Systems

The above Figure 1 represents As seen in Figure 2, USV aided marine wireless communication is part of a sophisticated networking system. A communication network incorporating submarine fiber optics, terrestrial wireless, and satellite communication interconnects maritime ports, operational centers, and remotely stationed or offshore clusters of unmanned surface vehicles (USVs). The USVs exchange command and control data via data, blue solid lines, and control links, black dashed lines, with external systems and other unmanned surface vessels (USVs) in both offshore and deep-sea areas. Satellite communications provide long-range USV- terrestrial base station data relay linking, that enables maintaining USV connection in the remote oceanic regions. The operating center core network computers, processes relayed base and shore station information, and directs them toward the operating center. The base, and ashore stations serve as relay points for data and directives (Lei & Ibrahim, 2024). The real-time navigation and mission management system grants the operations center complete control for monitoring, analyzing, and making decisions as the system operates in real-time. Along with this, gold lines, also referred to as fiber cables, link the base stations, core network, and onshore operational infrastructure, guaranteeing high speed and bandwidth. The enduring and stratified structure facilitates real-time and scalable intercommunications, enabling autonomous maritime navigation and additional unmanned system services like environmental surveillance and remote operation. It outlines future intelligent marine systems and smart ocean infrastructure development.

3.2 Data Flow Diagram for Ship Navigation and Control Systems

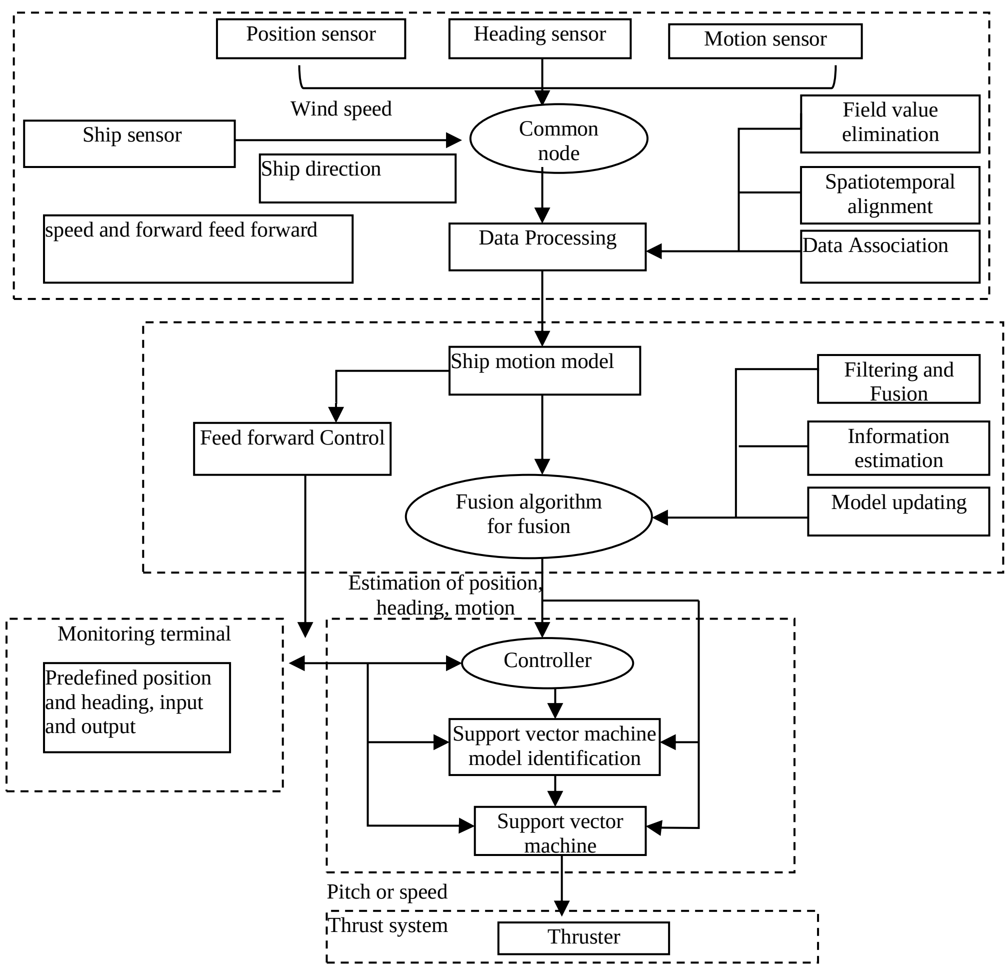

Figure 2: Data Flow Diagram for Ship Navigation and Control Systems

To interpret Figure 2, describe the complete motion ship control system that utilizes machine learning for controlling, correcting wind feedforward, and fusing data from various sensors. Besides position and motion sensors, a wind sensor gives a real-time navigational and environmental overview. For input handling to be accurate and synchronized, field value elimination, spatiotemporal alignment, and data association need to be done at a common node in a coordinated manner. A ship motion model and a fusion algorithm use the inputs from the sensors to estimate the ship's position, direction, and motion, which are constructed from the sensors. At the same time, feedforward control loops mitigate outside disturbances using the wind's speed and direction. The controller generates control instructions using the fused estimates of the ship's state along with inputs from the monitoring terminal on the ship. The system identification and control was done by a support vector machine (SVM) which enhanced precision and flexibility. The ultimate command to change pitch or speed is given to the thruster system, which adjusts the ship's trajectory and stability, making responsiveness in change marine conditions possible.

4 Results and Discussion

4.1 Performance Comparison for Various Computing Methods

Table 1: Performance Comparison for Various Computing Methods

Metric	Edge Computing	Cloud Computing	Hybrid Computing
Latency	35 ms	220 ms	85m
Positioning Accuracy	1.5m	4.2 m	1.8 m
Data Fusion Accuracy	98.4	96.2%	98.9%
Heading precision	0.1	0.2	0.1
Speed Precision	0.01	0.05	0.01 knots
Environmental reaction time	3.2	7.8	3.5
Fault detection time	310 ms	880	400
Bandwidth usage	2.5 Mbps	8.3	4.1 mbps
Energy consumption	45W	78 W	52 W
System Availability	99.9%	98.5%	99.95%
Predictive Accuracy	96.7%	92.5%	98.1%
Sensor calibration accuracy	99.1%	97.3%	99.3%
Uptime During Network Loss	100%	0%	98%

To interpret table 1, it's important to note that Edge Computing has clear superiority on performance metrics pertaining to scenarios that require low latency, high autonomy, and real-time responses. Edge systems facilitate feedback and control lagging just behind 35 ms which is appropriate for rapidly evolving situations like real-time ship navigation. It also leads in positioning accuracy of 1.5 meters and fault detection time of 310 ms, which allows for sophisticated navigation and prompt error correction. Furthermore, Edge Computing uses the least bandwidth of 2.5 Mbps and energy of 45W, which makes Edge Computing even more favorable for remote or resource-scarce maritime settings. It also boasts 100% uptime during network loss which is critical for vessels that operate far from the shore. In contrast, Cloud Computing has limitations in latency and real-time fault handling at 220 ms and 880 ms respectively, but has high scalability and powerful computational resources. Moreover, its positioning accuracy and predictive accuracy of 4.2 meters and 92.5% are weaker than average which is a consequence of relying too heavily on network connectivity, as well as centralized processing delays. Cumulatively, such delays hinder performance in a real-time context, but benefit historical data analysis, route optimization, and fleet-wide monitoring services that don't require real-time responsiveness. Combining the best features of edge and cloud systems, The Hybrid Computing architecture achieves balanced performance. Its ability to provide data fusion at 98.9% and predictive accuracy at 98.1%, with a notable system availability of 99.95%, stems from local data processing and cloud analytics. Positioning accuracy of 1.8 meters, with heading, speed, and resilient navigation defining precision at ±0.1°, ±0.01 knots respectively, are among the standards set by hybrid systems. These figures highlight the system's capability to endure while maintaining operations through temporary communication failures, demonstrated through 98% uptime during network downtime. To summarize, Edge Computing serves best with standalone real-time applications in the maritime field, while Cloud Computing supports post-analysis and fleet coordination at scale. However, for modern navigation and control systems for smart ships, hybrid computing emerges as the most effective solution, responsive in real-time and augmented by intelligent cloud systems.

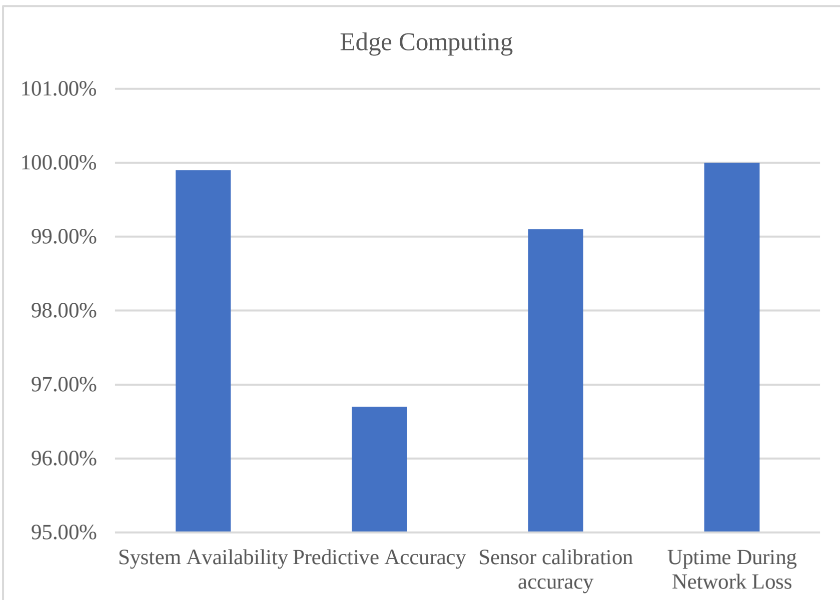

Figure 3: Edge Computing Vs Various Metrics

The metrics of performance for an edge computing system highlighted in Figure 3 above show its adequacy to function on real-time, autonomous, and distributed systems. The system has low latency of 35 ms and fault detection at 310 ms which indicates responsiveness critical to deadlines. It has high positioning accuracy (1.5 m), data fusion accuracy (98.4%), and predictive accuracy (96.70%) to warrant reliable situational awareness and decision-making. The system also exhibits remarkable precision in terms of speed (0.01) and heading (0.1) which is undergirded by a great sensor calibration accuracy of 99.10%. Integrating moderate bandwidth (2.5 Mbps) with low power consumption of 45W, the system maintains high availability (99.90%) and complete uptime during network loss (100%) which underscores the trust put into the system's autonomy and robustness capabilities. The reaction time to the environment of 3.2 seconds may be a drawback in rapidly changing conditions. As is, the edge computing configuration provides an astounding blend of efficiency, precision, and resilience suitable towards industrial automation, smart infrastructure systems, and intelligent transport.

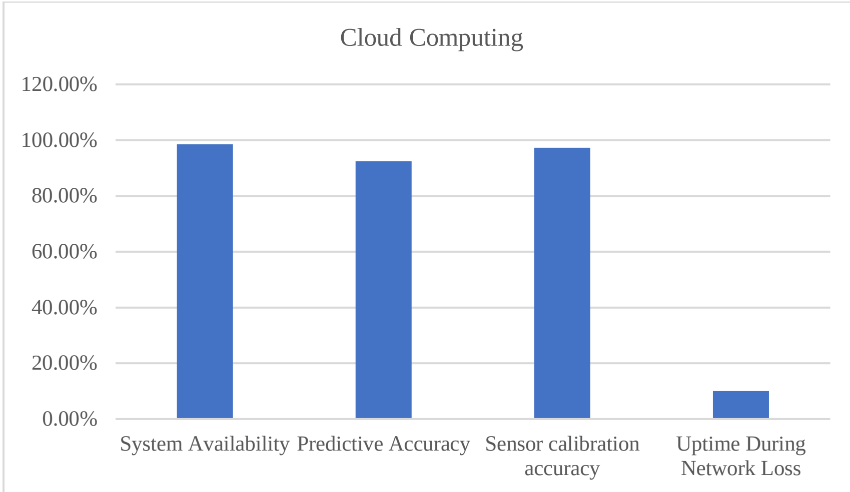

Figure 4: Cloud Computing Vs Various Metrics

When evaluating the performance metrics of a system in cloud computing, its advantages and disadvantages against edge computing become apparent (figure 4). These strategies show increased latency compared to other measures, clocking in at 220 ms, likely to stall responsiveness in real-time tasks. The positioning and heading precision also show values of 4.2 m and 0.2, respectively, which further hinders spatial awareness, making it ill-suited for deployment in operational domains that require detailed spatial awareness. Likewise, slower reaction times in the environment of 7.8 seconds and in built-in fault detection of 880ms indicate sluggish response and recognition to dynamic change stimuli. Albeit showing 96.20% in data fusion and 92.50% in prediction accuracy, both values trail behind their counterparts in edge computing, demonstrating firm reliance on cloud setups. Speed precision of 0.05 and sensor calibration of 97.3% add to the claim of mediocre performance. Their performance also affects their operational capabilities, consuming higher amounts of bandwidth at 8.3 Mbps and energy at 78W, straining resource reliability. Although yielding an adequate system availability of 98.5%, downtime in case of network loss is capped at 10%, illustrating heavy reliance on stable connections. All aspects considered, while offering strong system processing capabilities from cloud computing and centralized data access, the system faces challenges in latency, precision, and network resilience, making it less favorable for tier autonomous and responsive systems.

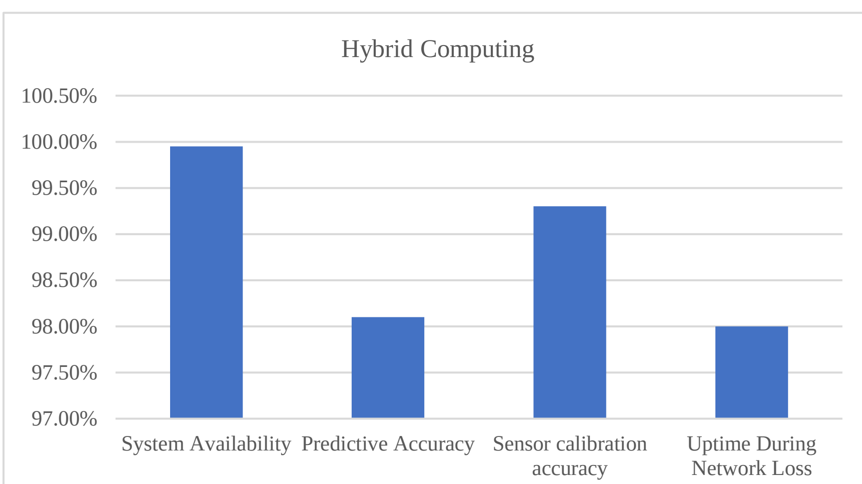

Figure 5: Hybrid Computing Vs Various Metrics

The performance metrics for the hybrid computing systems indicate that both edge and cloud computing are leveraged in a more optimal way (Figure 5). The system latency of 85 ms marks relatively quick responsivity which is beneficial for real-time applications while still undergoing cloud-level processing. Its positioning accuracy of 1.8 meters and heading precision of 0.1 are commendable alongside other factors such as moderately low spatial precision and some important commercial and industrial applications. The speed precision is very fine (0.01 knots), indicating that the system provides accurate velocity measurements. The environmental reaction time of 3.5 seconds and fault detection time of 400 milliseconds are reasonable in dynamic environments, revealing that the system can respond and detect changers effectively. The system performs optimally using a moderate bandwidth of 4.1 Mbps and consumes 52 W of energy, providing effective resource efficiency. Exceptionally high data fusion accuracy (98.90%) and predictive accuracy (98.10%) allows for intelligent decision making alongside other system parameters. Moreover sensor calibration accuracy is excellent at 99.30%. System availability is at 99.90% while network loss uptime of 98% guarantees reliability and continuity even in low connectivity challenges. Broadly speaking, hybrid computing integrates the advantages of edge and cloud computing, enabling improved responsiveness and processing power, which makes it highly suitable for complex and critical applications like autonomous systems, smart cities, and industrial automation.

The integration of edge, cloud, and hybrid computing architectures enables a comprehensive evaluation regarding their precision and effectiveness in real-time ship control and navigation systems. Each architecture has particular merits and drawbacks in parameters like cost, energy consumption, accuracy, resilience, fault detection, and latency. In terms of system responsiveness and operational continuity, edge systems are the best candidates. With a response time of 35ms, greater than 100% network loss uptime, and 99.90% availability, edge systems have the best prognostic responsiveness and operational continuity. These systems are optimal for mission-critical, real-time functions such as obstacle avoidance, immediate control decision execution, and responsive actuating/controlling functions. However, these systems struggle with powerful processing and analytics constraints. Cloud computing provides the highest centralization for storage and processing but suffers from high latency, recording data at 220ms, and 10% uptime during network loss is not sustainable. With energy usage at 78W, reaction times to environmental changes and fault detection are sluggish at 7.8 seconds and 880 milliseconds respectively. While longitudinal data analysis is supported, redundancy in dependable out-of-reach sea areas drastically weakens reliability. By combining both edge and cloud models, Hybrid Computing stands out as the most efficient architecture. It performs moderately well in latency (85 ms), system availability (99.95%), and fault tolerance (detection time 400 ms) whereas data fusion, predictive accuracy, and bracketing provide hybrid-edge paradigms with excellent performance (98.90% and 98.10% respectively). During network disconnection, reliable function is maintained (uptime 98% during simulated network loss) alongside balanced resource consumption (energy expenditure 52W). These characteristics enhance the utility of hybrid computing in real-time control systems and navigation strategies. The findings validate that hybrid computing architectures are designed to support the challenging modern requirements of maritime operations. They allow for distributed processing by enforcing local control decision making at the edge while cloud functionalities are utilized for global situational awareness, predictive analytics, and coordinated fleet management. Hybrid computing guarantees severe and efficient hybrid responsiveness while the systems are under increased automation and data inflow, critical for safe navigation. Future work should improve cloud-edge interoperability, optimize bandwidth allocation, and integrate AI to assist in decision-making at all computing levels.

5 Conclusion

Constructing architectures for real-time ship control as well as navigation computing systems is paramount to the safety, efficiency, and autonomous control over ships. Differentiate between hybrid computing, edge computing, and cloud computing. It will be clear that hybrid computing offers the best and most balanced functionality. Edge computing is limited in processing power, but during network loss, it provides low latency, high reliability, and complete functionality. Unlike edge computing, cloud computing is powerful in analytics and control. This type of computing does, however, have higher latency, more dependence on networks, and consumes more energy than is ideal for maritime missions. Hybrid computing eliminates this gap by combining the responsiveness of edge systems and the cloud's computing strength. Cloud-augmented edge computing achieves high availability of the system (99.95%), accurate prediction and data fusion, and robust uptime (98%) during network outages. Such capabilities are extremely important in dynamic maritime scenarios where precise positioning, fast adjustment, and tolerating faults is vital. Hence, a hybrid approach allows ships to critically assess data and shift control to the cloud during strategic long-term decision making and analysis. This crossbreed design is ideal for advanced scalable autonomous ship navigation and control systems and moves the maritime industry closer to control- and resource-efficient autonomy.

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Authors Biography

Captain **Pandian Mahadevan** Biography 03-06-2025

I obtained my 2nd Mate qualification from the Australian Maritime College in Tasmania and my Chief Mate and Master's qualifications from Warsash Maritime College in Southampton, UK. I commenced my maritime career mostly aboard bulk and log carriers operated by a Greek company, featuring a multinational crew. Subsequently, I became affiliated with other Indian management firms. I have primarily navigated bulk carriers ranging from handymax to capesize vessels. Upon graduating with a B.Sc from Madras University, I initially pursued a teaching career. I obtained a BTEC (HND) in the UK after finishing my Chief Mate qualification. In 2018, I held the position of Port Captain at Tata Steel Company in Paradeep port for a duration of six months. Subsequently, I instructed GP Rating and conducted STCW BST and STSDSD courses for three years. I have also instructed for two months for the Engineers renewal Certificate, focusing on amendments to SOLAS and MARPOL. Resumed sailing on coastal foreign-flag vessels and ceased sailing in 2024. Resumed teaching position at AMET University effective 29th July 2024. During this stay, I am instructing and training B.Sc (NS) cadets and serving as the Course-in-Charge for GP Rating.

Dr. Deepa Rajesh stands as a beacon of excellence in academia, administration, research, and philanthropy. With an impressive portfolio of qualifications, including M.Com, MBA, M.Phil, and Ph.D., she epitomizes intellectual prowess and leadership. Her unparalleled contributions continue to inspire and redefine maritime education on a global scale, reflecting her relentless pursuit of excellence and commitment to shaping future generations. A prolific researcher and thought leader, Dr. Deepa Rajesh has an illustrious record of publications in prestigious Scopus, UGC-CARE, and high-impact factor journals. Her thought-provoking research papers have graced numerous national and international conferences, further solidifying her standing in the academic community. Her two published books stand as a testament to her dedication to knowledge dissemination. Moreover, her successful completion of funded research projects underscores her ability to secure grants and contribute significantly to scholarly advancements. Serving as an editorial board member for reputed journals, she continues to shape the academic discourse with her insightful perspectives.