DEVELOPMENT AND TESTING OF IoT-BASED INTEGRATED SHIP SAFETY SYSTEM PROTOTYPE FOR EARLY DETECTION OF COLLISION AND FIRE HAZARDS

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Abstract

This research investigates the development and testing of an Internet of Things (IoT)-based integrated ship safety system prototype designed for early detection of collision and fire hazards on Indonesian vessels. Maritime accidents continue causing significant casualties, property losses, and environmental damages despite existing safety regulations, highlighting critical gaps in real-time hazard detection and response capabilities. Through qualitative analysis involving maritime safety experts, ship operators, marine engineers, and regulatory officials, this study examines technical requirements, system architecture, integration approaches, and operational effectiveness of IoT-enabled safety monitoring. Results demonstrate that integrated sensor networks combined with intelligent data analytics can reduce collision risk detection time by 60-80% and fire hazard identification by 70-85% compared to conventional manual monitoring approaches. Key implementation challenges include sensor reliability in harsh marine environments, system integration complexity with existing vessel infrastructure, cybersecurity vulnerabilities, and crew competency development for technology-enhanced safety management. Findings reveal that IoT-based safety systems represent transformative advancement toward proactive hazard prevention rather than reactive incident response, supporting maritime digitalization objectives and Industry 4.0 integration. This research contributes to maritime safety literature by providing empirical evidence for IoT application feasibility in developing maritime contexts, offering practical implementation frameworks for digital safety system deployment.

INTRODUCTION

Maritime safety remains a paramount concern for global shipping operations, with vessel accidents resulting in tragic loss of life, substantial property damage, environmental catastrophes, and disruption of critical maritime supply chains that underpin international trade and economic activity. Despite significant regulatory advancements, enhanced training requirements, and improved ship design standards implemented over recent decades, maritime accidents continue occurring with concerning frequency, particularly involving collision incidents during navigation and fire outbreaks onboard vessels (Zhang et al., 2022). The Indonesian maritime sector, operating within one of the world's most complex nautical environments characterized by dense traffic, narrow straits, challenging weather patterns, and diverse vessel types ranging from traditional wooden boats to modern commercial ships, faces particularly acute safety challenges requiring innovative technological solutions beyond conventional safety management approaches. Traditional maritime safety systems predominantly rely on manual monitoring, periodic inspections, and reactive responses to incidents after they occur, creating critical temporal gaps between hazard emergence and detection that often prove catastrophic as accidents develop rapidly from initial conditions to uncontrollable situations within minutes. The convergence of digital technologies, particularly Internet of Things capabilities enabling ubiquitous sensing, real-time data transmission, and intelligent analytics, creates unprecedented opportunities for transforming maritime safety from reactive incident response toward proactive hazard prevention through continuous automated monitoring and early warning systems that detect dangerous conditions before they escalate into accidents.

Internet of Things technology, encompassing networks of interconnected sensors, actuators, and computing devices that collect, transmit, and analyze data autonomously, has revolutionized safety management across various industries including aviation, manufacturing, and building management, achieving substantial accident reduction through early hazard detection and automated response capabilities (Yao et al., 2021). Maritime applications of IoT, however, remain considerably less developed compared to terrestrial domains, despite shipping environments' inherent hazards including navigation risks in congested waters, fire dangers from engine room equipment and cargo materials, flooding threats from hull breaches, and numerous other safety-critical conditions requiring constant vigilance. Collision hazards constitute leading causes of maritime accidents, resulting from inadequate situational awareness, human error during navigation decisions, equipment failures, poor visibility conditions, and inadequate communication between vessels operating in proximity. Fire incidents represent equally serious threats, with engine room fires, electrical system malfunctions, and cargo-related combustion creating rapid-developing emergencies that can overwhelm crew response capabilities within minutes, particularly on vessels lacking advanced fire detection and suppression systems. IoT-based integrated safety systems can address these hazards through distributed sensor networks monitoring critical parameters including vessel proximity and trajectory for collision avoidance, temperature, smoke, and gas concentrations for fire detection, hull integrity for flooding prevention, and equipment operational status for mechanical failure prediction, transmitting real-time data to intelligent analytics platforms that identify dangerous patterns and generate early

warnings enabling preventive interventions before incidents develop.

The research problem addressed in this study centers on developing and validating an IoT-based integrated ship safety system prototype specifically designed for early detection of collision and fire hazards while evaluating implementation feasibility, operational effectiveness, and adoption requirements for Indonesian maritime contexts. This research investigates: (1) what technical architecture, sensor configurations, and data analytics approaches enable effective real-time hazard detection with acceptable accuracy and reliability; (2) how IoT-based safety systems integrate with existing vessel infrastructure, crew operational procedures, and regulatory compliance frameworks; (3) what operational performance improvements in hazard detection speed, accuracy, and false alarm rates can realistically be achieved compared to conventional monitoring approaches; (4) what implementation barriers including technical complexity, cost constraints, cybersecurity risks, and organizational readiness factors constrain IoT safety system adoption; and (5) how context-appropriate deployment frameworks can support digital maritime safety advancement for diverse Indonesian vessel types and operational contexts. Specific research objectives include designing comprehensive IoT system architecture addressing collision and fire hazard detection requirements, developing functional prototype demonstrating core capabilities and integration approaches, conducting validation testing evaluating detection performance and operational viability, gathering expert stakeholder perspectives on implementation requirements and adoption barriers, and formulating practical recommendations for scaling IoT safety systems across Indonesian maritime operations. Maritime resilience frameworks increasingly recognize that robust safety monitoring infrastructure constitutes critical foundation for operational resilience and risk management (Kim et al., 2021).

The rationale for this research emerges from multiple compelling imperatives converging to make IoT-based safety innovation both urgent and strategically significant. From human safety perspectives, every preventable maritime accident represents tragic loss of life that technological innovation can potentially avert through earlier hazard detection enabling timely interventions. Indonesian maritime accidents claim hundreds of lives annually, with many incidents involving vessels lacking adequate safety monitoring systems, creating moral imperative for deploying proven technologies that could save lives. Economically, maritime accidents generate enormous costs including vessel losses, cargo damages, search and rescue operations, environmental cleanup, legal liabilities, and business disruption, with early hazard detection systems offering substantial cost avoidance through accident prevention. Environmental protection constitutes critical concern as maritime accidents frequently result in oil spills, cargo releases, and vessel groundings causing severe ecological damage to sensitive marine environments, with collision and fire prevention directly supporting environmental preservation objectives. From regulatory perspectives, international maritime safety regulations increasingly emphasize proactive risk management and technology-enhanced safety systems, with IoT capabilities aligning with regulatory trends toward real-time monitoring, data-driven decision support, and continuous improvement through performance analytics. The research addresses critical knowledge gaps, as existing maritime IoT literature predominantly examines cargo tracking, engine performance monitoring, and fleet management applications while significantly underexploring safety-critical applications despite their potentially life-saving importance. Regional maritime development increasingly emphasizes collaborative approaches to safety enhancement and technology

adoption that can benefit multiple nations facing similar challenges (Sun et al., 2021). Furthermore, successful IoT safety system demonstration in Indonesian contexts can catalyze broader digital maritime transformation supporting Industry 4.0 integration, smart shipping development, and positioning Indonesia as maritime technology adopter and potential innovator rather than merely technology consumer. Coastal region sustainable development recognizes that maritime safety infrastructure contributes to community wellbeing and regional economic stability (Hu & Chen, 2023).

Methodologically, this research employs mixed-methods approach combining prototype development and technical testing with qualitative inquiry gathering expert stakeholder perspectives to comprehensively evaluate IoT safety system feasibility, effectiveness, and implementation requirements. The prototype development component involves designing IoT system architecture integrating collision detection sensors (radar, AIS data integration, proximity sensors) and fire detection sensors (temperature, smoke, gas detection, thermal imaging) with edge computing analytics and alert generation capabilities, implementing functional prototype on test vessel enabling empirical validation, and conducting systematic testing evaluating detection performance, response times, accuracy metrics, and operational reliability under realistic maritime conditions. The qualitative inquiry component encompasses in-depth interviews with maritime safety experts possessing deep knowledge of accident causation, risk assessment, and safety management systems; ship operators and crew members understanding operational realities, safety procedures, and technology adoption constraints; marine engineers and IoT specialists providing technical expertise on system design, integration challenges, and cybersecurity considerations; and maritime regulatory officials knowledgeable about safety standards, compliance requirements, and approval processes for novel safety technologies. This integrated approach ensures that IoT safety system development remains grounded in both technical capabilities and operational realities while addressing genuine safety needs, regulatory requirements, and adoption prerequisites. By combining empirical prototype testing with rich stakeholder perspectives synthesized through systematic thematic analysis, this research develops comprehensive understanding of how IoT technologies can effectively enhance maritime safety while identifying practical pathways for sustainable deployment across Indonesian maritime operations, providing actionable guidance for vessel operators, technology developers, safety regulators, maritime education institutions, and policy stakeholders committed to advancing maritime safety through digital innovation.

RESEARCH METHOD

This research employs a mixed-methods methodology combining prototype development and empirical testing with qualitative stakeholder inquiry to comprehensively investigate IoT-based integrated ship safety systems for collision and fire hazard detection. The mixed-methods approach was selected because evaluating novel safety technology requires both objective performance assessment through technical testing and subjective evaluation of operational viability, implementation requirements, and stakeholder acceptance through expert perspectives. This integrated design enables triangulation across technical performance data and stakeholder insights, strengthening overall findings validity and ensuring research addresses both technological capabilities and real-world deployment considerations.

The prototype development component followed systematic engineering design

methodology beginning with requirements analysis defining functional specifications for collision and fire hazard detection based on maritime safety regulations, accident investigation reports, and expert consultation. The IoT system architecture was designed incorporating distributed sensor networks for continuous environmental and operational monitoring, edge computing capabilities for local data processing and preliminary analytics reducing bandwidth requirements and enabling rapid response, cloud connectivity for comprehensive data aggregation and advanced analytics, intelligent alert generation algorithms distinguishing genuine hazards from normal operational variations, and user interface components presenting safety information to crew through intuitive visual displays and audio warnings (Zhang et al., 2022). For collision detection capabilities, the system integrated multiple data sources including marine radar data for detecting nearby vessels and obstacles, Automatic Identification System data providing vessel identity, position, course, and speed information, GPS positioning for own-vessel location tracking, proximity sensors for detecting objects in blind spots, and analytics algorithms calculating collision risk based on closest point of approach, time to collision, and trajectory predictions. For fire hazard detection capabilities, the system incorporated thermal sensors monitoring temperature throughout vessel spaces, smoke detectors using optical and ionization technologies, gas sensors detecting combustible gases and carbon monoxide, thermal imaging cameras providing visual fire detection in critical areas like engine rooms, and pattern recognition algorithms identifying abnormal temperature rises, smoke presence, or gas accumulations indicating fire conditions. A functional prototype was implemented on a research vessel enabling empirical validation under realistic operational conditions, with sensor installations in representative locations, data collection infrastructure capturing real-time measurements, and monitoring interface displaying safety status to operators.

Testing and validation procedures systematically evaluated prototype performance across multiple dimensions including detection accuracy measuring true positive rates for genuine hazards and false positive rates for normal conditions, response time quantifying intervals between hazard occurrence and alert generation, reliability assessing system availability and failure rates during extended operations, integration effectiveness evaluating compatibility with existing vessel systems and crew procedures, and usability examining crew ability to interpret safety information and respond appropriately. Testing scenarios included controlled collision risk simulations using multiple vessels in coordinated maneuvers, fire hazard simulations using controlled smoke and heat sources, extended operational monitoring during normal vessel operations, and stress testing under challenging environmental conditions. Performance data was systematically recorded and analyzed to establish quantitative effectiveness metrics validating system capabilities.

The qualitative inquiry component employed purposive sampling to recruit participants with relevant expertise and experience for evaluating IoT safety system feasibility and implementation requirements (Caldas et al., 2024). Four stakeholder categories were targeted: maritime safety experts including accident investigators, safety auditors, and risk management consultants possessing deep knowledge of maritime hazards, accident causation, and safety system requirements; ship operators and crew members including masters, chief engineers, and safety officers understanding operational realities, existing safety procedures, and practical technology adoption considerations; marine engineers and IoT technology specialists with technical expertise in system design, sensor technologies, data analytics, cybersecurity, and maritime

equipment integration; and maritime regulatory officials and classification society representatives knowledgeable about safety regulations, compliance requirements, technology approval processes, and certification standards. Twenty-five participants were recruited across these categories ensuring diverse perspectives spanning technical, operational, regulatory, and safety management domains. Semi-structured interview guides addressed thematic areas including current safety monitoring practices and limitations, collision and fire hazard experiences and concerns, IoT technology awareness and perceptions, prototype system evaluation and feedback, implementation requirements including technical infrastructure and crew training, integration challenges with existing systems and procedures, regulatory compliance considerations, cybersecurity and reliability concerns, and adoption barriers encompassing cost, complexity, and organizational readiness (Buddha et al., 2024).

Data collection integrated technical testing data with qualitative interview data creating comprehensive evidence base. Prototype testing generated quantitative performance metrics including detection rates, response times, false alarm frequencies, and system availability statistics systematically logged during testing scenarios and operational monitoring periods. Interviews were conducted individually lasting sixty to ninety minutes, audio-recorded with informed consent, and supplemented by demonstration sessions where participants observed prototype system operation and provided real-time feedback. All interviews were transcribed verbatim with key technical content and stakeholder insights preserved for analysis. Technical documentation including system architecture diagrams, sensor specifications, data flow models, and performance logs was compiled providing objective system characterization.

Data analysis employed integrated approach combining quantitative performance analysis with qualitative thematic analysis. Technical performance data was analyzed using descriptive statistics calculating detection accuracy rates, mean response times, false alarm frequencies, and system reliability metrics, with comparative analysis evaluating prototype performance against conventional monitoring approaches and establishing improvement magnitudes. Qualitative data analysis followed thematic analysis methodology beginning with familiarization through repeated transcript reading, inductive coding generating themes from participant perspectives, theme organization addressing research questions, cross-stakeholder comparison examining consensus and divergence among safety experts, operators, engineers, and regulators, and narrative synthesis integrating findings into coherent understanding of IoT safety system potential, requirements, and implementation pathways. Technical performance findings were triangulated with stakeholder perspectives ensuring quantitative capabilities aligned with operational needs and implementation realities. The integrated mixed-methods analysis generated comprehensive understanding spanning technical validation, operational viability assessment, and implementation pathway development, providing robust evidence base for conclusions and recommendations.

RESULTS AND DISCUSSION
Results
The research findings provide comprehensive insights into IoT-based safety system capabilities, performance characteristics, and implementation considerations based on prototype testing and expert stakeholder evaluation.

Table 1: Prototype System Technical Specifications

System Component	Technical Configuration	Performance Characteristics	Implementation Notes
Collision Detection Sensors	Marine radar integration, AIS receiver, 4x proximity sensors	360° coverage, 12 nm radar range, real-time position tracking	Radar integration requires technical expertise
Fire Detection Sensors	15x thermal sensors, 8x smoke detectors, 6x gas sensors, 2x thermal cameras	Temperature monitoring ±1°C accuracy, smoke detection <30 seconds	Strategic placement critical for effectiveness
Edge Computing Unit	Industrial IoT gateway, quad-core processor, 8GB RAM	Local processing latency <500ms, 7-day local data retention	Ruggedized for marine environment
Connectivity Infrastructure	4G/LTE cellular, satellite backup, local WiFi network	99.2% uptime, automatic failover	Redundant connectivity ensures reliability
Analytics Platform	Cloud-based machine learning models, rule-based alert algorithms	Pattern recognition, predictive analytics, adaptive thresholds	Continuous improvement through learning
User Interface	Bridge-mounted touchscreen display, mobile app, audio alerts	Intuitive visualization, multi-level alerts, historical data access	Minimal training required for operation
Power Supply	Main vessel power with battery backup (72-hour capacity)	Uninterruptible operation during power fluctuations	Critical for safety system reliability
Cybersecurity	End-to-end encryption, secure authentication, network segmentation	Protection against unauthorized access and data tampering	Essential for system integrity

The prototype system demonstrates technically feasible integration of IoT capabilities within maritime operational constraints, with ruggedized components suitable for harsh marine environments, redundant systems ensuring high reliability, and processing architectures balancing edge computing for rapid response with cloud analytics for sophisticated pattern recognition. Cybersecurity measures including encryption and authentication address critical concerns about system integrity and unauthorized interference with safety-critical functions.

Table 2: Collision Detection Performance Results

Performance Metric	Conventional Approach (Manual Monitoring)	IoT Prototype System	Improvement Achieved	Statistical Significance
Detection Range	Visual observation limited by visibility	Radar detection up to 12 nm, AIS tracking >20 nm	3-6x range extension	$p < 0.001$
Detection Time (critical situations)	45-120 seconds average	8-18 seconds average	60-85% faster detection	$p < 0.001$
24-Hour Monitoring	Dependent on bridge watch	Continuous automated	100% vigilance maintenance	N/A

Coverage	alertness	monitoring		
Close Quarters Detection Accuracy	65-75% (variable by conditions)	92-96% (consistent performance)	25-40% accuracy improvement	$p < 0.01$
False Alarm Rate	N/A (subjective human judgment)	2.3 alarms per 100 operating hours	Acceptably low false positive rate	N/A
Blind Spot Coverage	Limited by vessel structure	Proximity sensors provide complete coverage	Eliminates detection gaps	N/A
Poor Visibility Performance	Severely degraded in fog, darkness, rain	Radar/AIS unaffected by visibility	Maintains performance in adverse conditions	N/A
Multi-Threat Tracking	2-3 vessels simultaneously monitored	50+ vessels tracked concurrently	>10x tracking capacity	N/A

Collision detection testing demonstrates substantial performance improvements over conventional manual monitoring approaches. The 60-85% faster detection time in critical situations represents potentially life-saving improvement, as every second matters during collision avoidance maneuvers. The 92-96% detection accuracy significantly exceeds human performance, particularly under fatigue or high workload conditions affecting bridge watch effectiveness. Continuous 24-hour monitoring eliminates vigilance gaps inherent in human operators, while multi-threat tracking enables comprehensive situational awareness in busy waters where numerous potential collision risks require simultaneous assessment. The 2.3 false alarms per 100 operating hours represents acceptable rate that maintains crew attention without creating alert fatigue from excessive false warnings.

Table 3: Fire Detection Performance Results

Performance Metric	Conventional Approach	IoT Prototype System	Improvement Achieved	Detection Time Advantage
Fire Detection Speed (engine room)	3-8 minutes (manual inspection)	15-45 seconds (automated sensors)	70-95% faster detection	Critical for rapid response
Early Warning Capability	Fire discovered after visible flames/smoke	Pre-fire condition detection (overheating, gas leaks)	Preventive rather than reactive	Enables intervention before ignition
Coverage Completeness	Periodic patrols miss unmanned spaces	Continuous monitoring all protected spaces	Eliminates monitoring gaps	Particularly valuable for unmanned areas
Temperature Anomaly Detection	Manual thermometer readings	Real-time thermal monitoring ±1°C accuracy	Continuous precision measurement	Identifies gradual overheating trends
Smoke	Depends on	Optical and	85-92%	Minimal false

	visual observation	ionization detection	detection accuracy	negatives
Detection Reliability				
Combustible Gas Detection	No capability in conventional systems	Real-time gas concentration monitoring	New capability enabling leak detection	Prevents explosion hazards
Thermal Imaging (critical areas)	Not available conventionally	Hot spot visualization and tracking	Visual confirmation of thermal anomalies	Supports maintenance decisions
Alert Specificity	Generic fire alarm	Location-specific alerts with hazard type identification	Faster, more effective response	Crew directed to exact problem location

Fire detection performance results demonstrate transformative improvements enabling early intervention before conditions escalate to uncontrollable fires. The 70-95% faster detection speed provides critical additional response time for suppression efforts before fires spread. Pre-fire condition detection—identifying overheating equipment, gas leaks, or abnormal thermal patterns before ignition—represents paradigm shift from reactive fire response toward proactive hazard prevention. Coverage completeness eliminates dangerous monitoring gaps in unmanned spaces where fires can develop undetected until discovered too late for effective suppression. Combustible gas detection provides entirely new capability absent from conventional systems, preventing explosion hazards through early leak identification. Alert specificity directing crew to exact hazard locations with hazard type identification accelerates response effectiveness compared to generic alarms requiring time-consuming investigation to locate problems.

Table 4: Stakeholder Evaluation and Perceptions

Evaluation Dimension	Safety Experts (n=7)	Ship Operators (n=9)	Engineers/Specialists (n=6)	Regulators (n=3)	Overall Assessment *
Safety Improvement Potential	4.8/5.0	4.6/5.0	4.7/5.0	4.9/5.0	Very High (4.75)
Technical Feasibility	4.5/5.0	3.9/5.0	4.8/5.0	4.2/5.0	High (4.35)
Operational Practicality	4.3/5.0	4.7/5.0	4.1/5.0	4.0/5.0	High (4.27)
Cost-Benefit Justification	4.6/5.0	3.8/5.0	4.2/5.0	4.4/5.0	Moderate-High (4.25)
Implementation Readiness	3.7/5.0	3.2/5.0	4.0/5.0	3.5/5.0	Moderate (3.6)
Regulatory Compliance Alignment	4.7/5.0	4.1/5.0	4.3/5.0	4.8/5.0	High (4.47)
Cybersecurity Adequacy	4.2/5.0	3.6/5.0	4.6/5.0	4.4/5.0	High (4.2)
Crew Acceptance Likelihood	3.9/5.0	4.2/5.0	3.8/5.0	3.7/5.0	Moderate-High (3.9)
Scalability Across Vessel	4.1/5.0	3.7/5.0	4.5/5.0	4.0/5.0	High (4.07)

Types

*Overall assessment calculated as mean across stakeholder groups; rated on 5-point scale: 1=very poor, 5=excellent

Stakeholder evaluation reveals strong consensus regarding IoT safety system's substantial safety improvement potential (overall 4.75), with regulators providing highest rating (4.9) reflecting recognition that technology addresses critical safety gaps. Technical feasibility received high ratings (overall 4.35) though operators expressed slightly more caution (3.9) than engineers (4.8), reflecting operators' concerns about integration complexity and reliability requirements. Operational practicality received strong endorsement particularly from operators (4.7) who would use systems daily, validating that design appropriately addresses real-world operational needs. Cost-benefit justification showed more variation, with operators rating lowest (3.8) reflecting their direct financial concerns, though safety experts (4.6) and regulators (4.4) strongly endorsed value proposition recognizing life-saving potential justifies investments. Implementation readiness scored lowest overall (3.6), indicating significant preparation needed before widespread deployment including infrastructure development, technical expertise building, and organizational capability enhancement. Regulatory compliance alignment scored high (4.47) with regulators rating highest (4.8), suggesting system design effectively addresses safety regulatory requirements and approval processes. Cybersecurity adequacy received solid ratings (4.2) though operators expressed most concern (3.6), highlighting need for security assurance communication and demonstration.

Table 5: Implementation Barriers and Requirements

Barrier/Requirement Category	Specific Challenges Identified	Severity Rating**	Proposed Mitigation Strategies
Initial Capital Investment	$35,000-75,000 per vessel system cost	4.5/5.0	Financing programs, phased implementation, risk-based cost-benefit analysis demonstrating ROI through accident prevention
Technical Integration Complexity	Integration with existing vessel systems, sensor installation challenges	4.2/5.0	Standardized installation procedures, technical support services, training programs for marine engineers
Crew Training Requirements	Operating IoT systems, interpreting alerts, maintenance procedures	4.0/5.0	Comprehensive training programs, simulation-based learning, ongoing competency development
Cybersecurity Vulnerabilities	Hacking risks, data integrity threats, system manipulation	4.4/5.0	Multi-layer security architecture, regular security audits, incident response protocols
Sensor Reliability (marine environment)	Harsh conditions, saltwater corrosion, vibration, temperature	4.3/5.0	Marine-grade ruggedized sensors, preventive maintenance programs, redundant sensor deployment

	extremes		
Connectivity Limitations	Unreliable cellular coverage in remote waters	3.9/5.0	Satellite backup connectivity, edge computing enabling local operation, offline mode capabilities
Regulatory Approval Processes	Unclear certification pathways for novel technology	3.7/5.0	Regulatory engagement, pilot program approvals, guidance document development
False Alarm Management	Risk of alert fatigue if false positives excessive	3.8/5.0	Algorithm refinement through machine learning, adjustable sensitivity thresholds, alert prioritization
Organizational Change Management	Resistance to technology adoption, cultural barriers	3.6/5.0	Stakeholder engagement, demonstration projects, change leadership training
Maintenance Service Availability	Limited technical support infrastructure	4.1/5.0	Service network development, remote diagnostics capabilities, spare parts availability

**Severity rated on 5-point scale: 1=minor obstacle, 5=critical barrier

Implementation barriers analysis reveals that initial capital investment (severity 4.5) constitutes most significant obstacle, particularly for smaller vessel operators with limited financial resources despite compelling safety justifications. Cybersecurity vulnerabilities (severity 4.4) emerged as critical concern requiring robust security architectures, as compromised safety systems could be catastrophically dangerous. Sensor reliability in harsh marine environments (4.3) necessitates careful component selection and preventive maintenance ensuring continuous monitoring capability. Technical integration complexity (4.2) and maintenance service availability (4.1) highlight needs for technical support ecosystems including trained engineers, standardized procedures, and service networks. Crew training requirements (4.0) reflect that technology effectiveness depends on competent human operators who understand systems, interpret alerts correctly, and respond appropriately—technology alone insufficient without human capability development.

Table 6: Recommended Implementation Framework

Implementation Phase	Duration	Key Activities and Milestones	Critical Success Factors
Phase 1: Pilot Program Development	6-9 months	System design finalization, pilot vessel selection, regulatory approval, installation, initial testing	Strong technical partnership, regulatory engagement, operator commitment
Phase 2: Operational Validation	12-18 months	Extended monitoring under real operational conditions, performance data collection, crew feedback, iterative refinement	Systematic data collection, responsive technical support, continuous improvement
Phase 3: Capacity Building	Parallel to Phase 2	Training program development, engineer certification, maintenance	Quality training delivery, hands-on learning, certification

		procedures, crew competency standards	credibility
Phase 4: Regulatory Framework Development	Parallel to Phases 1-2	Safety standards development, certification procedures, compliance guidelines, approval pathways	Regulatory authority engagement, industry input, international alignment
Phase 5: Scale-Up Preparation	12-15 months	Supply chain establishment, service network development, financing mechanisms, marketing and communication	Infrastructure investment, partnership development, market awareness
Phase 6: Graduated Rollout	24-36 months	Phased deployment prioritizing high-risk vessels, fleet-by-fleet implementation, performance monitoring	Risk-based prioritization, financial support, technical assistance availability
Phase 7: Continuous Improvement	Ongoing	Performance analytics, technology updates, lessons learned integration, ecosystem development	Long-term commitment, innovation openness, knowledge sharing

The implementation framework emphasizes graduated approach beginning with rigorous pilot programs demonstrating feasibility and building evidence base before attempting large-scale deployment. Parallel capacity building and regulatory framework development ensure human capabilities and institutional structures develop alongside technology deployment. Extended operational validation phase acknowledges that proving technology reliability under real maritime conditions requires substantial time before operators will trust safety-critical systems. Phased rollout prioritizing high-risk vessels (passenger ships, hazardous cargo carriers, vessels in dense traffic areas) ensures limited resources deploy where safety benefits are greatest. The framework recognizes that sustainable IoT safety system adoption requires coordinated development across technology, human capacity, regulatory frameworks, support infrastructure, and financing mechanisms rather than technology deployment alone.

Discussion

The research findings illuminate critical dimensions of IoT-based maritime safety innovation while revealing important factors distinguishing successful digital safety system implementation from unsuccessful technology deployments that fail to achieve intended safety improvements.

The prototype testing results demonstrating 60-85% faster collision detection and 70-95% faster fire detection represent potentially life-saving performance improvements, as accident response effectiveness depends critically on early warning providing sufficient time for intervention before situations become uncontrollable (Zhang et al., 2022). These improvement magnitudes validate fundamental premise that IoT technologies can meaningfully enhance maritime safety beyond what human vigilance alone achieves, addressing inherent human limitations including fatigue, distraction, inconsistent performance, and inability to maintain perfect vigilance across extended periods. The continuous monitoring capability eliminating detection gaps represents qualitative paradigm shift from periodic inspection approaches that inevitably miss hazards developing between observation intervals. The particularly strong performance in challenging conditions—maintaining detection effectiveness during poor visibility when human performance severely degrades—demonstrates that IoT systems provide

complementary capabilities augmenting human operators rather than merely replicating human functions, creating human-machine teams stronger than either alone. The acceptable false alarm rate of 2.3 per 100 operating hours achieves critical balance between sensitivity ensuring genuine hazards detected and specificity avoiding excessive false warnings creating alert fatigue undermining crew response. Maritime resilience frameworks increasingly recognize that robust real-time monitoring infrastructure constitutes critical foundation for proactive risk management rather than reactive incident response (Kim et al., 2021).

The pre-fire condition detection capability enabling preventive interventions before ignition represents transformative advancement beyond conventional fire detection systems that only identify fires after combustion begins. This preventive capability—detecting overheating equipment, gas leaks, abnormal thermal patterns indicating elevated fire risk—enables maintenance interventions eliminating hazards before fires start, fundamentally changing safety paradigm from damage control toward hazard prevention. The comprehensive coverage including unmanned spaces where fires can develop undetected addresses critical vulnerability in conventional monitoring approaches relying on human patrols that cannot continuously monitor all vessel spaces simultaneously. These findings extend maritime safety literature by demonstrating that IoT technologies enable not merely incremental improvements in detection speed but qualitative capability enhancements through continuous coverage, multi-parameter monitoring, and predictive analytics impossible with manual approaches, contributing empirical evidence supporting digital transformation arguments in maritime safety domain.

The stakeholder evaluation revealing strong consensus on safety improvement potential (4.75/5.0) across diverse perspectives—safety experts, operators, engineers, and regulators—provides robust validation that IoT safety systems address genuine needs and offer credible solutions rather than representing merely theoretical possibilities or technology-push innovations lacking practical value. The differentiated ratings across evaluation dimensions—highest for safety improvement potential and regulatory alignment, moderate for implementation readiness and cost-benefit justification from operator perspectives—reveal important nuances in stakeholder perceptions requiring attention in deployment strategies. Operators' lower cost-benefit ratings (3.8) compared to safety experts (4.6) reflect natural tension between those bearing implementation costs versus those evaluating societal benefits, suggesting that financing mechanisms, risk-based cost-benefit demonstrations quantifying accident prevention value, and potentially regulatory requirements may be necessary to overcome economic adoption barriers for safety technologies whose benefits accrue broadly rather than exclusively to investors. The moderate implementation readiness ratings (3.6 overall) acknowledge that technological possibility alone does not equal deployment readiness—substantial preparation including capacity building, infrastructure development, and ecosystem maturation remains necessary before widespread sustainable adoption becomes feasible. This sociotechnical perspective aligns with technology adoption literature emphasizing that successful innovation requires addressing human, organizational, institutional, and infrastructural dimensions alongside technical capabilities (Caldas et al., 2024). Regional cooperation frameworks emphasizing collaborative technology development and knowledge sharing can accelerate implementation readiness across maritime communities facing similar challenges (Sun et al., 2021).

The implementation barriers analysis revealing capital investment, cybersecurity, sensor reliability, and technical integration as highest severity obstacles provides actionable guidance for intervention priorities supporting adoption. The capital investment barrier (4.5 severity) suggests that economic support mechanisms—financing programs, subsidy schemes for safety technology, risk-based insurance premium reductions for equipped vessels—could catalyze adoption by addressing upfront cost obstacles despite compelling long-term value propositions. The cybersecurity concern (4.4 severity) reflects appropriate caution about introducing connected systems into safety-critical functions, as compromised safety systems could be weaponized creating catastrophic vulnerabilities. This finding emphasizes that cybersecurity cannot be afterthought but must be fundamental design principle with multi-layer defenses, continuous monitoring, and incident response capabilities. The sensor reliability concern (4.3 severity) acknowledges harsh marine operating environments create demanding conditions for electronic equipment, necessitating careful component selection, ruggedization, preventive maintenance, and redundancy ensuring continuous monitoring despite individual sensor failures. The technical integration and maintenance support barriers highlight that technology deployment requires comprehensive support ecosystems including trained engineers, standardized procedures, spare parts availability, and technical assistance services—infrastructure investments often overlooked in technology-focused discussions but essential for sustainable operations.

The recommended implementation framework's emphasis on graduated rollout beginning with rigorous pilot programs reflects learning from technology adoption literature showing that premature large-scale deployment before adequately validating performance, refining systems based on operational experience, and building support infrastructure frequently results in implementation failures undermining future adoption prospects. The parallel capacity building and regulatory framework development tracks acknowledge that technology, human capability, and institutional structures must develop coordinately rather than sequentially, as technology deployed without competent operators and appropriate regulations cannot achieve intended benefits. The extended timeline spanning years rather than months reflects realistic acknowledgment that building sustainable digital safety ecosystems requires substantial time for technology maturation, operator experience accumulation, service network development, and cultural adaptation—rushing implementation typically produces suboptimal outcomes. This temporally realistic approach contrasts with technology-optimistic narratives sometimes dominating digital transformation discourse, providing more credible guidance for maritime stakeholders navigating innovation adoption. Coastal region development perspectives increasingly recognize that maritime safety infrastructure contributes to community wellbeing and sustainable regional development (Hu & Chen, 2023).

This research addresses significant gaps in maritime IoT literature, which has predominantly examined operational efficiency applications (cargo tracking, engine performance monitoring, fleet management) while significantly underexploring safety-critical applications despite their potentially life-saving importance. The explicit focus on collision and fire detection—leading causes of maritime casualties—ensures research addresses highest-priority safety challenges rather than merely convenient technical applications. The mixed-methods approach combining objective prototype testing with subjective stakeholder evaluation generates richer insights than purely technical studies or purely perception-based research, validating that technological capabilities align with

operational needs and stakeholder expectations. The Indonesian developing economy context contributes important perspective to literature dominated by advanced economy studies, demonstrating IoT safety system feasibility under resource-constrained conditions and infrastructure limitations.

The practical implications extend across multiple domains. For vessel operators, the research demonstrates compelling safety performance improvements justifying IoT safety system investments, particularly for high-risk vessels where accident prevention value clearly exceeds implementation costs. For technology developers, the findings reveal substantial maritime safety market opportunities while highlighting design requirements including ruggedization, cybersecurity, user-friendly interfaces, and integration capabilities. For maritime safety regulators, the research provides evidence supporting regulatory recognition and potential requirements for IoT safety systems, while identifying certification pathway development needs. For maritime education institutions, the identified training requirements highlight curriculum development needs integrating IoT technologies, data analytics, and digital safety management into maritime training programs. For policymakers, the findings indicate where strategic investments in capacity building, financing mechanisms, infrastructure development, and regulatory frameworks could catalyze safety technology adoption supporting broader maritime safety improvement objectives.

Future research should pursue several important directions. Longitudinal studies tracking operational IoT safety systems over extended periods would generate evidence on long-term reliability, maintenance requirements, and sustained performance. Accident analysis comparing equipped versus non-equipped vessels would provide empirical evidence quantifying safety improvement magnitudes and economic benefits through accident prevention. Technical research developing advanced analytics including machine learning for pattern recognition, predictive algorithms identifying emerging hazards, and automated response capabilities would enhance system effectiveness. Human factors research examining optimal human-machine interaction designs, alert presentation approaches minimizing false alarm impacts, and training methodologies ensuring effective technology utilization would support human capability development. Economic research quantifying comprehensive costs and benefits including accident prevention value, insurance implications, and regulatory compliance costs would strengthen business case evidence. Comparative research examining implementation across different vessel types, operational contexts, and regulatory regimes would identify generalizable principles versus context-specific factors.

CONCLUSION

This research demonstrates that IoT-based integrated ship safety systems for collision and fire hazard detection offer transformative potential for advancing maritime safety through early warning capabilities enabling preventive interventions rather than reactive incident response. Prototype testing validates substantial performance improvements including 60-85% faster collision detection and 70-95% faster fire detection compared to conventional manual monitoring, with continuous coverage eliminating detection gaps and pre-fire condition identification enabling hazard prevention before ignition. Stakeholder evaluation reveals strong consensus regarding safety improvement potential while identifying critical implementation requirements including technical integration support, crew training programs, cybersecurity assurance,

and service infrastructure development. Implementation barriers particularly capital investment, cybersecurity vulnerabilities, sensor reliability requirements, and organizational readiness gaps necessitate comprehensive support ecosystems encompassing financing mechanisms, technical assistance, capacity building programs, and regulatory frameworks. The recommended graduated implementation framework emphasizes pilot program validation, parallel capacity building, regulatory framework development, and phased rollout prioritizing high-risk vessels. These findings contribute to maritime safety literature by providing empirical evidence validating IoT safety system feasibility and effectiveness, offering practical implementation guidance supporting digital maritime safety advancement aligned with Industry 4.0 integration and smart shipping development objectives.

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