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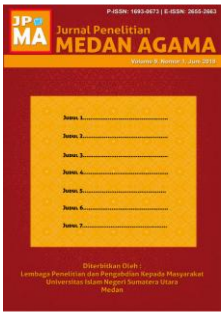

Development of an IoT-Based Autonomous Robot for Indoor Fire Detection and Evacuation Support

Pengembangan Robot Otonom Berbasis IoT untuk Dukungan Evakuasi dan Deteksi Kebakaran Dalam Ruang

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Abstract

Fire-related emergencies inside buildings expose first responders to severe risks caused by limited visibility, high temperatures, toxic gases, and rapidly changing structural conditions. Immediate entry without adequate situational awareness increases the probability of injury and operational failure. Autonomous robotic systems provide a promising approach to reduce human exposure by performing preliminary hazard assessment and environmental monitoring. This study presents the design and experimental evaluation of EVACo-Aid, an IoT-enabled autonomous robotic platform developed to support indoor fire rescue operations. The system integrates fire detection, obstacle avoidance, victim identification, and real-time data transmission within a compact mobile platform. An experimental prototyping methodology was employed, covering system design, hardware integration, control programming, and functional testing under controlled indoor conditions. Experimental results demonstrate that the proposed system can reliably detect fire sources, navigate autonomously around obstacles, and transmit operational data in real time. Although limitations remain regarding mobility on uneven terrain and sensor performance in extreme environments, the findings indicate that low-cost autonomous robots can enhance situational awareness and improve responder safety during indoor fire emergencies.

Keywords: *Autonomous robotics; Fire rescue; Indoor navigation; Internet of Things; Emergency response*

Abstrak

Keadaan darurat kebakaran di dalam gedung menempatkan petugas tanggap darurat pada risiko tinggi akibat visibilitas rendah, suhu ekstrem, gas beracun, serta perubahan kondisi struktur yang cepat. Untuk mengurangi paparan langsung dan meningkatkan kesadaran situasional, penelitian ini merancang dan menguji robot otonom berbiaya rendah untuk penilaian bahaya awal dan pemantauan lingkungan pada insiden kebakaran dalam ruangan. Studi ini mengembangkan EVACo-Aid, platform robot otonom berbasis IoT yang mengintegrasikan deteksi kebakaran, penghindaran rintangan, identifikasi korban, serta transmisi data secara waktu nyata dalam desain mobile yang ringkas. Pengujian dilakukan melalui prototipe eksperimental pada lingkungan dalam ruangan terkontrol untuk mengevaluasi fungsi navigasi, deteksi api, dan komunikasi data. Hasil uji menunjukkan EVACo-Aid mampu mendeteksi sumber api secara andal, bergerak secara otonom menghindari rintangan, dan mengirimkan informasi operasional secara real-time kepada operator. Meskipun masih terdapat keterbatasan pada mobilitas di medan tidak rata dan penurunan performa sensor pada kondisi ekstrem, temuan ini menunjukkan bahwa robot

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otonom berbiaya rendah berpotensi menjadi solusi pendukung yang efektif untuk meningkatkan keselamatan petugas dan kualitas pengambilan keputusan pada tahap awal penanganan kebakaran di dalam gedung.

Kata Kunci: Robotika otonom; Penyelamatan kebakaran; Navigasi dalam ruangan; Internet of Things; Tanggap darurat

1. PENDAHULUAN

Fire-related emergencies remain among the most dangerous operational scenarios faced by First Responders, particularly during indoor structural fires where environmental conditions evolve rapidly and unpredictably (van Manen et al., 2025; Ruan et al., 2025). Extreme temperatures, dense smoke, toxic gases, and progressive structural degradation collectively limit human perception and mobility, increasing the likelihood of injury or fatality during rescue operations (Ruan et al., 2025). Under such conditions, responders are frequently required to act with incomplete situational information, making rapid decision-making both necessary and hazardous (van Manen et al., 2025).

Indoor fire environments significantly constrain visual awareness and spatial orientation. Smoke accumulation reduces visibility to near-zero levels, while elevated temperatures accelerate physical fatigue and impair equipment performance (Ruan et al., 2025). In addition, combustion by-products such as carbon monoxide and hydrogen cyanide introduce immediate physiological threats, further reducing safe operational time (van Manen et al., 2025). Structural components weakened by prolonged heat exposure may fail without warning, creating dynamic obstacles and increasing the risk of secondary hazards (Ruan et al., 2025). These factors make manual assessment of fire conditions and victim locations inherently unreliable and place responders in situations where exposure risk is unavoidable.

Maintaining situational awareness in such environments is particularly challenging. Firefighters must simultaneously perceive environmental cues, interpret their significance, and anticipate future developments while operating under time pressure and cognitive stress (van Manen et al., 2025). Sensory limitations caused by protective equipment, noise, and heat further degrade perception and decision accuracy (Ruan et al., 2025). As a result, traditional firefighting tools often provide insufficient information to support safe and efficient indoor search and rescue operations.

Victim localization represents one of the most critical and resource-intensive tasks during indoor fire incidents. Victims may be unconscious, immobilized, or obscured by smoke and debris, making direct visual identification unreliable (Ryu & Kim, 2021). Auditory cues are frequently masked by alarms, structural noise, or active fire behaviour. Although thermal imaging cameras have improved detection capability in low-visibility conditions, their effectiveness may be reduced by high ambient temperatures, reflective surfaces, or physical obstructions (Ryu & Kim, 2021). Consequently, responders are often required to conduct manual searches in hazardous environments, increasing exposure time and operational risk.

Recent developments in autonomous robotics have created opportunities to support emergency response activities by enabling remote assessment of hazardous environments (Oyelami et al., 2024; Atef et al., 2023). Sensor-equipped robotic platforms can collect environmental data, detect hazards, and explore confined spaces without immediate human entry (Ryu & Kim, 2021). By operating ahead of responders, such systems have the potential to improve situational awareness and reduce unnecessary exposure to life-threatening conditions. However, many existing robotic systems are designed for outdoor environments or controlled settings and struggle to maintain reliable performance in complex indoor fire scenarios (Sharma & Singh, 2023).

Limitations commonly observed in existing platforms include restricted mobility, reliance on predefined navigation strategies, limited sensor integration, and high system cost (Li et al., 2012; Cai & Zhang, 2013). Wheeled robots may encounter difficulties in debris-filled or partially collapsed structures, while single-sensor approaches provide insufficient environmental understanding (Lei et al., 2015). Furthermore, many systems focus on isolated functions such as fire detection or suppression rather than integrated support for search and rescue operations (Ryu & Kim, 2021).

This research addresses these challenges through the design and experimental evaluation of EVACo-Aid, an autonomous, sensor-integrated robotic platform intended to support indoor fire-rescue operations. The system is designed to operate in confined environments, detect hazardous conditions, assist in victim identification, and transmit real-time data to remote operators. By emphasizing modular design, autonomous navigation, and low-cost implementation, this work aims to contribute a practical robotic solution capable of enhancing situational awareness and reducing operational risk for First Responders during indoor fire incidents.

2. RESEARCH METHODOLOGY

This research adopts an experimental engineering and system prototyping methodology to design, develop, and evaluate the EVACo-Aid autonomous fire-rescue robot. The selected approach emphasizes iterative design, hardware–software integration, and functional validation through controlled experimentation. This methodology is suitable for early-stage robotic systems intended for hazardous environments, where performance must be verified through direct testing rather than simulation alone (Oyelami et al. 2024).

The methodological process was structured into five sequential phases: functional requirement definition, system architecture design, hardware integration, software development, and experimental evaluation.

Functional Requirements Definition

The first stage involved identifying the operational requirements necessary for an indoor fire-rescue robotic platform. These requirements were derived from typical challenges encountered during structural fire incidents, including limited visibility, confined spaces, and dynamic obstacles (van Manen et al. 2025). Based on these considerations, the EVACo-Aid system was required to:

1) Detect the presence of fire sources,
2) Navigate autonomously while avoiding obstacles,
3) Identify potential human presence,
4) Transmit environmental data to a remote monitoring interface in real time.
5) These requirements served as the foundation for component selection and system design, ensuring that each subsystem directly supported the intended operational objectives.

System Architecture and Design

Following requirement definition, the system architecture was developed using a modular design strategy. A block-diagram representation was created to define interactions between sensing, control, actuation, and communication modules. The control unit of the system is an Arduino microcontroller, responsible for processing sensor inputs and executing control commands.

An ESP32-CAM module was incorporated to support human detection through image capture, while ultrasonic sensors (HC-SRF05) were used to measure distance and detect obstacles. Fire detection was achieved using flame sensors positioned to maximize coverage of the robot's forward movement path. Motor actuation was handled through an L298N motor driver connected to DC motors mounted on a four-wheel chassis, enabling stable indoor mobility.

Wireless communication was implemented through an integrated Wi-Fi module, allowing sensor data and system status information to be transmitted to a remote dashboard. A relay module was used to control a water pump, enabling automated activation when fire was detected.

Hardware Integration and Assembly

Once the system architecture was finalized, hardware components were physically integrated and assembled. All sensors were connected to the microcontroller using designated input pins, while actuators were interfaced through appropriate driver circuits. Power distribution was carefully managed to ensure stable operation of sensing, processing, and communication modules during runtime.

The robot chassis was selected to provide sufficient stability for indoor movement on flat and slightly inclined surfaces. Component placement was optimized to minimize wiring interference and maintain balanced weight distribution. Following assembly, individual subsystems were tested independently to verify electrical connectivity and functional responsiveness before full system operation.

Software Development and Control Logic

Software development was conducted using the Arduino Integrated Development Environment (IDE). The control logic was implemented as a set of modular routines responsible for sensing, decision-making, actuation, and communication.

Obstacle avoidance was achieved by continuously monitoring distance measurements from the ultrasonic sensors (Cai & Zhang 2013). When an obstacle was detected within a predefined threshold, the robot adjusted its direction to prevent collision. Fire detection routines monitored flame sensor outputs and triggered both local responses, such as pump activation, and remote notifications.

Human detection was facilitated through image data captured by the ESP32-CAM module, which was transmitted to the monitoring interface for operator awareness. IoT communication routines ensured that system status and alert data were transmitted in real time to web-based dashboards and messaging platforms (Ryu & Kim 2021).

Experimental Testing and Performance Evaluation

Experimental evaluation was conducted in controlled indoor environments to assess system performance, following common validation practices used in indoor firefighting and rescue robotics research (Ryu & Kim, 2021; Atef et al., 2023). The robot was tested for autonomous navigation, obstacle avoidance, fire detection accuracy, and communication reliability, which represent core functional capabilities required for robotic operation in hazardous indoor settings (Cai & Zhang, 2013; Oyelami et al., 2024). Performance metrics included response time, detection consistency, obstacle avoidance success rate, and data transmission stability, as these indicators are widely adopted to quantify effectiveness, reliability, and responsiveness in autonomous robotic systems (Atef et al., 2023; Oyelami et al., 2024).

Multiple test trials were conducted to observe system behaviour under repeated conditions. Data collected during these tests were recorded and summarized in tabular form to support quantitative analysis. Observations from experimental testing were used to identify system limitations and guide further refinement.

This structured methodology ensured that the EVACo-Aid prototype was developed and evaluated in a systematic and reproducible manner, providing a reliable basis for analyzing its suitability for indoor fire-rescue support applications.

3. RESULTS AND DISCUSSION

Experimental evaluation of the EVACo-Aid prototype was conducted to assess system functionality, operational efficiency, and suitability for indoor fire-rescue support. The results focus on power consumption characteristics, functional performance across key tasks, and the impact of robotic assistance on operational conditions.

Battery Usage and Operational Endurance

Power consumption analysis was performed to estimate the operational endurance of EVACo-Aid under typical indoor deployment scenarios. Each major subsystem was evaluated individually to determine its contribution to overall energy usage and expected operating time.

Table 1. Estimated battery usage of the EVACo-Aid system under different operating conditions.

Component	Operating Voltage (V)	Current (A)	Operational Time (hrs)	Remarks
ESP32	3.3–5	0.15	8	Manages sensors and
Arduino Uno	5	0.05	12	IoT communication
Ultrasonic sensor (H(C-	5	0.015	10	Motor control and sensor integration
SR04)	5	0.02	10	Distance and obstac
Flame sensor	12	1.2	2	detection
DC motor x4	5-12	0.02	8	Independent movement
Motor driver (L298N)	5	0.01	10	Motor speed and direction control
Relay for pump	5	0.01	10	Automatic activation
Water pump	12	0.5	1	of pump
Total estimated usage	Enables approximately 1–2 hours of semi-autonomous operation depending on motor and pump lo			

The results indicate that low-power components such as the microcontroller, sensors, and communication modules consume relatively stable and modest energy, allowing continuous operation over extended periods. These components support essential tasks including environmental monitoring, navigation decision-making, and real-time data transmission. As a result, EVACo-Aid can remain active for prolonged reconnaissance and hazard assessment missions without significant power degradation.

In contrast, high-energy components particularly the drive motors and water pump exhibit substantially higher power demands. Motor actuation during continuous navigation and pump activation during fire suppression significantly reduce overall operational duration. This finding suggests that EVACo-Aid is best utilized as an early-stage support system, prioritizing situational assessment and navigation assistance rather than prolonged suppression activities.

From an operational perspective, the observed energy distribution aligns with real-world deployment needs, where initial fireground intelligence and victim localization are critical before large-scale intervention. The battery usage profile highlights the importance of task prioritization and power management strategies in future system iterations.

Operational Impact Before and After EVACo-Aid Deployment

To assess the practical contribution of EVACo-Aid, operational conditions were compared before and after the introduction of the system. This comparison focused on situational awareness, response efficiency, and exposure risk during indoor fire scenarios.

The comparative outcomes are summarized in Table 2, highlighting key differences observed before and after EVACo-Aid implementation.

Table 2. Comparison of fireground operational conditions before and after EVACo-Aid deployment.

	Before EVACo-Aid	After EVACo-Aid
Risk to rescue teams	High, must enter hazardous area	Low, robot enters on behalf of humans
Response time	Relatively slow, relies on human effort	Fast, automatic detection of fire and
Fire detection	Manual or simple sensors	Automatic fire sensors with IoT
Navigation in hazardous area	Manual	Autonomous (ultrasonic sensors & AI camera)
Victim condition monitoring	Difficult, requires direct communication	Real-time via IoT dashboard
Rescue efficiency	Limited	Higher, can work continu-

The comparison demonstrates that the use of EVACo-Aid improves early hazard awareness and reduces the need for immediate human entry into hazardous zones. By providing preliminary environmental information and fire detection, the system supports better-informed decision-making. Although EVACo-Aid does not replace manual firefighting operations, it functions effectively as a risk-reduction and reconnaissance tool.

Functional Integration of System Components

The effectiveness of EVACo-Aid relies on the coordinated operation of its hardware and software components. Each subsystem contributes a specific function, including sensing, actuation, control, and communication. Evaluating component-level functionality is essential to confirm system integration and reliability.

The roles and operational functions of each component are detailed in Table 3, illustrating how individual elements contribute to overall system performance.

Table 3. Functional description of EVACo-Aid system components.

Component	Function
ESP32	Manages IoT communication and sensor data processing
Arduino Uno	Controls motors and basic sensor integration
Ultrasonic sensor (HC-SR04)	Detects distance and avoids obstacles
	Detects fire source and sends signal to ESP32 for extinguishing
Motor driver (L298N)	Regulates speed and direction of DC motors
Motor DC x 4	Drives robot (forward, backward, turn)
Relay	Automatically activates water pump
Water pump	Sprays water for fire extinguishing
Robot chassis	Mechanical structure to house all components and provide movement stability
AI webcam based on Pictoblox (Under development)	Visually detects hurnans
IoT module / Wi-Fi	Sends sensor data and robot sttatus to real-time monitoring dashboard

The component analysis confirms that sensor inputs, control logic, mechanical actuation, and IoT communication operate cohesively. The modular architecture allows individual components to perform dedicated tasks while supporting system-level autonomy. This design approach enhances maintainability and provides flexibility for future upgrades, such as additional sensors or alternative communication modules.

Integrated System Performance Discussion

When considered collectively, the results demonstrate that EVACo-Aid achieves its intended design objectives. Energy consumption remains manageable for indoor missions, functional integration is stable, and operational comparisons indicate a clear benefit in terms of safety support and situational awareness.

However, limitations remain. Battery capacity constrains operation time during extended suppression tasks, and system effectiveness depends on environmental conditions such as signal interference and surface accessibility. These findings highlight the importance of positioning EVACo-Aid as a supportive reconnaissance and early-response platform, rather than a standalone firefighting solution.

4. CONCLUSION

This study presented the design, development, and experimental evaluation of EVACo-Aid, a compact robotic platform intended to support indoor fireground operations through early hazard assessment, navigation assistance, and initial fire suppression. The results demonstrate that the proposed system is capable of operating autonomously within confined environments while providing meaningful support to emergency responders.

Experimental testing shows that EVACo-Aid achieves a balanced energy profile, enabling sustained sensing and navigation activities while reserving higher power consumption for targeted suppression tasks. This operational characteristic supports the system's intended role as a reconnaissance and early-response tool rather than a continuous suppression platform. Functional evaluation further confirms that the integration of sensing, actuation, and communication components enables coordinated system behaviour under indoor test conditions.

Comparative analysis of operational conditions before and after EVACo-Aid deployment indicates measurable improvements in situational awareness and response readiness. By enabling remote assessment of fire presence and environmental conditions, the system reduces the immediate need for human entry into hazardous spaces and supports more informed decision-making during the initial stages of an incident. These improvements align with the objective of minimizing responder exposure while maintaining operational effectiveness.

Despite these advantages, several limitations were identified. The system's operational duration is constrained by battery capacity during extended suppression activities, and its performance remains dependent on environmental factors such as surface accessibility and wireless communication stability. Additionally, the current prototype operates on wheeled locomotion, which may limit effectiveness in debris-dense or structurally compromised environments.

Future work will focus on enhancing energy management, improving mobility across uneven terrain, and expanding sensor capabilities for more robust victim detection and environmental assessment. Integration with advanced navigation strategies and adaptive control methods may further improve system autonomy and resilience in dynamic fireground conditions.

Overall, EVACo-Aid demonstrates the feasibility of a cost-effective, sensor-integrated robotic assistant for indoor fire rescue support. While not intended to replace human responders, the system contributes to improved situational awareness and risk reduction, offering a practical step toward safer and more informed fireground operations.

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