

Design of an Autonomous Guardian Robot for Fire and Hazard Detection to Enhance Resilience and Business Continuity

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Abstract. Fires remain a critical hazard with severe implications for safety, continuity of operations, and the protection of assets in both residential and commercial environments. Traditional detection systems, typically based on fixed sensors, provide limited coverage and cannot adapt to dynamic or obstructed spaces. This limitation has major consequences not only for individual safety but also for the continuity of essential services and the resilience of organizations and communities. Recent advances in mobile robotics highlight new opportunities for hazard detection and risk monitoring. However, most existing platforms are complex, costly, and primarily designed for industrial settings. This paper proposes the conceptual design of a compact, affordable, and autonomous mobile robot capable of detecting environmental hazards such as smoke, high temperature, toxic or flammable gases, and visible flames. The platform integrates multimodal sensing (LiDAR, gas/smoke sensors, temperature sensors, camera) with real-time data processing supported by a Raspberry Pi and STM32 microcontroller, while a dedicated web application provides instant alerts and situational awareness. The research adopts a design-oriented methodology, focusing on system modelling, component integration, and feasibility analysis through CAD simulations. Results indicate that the proposed robot can contribute to fire prevention, crisis management, and business continuity by enhancing early warning and enabling timely response. Although designed for small-scale environments such as homes and offices, its scalable architecture suggests potential applicability in critical infrastructure protection, where resilience and continuity of operations are essential. The contribution of this research lies in bridging robotics, embedded systems, and resilience studies, providing a framework that can support both academic research and practical innovation in disaster risk reduction and safety-critical systems.

Keywords: autonomous robot, fire detection, disaster risk reduction, resilience, business continuity management, crisis management, critical infrastructure

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Introduction

Fires represent a major risk to human safety, material assets, and organizational continuity, with severe consequences in residential, commercial, and industrial environments. Beyond their immediate destructive impact, fire incidents can disrupt business operations, affect the delivery of essential services, and compromise the resilience of communities. In the broader context of crisis management and disaster risk reduction, rapid prevention and detection of fires remain a priority, with direct implications for business continuity management (BCM) and the protection of critical infrastructure.

Traditional fire detection technologies rely on fixed systems—typically installed on ceilings or in key areas of buildings—that use smoke and temperature sensors. While these systems are cost-effective and easy to install, they present significant limitations. They provide coverage only in predefined areas, are unable to adapt to complex or obstructed environments, and cannot detect sources of fire or smoke in inaccessible spaces. These limitations reduce their effectiveness in ensuring continuous protection and resilience, especially in dynamic environments where operational continuity is crucial.

In parallel, recent research has explored the use of mobile robots for patrolling and fire detection. Such systems integrate autonomous navigation with environmental sensing through smoke detectors, thermal cameras, and advanced mapping algorithms. Although promising, most of these solutions are designed for large-scale or industrial environments where human access is hazardous. They are often costly, bulky, and difficult to maintain, limiting their

applicability in smaller settings such as homes, offices, or small commercial spaces. Moreover, much of the experimental literature focuses on navigation algorithms without sufficiently addressing the integration of practical, affordable, and multimodal sensors for detecting real risk factors such as smoke, high temperature, or flammable gases.

This reveals a gap in the literature concerning the development of compact, accessible, and flexible robotic solutions that can operate efficiently in everyday scenarios while supporting resilience and crisis management objectives. Addressing this gap requires combining mobility with multimodal sensing capabilities, thereby offering extended spatial coverage and adaptability to diverse environmental conditions.

In this context, the present research proposes the design of an autonomous guardian robot for fire and hazard detection, conceived as a scalable and cost-effective platform. The robot integrates LiDAR for mapping and obstacle avoidance, a video camera for visual flame recognition, and environmental sensors for smoke, gas, and temperature monitoring. A Raspberry Pi microcomputer coordinates sensor data processing and communication with a dedicated web application, while an STM32 microcontroller manages low-level sensor readings and motor control. This architecture ensures real-time monitoring, user notifications, and situational awareness.

Beyond its technical design, the system aims to contribute to resilience and continuity by providing early detection of hazards, real-time alerts, and rapid intervention support. Although primarily intended for small-scale environments, such as apartments, offices, or public buildings, the platform demonstrates potential applicability in the broader field of critical infrastructure protection, aligning with contemporary efforts in disaster preparedness, crisis management, and sustainable business continuity.

The research presented in this paper is guided by the following question: *How can an autonomous mobile robot contribute to fire and hazard detection in a way that strengthens resilience and supports business continuity management?* From this question, three working hypotheses are formulated:

H1: An autonomous guardian robot equipped with multimodal sensing technologies (LiDAR, gas/smoke, temperature, and visual detection) can provide more effective fire and hazard detection compared to traditional fixed systems.

H2: The proposed design contributes to organizational resilience and community by enabling early warning, timely intervention, and continuity of operations in the event of fire or environmental hazards.

H3: Although primarily conceived for small-scale environments, the scalability of the platform demonstrates potential applicability in broader crisis management contexts, including critical infrastructure protection.

Literature review

Mobile robotics and hazard detection

Recent advances in mobile robotics have significantly expanded the range of applications for autonomous systems in safety-critical environments. Fire detection robots, in particular, combine navigation algorithms with multimodal sensing (e.g., LiDAR, thermal imaging, smoke and gas sensors) to provide early warning and reduce disaster risks. Studies emphasize the potential of simultaneous localization and mapping (SLAM) in supporting autonomous navigation in complex environments, enabling robots to patrol, identify hazards, and generate spatial awareness in real time [1]. Research also highlights the integration of computer vision and machine learning algorithms to improve flame recognition and reduce false alarms [2]. While these approaches demonstrate high technological potential, most systems are developed for large-scale industrial applications, such as factories or warehouses, where human access is limited. Consequently, the literature still lacks compact, affordable, and easily deployable robotic platforms tailored to smaller environments such as residential or office spaces [3].

Resilience, business continuity and critical infrastructure

In parallel with technological research, the academic literature on resilience and crisis management stresses the importance of early detection systems in ensuring continuity of operations and protecting critical infrastructure. The concept of resilience is defined as the ability of systems to anticipate, absorb, adapt, and recover from disruptive events [4]. In the context of business continuity management (BCM), rapid hazard detection directly supports operational continuity by reducing downtime, preventing material losses, and protecting human lives [5]. Fire incidents are frequently cited among the disruptive scenarios that can affect critical infrastructure sectors such as energy, transport, and public safety [6]. Reports from the OECD [7] and UNDRR [8] underline that integrating intelligent technologies into early-warning systems enhances disaster risk reduction and contributes to more resilient organizations and communities.

Nevertheless, despite the clear link between hazard detection and resilience, the majority of robotic solutions reviewed in the literature remain disconnected from the strategic frameworks of BCM and critical infrastructure protection. They are often evaluated only from a technical perspective (navigation accuracy, sensor performance), without addressing their role in organizational continuity or crisis management. This research seeks to bridge this gap by exploring how an autonomous guardian robot, designed for hazard detection, can be positioned not only as a technological innovation but also as a resilience-oriented solution aligned with BCM principles.

Methodology

Although the current work focuses on conceptual modelling and system integration, the next phase of the research includes prototype implementation and experimental validation. The prototype will be tested in controlled indoor environments that simulate hazard conditions (smoke, elevated temperature, and gas presence). The evaluation will focus on quantitative performance indicators such as detection latency (time between hazard occurrence and alert generation), false-positive and false-negative rates for smoke, gas, and flame detection, navigation reliability during autonomous patrolling (path completion and obstacle avoidance performance), end-to-end alert transmission time through the web application, and battery autonomy during continuous monitoring. These metrics will provide objective evidence of the robot's feasibility and will strengthen methodological rigor by validating the contribution of the system to risk reduction and business continuity..[4][5][8]

Robot hardware structure

The hardware architecture was designed to ensure robust hazard detection while maintaining compactness, affordability, and scalability. The central control system integrates a Raspberry Pi single-board computer, responsible for high-level data processing, image recognition, and communication, and an STM32 microcontroller, which handles low-level sensor readings and motor control. This layered design ensures a reliable separation between computationally intensive tasks and time-critical hardware functions.[10][11]

Navigation and spatial awareness are supported by a LiDAR module, which enables simultaneous localization and mapping (SLAM) and obstacle avoidance. LiDAR-based mapping provides greater precision than ultrasonic sensors and supports autonomous exploration of complex environments.[1][2] Environmental monitoring relies on a multimodal sensor suite: smoke and gas detectors (MQ-series), a temperature sensor (DHT22), and a video camera for flame recognition.[2][9] Together, these components enable early detection of fires and hazardous gases, directly supporting risk reduction and continuity of operations in case of emergencies.

For mobility, the robot is equipped with a compact chassis powered by DC motors and controlled through H-bridge drivers. A rechargeable Li-ion battery ensures autonomy for continuous patrolling and monitoring. The modular hardware structure allows for future upgrades, such as the integration of additional sensors or communication modules, thus supporting scalability and adaptation to different operational contexts, including critical infrastructure facilities.

Robot software structure

The software architecture follows a modular design, combining navigation, environmental monitoring, data integration, and user communication. The obstacle avoidance and mapping system is based on LiDAR data processed through SLAM algorithms, enabling the robot to adapt dynamically to new environments and navigate autonomously.

Visual processing is implemented through the onboard camera and OpenCV libraries, allowing the system to recognize visible flames. This complements environmental sensor data, reducing false positives and strengthening overall system reliability. Sensor readings collected by the STM32 microcontroller are transmitted in real time to the Raspberry Pi for integration and risk-level assessment.

Communication and situational awareness are ensured through a dedicated web application connected via Wi-Fi. The application displays real-time environmental parameters, generates alerts in case of anomalies (smoke, gas concentration, flame detection, high temperature), and provides users with GPS coordinates of identified hazards.[4][12] This feature directly supports rapid crisis response and continuity planning, as timely alerts allow stakeholders to minimize damage and maintain operations.

The software also includes a basic security layer, with authentication protocols and encrypted communication channels, reflecting the importance of cybersecurity in resilience and critical infrastructure protection. The modular architecture ensures scalability, allowing for integration with Internet of Things (IoT) networks or connection to centralized monitoring platforms.[4][5][12]

Results and further discussions

This section presents the results of the work performed, the obtained results, as well as opportunities for future research and possible future developments, conceptually grouped as shown below.

Project status and CAD validation.

The project is currently in the conceptual modelling phase and has been fully developed in a CAD environment (Fusion 360 – Figure 1).

The hardware schematic is complete, covering the strategic placement of gas, smoke, and temperature sensors, the integration of the STM32 microcontroller with the Raspberry Pi module, and the configuration of the mobility components. The 3D model supports spatial evaluation, early detection of mechanical interferences, wiring routes, heat-dissipation constraints, and design optimization for subsequent prototyping. Figures 1–4 provide an integrated view of the system, as presented further.

Figure 1: 3D Design in Fusion
Source: Author's own contribution

Figure 2 illustrates the logical interaction between hardware and software modules, emphasizing the data flow from sensing to decision-making and communication. Each block represents a functional component of the system, and the arrows indicate how sensor data is propagated toward processing, fusion, and alert generation. The diagram highlights the separation of responsibilities between low-level embedded control (STM32) and high-level perception and network communication (Raspberry Pi), showing how multimodal inputs are aggregated, interpreted, and transmitted toward the web application for real-time monitoring and alerting.

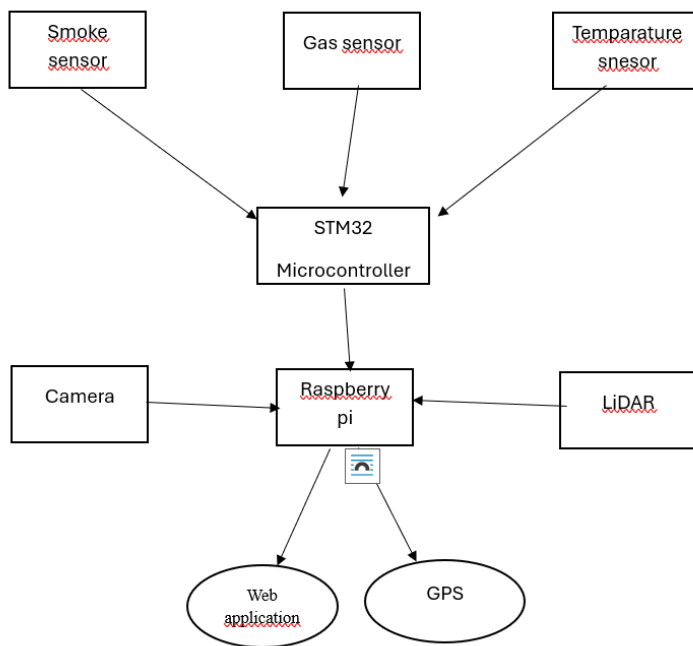


Figure 2: Component Diagram
Source: Author's own contribution

Legend

Hardware Component = 
Software Component = 

System architecture and data flow

The solution follows a layered architecture: (i) sensing & actuation (smoke, gas/alcohol MQ-series, temperature DHT22 or similar; camera; LiDAR; DC motors via H-bridges), (ii) embedded control (STM32 for low-latency sensing and motor control), (iii) edge processing & communications (Raspberry Pi for integration, perception and networking), and (iv) user layer (web application for monitoring and control). Data flows from sensors → STM32 preprocessing →

Raspberry Pi fusion & risk assessment → secure transmission to the backend → frontend visualization and alerts. LiDAR over UART supplies scan data for SLAM-based mapping and obstacle avoidance [1][2]; the CSI camera stream supports visual flame recognition with OpenCV and live video [2][9][10]. GPS tagging enables precise localization for response teams. This pipeline is designed for real-time operation, supporting early warning and situational awareness, which are essential for crisis response and continuity of operations.

In figure 3 there is presented the Connection diagram, with environmental sensors and communication modules, while in figure 4 there is presented the Connection diagram of Raspberry Pi with LiDAR and camera.

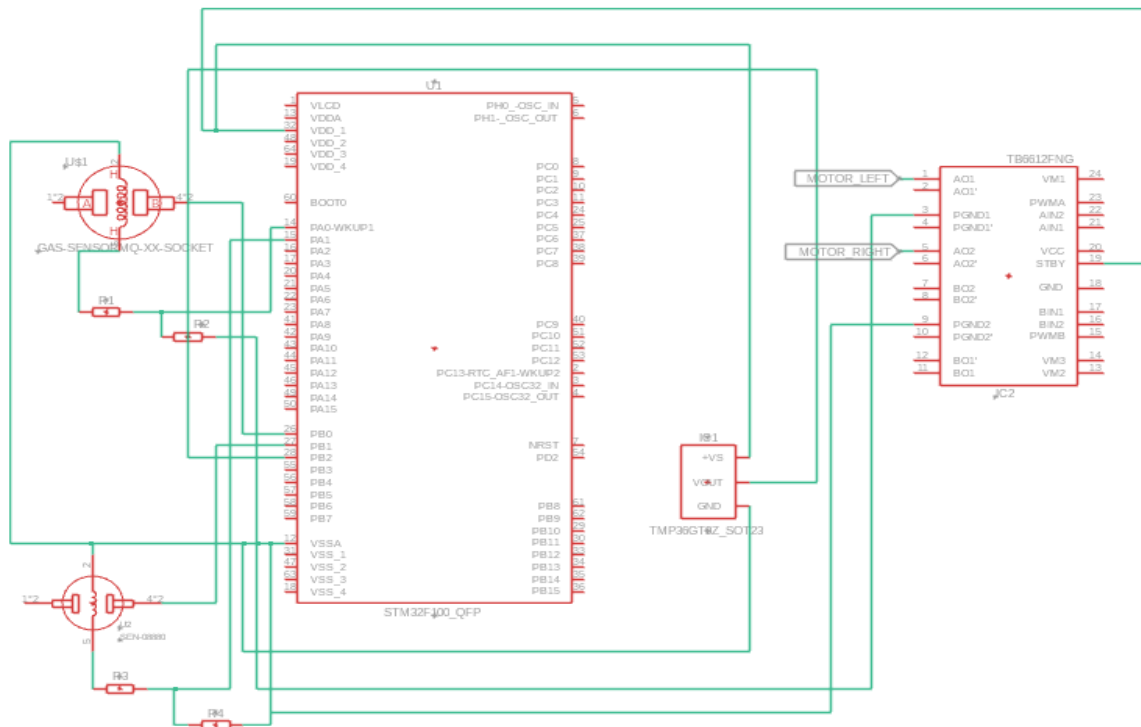


Figure 3: STM32 Connection Diagram with Environmental Sensors and Communication Modules
Source: Authors' own contribution.

Technical brief description - interfacing and connectivity

The Raspberry Pi exposes GPIO power rails (5V/3.3V), GND, and digital I/O needed for peripherals. The LiDAR module interfaces via UART (TX/RX) on GPIO 14/15, streaming scan data for 2D mapping and obstacle avoidance. The camera connects over the CSI interface and is used both for flame recognition (OpenCV-based) and live video streaming to the user layer. The STM32 aggregates smoke/gas/temperature readings and wheel encoder data and exchanges messages with the Raspberry Pi via UART/I²C/SPI depending on bandwidth and latency needs. A GPS module provides geo-coordinates of detected hazards, enabling precise localization for rapid intervention.

Robot software structure

Autonomous navigation uses LiDAR-based SLAM to generate a local map, plan safe paths, and adapt to dynamic layouts. Visual processing complements environmental sensing: flame-like regions are detected with color/shape/temporal cues, reducing false positives when combined with smoke/temperature thresholds. Sensor fusion on the Raspberry Pi computes a risk level from multimodal inputs (gas concentration, smoke density, temperature gradients, visual cues), triggering alerts when thresholds are exceeded and logging raw features for traceability. The STM32 firmware is responsible for deterministic timing in motor control and debounced sensor acquisition, ensuring stable closed-loop behavior even under computational load on the Pi.

Web application – user interface

The client-server web application constitutes the primary interface for real-time monitoring, map visualization, and alerting. It displays live streams of gas/smoke/temperature values, renders the SLAM map together with the robot's pose, and issues instant notifications when smoke, elevated temperature, gas presence, or visible flames are detected; in addition, operators can send basic tele-commands (emergency stop, reset, start scan) and review an event log for auditability. Security controls—authenticated access, HTTPS transport encryption, and backend validation—along with

support for standard notification services, enable scalability (multi-robot operation, cloud integration) and align with resilience/continuity expectations in safety-critical or regulated environments [4][5][12].

Architecturally, the application follows a client–server model with a lightweight backend that ingests data from the robot, applies rule-based alerting, and maintains historical storage, and a responsive frontend that provides visualization and operator control. This separation supports responsive user interaction while preserving deterministic processing on the server side, and it facilitates deployment in on-premises or cloud settings as required by organizational continuity plans [4][12].

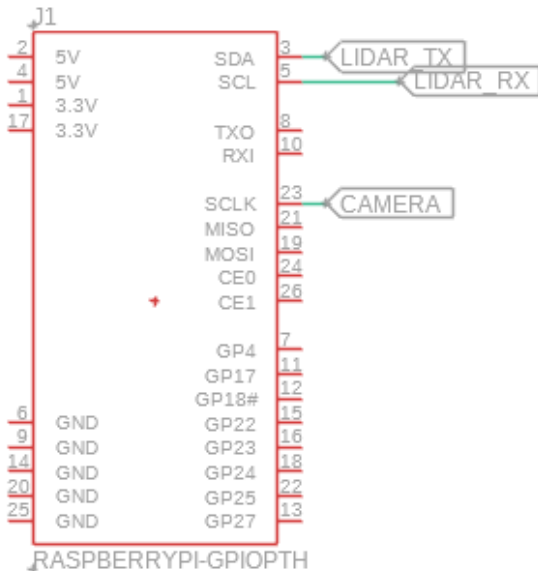


Figure 4: Connection Diagram of Raspberry Pi with LiDAR and Camera
Source: Author's own contribution

The end-to-end data flow proceeds from STM32 sensor acquisition to Raspberry Pi fusion and risk assessment, which forwards structured messages to the backend for final analysis and alert decisions; the frontend then renders dashboards and notifications for the operator in real time. This pipeline reduces bandwidth by transmitting fused features rather than raw streams, maintains low latency for time-critical alerts, and preserves traceability through event logging suitable for audits and post-incident review [10][11][12].

From a security and scalability standpoint, the system implements token-based authentication (e.g., JWT or Firebase Auth), TLS/HTTPS for all external communications, payload validation and rate-limiting at the backend, and multi-tenant handling for multiple robots under a single supervisory interface. Optional cloud integration enables centralized monitoring and advanced analytics (trend detection, anomaly scoring), which can strengthen early-warning capabilities and align the solution with resilience and business-continuity requirements, including those applicable to selected critical-infrastructure contexts [4][5][12].

Feasibility assessment

Although no physical tests have been conducted yet, the functional analysis of components and the defined data path confirm implementation feasibility. The selected toolchain (STM32, Raspberry Pi, OpenCV) is mature and well-documented, reducing integration risk and supporting cost-effective deployment in small-scale environments [9][10][11].

Implications for resilience and business continuity.

By extending coverage beyond fixed detectors, the robot helps mitigate blind spots, enhances early warning, and improves situational awareness through mobile sensing, live video, and geo-tagged alerts. These capabilities support BCM objectives—shorter detection-to-response cycles, reduced downtime, protection of personnel/assets—key outcomes in BCM and disaster risk reduction [4][5][7][8]. While designed for homes/offices, the modular architecture of the robot suggests transferability to critical-infrastructure contexts (annex buildings, service corridors, warehouses), where rapid detection and localized reconnaissance can support crisis management and continuity of operations [5][6].

Limitations and future work.

Key challenges for the next phase include energy consumption and battery autonomy, wireless link robustness in cluttered RF environments, cybersecurity hardening (device identity, secure boot, OTA updates), sensor calibration to minimize false alarms, and field validation across diverse layouts and airflows.

Future work will address software-in-the-loop/ hardware-in-the-loop simulations, build a physical prototype, and design controlled experiments to quantify detection latency, false-positive/false-negative rates, navigation reliability, and end-to-end alert time—metrics that map directly to resilience KPIs in BCM [4][5].

Conclusions

This paper proposed the design of an autonomous guardian robot for fire and environmental hazard detection, conceived as a compact, affordable, and scalable platform. The research addresses a documented gap in the literature—namely the lack of deployable, multimodal, small-form-factor robotic solutions suitable for residential, office, and small public spaces [1][2][3]—while positioning the solution within a broader resilience, business continuity management (BCM), and crisis management perspective [4][5][7][8]. The conceptual model was specified and validated at design level through CAD modelling (Fusion 360), a complete hardware schematic (sensor placement; STM32–Raspberry Pi integration; mobility), and a software architecture integrating LiDAR-based SLAM, computer vision for flame recognition, sensor fusion for risk assessment, and a web application for real-time monitoring, alerts, and auditability [1][2][9][10][11][12].

From a resilience perspective, the results suggest that mobile sensing complements fixed detectors by mitigating blind spots and enhancing early warning and situational awareness—capabilities that support disaster risk reduction agendas [7][8]. The system’s ability to generate geo-tagged alerts, stream live video, and expose a SLAM map supports faster detection-to-response cycles and aligns with continuity objectives (reducing downtime, protecting people and assets) [5]. Although primarily intended for small-scale environments, the modular architecture and security controls (authentication, encrypted transport, backend validation) indicate transferability toward selected critical-infrastructure contexts (e.g., annex buildings, service corridors, storage areas), where rapid reconnaissance can strengthen incident handling [5][6][12].

This paper also contributes methodologically by presenting a layered, replicable design that separates time-critical embedded control (STM32) from edge perception and communications (Raspberry Pi) [10][11], and by formalizing a data-flow pipeline (sensors → fusion/assessment → secure backend → user layer) that can be adapted to different operational needs [12]. Beyond engineering value, this provides an interdisciplinary framework at the intersection of robotics, embedded systems, and organizational resilience, with educational utility for training and prototyping in safety-critical applications [4].

Several limitations remain. The current work is a conceptual and architectural validation; no physical experiments have yet quantified detection latency, false-positive/false-negative rates, navigation robustness, battery endurance, or end-to-end alert times. Practical deployment will require attention to energy management, wireless robustness in cluttered RF environments, cybersecurity hardening (device identity, secure boot, update mechanisms), sensor calibration to reduce nuisance alarms, and privacy considerations when using cameras in occupied spaces—constraints typical of safety-critical systems that must be systematically addressed before operational use [4][5].

Future research will focus on prototype implementation and controlled testing across diverse layouts and airflow conditions, deriving quantitative performance metrics that map to resilience KPIs in BCM (e.g., mean time to detect, mean time to alert, continuity impact) [5]. Additional work will explore multi-robot coordination, integration with building management systems (for automated responses such as HVAC shutdown or zoned warnings), dataset curation for robust flame/non-flame classification [2], and cost–benefit analyses to evaluate the business case for adoption in small enterprises and selected critical-infrastructure facilities.

Overall, the proposed architecture demonstrates technical feasibility and resilience-oriented value: a compact, multimodal, and networked robotic platform that can enhance early detection, support crisis response, and contribute to business continuity—laying the groundwork for a practical, evidence-based pathway from conceptual design to operational prototypes and, ultimately, to resilient deployments in real-world environments [4][5][7][8].

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