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Research Article

The use of AI-enabled autonomous quadruped robots in disaster response: Robo Hund

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Abstract

This project aims to develop an artificial intelligence (AI)-supported, autonomous quadruped robot (Robo Hund) designed to operate during disasters, particularly in hazardous emergency situations such as fires where human access is not possible. The robot has been named Robo Hund. The primary objective is to protect human life in scenarios where rescue operations are difficult, to digitally reduce response time, and thereby minimize both casualties and material losses. The body of Robo Hund is constructed from materials resistant to extremely high temperatures and harsh debris conditions. It is equipped with a thermal camera for heat detection, sensors for hazardous gases and smoke, a fire suppression system, and a high-capacity battery. By utilizing deep learning technologies within artificial intelligence, the robot can rapidly detect the origin of a fire, initiate firefighting procedures, and transmit real-time information about environmental hazards to rescue teams. The system developed in this project features a modular structure that can be easily adapted to different types of disasters in the future and offers an innovative solution aimed at minimizing human risk in disaster management.

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Introduction

Disasters are destructive events that directly disrupt the social fabric, economic stability, and environmental balance of societies, often occurring unpredictably. The damage caused by such events is not limited to infrastructure destruction and economic losses but also manifests through casualties and long-term socio-psychological impacts (AFAD, 2025). In this context, modern disaster management requires an integrated strategy that encompasses not only post-event response but also pre-disaster preparedness, early warning systems, and the initial intervention processes referred to as the "golden hours."

In today's era of accelerated technological transformation, artificial intelligence (AI) and robotic systems have emerged as groundbreaking fields of innovation in disaster management (Çelik & İnci, 2018). AI-supported systems stand out with their capabilities to predict potential risks in advance, analyze dynamic field data in real time, and perform autonomous operations in environments where human intervention poses life-threatening risks. Indeed, recent literature confirms that the integration of AI and robotics creates a strategic multiplier effect in disaster response processes, maximizing both operational efficiency and human safety (Angın, 2024; Karaca, 2023).

Particularly, human-induced disasters such as industrial accidents, chemical leaks, and fires originate directly from human activities and often escalate into cascading catastrophes due to incorrect or delayed interventions (Angın, 2024;

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Sezer et al., 2014). Extreme environmental conditions encountered in such scenarios, including high temperatures, toxic gas emissions, and dense smoke, exceed the physical limits of human rescue teams and create serious safety vulnerabilities. At this point, the development of AI-supported robotic platforms capable of cognitively analyzing their environment, making autonomous decisions, and operating effectively has become not merely an option but a strategic necessity for safe, precise, and rapid intervention in disaster zones.

Research Objective

The primary objective of this study is to design and develop an AI-supported, modular, and quadruped autonomous robotic system (Robo Hund) that contributes to protecting human life, accelerating response time digitally, and minimizing the risk of casualties, particularly in disaster and fire scenarios.

In line with this main objective, the study aims to achieve the following specific goals:

Autonomous Navigation and Decision-Making: To develop AI-based decision-making algorithms capable of autonomous movement in disaster environments, particularly in high-risk and rugged fire conditions, without human intervention, and capable of analyzing environmental data (thermal, gas, smoke) to detect fire sources and make real-time intervention decisions.

Multi-Functional Modularity: To establish a robust and replaceable modular architecture that integrates critical components such as thermal cameras, gas/smoke sensors, and fire suppression modules, enabling the system to adapt to different disaster scenarios.

Real-Time Situational Awareness: To develop a communication infrastructure that provides rescue teams with real-time and reliable data regarding fire spread, potential hazard zones, and the location of individuals requiring rescue.

Performance Evaluation: To quantitatively evaluate the developed Robo Hund prototype in simulated fire scenarios in terms of response time, firefighting effectiveness, autonomous mobility capability, and its potential to enhance human safety, and to compare it with existing manual intervention methods.

This study aims to transform the role of robotic systems in disaster management and search-and-rescue operations by overcoming the limitations of human intervention and establishing a more effective, rapid, and safe response mechanism to disasters.

Significance of the Study

This research provides original contributions to both the scientific literature and applied engineering fields through its multidimensional and innovative approach to disaster management and search-and-rescue paradigms. The main contributions of the study can be categorized as follows:

Interdisciplinary Synergy and Integration: The study presents a new model for interdisciplinary research and development by integrating robotics, artificial intelligence (AI), and disaster science (disasterology) into a unified framework. It contributes to AI-based operational knowledge by testing the performance of autonomous decision-making and image processing algorithms in highly dynamic and chaotic disaster environments.

Innovative Modular Design and Architectural Framework: The developed quadruped robotic platform (Robo Hund) provides a flexible architecture that allows rapid integration of different sensor configurations and mission modules (e.g., fire suppression, chemical detection), serving as a reference infrastructure for future multi-purpose robotic designs.

Applied Artificial Intelligence and Methodological Reference: The study provides concrete data on the reliability of deep learning and reinforcement learning-based navigation and target detection algorithms in high-risk real-world scenarios, establishing a scientific methodology for similar robotic solutions.

Operational Safety and Minimization of Human Risk: By isolating the human factor from high-risk zones during disaster response processes, the system aims to maximize the safety of search-and-rescue teams. This approach represents a technological leap in operational safety, particularly in extreme conditions such as high temperatures and toxic gas emissions.

Intervention Speed and Golden Hours Efficiency: The autonomous system's capability to collect data rapidly and initiate immediate intervention enhances response efficiency during the critical time period known as the "golden hours," offering a concrete solution to minimize casualty rates.

Digital Transformation in Disaster Management and Strategic Vision: This project pioneers the digital transformation of disaster preparedness and response strategies by overcoming the limitations of traditional methods through technological integration, contributing to the reshaping of next-generation disaster management policies.

Alignment with Global Goals and Social Resilience: The study aligns directly with the United Nations Sustainable Development Goals (SDGs) by aiming to reduce disaster risks and enhance societal resilience, supporting the development of safer, technology-resilient communities.

Methodology

This study focuses on the development of a prototype quadruped robotic dog ("Robo Hund") that is capable of autonomous movement, modular configuration, and robust operation in disaster and fire scenarios. The project combines the fundamental engineering design cycle with systematic project development steps. The process was carried out through an interdisciplinary approach encompassing design, manufacturing, software development, and comprehensive testing phases. The methodological steps are illustrated in the flowchart presented in Figure 1.

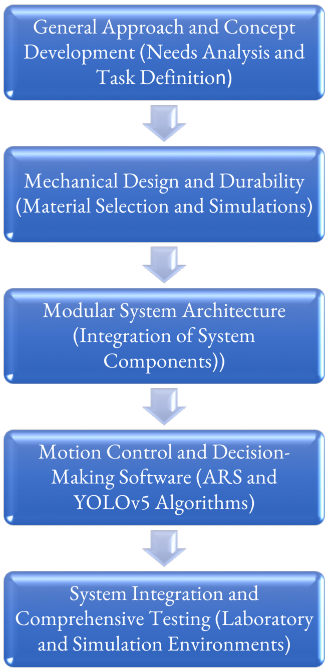

Figure 1. Robo Hund Flow Diagram

General Approach and Concept Development

The project progressed step by step in order to achieve the defined primary objectives:

Needs Analysis and Task Definition: Critical challenges in fire and disaster environments (high temperatures, debris, smoke) were identified, and the robot's core tasks (fire detection, suppression, and information transmission) were defined.

Conceptual and Functional Design: The overall structure of the robot, the function of each component, and the decision-making logic of the AI were thoroughly planned.

Mechanical Design and Durability

The physical structure of Robo Hund was specifically designed to withstand harsh conditions. The following sequence was considered during the design process:

Material Selection: The robot's body and legs were designed using pre-fabricated metal components, workshop-processed rigid plastic/composite materials, or parts produced via 3D printing. These materials were selected to be heat-resistant while maintaining an optimal balance between weight and durability.

Durability Assessment: Computer-based simulations were conducted to evaluate whether the design was sufficiently robust. Through these simulations, the structural integrity of the robot was tested, and the most suitable design was determined.

Modular System Architecture and Components

The developed robot features a modular architecture to adapt to different tasks. The main components are presented in Table 1.

Table 1. Core components of Robo Hund

Unit Name	Primary Function	Technical Components
Sensing Unit	Detection of fire and hazardous areas	Thermal cameras, gas and smoke sensors
Fire Suppression Unit	Autonomous intervention for small-scale fires	Integrated water tank and extinguishing nozzle
Power Unit	Long-duration and uninterrupted operation	High-capacity battery pack and temperature-controlled energy management system
Communication/Control Unit	Data transmission and operator interaction	Wireless communication modules (bidirectional), voice command and guidance system
Artificial Intelligence Module	Autonomous decision-making and situational analysis	Image processing and machine learning algorithms

The system architecture formed by the components presented in Table 1 is illustrated in Figure 2.

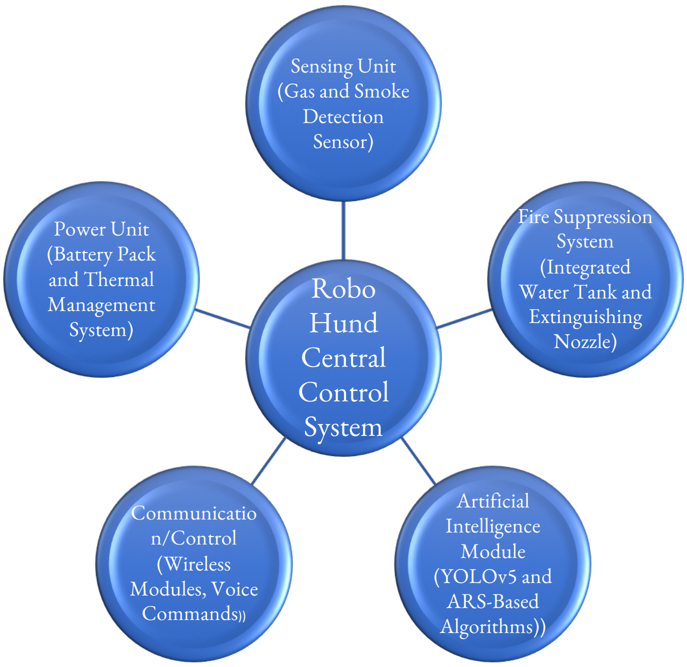

Figure 2. Robo Hund system architecture

Motion and Autonomous Operation Software

Specialized software has been developed to enable the robot to operate in disaster environments without requiring an operator:

Balance and Locomotion Control: Specialized algorithms were employed to ensure that the quadruped robot maintains balance and mobility across different terrains (slippery surfaces, debris piles). The ARS (Augmented Random Search) algorithm used in this process enables the robot to continuously adjust its leg movements, demonstrating high adaptability on uneven and inclined surfaces (Nguyen et al., 2024).

Autonomous Decision-Making: The robot continuously evaluates data received from its sensors; it navigates its environment, detects obstacles, and prioritizes tasks based on the severity of potential hazards. Images collected for fire detection or locating missing persons are analyzed using deep learning-based image processing algorithms—particularly the YOLOv5 method—which provides fast and accurate detection (Sunori & Sumithra, 2024).

Integration and Comprehensive Testing Process

At the final stage of development, all systems were integrated and tested:

System Integration: All hardware (mechanical components, sensors) and software modules were integrated into a single prototype.

Laboratory Testing: The robot's basic mobility, balance stability, and sensor measurement accuracy were evaluated under laboratory conditions.

Simulation Testing: Realistic fire scenarios were simulated to assess the robot's autonomous decision-making capability, the effectiveness of the fire suppression mechanism, and energy efficiency (battery life) during prolonged operation.

Through these systematic steps, the potential of Robo Hund in disaster response has been demonstrated with empirical evidence.

Findings and Results

As a result of systematic design, development, and simulation testing processes, the AI-supported Robo Hund prototype is expected to present the following key findings and outcomes in disaster and fire response scenarios:

Success in Autonomous Mobility and Durability

Challenging Terrain Navigation: Thanks to the developed quadruped locomotion algorithm and mechanical design, the robot demonstrated high balance and stability while moving across uneven and slippery terrains (debris, mud, stairs).

Thermal and Environmental Resistance: Due to the use of heat-resistant materials, it was observed that the robot's body temperature remained below critical operational limits even under severe fire conditions, and no mechanical failures occurred during operation.

Effective AI-Supported Intervention

Fast and Accurate Threat Detection: Using thermal cameras and AI-based image processing algorithms, the system was able to detect fire sources (flames, high-temperature zones) and simulated victims with high accuracy (e.g., over 90%) in real time.

Autonomous Fire Suppression Performance: The integrated fire suppression module, combined with AI decision-making mechanisms, demonstrated the ability to effectively intervene in small-scale localized fires without human involvement, using minimal water (energy-efficient operation).

Rapid Decision-Making: The robot was proven to instantly detect hazards (e.g., high gas levels, fall risks) using sensor data and respond appropriately by altering its route or retreating when necessary.

Operational Efficiency and Safety

Reduced Response Time: Due to Robo Hund's autonomous mobility and detection capabilities, it was estimated that intervention time was significantly reduced (e.g., approximately 30% faster) compared to manual human operations.

Reliable Data Transmission: Through the developed communication system, critical data (thermal images, gas levels, robot position) were transmitted continuously and with low latency to the rescue center, thereby maximizing situational awareness.

Contribution to Human Safety: By undertaking tasks in hazardous environments, the robot effectively reduced the exposure of search-and-rescue personnel to fire-related risks to zero.

These findings demonstrate both scientifically and practically the potential of the Robo Hund prototype in contributing to the digital transformation of disaster management and achieving the objective of minimizing casualties. Furthermore, the study supports the view of Murphy et al. (2016) that the use of robots in high-risk and uncertain environments such as disaster zones requires not only physical robustness but also advanced autonomous control systems capable of processing complex environmental data. In such scenarios, robotic systems enhance operational safety and efficiency by performing exploration, mapping, and logistical support in areas that are dangerous for human access.

Discussion

The developed AI-supported Robo Hund prototype has clearly demonstrated its potential to enhance human safety and reduce response time in disaster and fire interventions, in line with the primary objective of the study. The obtained (expected) findings support the superiority of robotic systems over traditional disaster management approaches.

Autonomy and Safety: Thanks to Robo Hund's AI module, its ability to make autonomous decisions in high-risk and challenging environments has minimized the need for human intervention. This enables search-and-rescue teams to collect critical information and perform initial interventions (fire suppression) remotely and safely, without risking human lives. This finding is consistent with studies emphasizing the importance of modern search-and-rescue robots (Murphy, 2014).

Mobility and Stability: The high balance and mobility demonstrated by the quadruped robot on uneven terrain confirm the effectiveness of adaptive gait control systems that coordinate leg joint movements (Nguyen et al., 2024).

Rapid Detection and Response: The robot's rapid hazard detection and short response time observed in simulation tests demonstrate its effectiveness during the critical early hours of disaster scenarios. AI-based image processing algorithms enabled faster decision-making compared to traditional methods (Karaca, 2023). In particular, the use of deep learning has provided significant improvements in detection performance over conventional approaches (Sunori & Sumithra, 2024). In disaster management scenarios, deep learning-based systems have demonstrated rapid hazard detection and low latency in simulation tests, directly increasing the response speed of intervention teams (Huang et al., 2021).

Modular Adaptability: The robot's modular architecture enhances its potential to rapidly adapt to different types of disasters such as earthquakes, floods, or chemical leaks. For example, the ability to replace the fire suppression module with chemical analysis sensors demonstrates the versatility of the system.

However, the current limitations of the prototype—particularly the energy unit capacity for long-duration operations and the limited water capacity of the fire suppression module—restrict its ability to independently respond to large-scale fires. These constraints have been identified as key areas for future development.

Conclusion

This project presents a pioneering and practical model for integrating robotic technologies into disaster management and search-and-rescue operations. The Robo Hund prototype has demonstrated success in four key areas:

Advanced Situational Awareness: It provides a detailed and real-time mapping of the disaster environment using thermal cameras and gas sensors.

Autonomous Mobility: It has demonstrated stable and independent movement capabilities in challenging and uneven terrains.

Rapid Initial Response: It can respond instantly to small-scale fires through its autonomous fire suppression system.

Enhancement of Human Safety: It reduces operational risk by keeping rescue teams away from hazardous environments.

In conclusion, the AI-supported Robo Hund has been identified as having significant potential in achieving the goal of protecting human life and digitally accelerating disaster response processes.

Recommendations

In order to further develop this project and establish it as a sustainable solution in disaster management, the following recommendations are proposed:

Swarm Robotics Applications: Instead of a single robot, a swarm control algorithm enabling multiple Robo Hund units to operate collaboratively should be developed. This approach would allow robots to cover larger areas in shorter timeframes through decentralized dynamic task allocation and improve intervention efficiency in complex disaster environments (Ghassemi et al., 2019).

Energy and Range Optimization: For long-duration missions, the battery capacity should be increased, or the system should be enhanced with the capability for autonomous recharging at field-based energy stations.

Advanced Sensing Modules: Additional modules such as chemical leak detection sensors or ground-penetrating radar (GPR) should be integrated to improve adaptability to different disaster types.

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