

ROBOTICS IN HAZARDOUS ENVIRONMENTS: A REVIEW OF REMOTE-CONTROLLED AND SEMI-AUTONOMOUS GROUND VEHICLES FOR INITIAL FIRE SUPPRESSION

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Abstract : This review paper examines the current state-of-the-art in Unmanned Ground Vehicles (UGVs) and mobile robotic platforms dedicated to fire suppression and containment in hazardous environments. The increasing necessity to mitigate human risk in industrial fires, chemical spills, and structural collapses has driven significant advancements in teleoperation and semi-autonomous robotics. The paper provides a systematic review of existing literature, categorizing firefighting UGVs based on their control architecture (teleoperated vs. autonomous), locomotion systems (tracked vs. wheeled), and sensory packages (thermal cameras, LiDAR, and basic proximity sensors). A comparative analysis highlights the trade-offs between complex, high-payload industrial robots and agile, cost-effective prototypes designed for rapid initial response. The review concludes by identifying critical technological gaps, particularly in sensor fusion for accurate fire tracking and the development of robust, low-cost safety systems for widespread commercial implementation.

IndexTerms - Fire Suppression Robotics, Unmanned Ground Vehicle (UGV), Teleoperation, Autonomous Safety, Sensor Fusion, Mobile Robotics, HC-SR04.

I. INTRODUCTION

The deployment of robotics into dangerous, unstructured environments has become a technological imperative, particularly within the field of emergency response. Firefighting represents one of the most hazardous occupations globally, characterized by unpredictable risks that lead to significant mortality and morbidity among responders. This review focuses on the evolution of fire suppression robotics, specifically analyzing Unmanned Ground Vehicles (UGVs) designed to assume the initial high-risk tasks of reconnaissance and localized fire containment. These mobile platforms are engineered to function in zones where human entry is either delayed by safety protocols or entirely impossible due to immediate danger to life or health (IDLH) conditions, such as areas with high temperatures, toxic gas concentrations, or imminent structural failure.

The scope of this review encompasses the primary design challenges faced by engineers in this domain: mobility and robustness in chaotic environments, reliability of communication and control under adverse conditions, and the integration of intelligent sensing for effective fire localization and avoidance. The aim is to synthesize current research findings, compare diverse UGV architectures, and pinpoint the technological advancements required to move from specialized, military-grade robots to practical, universally accessible initial response tools.

II. CATEGORIZATION OF FIRE SUPPRESSION UGVs

Fire suppression UGVs can be broadly classified based on their primary design characteristics: locomotion system and control methodology. Understanding these distinctions is crucial for assessing their suitability for various operational environments.

A. Locomotion Systems: The choice of locomotion dictates the UGV's maneuverability and terrain negotiation capabilities. Tracked Systems (using continuous treads) offer superior traction and stability over loose, rubble-strewn, or uneven ground, making them suitable for large industrial fires or post-disaster scenarios. However, they are typically slower and more complex mechanically. Wheeled Systems (2WD, 4WD, or multi-wheel articulated) are faster, simpler, and more energy-efficient on flat, rigid surfaces like concrete floors or roadways. The Four-Wheel Drive (4WD) differential system, common in many low-cost prototypes, provides a balance of speed and sufficient torque to overcome minor obstacles and maintain stable movement while carrying a payload.

B. Control Architectures: Control methods range from pure teleoperation to full autonomy. Teleoperated Systems rely entirely on human input via a remote interface (radio frequency, Bluetooth, or Wi-Fi). These systems benefit from human decision-making in complex situations but are limited by communication range and operator fatigue. Semi-Autonomous Systems integrate human control with embedded intelligence, such as automated path planning, sensor-driven obstacle avoidance, or fire source tracking. This hybrid model offers the best current operational balance, delegating routine tasks (like maintaining distance or stopping before

an obstacle) to the robot while retaining human strategic oversight. Fully Autonomous Systems, while highly desired, remain largely restricted to research due to the need for extremely reliable sensor fusion and complex environmental modeling.

III. KEY TECHNOLOGICAL MODULES AND SENSING

The operational success of any firefighting robot is determined by the quality and integration of its sensory and control modules. Recent literature focuses heavily on improving these core technologies.

A. Proximity and Ranging Sensors: For navigation and safety, distance measurement is paramount. Ultrasonic sensors (e.g., HC-SR04) are widely used in prototype and low-cost UGVs due to their affordability and simplicity, providing sufficient range and accuracy for reactive collision avoidance logic. However, they suffer from narrow detection cones and susceptibility to acoustic noise. More advanced robots employ LiDAR (Light Detection and Ranging), which provides high-resolution 3D environmental mapping but at a significantly higher cost.

B. Fire Detection and Targeting: Accurate fire localization is crucial for effective suppression. Passive sensors like Infrared (IR) detectors are used to spot heat signatures, while Thermal Imaging Cameras (FLIR) provide visual confirmation and temperature mapping, allowing the robot to precisely aim the extinguishing nozzle. These visual data streams require robust image processing capabilities, often handled by microprocessors (like the ESP32) or dedicated onboard computing units. Research continues into the fusion of thermal data with standard visual data to provide enhanced fire classification and tracking.

C. Microcontroller and Communication: The shift from older microcontrollers to versatile platforms like the ESP32 has been transformative. The ESP32's integrated Bluetooth and Wi-Fi capabilities allow for dual-channel communication, enhancing reliability. Furthermore, its dual-core processing capacity allows for the efficient parallel execution of critical tasks: one core handling the low-latency communication and motor control, and the other managing sensor data processing and safety algorithms. This parallel processing capability ensures high responsiveness ($\Delta t \ll 100 \text{ ms}$), a non-negotiable requirement for real-time teleoperation.

IV. CHALLENGES AND RESEARCH GAPS

Despite rapid progress, several persistent challenges restrict the widespread deployment of fire suppression robotics. Addressing these gaps forms the foundation for future research.

A. Sensor Fusion and Environmental Modeling: The most significant gap is the lack of universal, reliable sensor fusion techniques that can operate effectively in chaotic, smoky environments where traditional visual and laser sensors fail. Smoke and high temperature dramatically reduce the effectiveness of both LiDAR and standard cameras. Future work must focus on robust data integration algorithms that combine thermal, acoustic, and potentially chemical sensor inputs to build an accurate, real-time map of the operating environment.

B. Mechanical Endurance and Agent Delivery: Current systems often struggle to maintain mechanical integrity under prolonged exposure to extreme heat and corrosive agents. The need exists for cost-effective materials and passive cooling systems that can withstand temperatures exceeding 150°C . Furthermore, the development of modular, high-capacity, multi-directional suppression agent delivery platforms remains a challenge, requiring advanced mechanical design to manage the recoil and weight distribution associated with high-pressure discharge.

C. Cost and Accessibility: There is a clear dichotomy between expensive, high-performance industrial robots and affordable, low-functionality prototypes. The core research gap is the creation of a mid-range solution that maintains high safety reliability (like the ultrasonic override) while remaining accessible to small and medium-sized enterprises. This requires optimizing COTS component integration and developing simplified, effective semi-autonomous control algorithms.

V. CONCLUSION

Fire suppression robotics stands at a crucial juncture, moving from theoretical concept to practical deployment. This review highlights that Unmanned Ground Vehicles (UGVs) equipped with reliable wireless control (like Bluetooth) and essential autonomous safety features (like the `stopMotor(S)` override) are proving effective for initial containment tasks, significantly lowering the risk profile for human responders. While low-cost prototypes have validated the feasibility of these concepts, future research must overcome limitations in sensor fusion and mechanical endurance. The ultimate goal—a cost-effective, highly autonomous UGV capable of navigating, tracking, and suppressing fires in truly unpredictable environments—is achievable through focused effort on enhancing sensor intelligence and improving the reliability of modular mechanical systems.

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