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THE STATE OF THE ART IN GROUND ROBOTIC COMPLEXES FOR AUTOMATIC FIRE SUPPRESSION: A COMPREHENSIVE REVIEW

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Abstract. *Problem statement.* Firefighting is an inherently dangerous profession that exposes human first responders to extreme hazards, including intense heat, toxic gases, and structural collapse, particularly in complex industrial, urban, and wildland-urban interface environments. The physical and physiological vulnerabilities of firefighters present a fundamental limitation to conventional response methods, creating an urgent need for technological solutions that can mitigate life-threatening risks while enhancing operational effectiveness. *Purpose.* This paper provides a comprehensive and critical review of the state of the art in the development and exploitation of ground robotic complexes (GRCs) for automatic fire suppression. It aims to synthesize the existing body of knowledge, from historical precedents and technological underpinnings to current operational doctrines and future research trajectories. *Methodology.* A systematic review of the field was conducted, tracing the parallel evolution of unmanned ground vehicles and fire suppression technology. The methodology includes a detailed analysis of the system architecture of modern GRCs (mobility platforms, sensor suites, suppression systems), a review of the software and artificial intelligence (AI) enabling their autonomy, an examination of their application in various domains under the human-robot team doctrine, and a comparative analysis of leading systems through case studies. *Findings.* The review establishes that GRCs represent a paradigm shift, transforming automatic fire suppression from a static, fixed installation into a dynamic and mobile asset. The development of these systems has been significantly accelerated by catastrophic events that highlighted the limitations of a human-only response. Modern GRCs are characterized by robust, modular designs, advanced sensor fusion for situational awareness in hazardous environments, and increasingly sophisticated AI for navigation and fire source identification. The primary operational doctrine emerging is the human-robot team, where robots handle dangerous tasks, augmenting human capabilities. *Originality.* This work reframes the discourse on firefighting robotics by positing GRCs as the next evolutionary stage of automatic fire suppression. It moves beyond a simple review of a new tool to a critical analysis of a fundamental shift in fire engineering and emergency response doctrine, emphasizing the concept of a “mobile Automatic Fire Suppression System.” *Practical value.* The findings demonstrate that GRCs are a proven technology that enhances firefighter safety, enables interventions in previously inaccessible “no-go” zones, and provides incident commanders with superior situational awareness. This leads to safer, faster, and more effective fire suppression outcomes. *Scopes of further investigations*. Future research trajectories identified include the development of swarm robotics for distributed and resilient operations, the advancement of AI towards greater autonomy within a framework of meaningful human control, and the enhancement of human-robot symbiosis through more intuitive interfaces.

Keywords: ground robotic complexes, automatic fire suppression, firefighting robotics, unmanned ground vehicles, emergency response, autonomous systems, human-robot team, artificial intelligence, swarm robotics.

Introduction

The enduring challenge of firefighting in complex environments. Firefighting is an inherently dangerous profession, placing human first responders in environments characterized by extreme and often unpredictable hazards. The primary threats include intense heat, which can exceed 900°C in structural fires, the presence of toxic and asphyxiating gases in smoke-filled atmospheres, and the ever-present risk of structural collapse [1], [2]. In industrial settings, these dangers are amplified by the potential for explosions, the release of hazardous materials (HAZMAT), or radiological contamination [1], [3], [4]. Modern society presents an increasingly complex fire ground; urban expansion leads to denser construction and more challenging access, while industrial facilities house complex machinery and flammable substances that can escalate incidents with catastrophic speed [4], [5].

Furthermore, the global challenge of climate change has intensified the frequency and severity of wildland fires, creating volatile Wildland-Urban Interface (WUI) scenarios where traditional firefighting methods are stretched to their limits [5], [6]. These evolving risks underscore a fundamental limitation of human-led response: the physical and physiological vulnerability of the firefighter. The need to mitigate these life-threatening exposures while improving operational effectiveness has become a primary driver for technological innovation within the fire service [7], [8], [9].

The emergence of robotic systems in emergency response. In response to these challenges, the integration of robotic systems into emergency response has emerged as a transformative solution, shifting from a futuristic concept to a strategic imperative [1], [5]. Unmanned systems are engineered to assist and, in some cases, replace human firefighters in the most perilous situations, acting as force multipliers that extend the capabilities of a fire crew [1], [10]. The core value proposition of deploying robotics in firefighting is twofold: immediate risk reduction and enhanced operational capability. By sending a machine into an area too hazardous for a human, fire departments can perform critical tasks such as initial reconnaissance, direct fire suppression, and environmental monitoring without endangering personnel [8], [11]. This not only safeguards lives but also enables interventions in previously inaccessible or “no-go” zones, potentially altering the outcome of an incident by allowing for a more aggressive and sustained attack on the fire [5], [10].

From static to mobile: redefining automatic fire suppression. The concept of automated fire control is not new. For decades, Automatic Fire Suppression Systems (AFSS) have been a cornerstone of fire protection engineering. These systems are defined by their ability to detect and extinguish fires without human intervention [12], [13]. Examples are ubiquitous and include fire sprinkler systems, gaseous suppression agents for sensitive environments like data centers, and condensed aerosol or foam systems for industrial applications [14], [15], [16]. These systems are highly effective but share a fundamental limitation: they are static. An AFSS is an engineered, fixed installation designed to protect a specific, predefined space – a room, a building, or a piece of equipment.

This review posits that Ground Robotic Complexes (GRCs) for firefighting represent a paradigm shift in this philosophy. They are the next evolutionary stage of automatic fire suppression, transforming the concept from a fixed, building-integrated defense to a dynamic, mobile, and intelligent response asset. As GRCs incorporate increasingly sophisticated artificial intelligence (AI), their capacity for autonomous operation grows, allowing them to detect a fire, navigate to its source, and execute suppression tactics with minimal human oversight [1], [17], [18]. By combining the mobility of an unmanned ground vehicle with the core function of an AFSS, these platforms effectively create a "mobile AFSS" that can be deployed on demand to various unstructured environments. This reframing elevates the discussion from a simple review of a new tool to a critical analysis of a fundamental shift in fire engineering and emergency response doctrine.

Objectives and structure of the review. The primary objective of this paper is to provide a comprehensive and critical review of the state of the art in the development and exploitation of ground robotic complexes for automatic fire suppression. It aims to synthesize the existing body of knowledge, from historical precedents and technological underpinnings to current operational doctrines and future research trajectories.

To achieve this, the review is structured as follows. The following (second) section provides a historical context, tracing the parallel evolution of unmanned ground vehicles and fire suppression technology, and highlighting key milestones that have shaped the field. The third section presents a detailed analysis of the system architecture of modern GRCs, examining their mobility platforms, sensor suites, suppression systems, and communication infrastructure. The fourth section delves into the core of their autonomy, reviewing the software and AI that enable intelligent navigation, fire source identification, and decision-making. The fifth section focuses on the exploitation of these systems, outlining their application in various domains and the emerging doctrine of the human-robot team. The sixth section provides detailed case studies of prominent GRCs, analyzing their performance in real-world deployments. The seventh section surveys the current industry landscape and offers a comparative analysis of leading systems. The eighth section discusses the current challenges and future trends, including the promise of swarm robotics. Finally, the ninth section concludes by synthesizing the key findings and reflecting on the transformative impact of this technology.

Historical Context and Technological Evolution

The emergence of modern firefighting GRCs is not an isolated phenomenon but the confluence of two distinct yet complementary streams of technological development: the century-long advancement of unmanned ground vehicles (UGVs) and the continuous evolution of fire suppression equipment. The history of this field is also notable for a series of catastrophic events that have served as powerful catalysts for innovation and adoption.

Century of unmanned ground vehicles: from Telekino to modern UGVs. The conceptual origins of UGVs can be traced back to the early 20th century. In 1904, Spanish engineer Leonardo Torres Quevedo demonstrated a radio-based control system named "Telekino," which he first tested on a three-wheeled land vehicle, marking the first known example of a UGV [19]. By the 1920s, working radio-controlled cars were being reported, with speculation that the technology could be adapted for military tanks [19].

This military application became the primary driver of UGV development for the next several decades. In the 1930s, the Soviet Union developed the "Teletank," a remotely controlled small tank armed with a machine gun that saw action in the Winter War [19]. During World War II, the German Wehrmacht deployed the Goliath tracked mine, a cable-controlled demolition vehicle (see Fig. 1), while the British experimented with a radio-controlled version of their Matilda II tank, known as the "Black Prince," intended for drawing enemy fire or demolition missions [19].

The post-war era, particularly the Cold War, saw a shift towards more intelligent systems, largely spearheaded by the U.S. Defense Advanced Research Projects Agency (DARPA). The "Shakey" robot (see Fig. 2), developed in the 1960s, was a seminal project that integrated a TV camera, sensors, and a computer, allowing it to perform simple tasks based on commands and perceive its environment [19]. This foundational research culminated in DARPA's Strategic Computing Initiative of the 1980s, which led to the development of the Autonomous Land Vehicle (ALV). The ALV was the first UGV capable of navigating autonomously at useful speeds, both on and off-road, laying the groundwork for the intelligent navigation systems used in modern robotics [19], [20].

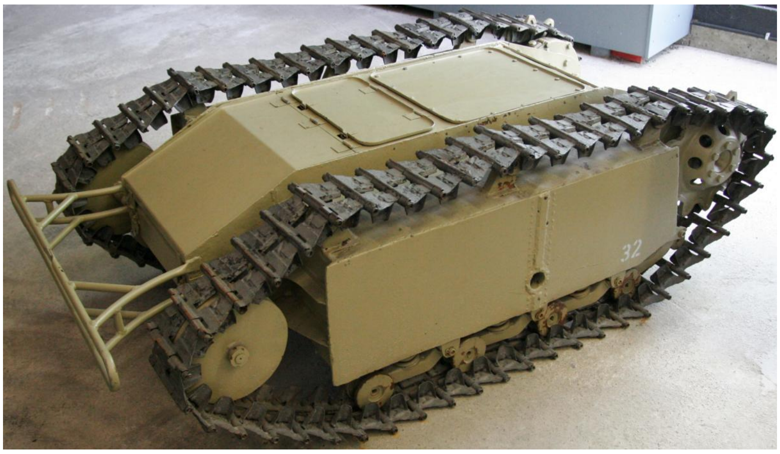

Fig. 1. Goliath tracked mine [19]

The evolution of fire suppression technology. Concurrently, the tools and methods of firefighting were undergoing their own technological evolution. The practice has progressed from the rudimentary bucket brigades of ancient Rome to more organized systems [21], [22]. The 17th century saw the invention of the manual fire pump, which allowed water to be projected from a distance [21], [23]. The Industrial Revolution was a major catalyst, introducing steam-powered fire engines in the 19th century that offered significantly greater water pressure and volume, reducing the reliance on manual labor [21], [24], [25]. The early 20th century marked another pivotal moment with the transition from horse-drawn apparatus to motorized fire engines, which dramatically increased speed, reliability, and the amount of equipment that could be carried to an incident [21], [25], [26]. This long history demonstrates a consistent trend within the fire service: the adoption of technology to increase efficiency, extend capability, and improve safety.

Milestones in firefighting robotics. The specific application of robotics to firefighting began with early, often experimental, systems developed from the 1960s through the 1980s. These were typically rudimentary, remote-controlled vehicles equipped with basic water hoses, designed primarily for use in high-risk industrial environments such as nuclear facilities or chemical plants where human entry was deemed impossible [27], [28].

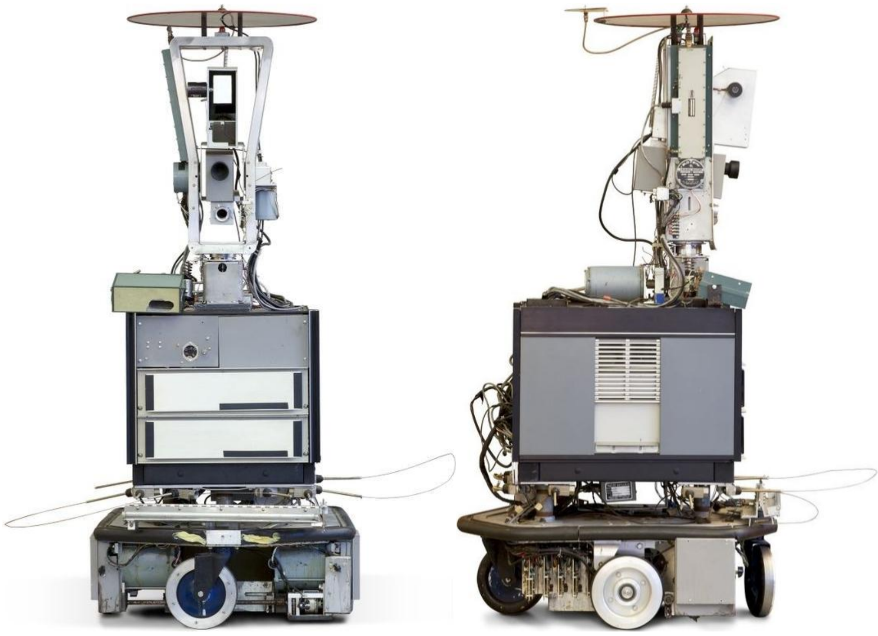

Fig. 2. The “Shakey” robot [20]

A pattern quickly emerged in which the development and adoption of these systems were not driven by a steady, linear progression but were instead punctuated and accelerated by catastrophic events that starkly revealed the limitations of human-only response. These "catalytic disasters" served as both proving grounds for nascent robotic technologies and powerful justifications for further investment and development.

The Chornobyl catalyst (1986). The first and perhaps most dramatic example of this pattern occurred in the aftermath of the Chornobyl nuclear disaster. According to a telegram from the Minister of Internal Affairs of the USSR, the first firefighting robots developed by engineers from Karelia were dispatched to the site. These machines were used to clean up a significant portion of the highly radioactive debris from the roof of the reactor building at a height of 70 meters. This task, which would have otherwise required soldiers to perform manually, saved countless personnel from lethal doses of radiation. A subsequent report from the Chornobyl NPP management noted the "good prospects" of these technical solutions, leading directly to a decision by the State Committee on Atomic Energy to create dedicated robotic firefighting complexes for all nuclear power plants in the Soviet Union [29].

The 9/11 precedent (2001). While not a firefighting application, the collapse of the World Trade Center towers on September 11, 2001, marked the first known use of robots for Urban Search and Rescue (USAR) in a real-world disaster. Small, teleoperated robots were used to search for victims in void spaces within the rubble pile that were too small or unstable for humans or search dogs to enter [19], [30], [31]. This event established the viability of ground robots in complex disaster environments and propelled the field of rescue robotics forward.

The Fukushima impetus (2011). The Fukushima Daiichi nuclear disaster provided another powerful catalyst, specifically for the commercial firefighting robotics sector. The challenge of how to get water into the heavily contaminated reactor buildings without exposing first responders to extreme radiation directly inspired the development of what would become the first commercially sold firefighting robot in the United States [32]. In 2012, Howe & Howe Technologies, leveraging technology originally developed for the U.S. Army, unveiled the RS1-T2 Thermite. This marked the beginning of the modern era of purpose-built, commercially available GRCs for municipal and industrial fire departments [26], [33].

The Notre Dame turning point (2019). The 2019 fire at the Notre-Dame Cathedral in Paris became a high-profile, globally televised demonstration of the capabilities of a modern GRC. As temperatures inside the nave exceeded 900°C and molten lead flowed from the roof, conditions became too hazardous for human entry [2]. At this critical juncture, the Paris Fire Brigade (BSPP) deployed "Colossus," a robust tracked robot developed by Shark Robotics. Operating for nearly 10 hours, Colossus entered the nave, used its water cannon to cool the structure and suppress the fire, and provided invaluable situational awareness to commanders via its thermal and visual cameras [1], [2], [34], [35]. The successful deployment was widely credited with helping to save the cathedral's main structure and was hailed by the BSPP spokesperson as a pivotal contribution.2 This event served as a powerful turning point, bringing firefighting robotics into the public consciousness and solidifying its role as an essential tool in modern emergency response [2], [26].

This historical trajectory reveals a clear pattern: progress in the field is reactive. Major leaps in development, funding, and public acceptance are directly correlated with high-profile failures of conventional methods in the face of overwhelming or uniquely hazardous disasters. The history of firefighting robots is, therefore, a history of learning from tragedy and adapting technology to overcome the absolute limits of human resilience.

System Architecture of Modern Ground Robotic Complexes

The effectiveness of a modern GRC is a product of the integration of four key subsystems: a mobility platform for traversing the environment, a perception suite for situational awareness, suppression and manipulation systems for interacting with the fire and its surroundings, and a robust command and control infrastructure. The architectural design of these systems reflects a clear philosophy of achieving resilience through redundancy and modularity, a direct engineering response to the chaotic and unpredictable nature of fire environments where single points of failure can lead to mission failure.

Mobility and platform design: traversing hazardous terrains. The foundational component of any GRC is its mobility platform, which must be capable of navigating the challenging and often hostile terrain of a fireground. The most prevalent designs are categorized by their method of locomotion.

Tracked systems. Caterpillar-style tracks (see Fig. 1 and Fig. 3) are the most common and versatile mobility solution for firefighting GRCs [10], [36]. They provide superior traction and stability on a wide variety of surfaces, including uneven ground, mud, and debris-laden areas typical of a structural collapse or industrial accident [10], [17]. This robust design allows tracked platforms to climb steep inclines, traverse rubble, and carry heavy payloads such as large water cannons and modular equipment [10], [37]. Prominent examples like the Thermite RS3, Shark Robotics Colossus, and the Ukrainian military's GRC all utilize tracked chassis for their durability and all-terrain capability [17], [28], [37].

Fig. 3. Ukraine's first ground-based firefighting robot approved for use in the Armed Forces [37]

Wheeled systems. Wheeled GRCs (see Fig. 2 and Fig. 4), which often resemble small, rugged vehicles, are optimized for speed and rapid deployment on relatively smooth or semi-rough surfaces [9], [10]. They are well-suited for urban environments or large industrial facilities like factory floors and warehouses where paved surfaces are common [10].

Fig. 4. MVF-5 Autonomous Firefighting Robotic Vehicle [9]

Legged systems. While less common in current deployment, legged robotics (see Fig. 5) represents a significant area of research for navigating environments that are inaccessible to both wheels and tracks. Inspired by animal locomotion, legged systems are designed to handle highly cluttered spaces and, most importantly, to climb stairs [10]. The development of humanoid robots such as the Shipboard Autonomous Firefighting Robot (SAFFiR) by the U.S. Navy and the THOR robot from Virginia Tech demonstrates the potential of bipedal and quadrupedal locomotion for complex indoor navigation, including opening doors and operating equipment [6], [38], [39].

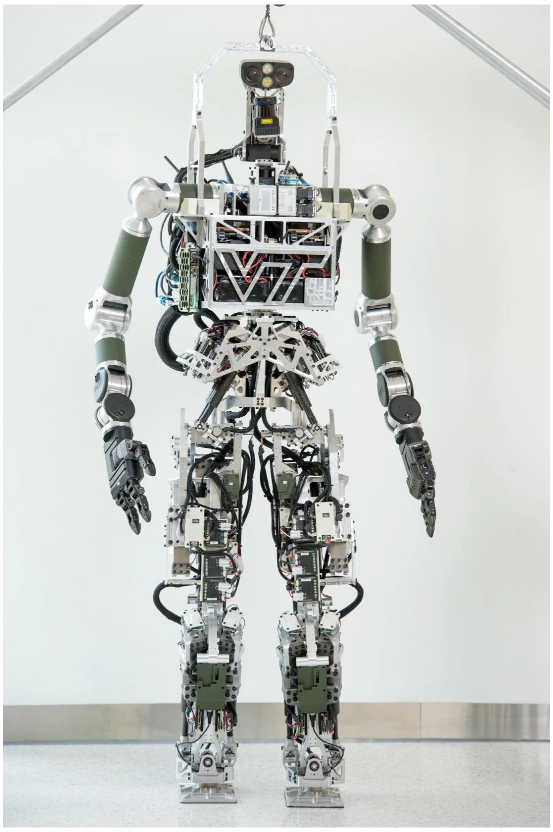

Fig. 5. Shipboard Autonomous Firefighting Robot (SAFFiR) [38], [39]

Specialized designs. Niche applications have given rise to unique mobility concepts. The “Anna Konda” prototype, for instance, is a snake-like robot that slithers and is guided by water pressure, designed specifically for extinguishing fires in extremely confined spaces like tunnels or ventilation shafts where conventional platforms cannot operate [1], [7], [18].

Perception and situational awareness: advanced sensor fusion. The ability of a GRC to operate effectively, whether via remote control or autonomously, depends entirely on its sensor suite – the “eyes and ears” that allow it to perceive and interpret its environment. State-of-the-art systems do not rely on a single sensor but rather integrate data from multiple, complementary sources through a process known as sensor fusion. This approach creates a redundant and resilient perception system that can function even when one sensor type is degraded or disabled, such as when dense smoke renders a visual camera ineffective [18], [40].

Visual and thermal imaging. This is the foundational sensor pairing for firefighting robotics. High-definition (HD) and low-light cameras (see Fig. 6*a*) provide a real-time video feed to the remote operator, offering crucial visual information for navigation and assessment [10], [41]. Thermal imaging cameras (see Fig. 6*b*) are arguably the most critical sensor, allowing the robot to “see” through thick smoke and darkness by detecting heat signatures. This capability is essential for identifying the seat of the fire, locating hotspots within walls or ceilings, and searching for victims [1], [9], [17], [18], [27].

a

b

c

d

Fig. 6. Main types of cameras and sensors used in ground robotic complexes: *a* – high-definition low-light camera; *b* – thermal imaging cameras; *c* – light detection and ranging (LiDAR) sensor; *d* – ultrasonic sensors

LiDAR and ultrasonic sensors. Light detection and ranging (LiDAR) sensors (see Fig. 6*c*) use laser pulses to create detailed 3D maps of the surrounding environment. This data is fundamental for autonomous navigation, enabling tasks like obstacle avoidance, path planning, and Simultaneous Localization and Mapping (SLAM) [11], [18], [42]. Ultrasonic sensors (see Fig. 6*d*) serve a similar purpose for short-range obstacle detection [43].

Chemical and gas detectors. For operations in industrial or HAZMAT scenarios, GRCs are equipped with specialized sensors to detect and identify a range of threats, including toxic industrial chemicals, flammable gases, and radiation [1], [3], [4], [17]. This allows the robot to assess the atmosphere for explosive potential or human toxicity from a safe standoff distance.

Inertial measurement units (IMUs) and GPS. An IMU, which typically includes accelerometers and gyroscopes, provides data on the robot's orientation, pitch, and roll. This is fused with data from wheel encoders and, when available, a Global Positioning System (GPS) to provide a robust estimate of the robot's position and trajectory. In GPS-denied indoor environments, the fusion of IMU and other sensor data is critical for accurate localization [18], [40], [44].

Suppression and manipulation systems: the tools of robotic firefighting. The "end effectors" are the tools the GRC uses to interact with the fire and its environment. Modern systems are trending towards modular designs, allowing a single platform to be adapted for various tasks.

Water and foam cannons (monitors). The primary tool for fire suppression is a high-volume water or foam cannon (see Fig. 7*a*), also known as a monitor. The capabilities of these systems vary significantly, reflecting different design philosophies. For example, the Thermite RS3 is built for overwhelming force, capable of delivering up to 2500 gallons per minute (9464 LPM) [45], [46]. In contrast, the Shark Robotics

Colossus features a monitor that can deliver up to 3800 L/min (approx. 1003 GPM) but is part of a modular system that prioritizes adaptability and endurance [47]. These systems allow for the precise application of extinguishing agents from a safe distance, minimizing risk to personnel and potentially reducing water damage [1], [8].

Manipulator arms. An increasingly important capability is the integration of robotic arms (see Fig. 7*b*) for tasks beyond direct suppression. These manipulators can be used to open doors, clear debris to create access paths, carry heavy equipment like hoses or tools, and, in future applications, assist in casualty extraction [6], [39]. The design of manipulators capable of exerting the high forces needed to open heavy industrial doors or move rubble remains a significant engineering challenge [48], [49], [50], [51].

a *b*

Fig. 7. Water-foam cannons (*a*) and manipulators (*b*) used in modern firefighting GRCs

Modular payloads. The state of the art is moving towards hyper-modular platforms. The Colossus robot, for instance, features 10 interchangeable mission modules that can be swapped in under 30 seconds [35]. This allows a single robotic chassis to be configured for a variety of missions, equipped with tools such as a large-flow positive pressure ventilation (PPV) fan for smoke removal, a stretcher support for casualty evacuation, a motorized bull bar for pushing obstacles, or specialized sensor trays [8], [35], [47]. This modularity provides immense tactical flexibility and is a direct response to the operational uncertainty of emergency incidents.

Command, control, and communications (C3): the digital lifeline. The C3 system is the vital link that connects the GRC to its human operator and the incident command structure. Its reliability is paramount to mission success.

Remote control interfaces. The primary human-robot interface is typically a portable operator control unit, such as a "belly-pack" controller. These units feature joysticks for maneuvering the robot and its tools, and a screen that displays real-time video feeds from the robot's cameras along with critical telemetry data like battery status, temperature readings, and sensor alerts [1], [32], [33].

Communication technologies. A robust wireless communication link is essential. Systems employ a range of technologies to ensure a stable, high-bandwidth connection. These include hardened radio frequency (RF) systems, commercial cellular networks like CDMA (Code Division Multiple Access) and

HSDPA (High-Speed Downlink Packet Access), and emerging 5G and private LTE modules that offer very low latency for real-time control [52], [53], [54], [55], [56]. The operational range can be significant, with some systems capable of being controlled from up to 2 km away in open terrain [37].

Challenges in fire environments. The fire ground is one of the most challenging environments for wireless communications. Thick concrete walls, steel structures, and dense smoke can severely attenuate or block radio signals [54], [57]. To overcome this, advanced systems may deploy communication relay robots or use aerial drones as mobile communication nodes to establish a reliable line-of-sight link with units operating deep inside a structure or in complex terrain [54].

The Core of Autonomy: Intelligence and Decision-Making

While early firefighting robots were primarily teleoperated tools, the state of the art is rapidly advancing towards greater autonomy. This “intelligence” is not a single feature but a complex interplay of software and AI algorithms that govern navigation, perception, and strategic decision-making. The progression towards full autonomy, however, is not a simple linear path. It is a nuanced negotiation between what is technically possible and what is operationally practical and ethically responsible, leading to the emergence of “variable autonomy” as the most promising framework for the near future.

Navigation and path planning in unstructured, hazardous environments. The ability for a robot to move purposefully and safely through a cluttered, dynamic, and dangerous environment is the foundation of its utility. This requires sophisticated algorithms for localization, mapping, and path planning.

SLAM and mapping. A key technology that enables autonomy of robotic complexes is SLAM (Simultaneous Localization and Mapping). Using data from sensors like LiDAR, cameras, and IMUs, SLAM algorithms allow a robot to build a map of a previously unknown environment while simultaneously tracking its own position within that map [18], [42], [52]. This is critical for operating in indoor or underground settings where GPS is unavailable [40].

Path planning algorithms. Once a map exists, path planning algorithms are used to compute a collision-free route from the robot’s current position to a goal. Research in this area explores various approaches, including graph-based methods like the A* algorithm, sampling-based methods such as the Rapidly-exploring Random Tree (RRT), and increasingly, machine learning-based techniques that can learn to navigate from experience [44], [58], [59], [60]. Advanced planners can also incorporate environmental risk factors, such as generating paths that avoid known high-temperature zones or areas with hazardous gas concentrations [61], [62].

Challenges in fire environments. Navigation in a live fire scenario presents unique and severe challenges. Thick smoke and dust can obscure optical sensors and LiDAR, rendering many standard SLAM algorithms ineffective. High temperatures can interfere with electronics and distort sensor readings. To overcome these issues, robust navigation systems must rely on multi-sensor fusion. For example, an improved Adaptive Unscented Kalman Filter (AUKF) can be used to fuse data from sources that are less affected by smoke, such as an IMU, wheel odometry, and Ultra-Wideband (UWB) positioning systems, to maintain an accurate location estimate even when primary visual sensors fail [40].

AI-driven fire source identification and threat assessment. Beyond simply navigating, an autonomous GRC must be able to “understand” the fire it is meant to fight. This involves using AI to interpret sensor data to identify the fire’s location, intensity, and nature.

From simple sensors to machine learning. The evolution of fire detection has moved from simple flame sensors, which detect infrared radiation within a specific wavelength range (typically 760 to 1100 nm), to sophisticated computer vision techniques [43], [63], [64]. While basic sensors are effective for simple detection, they are prone to false positives from other bright light or heat sources.

Computer vision and deep learning models. Modern systems leverage machine learning, particularly deep learning models like Convolutional Neural Networks (CNNs) and object detection architectures such as YOLO (You Only Look Once). These models are trained on vast datasets of fire and non-fire images and videos. By analyzing the visual feed from the robot’s cameras in real-time, they can identify the unique visual characteristics of fire – such as its color, shape, and dynamic flickering motion – with high accuracy, significantly reducing false alarms compared to simpler methods [18], [65], [66], [67], [68], [69], [70].

Multi-modal threat assessment. True threat assessment involves more than just identifying flames. Advanced AI systems fuse data from multiple sensor modalities. By combining the visual flame detection from a CNN with the quantitative heat data from a thermal camera and atmospheric readings from gas sensors, the robot can build a more comprehensive picture of the threat. This allows it to assess the fire's size and intensity, identify the type of materials burning (e.g., Class B liquid fire vs. Class A solid fire), and inform a more appropriate suppression strategy, such as selecting foam instead of water [18], [71].

Autonomous decision-making frameworks for suppression strategy. The highest level of autonomy involves the robot making its own tactical decisions about how to engage a fire. This remains a significant area of research, with most currently deployed systems relying on a human for strategic command.

The spectrum of autonomy. Robotic operation exists on a spectrum. At one end is full teleoperation, where a human directly controls every movement and action. In the middle are semi-autonomous modes, where the robot might autonomously handle navigation to a waypoint designated by the operator, who then takes over for suppression. At the far end is full autonomy, where the robot would independently detect a fire, plan a path to it, and execute a suppression strategy without human intervention [1], [9], [11].

Decision-making algorithms. Research into fully autonomous decision-making explores algorithms such as genetic algorithms, which can evolve optimal suppression strategies over many simulated iterations, and reinforcement learning, where an AI agent learns through trial and error to take actions that maximize a "reward," such as reducing the fire's temperature [72], [73], [74], [75].

Variable autonomy and meaningful human control. The practical and ethical complexities of allowing a machine to make life-and-death decisions in a chaotic environment have led to a focus on a more collaborative model. The current state-of-the-art research centers on "variable autonomy," where the level of robot autonomy is dynamic and context-dependent [76]. This framework is designed to ensure "Meaningful Human Control" (MHC). In such a system, the robot might be granted full autonomy for non-moral tasks it excels at, like navigating a complex space or maintaining a steady stream on a target. However, when the system identifies a situation with moral sensitivity – for example, a choice between protecting property and searching a potential victim area – it can automatically cede control back to the human operator, presenting them with the relevant data to make the critical judgment call [76]. This approach avoids the brittleness of full autonomy while alleviating the cognitive burden of full teleoperation, creating an optimal synthesis of human and machine intelligence.

Exploitation: Application Domains and Operational Doctrine

The successful "exploitation" of GRCs in firefighting is not merely a function of their technical specifications but is defined by their effective integration into operational workflows across various high-risk domains. This integration is catalyzing a fundamental shift in firefighting tactics, moving away from a model of direct human intervention towards a new doctrine centered on the "Human-Robot Team." The value of the technology is realized not just by its acquisition but by the organizational evolution required to leverage it effectively.

Industrial environments: mitigating high-stakes risks. Industrial facilities such as chemical plants, oil refineries, nuclear power plants, and large warehouses represent a primary application domain for firefighting GRCs. These environments are characterized by high-stakes risks that often preclude or severely limit human entry during an incident. The presence of flammable liquids and gases, toxic chemicals, and the potential for catastrophic explosions make these scenarios uniquely suited for robotic intervention [1], [3], [4], [9], [34]. GRCs can be deployed to enter these hazardous zones to provide initial reconnaissance, assess the nature of the chemical spill or fire, and begin suppression or cooling operations from a safe standoff distance, preventing an incident from escalating. Case studies from China, such as the 2019 Shandong Chemical Plant Fire, demonstrate the use of robots to approach and extinguish fires in highly flammable areas where manual entry was deemed too dangerous [52].

Urban and structural scenarios. In urban settings, GRCs are valuable assets for tackling large and complex structural fires. This includes incidents in high-rise buildings, underground tunnels, car parks, and large commercial structures like shopping centers or warehouses [1], [42]. In these scenarios, robots can be used to drag heavy fire hoses deep into a building, provide continuous water streams in high-heat areas where human crews would require frequent rotation, and conduct searches in smoke-filled, GPS-denied environments. The immediate operational value of these systems was vividly demonstrated by the Los Angeles Fire Department (LAFD), which deployed its newly acquired Thermite RS3 to a major commercial structure fire on its very first day in service. The robot was able to perform safe interior fire operations where it would have been too dangerous for firefighters [45], [77].

Wildland-urban interface (WUI) and forest fire support. While aerial drones are often the primary robotic tool in wildland firefighting, ground-based GRCs play a crucial and growing support role, particularly in the Wildland-Urban Interface (WUI). In these scenarios, GRCs can be used to perform physically demanding and hazardous tasks for extended periods. Specialized robots like the Guoxing KT-500 (see Fig. 8*a*) and the Vallfirest Dronster (see Fig. 8*b*) are designed as remote-controlled forestry mulchers, capable of rapidly clearing vegetation to create firebreaks and control lines [78], [79]. Other tracked platforms can be used to establish structural defense lines, such as applying water or retardant to protect homes at the edge of a fire. They are also valuable for patrolling and extinguishing hotspots after the main fire front has passed, a tedious and dangerous task for human crews [11], [80], [81]. Increasingly, operations in this domain involve the collaboration of ground and aerial systems, where UAVs provide high-level situational awareness to guide the deployment of UGVs on the ground [72], [74], [82], [83].

The human-robot team: a new paradigm in fire ground operations. The most profound impact of GRCs is not the replacement of firefighters but their augmentation, leading to the formation of a new operational paradigm: the human-robot team [5], [6], [7]. The successful integration of robotics requires a reevaluation of fireground tactics and command structures, treating the robot as a specialized team member with unique capabilities and limitations.

Role allocation. In this new doctrine, roles are allocated based on strengths. The robot is assigned the tasks that are dull, dirty, and dangerous. This includes being the first to enter a hazardous area for reconnaissance, performing prolonged suppression tasks in extreme heat without fatigue, transporting heavy equipment over long distances, and clearing debris [1], [8], [11], [17], [52]. This frees up human firefighters to focus on higher-value, cognitive tasks that require dexterity, complex problem-solving, and empathy, such as rescuing victims, providing medical aid, and making strategic decisions.

a *b*

Fig. 8. Specialized robots for forest fire support [78], [79]: *a* – Guoxing KT-500; *b* – Vallfirest Dronster

Enhanced situational awareness. The human operator or incident commander assumes the role of a strategic overseer, operating from a safe location. The robot acts as a forward-deployed sensor platform, streaming a rich, continuous flow of data – including high-definition video, thermal imagery, and gas readings – back to the command post [3], [4], [52]. This real-time intelligence provides commanders with an unprecedented level of situational awareness, allowing them to make faster, more informed tactical decisions about resource allocation and crew safety.

Training and trust. The effective implementation of this paradigm is contingent on building trust and proficiency. This requires dedicated and continuous joint training exercises where firefighters and robot operators work together in simulated emergency scenarios [52]. These exercises are crucial for building operator familiarity with the system's capabilities and limitations, developing effective collaborative tactics, and fostering the trust necessary for commanders to confidently deploy the robotic asset in real-world incidents. The cultural and organizational challenges of adoption, such as resistance from personnel accustomed to traditional methods, are often as significant as the technical ones, highlighting that the successful exploitation of GRCs is fundamentally an exercise in organizational change management [84].

Performance in the Field: Case Studies and System Analysis

The theoretical capabilities of GRCs are best understood through the analysis of specific systems deployed in real-world scenarios. These case studies reveal different design philosophies, technical trade-offs, and the practical impact these robots have on firefighting operations.

The Thermite RS3. The Thermite series of robots (see Fig. 9), developed by Howe & Howe Technologies (a subsidiary of Textron), represents one of the most prominent and powerful GRCs on the market, particularly in the United States.

Development and philosophy. The development of the Thermite was directly catalyzed by the 2011 Fukushima nuclear disaster. The central challenge of that event – delivering cooling water into a highly radioactive and structurally compromised environment – drove the design philosophy of a robot focused on high-volume, remote-controlled fire suppression for the most extreme industrial hazards [32].

Fig. 9. Thermite RS3 firefighting robot [45], [46]

Technical specifications. The Thermite RS3 is a formidable machine, built for power and durability. It is a tracked vehicle weighing approximately 1,588 kg (3,500 lbs) and is powered by a 36.8 hp diesel engine, providing an operational endurance of up to 20 hours without refueling. Its defining feature is an exceptionally powerful water cannon capable of delivering a flow rate of up to 2500 gallons per minute (9464 LPM), with a horizontal stream reach of over 90 meters (300 ft). Its robust chassis can be equipped with a front plow blade to push debris, including vehicles, out of its path [45], [46], [85], [86].

Operational debut. In October 2020, the Los Angeles Fire Department (LAFD) became the first municipal fire department in the United States to officially put the Thermite RS3 into service. Its value was proven almost immediately. On the very morning of its public debut, the robot was deployed to a major emergency commercial structure fire in the fashion district. It was used to breach a wall and provide safe interior fire attack in a building that was deemed too hazardous for human entry, demonstrating its practical utility from its first day on the job [26], [45], [77].

The Colossus. The Colossus robot (see Fig. 10), from French manufacturer Shark Robotics, embodies a different design philosophy, emphasizing modularity, endurance, and adaptability for a wider range of mission profiles.

Development and philosophy. The Colossus was developed in close collaboration with the Paris Fire Brigade (BSPP), one of the world's most elite firefighting units. This partnership ensured the robot's design was grounded in the practical needs of urban firefighters, leading to a focus on hyper-modularity and operational flexibility [35], [80].

Technical specifications. Compared to the Thermite, the Colossus is a more compact and lighter platform, weighing 578 kg (1274 lbs). It is fully electric, powered by six hot-swappable lithium-ion batteries that provide an impressive operational endurance of up to 12 hours. Its water cannon delivers up to 3800 L/min (approx. 1003 GPM). The robot's key feature is its modularity; it can be fitted with up to 10 different mission modules, including a large-flow ventilator, a stretcher for casualty evacuation, a motorized bull bar, and various sensor trays. These modules can be exchanged in the field in less than 30 seconds, allowing a single platform to adapt to evolving incident needs [35], [47], [87], [88].

Fig. 10. Colossus firefighting robot [35], [80]

Trial by fire at Notre Dame. The Colossus gained international acclaim for its crucial role during the 2019 Notre-Dame Cathedral fire. As the fire raged and the structural integrity of the nave became compromised, the BSPP deployed Colossus into the heart of the inferno. Operating for nearly 10 hours in temperatures exceeding 900°C, the robot used its water cannon to cool the structure and extinguish flames while providing critical thermal and visual reconnaissance to commanders outside. Its deployment was a pivotal moment that showcased the resilience and effectiveness of modern GRCs in a scenario of immense historical and cultural significance [1], [2], [26], [34], [35].

The SAFFiR (shipboard autonomous firefighting robot). The SAFFiR project (see Fig. 5) represents a different evolutionary path in firefighting robotics, focusing on a humanoid form factor to navigate the uniquely challenging environment of a naval vessel.

Development and context. Developed by researchers at Virginia Tech in collaboration with the U.S. Navy's Office of Naval Research, SAFFiR was designed to address the critical threat of fire aboard ships at sea [1], [38]. Naval vessels are dense, confined environments filled with narrow passageways, steep ladders (stairs), and watertight hatches (doors), a terrain that is exceptionally difficult for traditional tracked or wheeled robots to navigate.

Capabilities. SAFFiR is a bipedal humanoid robot standing 5 feet 10 inches tall and weighing 140 pounds. It is capable of walking with stability on uneven and slanted surfaces, traversing hatches, and climbing stairs. Its sensor suite includes stereo cameras, laser scanning for distance measurement, and stereo thermal imaging to see through smoke. Crucially, it has hands and arms capable of manipulating objects in a human-like way, such as holding and aiming a fire hose. In a milestone demonstration aboard the decommissioned USS Shadwell, the robot successfully navigated a passageway, located a fire source behind a door, and used a hose to suppress the flames [38], [39].

Significance. While still in a research and development phase, SAFFiR highlights the potential of legged and humanoid robotics for complex manipulation and navigation tasks. It represents a long-term vision for a robot that can not only suppress fires but also use human tools and move through human-designed spaces with a high degree of agility.

Emerging systems and regional deployments. The global landscape of firefighting robotics is diverse, with several other nations and companies developing and deploying specialized systems.

Ukrainian GRC. In a testament to the utility of these systems in extreme environments, the Ministry of Defence of Ukraine has officially adopted a domestically developed tracked GRC (see Fig. 3) for use by its Armed Forces. This platform is specifically intended for high-risk military scenarios, such as fighting fires near unexploded ordnance or burning equipment where ammunition detonation is a risk. The military's requirements led to enhancements in the chassis durability, control range, and battery life [37].

Chinese systems. Chinese manufacturers like Shandong Guoxing Intelligent Technology Co., Ltd. have developed a range of robust, all-terrain tracked robots, such as the RXR-MC80BD and RXRM40D. These systems have been deployed in numerous real-world incidents in China, including industrial fires at chemical plants and fires in urban tunnels, showcasing their growing integration into the country's emergency response framework [34], [52], [89].

Fig. 11. MHI Water Cannon Robot [90]

Mitsubishi Heavy Industries (MHI) system. In Japan, a national project led by the Fire and Disaster Management Agency resulted in the development of a unique robotic system by MHI, specifically for large-scale industrial disasters at petrochemical complexes. This system consists of two collaborating robots: a "Water Cannon Robot" (see Fig. 11) that moves to the fire scene to apply water and foam, and a "Hose Extension Robot" that autonomously travels from the water source, laying a 300-meter, 150-mm diameter fire hose to supply the cannon robot [90]. This two-robot approach solves the logistical challenge of supplying a high-volume monitor in a large, open area.

Industry Landscape and Comparative Analysis

The development and production of firefighting GRCs have matured into a specialized global market, with key industrial players and defense contractors competing to offer advanced solutions to fire departments and emergency response agencies. The market is projected to experience significant growth, with one study forecasting a compound annual growth rate (CAGR) of over 12% through 2032, reflecting the increasing recognition of the technology's value [27].

Key manufacturers and market dynamics. The landscape of GRC manufacturers includes a mix of specialized robotics firms and large industrial conglomerates. Based on market analysis and deployed systems, the leading companies in this sector include [91]:

- Howe & Howe (a subsidiary of Textron Systems, USA): the manufacturer of the Thermite series, one of the most well-known and powerful GRCs on the market [33].
- Shark Robotics (France): the developer of the Colossus and Rhyno Protect robots, known for their modularity and proven performance in high-profile incidents [92].
- Shandong Guoxing Intelligent Technology Co., Ltd (China): a major Chinese manufacturer with a comprehensive range of specialized robots for high-risk environments [4], [91].
- Mitsubishi Heavy Industries, Ltd. (Japan): a major industrial corporation that developed a specialized two-robot firefighting system in a national project [90].
- DOK-ING d.o.o. (Croatia): a manufacturer of robotic systems for hazardous environments, including the MVF-5 autonomous firefighting vehicle [9], [91].
- Angatec (Germany), Vimal Fire (India), EmiControls (Italy), QinetiQ (UK), and Ryland Research Limited (UK) are also identified as key players in the market [91].

Comparative technical specifications of leading GRCs. A direct comparison of the technical specifications of the leading GRCs reveals the different engineering trade-offs and design philosophies pursued by their manufacturers. Table 1 synthesizes data for three of the most prominent systems discussed in this review, highlighting their distinct approaches to solving the challenges of robotic firefighting. The corresponding data have been compiled from sources [46], [47], [90].

Table 1

Comparative analysis of leading firefighting ground robotic complexes

Specification	Howe & Howe Thermite RS3	Shark Robotics Colossus	MHI Water Cannon Robot
Dimensions (Length × Width × Height)	214×166×164 cm	159×78×76 cm	217×146×207 cm
Weight	1588 kg	578 kg	1600 kg
Propulsion System	36.8 hp diesel engine	2×4000 W electric motors	4-Wheel Drive
Max Speed	13 kph	3.5 kph	7.2 kph
Endurance	20 hours	12 hours (hot-swappable batteries)	Not specified
Mobility Platform	Tracked	Tracked	Wheeled
Max Water/Foam Flow	9464 LPM (2500 GPM)	3800 LPM (1003 GPM)	4000 LPM
Key Feature	Extreme volume suppression	Hyper-modularity, high endurance	Autonomous navigation to the scene
Notable Deployments	Los Angeles Fire Department	Paris Fire Brigade (Notre Dame)	Petrochemical Complexes (Japan)

The data presented in the table crystallize the different strategic approaches to GRC design. The Thermite RS3 (Fig. 9) is engineered as a heavy-duty, diesel-powered platform focused on a single primary mission: delivering the maximum possible volume of water to a fire. Its size, weight, and power are all optimized for this overwhelming suppression capability. In contrast, the Shark Robotics Colossus (Fig. 10) is a lighter, more compact, electric-powered platform. Its design prioritizes operational endurance (12 hours) and tactical flexibility through its hyper-modular payload system. It is not designed to match the Thermite's raw flow rate but to serve as a versatile "multi-tool" on the fire ground. The MHI Water Cannon Robot (Fig. 11) represents a third approach, with a strong emphasis on integrating a high level of autonomy for navigation and deployment, a key focus of the Japanese national project under which it was developed. This comparative analysis demonstrates that there is no single "best" design, but rather a spectrum of specialized solutions tailored to different operational priorities and hazard environments.

Current Challenges and the Future Trajectory

Despite their proven success and growing adoption, the widespread implementation of GRCs in firefighting faces significant technical, operational, and economic hurdles. Overcoming these challenges while leveraging emerging technologies like swarm intelligence and advanced AI will define the future trajectory of the field. The evolution of these systems appears to be heading towards a model of distributed, resilient, and symbiotic human-robot collaboration.

Overcoming technical, operational, and economic hurdles. The barriers to the broader adoption of firefighting GRCs can be categorized into three main areas:

- Technical challenges. At a fundamental level, the hostile fire environment continues to push the limits of robotic technology. Key technical limitations include the finite battery life of electric platforms, which restricts operational duration without recharging or swapping [11]. Maintaining robust, high-bandwidth communication links deep inside complex structures or in rugged terrain remains a persistent difficulty [6], [42]. While navigation in open spaces is largely a solved problem, reliably traversing highly cluttered, multi-level, and dynamically changing disaster scenes is an ongoing research challenge [93]. Perhaps the greatest technical hurdle is achieving true, reliable autonomy in decision-making, where a robot can improvise and make sound judgments in novel situations with the same flexibility as an experienced human firefighter [94].

- Operational challenges. The integration of a fundamentally new technology into the established, tradition-rich culture of the fire service presents significant operational hurdles. There can be resistance from personnel to relying on machines for critical tasks, stemming from concerns about reliability or a perceived threat to hard-earned skills [6], [84]. The effective use of GRCs requires the development of entirely new operational doctrines and extensive training programs for operators, commanders, and maintenance personnel [84]. Furthermore, the logistics of transporting, deploying, and maintaining large, heavy robotic systems can be a challenge for departments with limited space and resources [84].

- Economic challenges. The high initial acquisition cost of advanced GRCs is a major barrier for many public safety agencies, particularly smaller municipal fire departments operating on tight budgets. A state-of-the-art system like the Thermite RS3 can cost around $300,000, an investment that is difficult for many organizations to justify [6], [84]. In addition to the purchase price, departments must also account for ongoing costs related to maintenance, training, and potential upgrades, further complicating the economic calculus of adoption [6], [11].

The next frontier: swarm intelligence, enhanced autonomy, and human-robot symbiosis. The future of robotic firefighting is being shaped by several key research and development trends that aim to address current limitations and unlock new capabilities.

Swarm robotics. One of the most promising future directions is the application of swarm intelligence. This concept involves deploying a large number of smaller, often simpler and less expensive, robots that work together in a coordinated, decentralized manner [1], [11], [17], [95]. This approach is a direct strategic response to the primary challenges of cost and resilience associated with current large, monolithic GRCs. A swarm of robots could tackle large-scale fires, such as those in industrial complexes or wildlands, by surrounding the fire, performing parallel tasks like suppression and search, and providing a much larger sensor footprint [96], [97], [98]. The swarm is inherently resilient; the loss of one or several individual units does not lead to mission failure, overcoming the single-point-of-failure risk of a single large robot [96]. This shifts the paradigm from a "single hero robot" to a "distributed, resilient system."

Greater autonomy. The continuous advancement of AI and machine learning will inevitably lead to GRCs with more sophisticated autonomous capabilities. This will further reduce the cognitive load on human operators, allowing robots to handle more complex tasks independently, such as autonomously identifying and prioritizing multiple fire sources or dynamically re-planning paths in response to changing conditions [1], [17], [28].

Human-robot symbiosis. The ultimate trajectory of this field is not the replacement of human firefighters but the creation of a seamless, symbiotic partnership. Future developments will focus on enhancing the human-robot interface to foster more intuitive and effective collaboration.

The Authors' Contribution to the Field

A key area of the authors' work involves the development of specialized robotic manipulators and end-effectors. The authors have conducted comprehensive structural, kinematic, and force analyses of a pantograph-based industrial gripper, optimizing its design for precise and energy-efficient operation in automated "pick and place" tasks [99]. An overall view of the authors' proposed gripper is shown in Fig. 12. Via the mounting plate 1 it is attached to a rotary gear sector, which allows rotation about a bearing assembly mounted at the free end of the second section of a SCARA-type manipulator. A stepper motor 2 is fixed on plate 1 and, through a system consisting of one drive pulley and two tensioning pulleys 3, drives a belt 4 that provides vertical motion of the gripper plate 5 along the profiled linear guide 6. The gripper itself is a lever-type pantograph (parallelogram) mechanism whose links are actuated by a servomotor 7 via a screw-nut drive 8. This expertise in manipulator design has been directly applied to the field of emergency response, military operations, and firefighting systems.

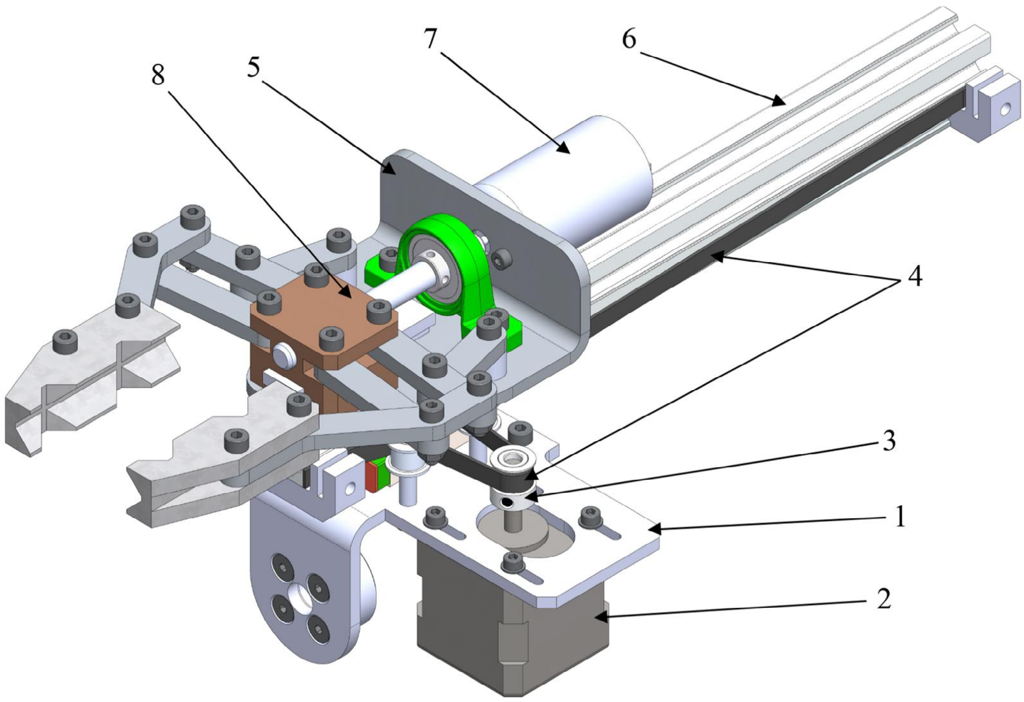

Fig. 12. Overall view of the gripping device developed by the authors

In addition, the authors have presented a detailed design and kinematic analysis of a five-degree-of-freedom (5-DOF) articulated robotic manipulator specifically tailored for controlling fire monitors [49].

This research provides a foundational kinematic model, complete with forward kinematic equations and workspace simulations, which is essential for the development of precise and agile robotic firefighting systems. An overall view of the industrial robot manipulator is shown in Fig. 13. The robot has an articulated linkage construction with a revolute-jointed kinematic scheme, meaning all moving joints are rotational, which provides high maneuverability and flexibility within the workspace. The robot can be stationary, with the base 1 anchored directly to the building foundation or a support column, or mobile, with the base 1 mounted on a wheeled or tracked platform. The main structural elements are as follows. The base plate 1 serves as the mounting foundation for the entire manipulator, ensuring stability and rigidity during process operations. The horizontal rotation drive of the manipulator 2 comprises an electric motor 8 with a worm gear 11, which provides rotation about the vertical axis. The upper arm 3, the first link of the manipulator, is connected to the horizontal-rotation drive plate 2 by a revolute kinematic pair, and its angular position relative to the horizontal is adjusted by a linear electromechanical actuator 15. The elbow 4, the second link, is connected to the upper arm 3 by a revolute pair, and its angular position relative to the upper arm is controlled by a linear actuator 16. The forearm 5, the third link, is connected to the elbow 4 and can rotate about its longitudinal axis via motor 9 and rotary mechanism 12. The wrist 6 is connected to the forearm 5 by a revolute pair (bearings 14); its angular position relative to the forearm is adjusted by motor 10 through a gear–belt transmission 13. In the proposed design the wrist 6 has six degrees of freedom, enabling arbitrary spatial orientation of the gripper 7. The gripper 7 is a device for grasping and holding objects; in this case a mechanical pinch-type gripper with two clamping fingers (jaws) is proposed.

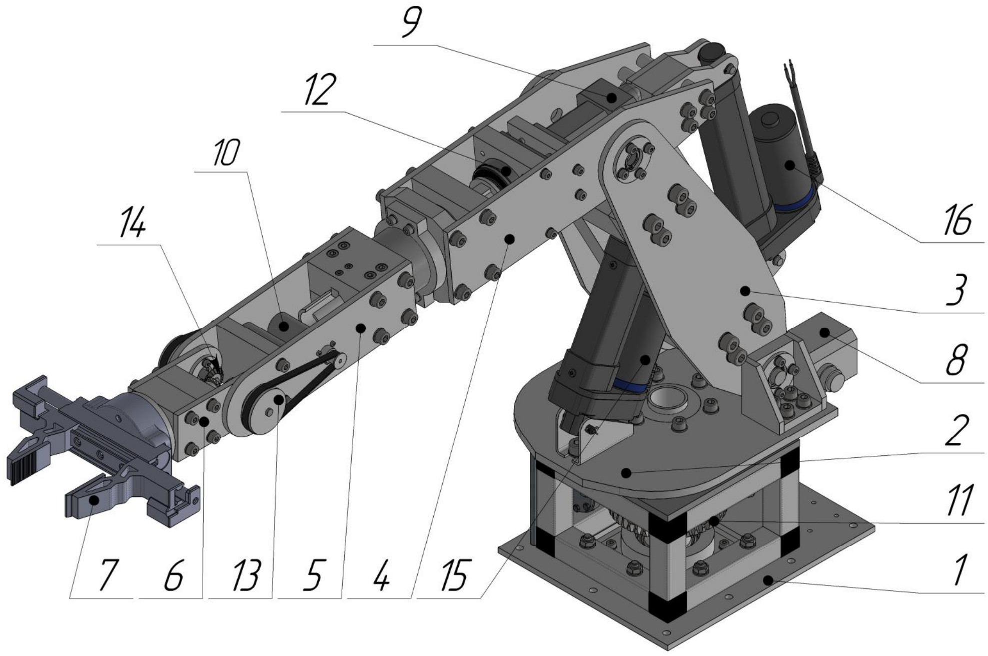

Fig. 13. Overall view of the robotic manipulator developed by the authors

Furthermore, the authors' work extends to the integration of these grippers and manipulators onto mobile platforms. The authors have proposed and analyzed an autonomous robotic complex featuring a SCARA-type manipulator mounted on a tracked chassis [100]. This research included determining the manipulator's operational workspace and conducting experimental tests on the mobile platform's dynamic performance on rugged terrain, with applications targeted at hazardous tasks such as demining. An overall view of the mobile tracked platform developed by the authors is shown in Fig. 14. The machine's main components are: the tracked undercarriage 1, comprising two powered sides with rubber tracks and two independent drive electric motors; the frame 3, fabricated from sheet-metal parts joined by threaded fasteners; and the control-and-power unit 2, which houses the power supply elements (rechargeable batteries) and programmable controllers that enable remote control of the mobile robot. The tracks are driven by two DC motors with a rated voltage of 120 V and a rotational speed of 3000 rpm. To provide the required travel speed and the capability to climb steep grades, the drivetrain employs a worm gear and a chain drive. The use of a worm gearbox is justified by its self-locking property, which prevents motion of the robot when motor power is switched off.

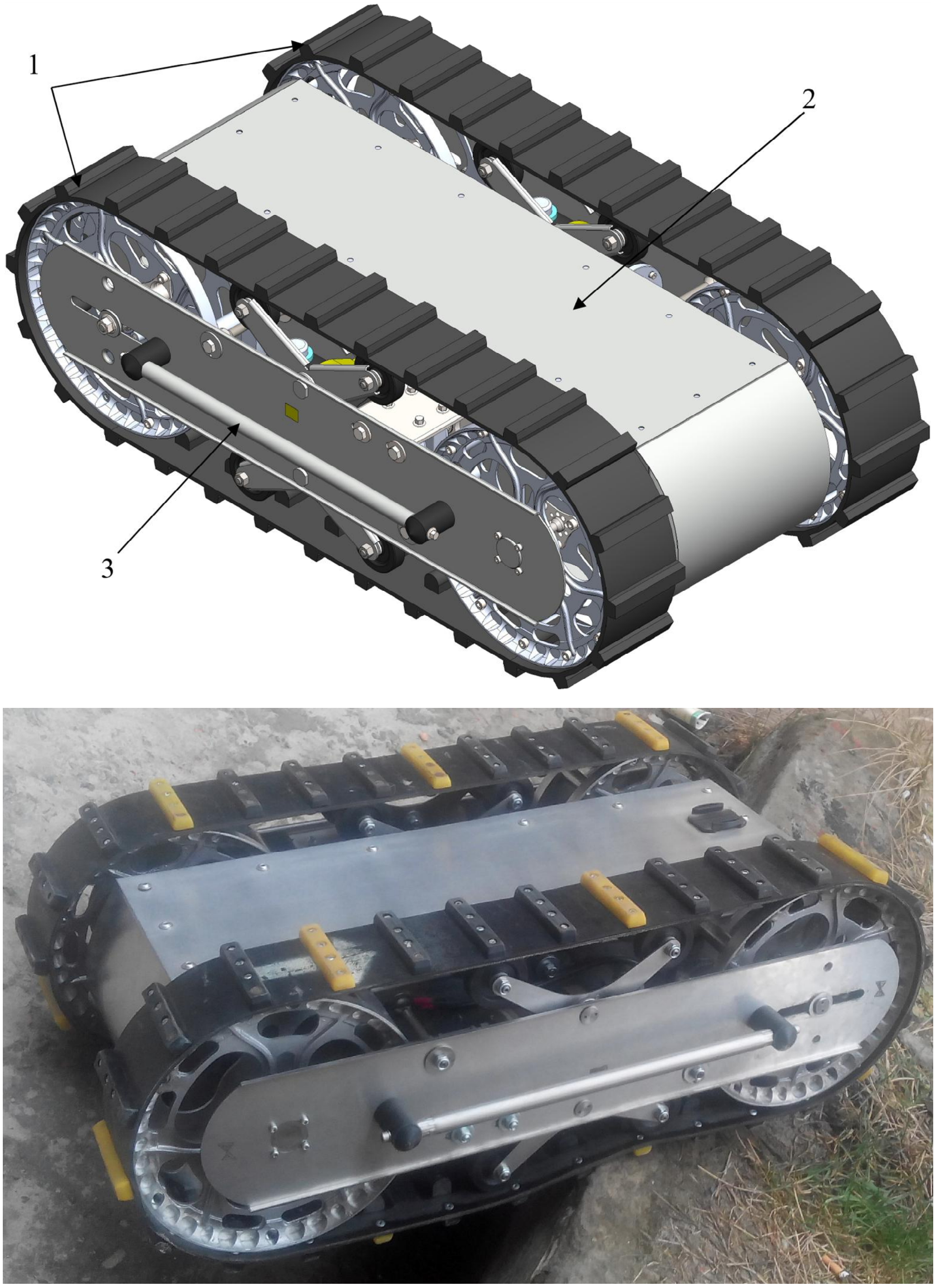

Fig. 14. Overall view of the tracked robotic platform developed by the authors

In [49], [99], and [100], the authors have made notable contributions to the design and analysis of robotic systems for industrial automation and hazardous environment operations, with a specific focus on manipulator kinematics and mobile platforms. The authors' research is distinguished by a rigorous engineering approach that combines detailed analytical modeling with validation through numerical and computer-aided simulations. Collectively, the authors' body of work provides a robust engineering foundation for the development of advanced manipulators and mobile robotic systems for both industrial and emergency response applications.

Conclusions

This review has charted the development and exploitation of ground robotic complexes, framing them as a transformative evolution of automatic fire suppression systems. The analysis has demonstrated that GRCs are no longer a conceptual novelty but a proven and increasingly indispensable asset in modern emergency response. Their historical development, catalyzed by catastrophic events that exposed the limits of human intervention, has led to the creation of robust, technically sophisticated platforms. The architecture of modern GRCs – built on a foundation of resilient mobility, multi-modal sensor fusion, and modular payloads – is a direct engineering response to the extreme and unpredictable nature of fire environments.

The state of the art in autonomy is characterized by a pragmatic shift from the pursuit of full autonomy to the development of variable autonomy frameworks that ensure meaningful human control. This collaborative model, which defines the human-robot team, leverages the tireless strength and sensory acuity of the machine while retaining the strategic oversight and ethical judgment of the human commander. Field deployments, from the radioactive ruins of Chornobyl to the hallowed nave of Notre Dame, have provided irrefutable evidence of the value of these systems in mitigating risk and enhancing operational effectiveness in scenarios where human entry is either impossible or unacceptably dangerous.

The integration of intelligent robotic systems is irrevocably altering the landscape of firefighting. While significant challenges related to cost, training, and technical limitations remain, the trajectory is clear. The continued advancement in AI, sensor technology, and robotics will produce systems that are ever more capable, autonomous, and adaptable. Future paradigms, such as swarm robotics, promise to address current economic and operational barriers, potentially enabling the deployment of distributed, resilient robotic teams on a scale not currently feasible.

Ultimately, the story of firefighting robotics is not one of machines replacing humans, but of technology augmenting human capability. It is about equipping brave men and women with tools that allow them to project their skills and experience into the most hazardous environments from a position of safety. As this technology matures, it will continue to redefine the boundaries of what is possible in emergency response, promising a future where human courage is amplified by machine resilience, leading to safer and more effective outcomes in the enduring struggle against one of humanity's oldest and most destructive threats.

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