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An autonomous ground robot to support firefighters' interventions in indoor emergencies

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Abstract

Intervention teams act in hostile scenarios where reducing mission times and accident risks is critical. In these situations, the availability of accurate information about the environment plays a key role in ensuring the well-being of rescuers and victims. This information required to plan the interventions in indoor emergencies encompasses the location of fires and the presence of dangerous gases. Robotics and remote sensing technologies can help emergency teams to obtain this information in real-time without exposing themselves. Additionally, the accurate simulation of the environments allows the teams to plan their interventions, creating routes to safely access the affected areas and evacuate the victims. This article presents a robotic solution developed to satisfy the demands of intervention teams. More specifically, it describes an autonomous ground robot that can obtain real-time location and environmental data from indoor fires, as well as a simulator that reproduces these emergency scenarios and facilitates mission planning. In this way, emergency teams can know the conditions in the scenario before, during, and after the intervention. Thus, risks are minimized by improving their situational awareness and reducing their exposure times during the mission. The system has been developed and validated in collaboration with the end-users and under realistic harsh environments. During these experiments, the robot was used to detect fire sources and cold smoke and provide environmental information to firefighters. Additionally, the simulator provided alternative routes for accessing and exiting the scene faster and safer by dodging potentially dangerous areas.

KEYWORDS
emergency, environmental monitoring, fire detection, robot, sensing, simulation

1 | INTRODUCTION

The studies about the evolution of fires provided by the Spanish Ministry for the Ecological Transition and the Demographic Challenge (Subdirectorate General for Forest Policy and Combating Desertification, 2020)

and the report of victims in fires in Spain carried out by the Mapfre Foundation in collaboration with the Professional Association of Fire Technicians (APTB, 2020) report 130,000 interventions caused by fires and 165 victims per year during the last decade in Spain. In 2019, Spanish firefighters performed 129,544 interventions related to 34,029 fires in

buildings (APTB, 2020) and 10,883 forest fires (including 14 large forest fires that affected more than 500 ha) (Área de Defensa contra Incendios Forestales, 2020), among other emergencies. Although forest fires tend to affect larger areas and require the intervention of more professionals and machinery, fires in buildings present even more risks for professionals. According to APTB (2020), 77% of the accidents suffered by firefighters in Spain in 2019 took place in closed spaces. This information can be generalized to other countries. The National Fire Protection Association of the United States generates an annual report with the injuries and illnesses suffered by firefighters while on duty Fahy et al. (2020). In 2019, 48 firefighters died in the United States due to toxic gases, explosions, burns, or entrapment. A remarkable fact is that 46% of firefighters older than 60 years die due to chronic diseases caused by the lack of information about the air quality in old interventions.

These statistics reveal the need for firefighters to know the environment before intervening. All the information about the location of the fires, the presence of harmful gases, and the possible paths is relevant to carry out more effective and safe interventions. The survey by Roldán-Gómez et al. (2021) shows that Spanish firefighters consider that the health risks and the lack of real-time information of the fires are the most critical problems in extinguishing tasks, even more than the lack of human and material resources and the coordination of teams. These problems are even more critical indoors than outdoors, given that these scenes complicate the evacuation of gases and the movements of firefighters.

In the context of indoor fires, the main goals of intervention teams are assessing the building state, putting out the flames, and rescuing potential victims. For this purpose, they start analyzing the emergency situation, trying to identify the sources of the fire, as well as the potential hazards in the scenario. Once this work is done, they plan safe routes from their current positions to the targets and the closest exits.

Autonomous robots play an important role in emergency response missions (Luneckas et al., 2021), including search and rescue missions after natural or human-made disasters (Grogan et al., 2018; Murphy, 2012) and interventions during emergencies, like, chemical, biological, radiological, and nuclear (Guzman et al., 2016) and wildfires (Baudoin et al., 2009). They are used for the first response in disaster scenarios to gather the information required for later human intervention (Baudoin et al., 2009). In these operations, fast and realistic simulations of environments, robots, and missions are useful for planning interventions and training rescue teams. Integration of new technologies, like, data analysis, artificial intelligence, and predictive modeling can improve efficiency and safety in these missions.

This work aims to integrate these technologies in an accessible way to support firefighters in hostile conditions, limiting their exposure to hazardous environments and helping them be located and guided outside buildings. The main objective is to foresee and minimize possible accidents and risk situations in indoor spaces by obtaining prior and real-time information about the intervention. For this purpose, all the developed technologies must be cost-effective and easy to use.

The main contributions of this paper are:

1. The design and development of a mobile robot to intervene in indoor fires adapted to the necessities expressed by firefighters.
2. The validation of this platform in both highly realistic simulations and real scenarios involving its end-users.

The remainder of the paper is organized as follows: Section 2 summarizes the state-of-the-art related to this work, Section 3 presents the hardware and software architectures of the autonomous robot, Section 4 describes the simulator developed for mission planning and system validation, Section 5 reports the experiments performed to validate all these developments, and Section 6 summarizes the main conclusions of the work.

2 | LITERATURE REVIEW

The literature contains multiple proposals of robots for firefighting. There are reviews on multiple topics, such as fire extinguishing robots (Liu et al., 2016), fire detection sensors (Fonollosa et al., 2018; Gaur et al., 2019), and robot-assisted evacuation (Bahamid et al., 2020). We have addressed a systematic search of fire detection, monitoring and extinguishing robots, finding the relevant works collected in Table 1.

As shown in Table 1, ground and aerial robots are proposed for detection, monitoring, and extinguishing in outdoor and indoor scenarios. Typically, aerial robots are proposed for detecting and monitoring fires outdoors because they cover larger terrains in less time. In contrast, ground robots are recommended for extinguishing fires indoors because of their robustness and payload capacity. Nevertheless, some works propose UAVs in indoor missions (Aydin et al., 2019; Spurny et al., 2021), taking advantage of their agility and trying to compensate their fragility. The cooperation between both types of robots is explored by Ghamry et al. (2016).

Our proposal is a complete approach to fire detection, developing a platform and programming it to perform these tasks in indoor scenarios. Other proposals use commercial platforms to focus on specific aspects, like, path planning and computer vision. One strength of our proposal is that the design, development, and testing process has involved the firefighters. They have contributed with their knowledge of the scenarios, the intervention protocols, and the potential risks, whereas we have developed a low-cost platform that adapts to them as end-users.

3 | ARCHITECTURE

We designed the robot's architecture considering two main requirements: the accurate localization and navigation indoors and the real-time measurement of relevant variables. Indoor localization and navigation are challenging due to the lack or deterioration of the Global Navigation Satellite System (GNSS) signals.

This challenge is even more complicated in an emergency scenario with high uncertainty. The fire could have modified the layout (e.g., blocking the planned route), and the smoke could limit

Reference	Robot	Development	Task	Scene	Test
Baudoin et al. (2009)	UGV	Mission planning	Det/Mon	In/Out	FE
Zhang (2020)	UGV	Path planning	Det	Out	LE
Mizuno et al. (2019)	UGV	Path planning	Ext	Out	FE
Tamura et al. (2020)	UGV	Teleoperation	Mon/Ext	Out	FE
Kim et al. (2016)	UGV	Energy saving	Mon/Ext	In	Sim
Dhiman et al. (2021)	UGV	Computer vision	Det/Ext	Out	LE
Guo et al. (2019)	UGV	Computer vision	Det	In	LE
Yuan et al. (2016)	UAV	Computer vision	Det	Out	LE/FE
Innocente and Grasso (2019)	UAV	Swarm intelligence	Det/Mon	Out	Sim
Ghamry et al. (2017)	UAV	Swarm intelligence	Det	Out	Sim
Ghamry et al. (2016)	MRS	Air–ground cooperation	Det	Out	Sim
Aydin et al. (2019)	UAV	Extinguishing balls	Ext	In/Out	LE
Spurny et al. (2021)	UAV	Sw development	Det/Mon	In	Sim/FE
Here	UGV	Hw/Sw development	Mon	In	Sim/FE

TABLE 1 State-of-the-art on firefighting robots

Abbreviations: Det, Detection; Ext, Extinguishing; FE, Field Experiment; Hw, Hardware; In, Indoor; LE, Laboratory Experiment; Mon, Monitoring; MRS, MultiRobot System; Out, Outdoor; Sim, Simulation; Sw, Software; UAV, Unmanned Aerial Vehicle; UGV, Unmanned Ground Vehicle.

the visibility. Additionally, detections must be accurately referenced to robot pose to facilitate subsequent human intervention.

This challenge has been addressed using the Ultra-Wideband (UWB) system,[1] which provides real-time communications to get the accurate location of the robot. This radio technology can easily penetrate objects by using radio waves (Esfahlani, 2019; Munguía-Alcalá & Grau-Saldes, 2013). It relies on transmitting an ID and timestamp over UWB for positioning, not merely on signal strength. The radio waves are sent from one module to another and measure the time of flight.

The beacons allow knowing the position of the robot in real-time. Before the intervention, we placed four beacons in the scenario and another on the robot. A beacon is taken from the wall as a reference system, being able to identify the position in X, Y, and Z in a two-dimensional plane. An algorithm works with these coordinates to calculate the X and Y positions of the moving beacon using the UWB system. This location system could not be viable in real interventions since it would be necessary to install the beacons before the mission. However, in some scenarios, the emergency team can place the beacons in safe places surrounding the affected area. Additionally, the rescuers can teleoperate the robot to place the beacons in a first exploration of the scenario.

Some alternatives of UWB are WiFi, Bluetooth, or Bluetooth Low Energy (Herrera Vargas, 2016), which obtain the position of the device to be located with an error of 2 m approximately. The problem is that these systems depend on parameters of the environment that cause interface and errors in positioning. These are the reasons why UWB is the best option for this purpose.[2]

Apart from these communication technologies, some algorithms can localize the robot in the scene using data from sensors, such as the Simultaneous Location And Mapping (SLAM; Zafari et al., 2019). SLAM creates a global map of the environment through the superposition of partial maps obtained in different moments and places. For the integration of these maps, it usually applies the General Closest Point Method algorithm, which extracts and matches attributes from the maps. In the interventions caused by indoor fires, sensors may be affected by dense smoke. This way, SLAM algorithms could have difficulties integrating this information affected by noise into a coherent map. In its place, they may find multiple partial maps that cannot be fused taking into account their similarities. As a result, the final map could not be well defined, so the robot cannot use it for its localization and navigation.

In addition to the localization sensors, the platform is equipped with environmental sensors. These sensors measure environmental parameters that are relevant for emergency interventions, such as temperature, relative humidity, and air quality (mainly carbon dioxide, volatile organic compounds, hydrogen, and ethanol concentrations). This infrastructure allows the exchange of information between the robot, which is inside the building, and the firefighters, located in a safe area before the intervention. These variables were chosen

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[1]For more information about the UWB system, see "How positioning works" at the Pozyx Academy website https://www.pozyx.io/pozyx-academy/how-does-positioning-work.

[2]For more information about the UWB performance, see "Ultra-wideband and obstacles" at the Pozyx Academy website https://www.pozyx.io/pozyx-academy/ultra-wideband-and-obstacles.
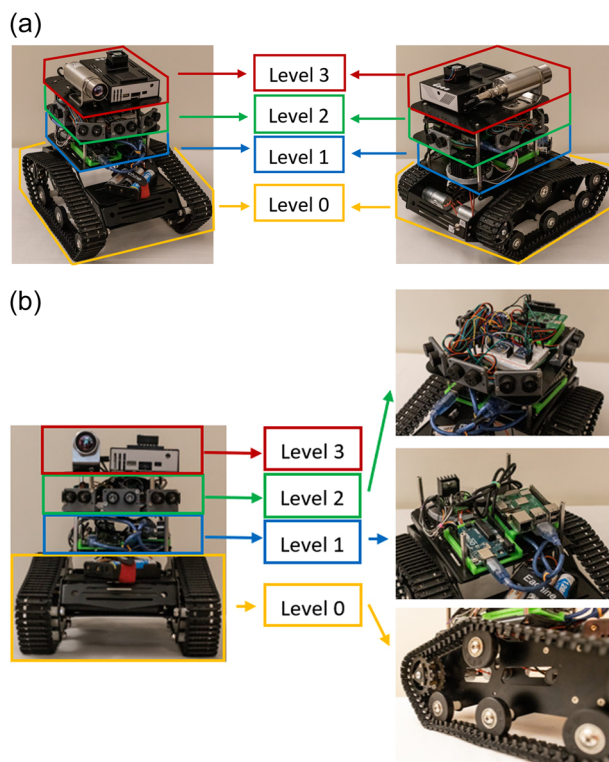
FIGURE 1 Hardware architecture of the autonomous agent: level 0 corresponds to power and locomotion, level 1 to the control of sensors and actuators, level 2 to perception and communication, and level 3 is available for future expansions

considering the sensors' availability, as well as their impact on mission efficiency and safety. The behavior of fires is defined by three aspects: fuel characteristics, ignition sources or meteorological parameters, and source locations. In indoor spaces, the last two factors have a small impact, so the temperature, relative humidity, and air quality would be measured. In this way, firefighters can avoid passing through areas with extreme temperatures or toxic gases.

The complete architecture of the autonomous agent is modular, so new hardware and software components can be added in future works. Figure 1 shows the hardware architecture of the system, divided into four levels with different functionalities. As shown in Figure 2, the maximum size of the robot is 280.96 × 220.50 × 230.00 mm, so it can move through narrow pathways and access hard-to-reach places while keeping desired levels of robustness and performance.

Table 2 includes all the technology used to build the robot.

Level 0 powers the robot and executes its movements. This level corresponds to the robot chassis that consists of two tracks guided by six wheels, two DC motors (GM25-370), a lithium battery with 5 V and 10.800 mAh for the payload, and three rechargeable lithium-ion batteries with 3.7 V and 12.800 mAh for the motors. It also has a switch to start and stop the robot easily.

Level 1 is devoted to the control of the robot and its sensors. For this purpose, it contains a motor driver (SKU DRI0002) and two microcontrollers (Arduino UNO WiFi REV2 and Raspberry Pi 4). The Arduino board does the low-level control of the robot, generating the voltage inputs for the motors according to the received speed commands. The Raspberry Pi board performs high-level functions related to the robot's perception, decision-making, actuation, and communications. This layer generates speed commands from the planned path in autonomous mode or the user commands in the manual one. In the others, it coordinates the communications between the robot and base station, having access to all the information generated by the sensors. This microcontroller also facilitates integrating new software: for example, autonomous navigation and mapping algorithms and computer vision methods for fire detection.

Level 2 performs the perception and communication functions of the robot. It has six ultrasonic sensors (SEN0304) that cover the robot perimeter, allowing it to detect obstacles: one in the front, two in the sides, two at 45° in the advance direction, and one in the back. Additionally, it is equipped with two environmental sensors: one (HTU21D-F) to measure air temperature and relative humidity and another (SGP30) to determine air quality. This last sensor measures the concentration of different gases: eCO_2 (estimated carbon dioxide concentration) with a range of 400–60,000 ppm, Total Volatile Organic Compounds (TVOCs) with a range of 0–60,000 ppm, hydrogen, and ethanol. These measurements allow firefighters to determine which areas are safe and which avoid during the intervention. This layer also integrates a Pozyx flag,[3] which is a mobile beacon that can communicate via UWB with the Pozyx infrastructure to localize the robot and exchange relevant information. Another Arduino UNO WiFi REV2 board integrates localization, navigation, and environmental sensors.

Finally, level 3 is ready to expand the system's functionalities. Some examples are housing a thermal camera, which is helpful in firefighting missions and integrating other types of beacons, such as Pycom, Deep Beacon, and so forth.

An analysis of the considered mission reveals that, in some phases, autonomous control may be preferred for its speed and safety, but, in some others, manual control may provide more accurate detections. Therefore, we have provided multiple operating modes to allow intervention teams to choose the most effective according to the situation. For instance, the robot can autonomously explore the room and avoid obstacles to detect potential threats. Then an operator can teleoperate it to the points of interest to check these threats closer.

We have programmed three operating modes, as shown in Figure 3: manual, autonomous, and evacuation.

Manual mode allows an operator to remotely control the robot (see the yellow path in Figure 3). In this mode, the operator can use a keyboard, joystick, or joypad to generate speed commands for the robot. These commands are processed by the Raspberry Pi and then applied to the motors by the Arduino UNO. The operator can teleoperate the robot with a direct view or a graphical user interface.

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[3]For more information about the Pozyx devices, see "Pozyx anchors" at the Pozyx Academy website https://www.pozyx.io/products/hardware/hardware-anchors?_ga=2.52209838.626958850.1638551771-1496953757.1638551771
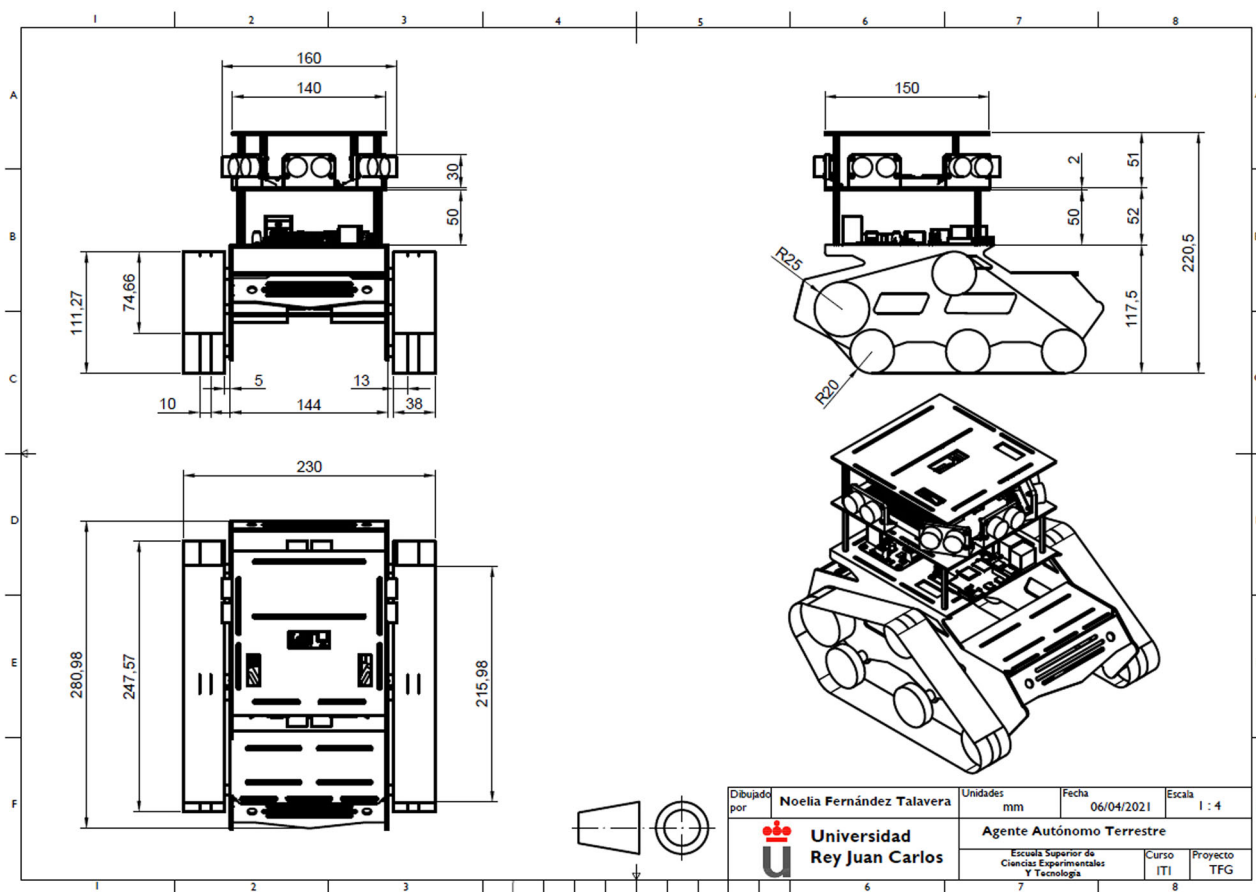
FIGURE 2 Design drawing with all the relevant dimensions of the autonomous agent

TABLE 2 Hardware components used to build the robot and their main features

Component	Number	Features
Motors (GM25-370)	2	12 V y 150 ± 10 rpm
Power bank (Ansmann)	1	10.800 mAh, 5 V, and 2,4 A
Rechargeable lithium-ion batteries (Okoman)	3	3,7 V and 12.800 mAh
Motor driver (SKU DRI0002)	1	Logic input part: 6–12 V. Driven part: 4,8–46 V. With Pulse Width Modulation (PWM)
Air temperature and relative humidity sensor (HTU21D-F)	1	Temperature: ±1°C from −30°C to 90°C. Humidity: 5%–95% RH
Air quality sensor (SGP30)	1	eCO_2: 0–60,000 ppm; TVOC concentration: 0–60,000 ppb
Creator Anchor (Pozyx flag)	1	A short-range communications technology that uses a large portion of the radio spectrum
Open-source electronics platform (Arduino UNO WiFi REV2)	2	ATECC608 crypto chip Accelerator, ATmega4809 8-bit microcontroller from Microchip, u-blox NINA-W102, LSM6DS3TR
Credit-card-sized computer (Raspberry Pi 4)	1	Broadcom BCM2711, Quad core Cortex-A72 (ARM v8) 64-bit SoC 1.5 GHz, 8 GB LPDDR4-3200 SDRAM, 5.0 GHz IEEE 802.11ac wireless, Bluetooth 5.0, BLE. Gigabit Ethernet, 2 USB 3.0 ports; 2 USB 2.0 ports
Ultrasonic sensor (SEN0304)	6	Resolution of 1 cm and accuracy of ±1% and ranging within 2–500 cm

Abbreviations: BLE, Bluetooth Low Energy; TVOC, Total Volatile Organic Compounds; USB, Universal Serial Bus.
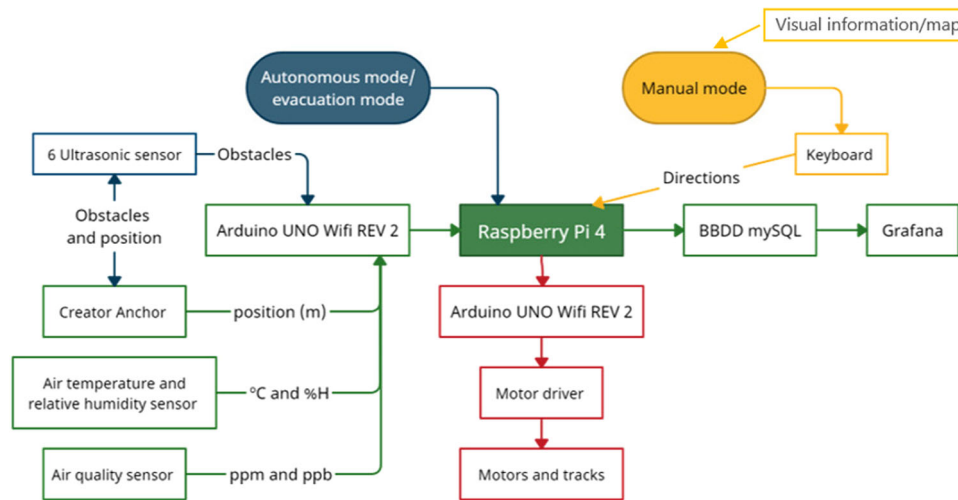
FIGURE 3 Diagram of system operation: manual mode (yellow) allows an operator to remotely control the robot using its camera, whereas autonomous and evacuation modes (blue) allow the robot to explore its environment knowing its position and the surrounding obstacles

In this last case, the interface must provide information to keep the situational awareness of the operator, such as the map of the scene, the accurate location of the robot, images of its camera, and so forth.

Autonomous mode (see the blue path in Figure 3) explores the environment avoiding potential obstacles. For this purpose, we have developed a coverage path planning algorithm that runs on the Raspberry Pi. This algorithm uses the information provided by the sensors to locate the robot and identify the obstacles around it. Then, it guides the robot through a set of waypoints related or not to the deployed beacons. In this way, the robot can cover entire rooms, providing local information on the environmental conditions.

Finally, evacuation mode (see the blue path in Figure 3) creates fast and safe routes toward targets. This mode uses the prior knowledge of the scene to compute the shortest path from the current position to the target position. The target position can be the exit of the building or the location of a victim, among other things. This mode is also executed in the Raspberry Pi with the information provided by the sensors.

In all these modes, the Raspberry Pi stores the data collected by sensors into a database, in this case, MySQL, to be visualized later with Grafana[4] (green path in Figure 3). Note that the Raspberry Pi simultaneously receives data from sensors, runs the control algorithm, and sends data to the database. Thus, it must work with a transmission speed of milliseconds to avoid data losses.

The power supply is divided into two parts to make the system work. On the one hand, three rechargeable lithium-ion batteries (each one with 3.7 V and 12,800 mAh capacity) power the motors of the autonomous agent through the motor controller. On the other hand, a portable lithium power bank with 10,800 mAh power the sensing and control electronics. The division of power supplies

between physical and electronic components is a surefire way to avoid potential overloads and short circuits.

As mentioned in the motivation of this document, one of the main challenges is to develop a solution easily transferable to the emergency services within the HelpResponder project. As shown in Table 3, we have provided the emergency teams with a cost-effective solution, which can be used in hazardous environments where it could be lost.

4 | SIMULATION

Simulations are valuable before, during, and after interventions. In the first case, they allow preparing missions, train operators, and test algorithms. The second one permits supervising missions and testing actions before applying them. In the last case, they evaluate mission performance and develop new plans for future operations.

We have developed a realistic simulator using the Unity game engine. This platform was created for developing video games but is becoming popular in the context of robotics to create simulators (Konrad, 2019), operator interfaces (Roldán et al., 2019), and data sets (Borkman et al., 2021). In the context of this work, Unity offers a flexible environment to develop a realistic but light simulator.

This simulator reproduces the physical appearance and behavior of the robot. As shown in Figure 4a, the autonomous agent has been modeled using the AutoCAD software, including all its mechanical and electronic components, as well as its accurate dimensions.

In addition, the simulator reproduces the facilities of the Unified Security Center (USC), located in Alcorcón, Madrid, Spain (latitude: 40.33449°; longitude: −3.83199°), where the experiments with the robotic platform were performed. Specifically, we modeled the basement and first floor of the Alcorcón Fire Tower with all its elements (e.g., pallets, furniture, and fences), as shown in Figure 4b,c, respectively.

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[4]For more information about Grafana, see the website of this application https://grafana.com/.

TABLE 3 Costs of the materials used to build the autonomous agent

| Device	Price/ UD (€)	Units	Total price ($)
Autonomous agent chassis + engine	63.53	1	65.83
ON/OFF switch	2.50	1	2.59
Power bank (Ansmann)	24.74	1	25.63
Rechargeable lithium-ion batteries	5.37	4	22.26
Motor driver (SKU DRI0002)	14.44	1	14.96
Air temperature and relative humidity sensor (HTU21D-F)	13.51	1	14.00
Air quality sensor (SGP30)	24.40	1	25.12
Creator Anchor (Pozyx flag)	847.00	1	877.62
Open-source electronics platform (Arduino UNO WiFi REV2)	38.08	1	39.46
Credit-card-sized computer (Raspberry Pi 4)	97.27	1	100.79
Ultrasonic sensor (SEN0304)	10.93	6	67.95
Cable	8.18	6	8.48
Mounting for sensors	4.20	6	26.11
Metal separator	5.51	1	5.71
Mounting for batteries	6.19	1	6.41
SD card	7.05	1	7.30
Adapter for SD card	6.34	1	6.57
Energy sensor	10.89	1	11.28
Separating metal plates	7.50	2	15.54
Resistances	3.01	2	6.24
TOTAL (without VAT)			1148.23
TOTAL (with VAT)			1389.36

Note: The conversion between euros and dollars was performed considering the official exchange rate on November 14, 2022.
Abbreviations: SD, Secure Digital; VAT, Value-Added Tax.

All this simulation environment—including the models of the robot and scenarios, the scripts that drive the simulations, and some videos of the simulated and real-world experiments—is available at our GitHub repository Talavera (2021).

5 | EXPERIMENTS AND RESULTS

We carried out two interventions at the Unified Safety Center of Alcorcón, in collaboration with the Fire Department of that city. In these missions, we validated the robot prototype (testing its motion, obstacle avoidance capability, load capacity, and autonomy), as well as the mission (performing multiple routes and registering
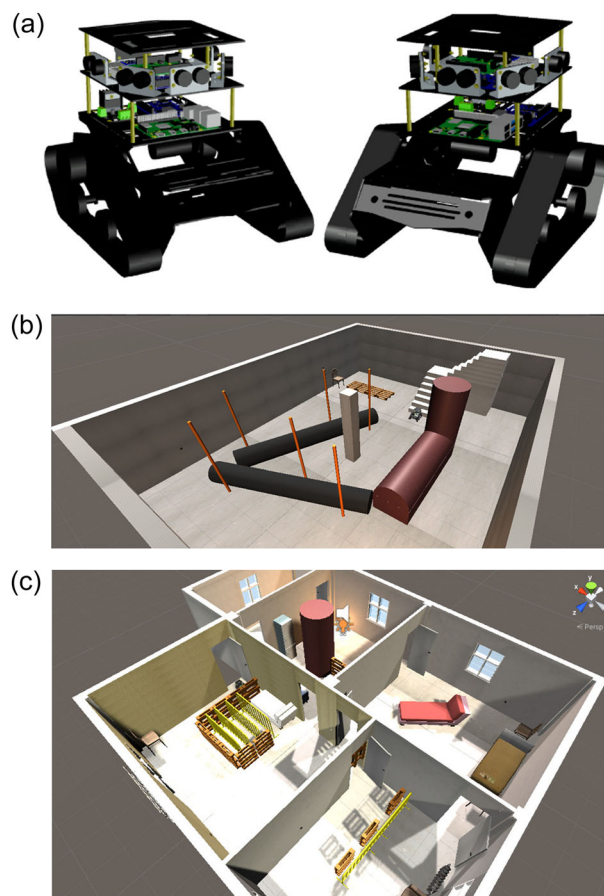

FIGURE 4 Screenshots with the models of the real agent and scenario implemented in the simulator: (a) autonomous agent, (b) USC basement, and (c) USC first floor. USC, Unified Security Center.

environmental parameters). During these experiments, we tried both the manual and autonomous modes described above, but in this section, we will only describe the most relevant autonomous missions. The condition for success in these experiments is that the robot covers its routes through the building, providing real-time information on the environmental conditions and helping to locate the sources of the fire.

The first tests were performed in the basement of the USC without the presence of fire. Some pictures are shown in Figure 5a. During these tests, the robot was able to cover an area of 125.25 m^2 with a path of 36.00 m in 57 s. It reached speeds between 0.25 and 0.5 m/s and could overcome the obstacles present in the scene, such as wooden planks and pebbles. As shown in Figure 5b, the deviations between the planned path and the actual route were negligible, lower than 10 cm in the worst case. The following average values for the environmental variables were collected by the robot: temperature of 16.31°C, relative humidity of 71.35%, eCO$_2$ of 403.14 ppm, and TVOC of 18.72 ppb. A video of these first tests can be found at the following link: https://youtu.be/li0AAESpnBk.
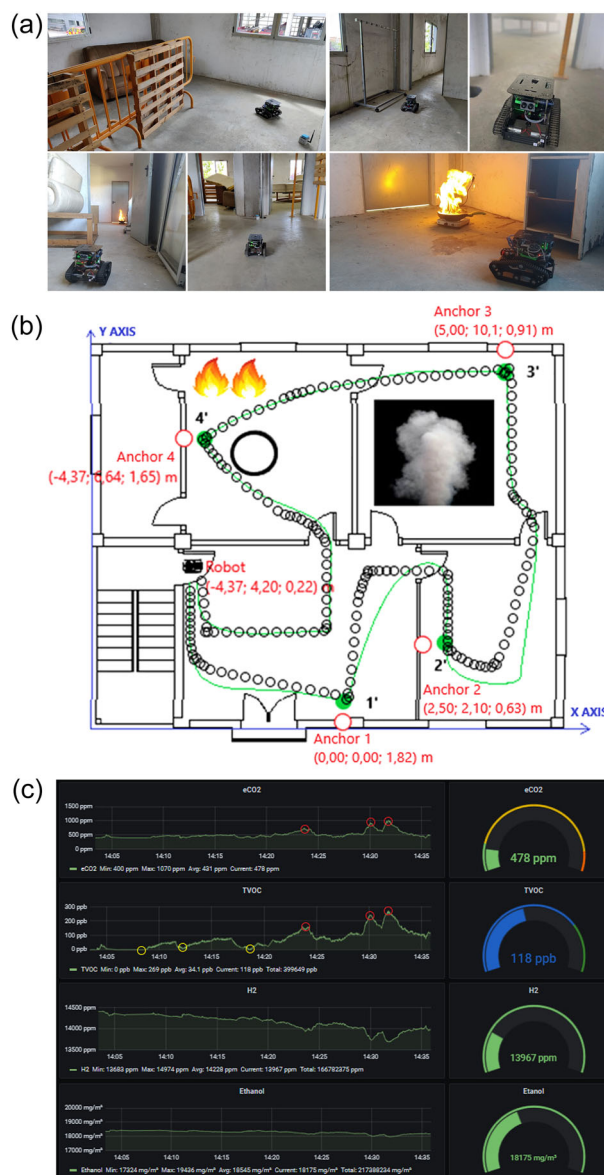
The second test was performed on the first floor of the USC, which consists of multiple rooms of different sizes and shapes. Some pictures are shown in Figure 6a. In this case, we used actual fire and
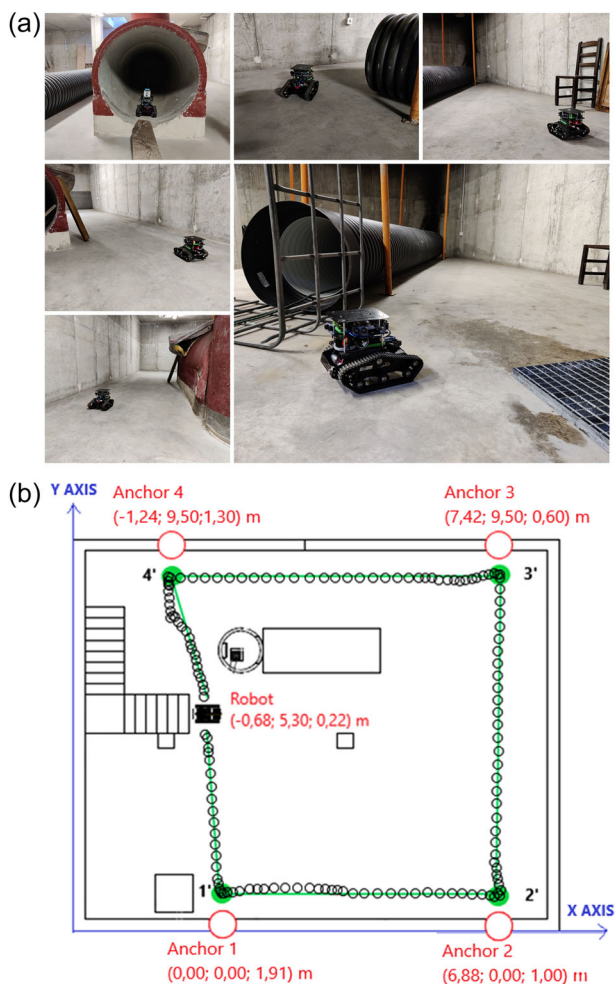
FIGURE 5 Tests performed in the basement of the USC without fire: (a) some pictures of the robot while performing this mission, and (b) planned path (green line) and actual path (black circles) of the autonomous agent. USC, Unified Security Center.

FIGURE 6 Tests performed on the first floor of the USC with fire and cold smoke: (a) some pictures of the robot while performing this mission, (b) planned path (green line) and actual path (black circles) of the autonomous agent, and (c) Air quality data collected by the robot and shown by the application. USC, Unified Security Center.

cold smoke to reproduce the conditions of real emergency scenarios. The robot covered a similar area than in the previous mission but performed a path of 50.00 m in 2 min and 17 s. These results can be explained by the division of the space in multiple rooms and the high density of obstacles. The speeds were again in the range between 0.25 and 0.5 m/s. As shown in Figure 6b, there were more significant deviations between planned and actual paths, but they were caused by the obstacles correctly avoided by the robot. In this case, the robot registered an average temperature of 28.06°C with a maximum of 30°C and average relative humidity of 34.97%. As it can be seen in Figure 6c, the robot detected the fire sources, providing peaks of 1070 ppm of eCO_2 and 269 ppb of TVOC (red circles in the graphics). A video of these second tests can be found at the following link: https://youtu.be/W9kNVwnYAps.

During all the interventions explained above, the robot with its payload weighed 2.07 kg and had a maximum autonomy of 9 h and 36 min. Additionally, the capability of the robot to go through narrow spaces and cross tubes with a minimum diameter of 0.5 m was

validated. We calculated this autonomy theoretically and experimentally using a linear electricity sensor based on the Hall effect, which determines the total power consumption of the components connected to each power supply. Table 4 shows the results of the total consumption. Therefore, the autonomy of rechargeable batteries and portable power banks is 76 h 11 s and 9 h 36 min, respectively.

The interventions in the real scenario reported previously were designed and prepared using the simulator. As shown in Figure 7, the environment developed in the Unity game engine was helpful in systems validation and risk assessment. This way we could determine the best path in terms of efficiency and safety and avoid problems

	Theoretical calculation (mAh)	Experimental calculation (mAh)
Rechargeable lithium-ion batteries	505	515
Portable power bank	1125	1123
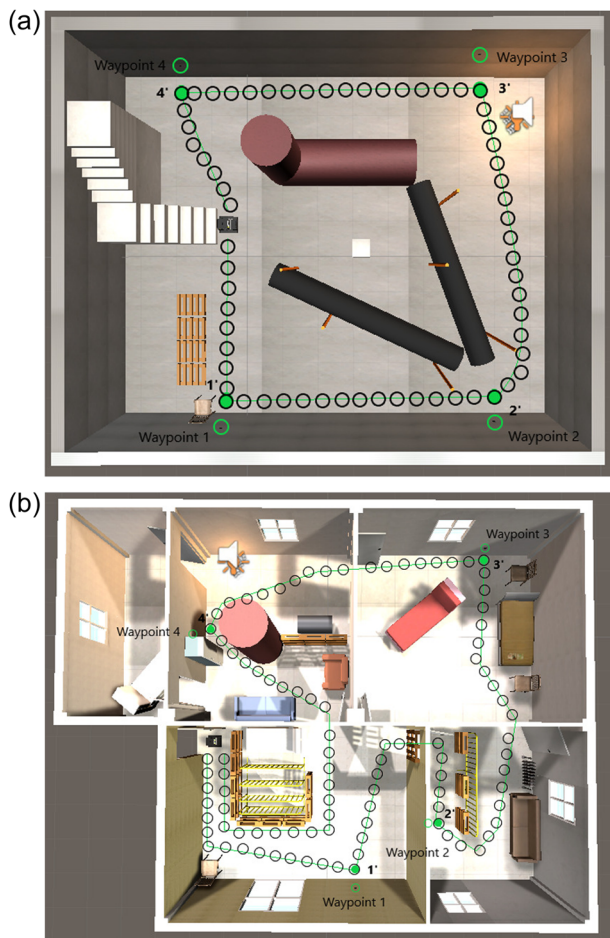
FIGURE 7 Simulations in the (a) USC basement and (b) USC first floor. Planned paths (green lines) versus simulated routes (black circles). USC, Unified Security Center.

during the interventions. The simulated interventions had a mean duration of 44 s and 2 min and 32 s, revealing a certain reality gap between the simulator and the real world. Nevertheless, the simulator proved to be a powerful tool for preparing interventions, testing the guidance, control, and navigation algorithms, and showing high realism in the robot movements and turns. Some videos of these simulations can be found at the links https://youtu.be/P-pUiE7IAQs and https://youtu.be/GUqyOBWUdCU.

Moreover, we tried the autonomous and evacuation robot modes in the simulation environment. The autonomous mode was developed as a state machine, where the robot must follow a list of waypoints to cover the area, dodging the obstacles and fires present

between them. The paths in Figure 8a lasted 40 s to cover the basement and 1 min and 44 s to do the same on the first floor.

The evacuation mode takes advantage of the Unity navigation system to find a path between the initial robot position and the potential target position (see Figure 8b). This navigation system analyzes the available space where the robot can move without risk, removing areas occupied by objects and fires (see Figure 8c). This information allows the autonomous agent to find the fastest and safest path to the target. For this purpose, it integrates an A* algorithm with some efficiency and safety constraints.

The main advantage of this mode is that the target can be modified at any time, even if the autonomous agent has already started its route in the emergency scenario. This functionality provides the intervention teams with flexibility for their operations. For instance, if they are looking for victims in one location and receive new information that prioritizes another place, they can update the target so the system can replan the route close to real-time and go toward the new objective.

Finally, although simulation is a helpful tool in interventions, there are similarities and differences between real and simulated environments. Figure 8d shows the theoretical (green), simulated (black), and real paths (red). As can be seen, the real path presents some deviations from the theoretical and simulated ones, probably caused by the real-world uncertainty that cannot be modeled in the simulation environment. Two videos comparing simulated and real scenarios can be seen at the following links: https://youtu.be/NqTfmxBixew and https://youtu.be/omUY7O7uIcw.

The following similarities between the simulations and experiments were found after an analysis of results:

- The esthetics of the environment and autonomous agent. All the components are similar to the real ones, with the same dimensions and colors. The terrestrial robot has also been designed with the same weight as the real one and with the same friction that it suffers in the field of the tests.
- The management of the autonomous agent is done with the keyboard, and the movement keys are the same in both situations. In addition, the same motion functions have been programmed in both cases, except for approximations. However, this possibility of making approximations exists in the simulation by pressing two keys simultaneously (front-right or front-left) to move the automaton diagonally and thus be able to redirect it.
- The terrestrial agent rotates on the Z-axis, rotating the same degrees in the real and simulated situations. Additionally, the
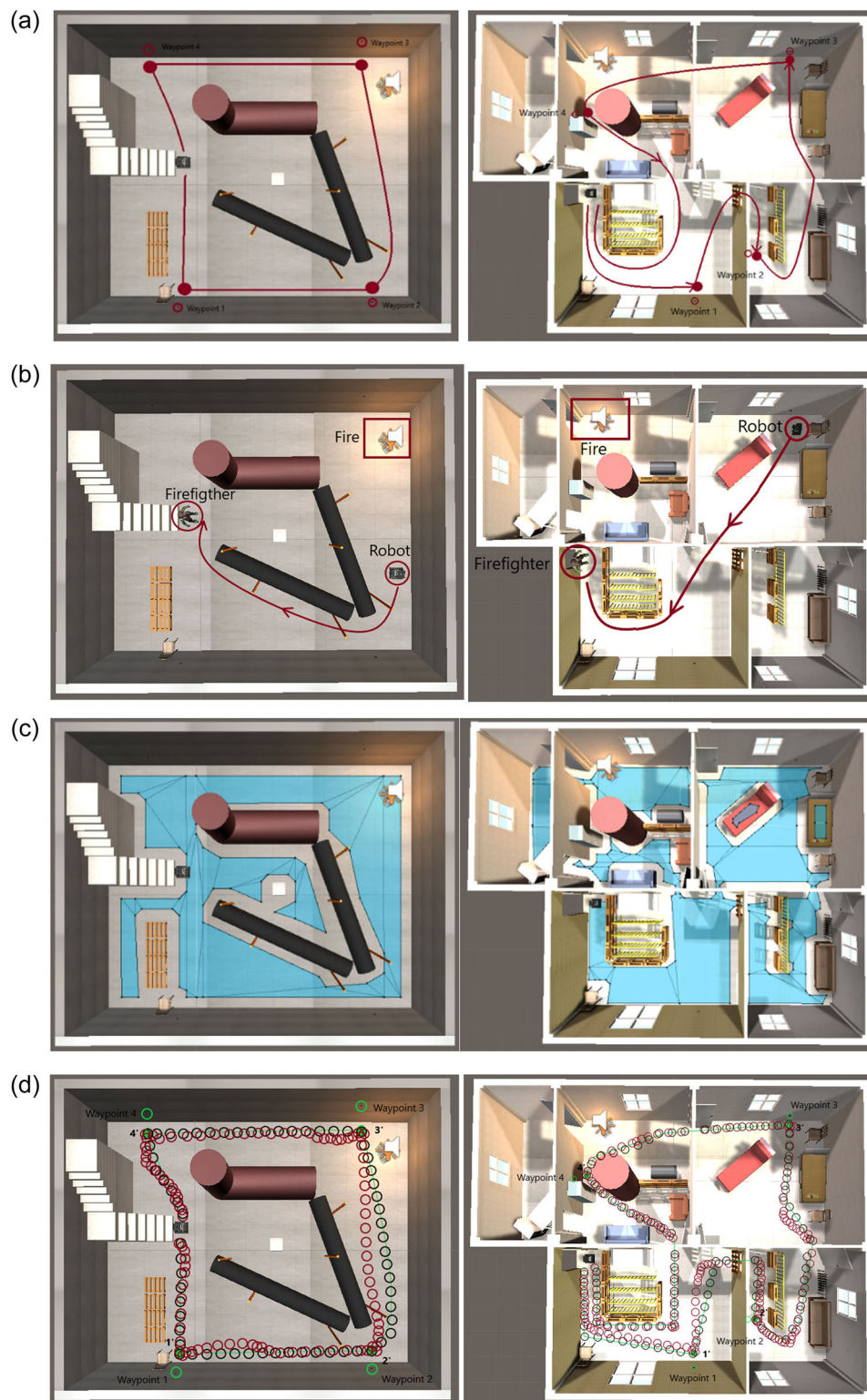
FIGURE 8 Development of the autonomous control of the robot in the simulation environment: (a) planned trajectories for the autonomous mode, (b) navigation areas generated by the Unity navigation system, (c) planned trajectories for the evacuation mode, and (d) theoretical (green lines), simulated (black circles), and real paths (red circles) in the scenarios

function of a 360° camera has been included in the simulation so that the field of view in both cases is the same.

- An ultrasonic sensor has been included in the front of the autonomous agent to measure the distance in real-time of the objects in front of it. Similarly, fire movement with sound has been included to simulate a fire.
- Finally, the speed of the automaton in reality and the simulation can be modified so that both are equal and can be adjusted to the situation. In this way, the tests carried out in the simulation to reduce intervention times will be similar to the real ones.

However, some differences and limitations were also found and must be corrected in future works:

- The main difference is that all the motion commands have the same speed in the simulation. In addition, the turn of the autonomous agent is instantaneous and faster than the real one.
- The fire does not spread as it would in a real situation. Also, cold smoke has not been included in the experiments.

6 | CONCLUSIONS

This paper presents a complete and functional robot to monitor fires in indoor places. This system has been tested and validated in simulated and real environments with fires and cold smoke.

According to the results presented in this paper, the system shows the versatility of functions, speeds, and movements to adapt to the characteristics of the emergency environment. In addition, the consumption of its elements has been reduced, thus increasing the operating autonomy. The air quality sensors collect valuable information to identify the fires' location during the intervention accurately.

Finally, the simulation environment has shown its potential as a tool to plan interventions and train firefighters. This simulator integrates the dynamics and operating modes of the real robot, which is reflected in the similarity between the simulated and actual routes.

AUTHOR CONTRIBUTIONS

N. Fernández Talavera, Juan Jesús Roldán-Gómez, and M. C. Rodriguez-Sanchez Conceived and designed the experiments. N. Fernández Talavera and M. C. Rodriguez-Sanchez performed the experiments. N. Fernández Talavera, Juan Jesús Roldán-Gómez, and M. C. Rodriguez-Sanchez analyzed the data. N. Fernández Talavera, Juan Jesús Roldán-Gómez, and M. C. Rodriguez-Sanchez contributed material. All authors wrote the paper. All authors have read and agreed to the published version of the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Senialab-code at https://urjc-my.sharepoint.com/:f:/g/personal/cristina_rodriguez_sanchez_urjc_es/EhZ5WKv7ApNOjap4pOi6JasBYJEw3grmw97hCn84tJxHdA?e=RgJzbe.

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REFERENCES

APTB y Fundación MAPFRE. (2020) APTB study of victims of fires in Spain. Available at: https://documentacion.fundacionmapfre.org/documentacion/publico/es/media/group/1164.do

Área de Defensa contra Incendios Forestales, G. d. E., Ministerio para la Transición Ecológica y el Reto Demográfico. (2020) *Los incendios forestales en españa: Avance informativo 2019, Technical Report*. Available at: https://www.mapa.gob.es/es/desarrollo-rural/estadisticas/avance_1_enero_31_diciembre_2019_tcm30-537398.pdf [Retrieved 2021-12-31].

Aydin, B., Selvi, E., Tao, J. & Starek, M.J. (2019) Use of fire-extinguishing balls for a conceptual system of drone-assisted wildfire fighting. *Drones*, 3(1), 17.

Bahamid, A., Ibrahim, A.M., Ibrahim, A., Zahurin, I.Z. & Wahid, A.N. (2020) Intelligent robot-assisted evacuation: a review. *Journal of Physics: Conference Series*, 1706, 012159.

Baudoin, Y., Doroftei, D., De Cubber, G., Berrabah, S.A., Pinzon, C., Warlet, F., Gancet, J., Motard, E., Ilzkovitz, M., Nalpantidis, L., et al. (2009) View-finder: robotics assistance to fire-fighting services and crisis management. In: *2009 IEEE international workshop on safety, security & rescue robotics (SSRR 2009)*. Denver, CO, USA: IEEE, pp. 1–6. Available at: https://doi.org/10.1109/SSRR.2009.5424172

Borkman, S., Crespi, A., Dhakad, S., Ganguly, S., Hogins, J., Jhang, Y.-C., Kamalzadeh, M., Li, B., Leal, S., Parisi, P., et al. (2021) Unity perception: generate synthetic data for computer vision. Available at: https://arxiv.org/abs/2107.04259

Dhiman, A., Shah, N., Adhikari, P., Kumbhar, S., Dhanjal, I.S. & Mehendale, N. (2021) Firefighting robot with deep learning and machine vision. *Neural Computing and Applications*, 1–9.

Esfahlani, S.S. (2019) Mixed reality and remote sensing application of unmanned aerial vehicle in fire and smoke detection. *Journal of Industrial Information Integration*, 15, 42–49.

Fahy, R.F., Petrillo, J.T. & Molis, J.L. (2020) Firefighter fatalities in the United States, 2019.

Fernández Talavera, N. (2021) Sistema de navegación autónomo en entornos reales y simulados para situaciones de emergencia, pp. 1–141. Available at: https://burjcdigital.urjc.es/handle/10115/18048 [Retrieved 2021-08-01].

Fonollosa, J., Solórzano, A. & Marco, S. (2018) Chemical sensor systems and associated algorithms for fire detection: a review. *Sensors*, 18(2), 553.

Gaur, A., Singh, A., Kumar, A., Kulkarni, K.S., Lala, S., Kapoor, K., Srivastava, V., Kumar, A. & Mukhopadhyay, S.C. (2019) Fire sensing technologies: a review. *IEEE Sensors Journal*, 19(9), 3191–3202.

Ghamry, K.A., Kamel, M.A. & Zhang, Y. (2016) Cooperative forest monitoring and fire detection using a team of UAVs–UGVs. In: *2016 International conference on unmanned aircraft systems (ICUAS)*. Arlington, VA, USA: IEEE, pp. 1206–1211. Available at: https://doi.org/10.1109/ICUAS.2016.7502585

Ghamry, K.A., Kamel, M.A. & Zhang, Y. (2017) Multiple UAVs in forest fire fighting mission using particle swarm optimization. In: *2017 International conference on unmanned aircraft systems (ICUAS)*. Miami, FL, USA: IEEE, pp. 1404–1409. Available at: https://doi.org/10.1109/ICUAS.2017.7991527

Grogan, S., Pellerin, R. & Gamache, M. (2018) The use of unmanned aerial vehicles and drones in search and rescue operations—a survey. In: Proceedings of the PROLOG.

Guo, J., Hou, Z., Xie, X., Yao, S., Wang, Q. & Jin, X. (2019) Faster R-CNN based indoor flame detection for firefighting robot. In: *2019 IEEE symposium series on computational intelligence (SSCI)*. Xiamen, China: IEEE, pp. 1390–1395. Available at: https://doi.org/10.1109/SSCI44817.2019.9002843

Guzman, R., Navarro, R., Ferre, J. & Moreno, M. (2016) Rescuer: development of a modular chemical, biological, radiological, and nuclear robot for intervention, sampling, and situation awareness. *Journal of Field Robotics*, 33(7), 931–945.

Herrera Vargas, M. (2016) Indoor navigation using Bluetooth low energy (BLE) beacons. Turun ammattikorkeakoulu, Turku University of Applied Sciences. p. 54.

Innocente, M.S. & Grasso, P. (2019) Self-organising swarms of firefighting drones: harnessing the power of collective intelligence in decentralised multi-robot systems. *Journal of Computational Science*, 34, 80–101.

Kim, J., Dietz, J.E. & Matson, E.T. (2016) Modeling of a multi-robot energy saving system to increase operating time of a firefighting robot. In: *2016 IEEE symposium on technologies for homeland security (HST)*. WLTHm, MA, USA: IEEE. pp. 1–6. Available at: https://doi.org/10.1109/THS.2016.7568971

Konrad, A. (2019) Simulation of mobile robots with unity and ROS: a case-study and a comparison with gazebo.

Liu, P., Yu, H., Cang, S. & Vladareanu, L. (2016) Robot-assisted smart firefighting and interdisciplinary perspectives. In: *2016 22nd international conference on automation and computing (ICAC)*. Colchester, UK: IEEE, pp. 395–401. Available at: https://doi.org/10.1109/IConAC.2016.7604952

Luneckas, M., Luneckas, T., Kriaučiūnas, J., Udris, D., Plonis, D., Damaševičius, R. & Maskeliūnas, R. (2021) Hexapod robot gait switching for energy consumption and cost of transport management using heuristic algorithms. *Applied Sciences*, 11(3), 1339.

Mizuno, N., Ohno, K., Hamada, R., Kojima, H., Fujita, J., Amano, H., Westfechtel, T., Suzuki, T. & Tadokoro, S. (2019) Enhanced path smoothing based on conjugate gradient descent for firefighting robots in petrochemical complexes. *Advanced Robotics*, 33(14), 687–698.

Munguía-Alcalá, R.F. & Grau-Saldes, A. (2013) Slam con mediciones angulares: método por triangulación estocástica. *Ingeniería, investigación y tecnología*, 14(2), 257–274.

Murphy, R.R. (2012) A decade of rescue robots. In: *2012 IEEE/RSJ international conference on intelligent robots and systems*. Vilamoura-Algarve, Portugal: IEEE, pp. 5448–5449. Available at: https://doi.org/10.1109/IROS.2012.6386301

Roldán, J.J., Peña-Tapia, E., Garzón-Ramos, D., de León, J., Garzón, M., del Cerro, J. & Barrientos, A. (2019) Multi-robot systems, virtual reality and ROS: developing a new generation of operator interfaces. In: *Robot operating system (ROS)*. Cham: Springer, pp. 29–64.

Roldán-Gómez, J.J., González-Gironda, E. & Barrientos, A. (2021) A survey on robotic technologies for forest firefighting: applying drone swarms to improve firefighters' efficiency and safety. *Applied Sciences*, 11(1), 363.

Spurny, V., Pritzl, V., Walter, V., Petrlik, M., Baca, T., Stepan, P., Zaitlik, D. & Saska, M. (2021) Autonomous firefighting inside buildings by an unmanned aerial vehicle. *IEEE Access*, 9, 15872–15890.

Subdirectorate General for Forest Policy and Combating Desertification. (2020) Information coordination centre on forest fires.

Talavera, N.F. (2021) Noelia-vera/tfg-noelia-fernandez-talavera. Available at: https://github.com/Noelia-vera/TFG-Noelia-Fernandez-Talavera [Retrieved 2021-06-12].

Tamura, Y., Amano, H. & Ota, J. (2020) Analysis of firefighting skill with a teleoperated robot. *ROBOMECH Journal*, 7(1), 1–14.

Yuan, C., Liu, Z. & Zhang, Y. (2016) Vision-based forest fire detection in aerial images for firefighting using UAVs. In: *2016 international conference on unmanned aircraft systems (ICUAS)*. Arlington, VA, USA: IEEE, pp. 1200–1205. Available at: https://doi.org/10.1109/ICUAS.2016.7502546

Zafari, F., Gkelias, A. & Leung, K.K. (2019) A survey of indoor localization systems and technologies. *IEEE Communications Surveys & Tutorials*, 21(3), 2568–2599.

Zhang, Z. (2020) Path planning of a firefighting robot prototype using GPS navigation. In: *University of electronic science and technology of China, Chinese. Proceedings of the 2020 3rd international conference on robot systems and applications*. Ney York, NY, USA: Association fot Computing Macheinery. pp. 16–20.