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Research article

SAFE: An ICT platform for supporting monitoring, localization and rescue operations in case of earthquake

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ABSTRACT

Earthquakes are unpredictable natural events that cause a high number of casualties every year. During an earthquake, furniture and mobile equipment can either become obstacles or act as passive life safety systems by providing safe shelter for people involved in the event. The combination of Internet of Things (IoT) devices and anti-seismic furniture could serve as a means to transform them into intelligent protection systems to protect people in case of an earthquake, facilitating their detection and localization during the rescue operations through the integration of a supportive Information and Communication Technology (ICT) infrastructure. In this article, we report about the design and development of the SAFE ICT Platform which comprises wireless IoT devices integrated into anti-seismic furniture that activate in response to earthquakes to signal the presence of individuals needing rescue. The SAFE ICT Platform also includes local and cloud computing systems for device management and monitoring, alongside a localization and support system to assist rescuers in pinpointing and aiding individuals. A comprehensive evaluation scenario of the proposed solution is also discussed.

1. Introduction

Natural hazards (earthquakes, floods, extreme weather conditions, landslides) are responsible for severe damages, service interruptions, economic loss, and casualties, even in developed countries with engineered buildings [1,2]. As recognized by the United Nations Office for Disaster Risk Reduction,[1] addressing resilience building and disaster risk reduction, when curtailing climate change mitigation priorities, is a vital necessity. Developing urban resilience is the subject of a global effort and is enshrined in several global and regional processes all of which recognize the importance to create inclusive, safe, resilient and sustainable human settlements.

The Italian multidisciplinary research project "Sustainable design of Antiseismic Furniture as smart life-saving systems during an Earthquake" (SAFE)[2] stands out as one initiative aimed at improving, in public contexts (schools and offices), readiness and resilience to earthquakes. The main project idea started with the observation that, in case of an earthquake, furniture, mobile equipment, and non-structural elements become a further source of danger and cause of causalities. Nevertheless, the same elements might casually transform into human life protection systems. Consequently, within the project scope, anti-seismic furniture integrated with Information and Communication Technology (ICT) technologies have been designed so to act as intelligent security systems effectively contributing to the protection of life and to the location and discovery of people in case of an earthquake [3]. The

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[1] https://www.undrr.org/

[2] http://www.safeproject.it/

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resulting SAFE furniture, designed to be resistant to earthquakes, are capable of understanding that an earthquake is occurring, detecting and locating the presence of people after a collapse, and processing and sending useful information to the rescue teams.

The role of the ICT technology in the project was pivotal and led to the design and development of the SAFE ICT Platform which we report in this article. The SAFE ICT Platform introduces a set of tools and innovations based on information technology capable of improving the activities of monitoring, localization, and rescue of people after an earthquake. Such innovations are based on the introduction of the *SAFE IoT devices* that are integrated with *SAFE furniture*. The devices are able to monitor the state of people both before and after a seismic event. The SAFE ICT Platform also introduces a multi-layer *monitoring system* able to: (i) monitor the sensors in peacetime; (ii) detect the occurrence of an imminent earthquake in order to activate pre-alert logic; and (iii) send the collected data to a remote and decentralized cloud. The SAFE ICT Platform is completed with an innovative localization and rescue system that combines drones and data analysis techniques for the localization of the device hardware. The system is able to: (i) identify the heat sources emitted and detected by the device, which are signaling the presence of people to be rescued; (ii) estimate their position with respect to the site affected by the event analyzing the radio signals of the devices; (iii) provide geographical and direction indications to the rescue teams, increasing the effectiveness and timeliness of interventions. The SAFE ICT Platform offers a series of unique elements that, through the integration of technological components such as hardware devices and software modules, make it possible to provide an advance in the state of the art in the field of post-seismic event rescue.

To design and develop the SAFE ICT Platform we adopted the Design Science Methodology (DSM) [4,5]. The primary objective of DSM is to design and create innovative solutions or artifacts that can solve specific problems, improve existing systems, or create entirely new systems or products. Our adoption of the DSM is also reflected in the structure of the present article which is organized as follows. Section 2 describes the methodology we adopted to develop the SAFE ICT Platform. Section 3 presents the motivational scenario that is basis for this research. Section 4 discusses the requirements we defined interacting with Italian Urban Search and Rescue teams, while Section 5 and Section 6 present, respectively, the platform conceptual model and the related design and implementation. Section 7 describes the demonstration and evaluation set up and conducted at the University of Camerino. Section 8 illustrates, by means of a fictitious scenario, the advantages derived by adopting the SAFE ICT Platform. Section 9 introduces relevant related works and locates our contribution with respect to the literature. Section 10 describes limitations that we identified in our research and presented solution. Finally, Section 11 concludes by summarizing the provided contributions, and pointing out limitations and future work.

2. Methodology

The DSM begins with the identification and definition of a practical problem or need (Problem Identification), followed by the establishment of clear objectives and constraints for the design project (Objectives and Constraints). The core of DSM involves the creative process of designing and developing an artifact or solution to address the identified problem (Design and Creation), which is then rigorously evaluated to ensure it meets the specified objectives (Evaluation). Reflection on the evaluation results ensues, leading to potential revisions or improvements (Reflection). The findings and the designed artifact are documented and communicated to the relevant academic and practitioner communities (Communication). Finally, if deemed successful, the artifact may be implemented in a real-world context (Implementation). In the following we describe how we conducted each phase of the DSM.

2.1. Problem identification

In this phase, our objective was to gain a deep understanding of the context, empathize with users, and identify the underlining challenges to handle with the research. This involved a literature review in the scientific area, conducting interviews with the users, and exploring existing solutions and current practices.

Significant effort was dedicated to engaging with users to understand the implications of providing assistance after an earthquake and the challenges to be overcome. To achieve this, we involved the direct stakeholders, namely the rescue teams, to discuss their firsthand experiences, identify the challenges during rescue operations, and outline how technology could make a meaningful contribution. We organized several meetings with the Italian Civil Protection Department and the Italian Department of Firefighters who participate in rescue operations after a disaster, such as, for example, victim detection and extraction from the rubble. The objective of the meetings was to obtain key information about the practical aspects to consider in the response phase after an earthquake, including the practices and tools commonly used by the response teams. We report the result of this phase in Section 3.

2.2. Objectives and constraints

In this phase, we involved the stakeholders to define a clear definition of the objectives and requirements that a possible solution should incorporate. To do so, we created a specific focus group with the key stakeholders and performed unstructured interviews similar to the example described in Section 4.1. At the end of several interactions, we managed to define a set of requirements and characteristics to consider during the design phase. We report the result of this phase in Section 4.

2.3. Design

This phase is about generating ideas and exploring potential solutions. The emphasis is on the collaboration among the partners, with the aim of generating a wide range of ideas that can later be evaluated. With this objective, during the project, the partners were involved in brainstorming sessions to define the conceptual model of the SAFE ICT Platform and plan the related functionalities. The design took into consideration two types of requirements. The first one included the requirements derived from meetings with stakeholders. The second type of requirement referred to the integration of the devices within the SAFE furniture. This led to a close collaboration between the Industrial Design and Computer Science areas, which allowed us to formulate the design principles for the SAFE devices and how they integrate within the furniture. We report the result of this phase in Section 5.

2.4. Creation

This phase focuses on prototyping, testing, and refining the ideas and solutions identified in the design phase. Usually, this is an iterative approach that aims to validate the proposed solution until it meets the desired objectives and user requirements. The partners worked in cooperation to build the conceptual model described in Section 5. In particular, they were organized in three main areas. The first one refers to the implementation of IoT devices. This also involved collaboration with industrial design to integrate the IoT device into the SAFE furniture. The second area refers to ICT infrastructure, both locally in the building and remotely in the cloud. This involved the implementation of the data management systems, communication protocols, and user interfaces. The third area refers to the implementation of the algorithms and the tools aimed at supporting the rescue teams.

The close collaboration and communication among the partners in these three areas ensured the seamless integration of hardware, software, and algorithms, resulting in a comprehensive and functional SAFE ICT Platform. We report the result of this phase in Section 6.

2.5. Evaluation

Testing activities and demonstrations were conducted during the project's meeting in order to collect important feedback from the user and further refine the final solution. To evaluate the SAFE ICT Platform we set up a test environment at the Computer Science department at the University of Camerino. This allowed us to test the ideas underlying the conceptual model of the SAFE ICT Platform described in Section 5. We divided the evaluation in three different phases. In the first phase, we observed data collected by the platform before the earthquake. In the second phase, we observed the platform behavior in the case of an earthquake situation. Finally, in the third phase, we placed the SAFE devices inside the building and we used the localization and rescue system as described in Section 6.5 in order to estimate their original position. We report the result of this phase in Section 7.

2.6. Reflection

In Section 8, we present a fictitious scenario to reflect on the potential advantages of implementing the SAFE ICT Platform in the event of an earthquake. Through the description of this hypothetical situation, we aim to illustrate the benefits that could be achieved by integrating the solutions proposed by the SAFE project. This includes considering the impact of using SAFE furnishings and employing the technology proposed by the SAFE ICT Platform. In addition, in Section 11, we summarize the results we obtained and we discuss possible future work.

2.7. Communication

Two public presentations of the project took place, one at the beginning of the project and one at the end. The first one took place at the Sala dei Baroni, inside Castel Nuovo, in Piazza del Municipio in Naples on Thursday, October 11, 2019. The day was an opportunity to expose for the first time to the general public the aims, expected results, structure, and partners of the SAFE project. The second public presentation took place at the Milan headquarters of the ADI Design Museum in Piazza Compasso d'Oro 1, Thursday, October 12, 2021. The day was an opportunity to present the results achieved by the project to the public.[3]

For what concerns the dissemination of the SAFE project within the academic community, several publications focused on reporting about the designed SAFE furniture have been presented in international publications [3,6–8] by the School of Architecture and Design of the University of Camerino. In addition, the SAFE ICT platform is the subject of an Italian patent [9].[4] This article will contribute to disseminating the results of the project, which concerns the Computer Science aspects of the SAFE ICT Platform.

[3] SAFE project presentation, 12 October 2021, ADI Design Museum, Milan: https://youtu.be/o4zxe_dDlt8?si=gaS4WKFFLlpg8Zyd

[4] https://arit.unicam.it/it/brevetti/piattaforma-hwsw-monitoraggio

2.8. Implementation

All the components of the SAFE ICT Platform have been implemented and tested in a prototype version, as described in Section 7, reaching a Technology Readiness Level 6 (TRL 6) [10]. Considered the promising results, an ongoing implementation of the SAFE system is under development within the project called VITALITY,[5] a research project founded by the National Recovery and Resilience Plan (Piano Nazionale di Ripresa e Resilienza, PNNR). One of the research areas of the project is about the innovation and safety of living environments in the digital transition era. Part of the activities will be related to the exploitation of the SAFE project with the actual implementation of the SAFE life-saving furniture and the related SAFE ICT Platform. The objective is to reach TRL 7 at the end of the project VITALITY with the set up of the SAFE system in a real operational environment.

3. Earthquake scenario

In this section, we provide an overview of earthquakes in the context of disaster management, describing the main phases involved in managing earthquake-related disasters. In particular, we focus on the response phase to the earthquakes and the commitment of the Urban Search and Rescue teams to searching and rescue operations for people under the rubble.

3.1. Earthquakes and disaster management

Earthquakes are geological events characterized by the sudden release of seismic energy in the Earth's crust, resulting in ground shaking, surface rupture, and potential damage to structures and human settlements [11]. Due to their unpredictable nature and potentially devastating consequences, earthquakes cause victims worldwide [12].

Effective disaster management is crucial for minimizing the impact of earthquakes and ensuring a prompt and coordinated response aimed at minimizing the impact of disasters, such as earthquakes, on human lives, infrastructure, and the environment [13]. The disaster management cycle [14,15] encompasses the continuous and interconnected stages involved before the disaster to reduce human and property losses caused by a potential hazard, *mitigation* and *preparedness*, and after the disaster to achieve early recovery and rehabilitation of affected communities, *response* and *recovery*. The mitigation phase focuses on reducing the impact of future earthquakes. It encompasses measures such as enforcing building codes and regulations, conducting seismic assessments on the infrastructure, retrofitting vulnerable structures, etc. The preparedness phase encompasses activities undertaken when the earthquake occurs to enhance readiness in responding to the event. It involves the definition of emergency response plans, risk assessments, public awareness campaigns, training programs, and the d development of early warning systems. The response phase is immediately after the event and involves emergency actions to minimize the consequences of the disaster. It involves the mobilization of emergency resources, exploiting search and rescue operations, medical triage, evacuation, and the provision of emergency shelter. The recovery phase starts after the response activities to restore essential services, repair damaged infrastructure, and support the communities in rebuilding their lives. Recovery efforts may include housing assistance, financial support, reconstruction, and rehabilitation planning.

3.2. Urban search and rescue

To standardize the disaster management response, the International Search and Rescue Advisory Group (INSARAG),[6] established in 1991 by the United Nations International Search and Rescue Advisory Group, introduced the international *Urban Search and Rescue* (USAR) [16]. Each country trains its own USAR teams under the same INSARAG guidelines. In this way USAR teams can be employed across the countries in order to provide an effective disaster management response across the territories [17,18].

The role of a *USAR team* is to locate, extract and provide initial medical assistance to individuals trapped or injured in urban or structural collapse incidents, such as earthquakes. The teams consist of specialized staff, which employ skills, equipment, and techniques to conduct search and rescue operations in urban or structural disaster environments. Based on the operational capability level and the involved members (management, search, rescue, medical, and logistics), USAR teams are classified in Light, Medium and Heavy, deployed based on the disaster size.

The *USAR response cycle* [19] defines the structured approach that guides the activities of USAR teams during a disaster response, including preparedness activities and training during peacetime, mobilization of specialized personnel and resources during the emergency response, execution of search and rescue operations at the disaster site, up to the demobilization and post-mission activities. The core part of the USAR response cycle include:

- *Search and Rescue* operations to search for survivors in the collapsed structures. These efforts may involve using search dogs, listening devices, cameras, and technical equipment to identify and access survivors.
- *Medical triage* to provide immediate medical attention once survivors are located. This involves providing first aid, stabilizing injured individuals, and performing basic medical procedures to ensure their well-being until they can be safely evacuated and handed over to medical professionals.
- *Technical rescue* operations, including rope rescue, confined space rescue, and trench rescue.

[5] https://vitality-spoke6.unicam.it/en/

[6] International Search and Rescue Advisory Group - https://www.insarag.org/.

- *Structural assessment* to assess the stability of damaged buildings and determine the feasibility of rescue operations, avoiding potential hazards of both rescuers and survivors.

Search methods in USAR operations rely on standardized procedures and specific equipment.[7] Traditional methods include the *call-out* and *visual communication* techniques, where rescuers use voice commands and visual signals to make contact with individuals potentially trapped under debris. *Listening devices*, which amplify faint sounds, aid in detecting survivor calls or movements. *Canine (K9) units* also play a crucial role in locating survivors by identifying scents and sounds. Additionally, *camera-based devices* such as infrared and thermal cameras, fiber optics, and boroscope cameras are widely used. Technological advancements have led to significant efforts to integrate new types of equipment into USAR teams to enhance and expedite search operations. These advancements include sensor-based systems for improved detection and location accuracy [20,21], robots for navigating hazardous terrains and debris [22,23], and Unmanned Aerial Vehicles (UAV) for aerial surveillance and mapping [24], thereby significantly augmenting the capabilities of search and rescue operations.

To enhance the coordination of rescue operations, international USAR teams employ the *INSARAG Coordination and Management System* [25] platform, which offers a comprehensive suite of mobile and computer applications to facilitate information sharing and support decision-making during emergency responses. The platform supports Geographic Information System (GPS) viewers, operations dashboards, data information forms and remote support, enhancing the operational efficiency.

3.3. Search and rescue challenges

Search and rescue are very challenging activities since they require a combination of skilled personnel, established methodologies, and proper equipment. One of the primary challenges in post-earthquake scenarios is locating survivors trapped under rubble [26]. This task is complicated by the vast area of destruction, aftershocks, and unstable structures, which pose significant risks for both people and rescuers. Additionally, communication and coordination can be challenging, as earthquakes often disrupt communication infrastructure, complicating coordination efforts among various rescue teams and with command centers.

According to the INSARAG guidelines, USAR teams conduct search and rescue operations at the disaster site, relying on standardized practices and specialized equipment. However, these tools have inherent limitations due to their specific technology or environmental conditions. Listening devices often have limited range, especially in dense urban environments or under thick layers of rubble, where background noise can also interfere with the detection of survivor sounds. Camera-based devices have a limited field of view and cannot penetrate deep layers of rubble. Their effectiveness is also affected by environmental conditions, restricting their utility in comprehensive searches. K9 units are limited by physical and endurance constraints and may be less effective in situations with strong odors or hazardous materials. More advanced equipment, such as sensor-based systems, robots, and UAVs, requires robust and fail-safe communication networks for effective control and data transmission. Their application is also heavily dependent on limited battery life and operational time. Solutions based on Artificial Intelligence and simulation exist [27–29] but they may require large datasets for effective application and might not be fully reliable in unpredictable scenarios.

In the above scenario, it emerges that USAR teams in general lack of actionable information able to support the identification of the survivals under the rubble and their localization. The SAFE project with IoT devices and the related ICT infrastructure not only complements existing search and rescue methods but also introduces new capabilities, paving the way for a more effective response to earthquake disasters.

4. Requirements definition

The definition of the SAFE ICT platform is based on a thorough analysis of the USAR domain and rescue operations following an earthquake event. This analysis was conducted through interactions with the Italian Civil Protection, which activates immediate rescue intervention procedures, and the Italian National Fire and Rescue Service as expert USAR teams. These interactions helped us to define the main requirements of the platform, in terms of both hardware devices and computational components. Below, we report a summary of two of the various meetings we conducted. We also report the list of requirements derived from the entire interaction.

4.1. Meetings with stakeholders

We carried out an initial meeting with the technical stakeholders of the Italian Civil Protection. The stakeholders concluded that the earthquake early warning solutions [30] are not sufficiently effective in the Italian context, preferring instead to focus on operations occurring during and after the earthquake. Concerning the phase during the earthquake, the stakeholders suggested focusing on the design of furniture suitable for the protection of people and on IoT devices that could be distributed within the building to monitor the environment and support the detection of people possibly trapped under the rubble. The stakeholders emphasized that these devices must be designed to withstand power interruptions, as earthquakes often disrupt the power supply, leading to blackouts. In the rest of the meeting, the stakeholders described the post-earthquake phase, during which rescue operations are managed and collaboration with firefighters and USAR teams. They highlighted the need to acquire as much information as possible about the affected area so as to make assumptions about the consequences for the buildings and people and establish an

[7] Fema national user response system rescue specialist training manual: https://www.fema.gov/pdf/emergency/usr/appen_a.pdf

intervention plan. Therefore, they asserted that any device or platform that can add information or make information gathering faster or more reliable is of extreme importance.

A second meeting took place with the members of the Italian USAR team of the Fire and Rescue Service. At the beginning, the stakeholders described how the USAR evaluates the scenario after an earthquake. The objective of this phase is to gather information to understand the types of constructions that have been affected by the earthquake, their status, and the possible survival spaces. While part of the information is acquired from static data (e.g., the cadastral plan of the area), the USAR team tries to acquire information directly from the disaster area by interacting with the local police offices. Additional information is obtained with the collaboration of the Agenzia Spaziale Italiana (ASI) to acquire the satellite and radar images before and after the event. The USAR is then able to formulate an evaluation scenario from such images after a couple of hours. They also emphasized the importance of interactions with the local population, which take place once the first USAR rescue teams reach the disaster area, in order to better understand the effect of the event and to start the rescue operations. In this phase, the USAR rescue teams employ all the procedures and tools as described in Section 3.3 such as K9 units, microphones, thermal cameras, etc. The stakeholders also reported that a fleet of drones is employed in the rescue operations. The meeting then focused on the importance of new devices that could provide additional and valuable information to guide the direction of search and rescue operations. The stakeholders pointed out the possibility of using different types of detection systems based on microphones, humidity sensors, CO_2 sensors, thermal sensors, and cameras. Such devices should be very small to be transportable by the drones, possibly in areas not yet reached by the rescuers, and they could autonomously detect the presence of people and estimate their location.

4.2. Requirements

During the project, we conducted several meetings with the rescue teams, as described above. The objective was to identify the main requirements that a possible new solution should satisfy in order to effectively support the monitoring, localization, and rescue of people trapped under rubble. Especially, the USAR team expressed the need to:

- *Understand the situation*, which means to have a visual representation of the disaster area and of the location where to search for people to be rescued.
- *Organize the operations*, which means to direct rescue teams to the locations where the presence of people has been detected, so to avoid wasting precious time searching in empty areas.
- *Extending the survival time* of people trapped under rubble, as it provides rescuers with a greater opportunity to reach them.

Besides the need for enhanced protection systems for people, a common theme across all meetings was the necessity of gathering more accurate information from the environment. These details should be made directly accessible to USAR teams to better organize the search and rescue operations.

The SAFE project tackled these needs through the design and development of (i) anti-seismic furniture, (ii) technological components such as IoT devices, and (iii) a dedicated ICT platform. The reference scenario of the identified solution is a building (classrooms, offices, etc.) in which anti-seismic furniture and technological components work in combination to enable the functionalities for the protection, localization, and support of people trapped under rubble. While the anti-seismic furniture provides protection to people by creating survival spaces, the technological components enable services for rescue teams.

To guide the design and development, more specific requirements have been defined for IoT devices, including the communications to be adopted, the localization system, and the data collection mechanism. We report below a list of specific requirements.

- Modular IoT devices should be designed so that they could be equipped in furniture.
- The device should continue working even after an earthquake, possibly without an Internet connection.
- The IoT devices should be battery-powered and continue to operate after a seismic event.
- Low-energy and long-range communication protocols should be preferred in the design of the IoT devices.
- The IoT devices should implement firmware logic for recognizing, even automatically, situations of pre-event and post-event and dynamically changing the behavior accordingly.
- The IoT device data should be retrievable before, during, and after the earthquake. Therefore, a platform to store and access such data should be defined.
- The IoT device data should contribute to identifying the presence of people taking shelter under the resistant furniture. Therefore, a localization system that processes such data should be defined.
- Information should be made available to rescue teams on-site, even without an Internet connection.

5. The SAFE ICT platform conceptual model

In this section, we describe the ICT solution defined to fulfill the stakeholders' requirements. Our aim was to turn the SAFE furniture into an *active protection system* thanks to the integration of new IoT hardware devices and the definition of a related ICT infrastructure. According to this, we defined the conceptual model of our solution as depicted in Fig. 1 which represents a generalization of the hardware and software components that realize the SAFE ICT Platform architecture. The conceptual model relies on the following concepts: (i) the SAFE furniture with the integrated SAFE devices installed locally in the building; (ii) a local Stationary Gateway that acts as an integration layer; (iii) a remote monitoring cloud; (iv) the localization and rescue support system

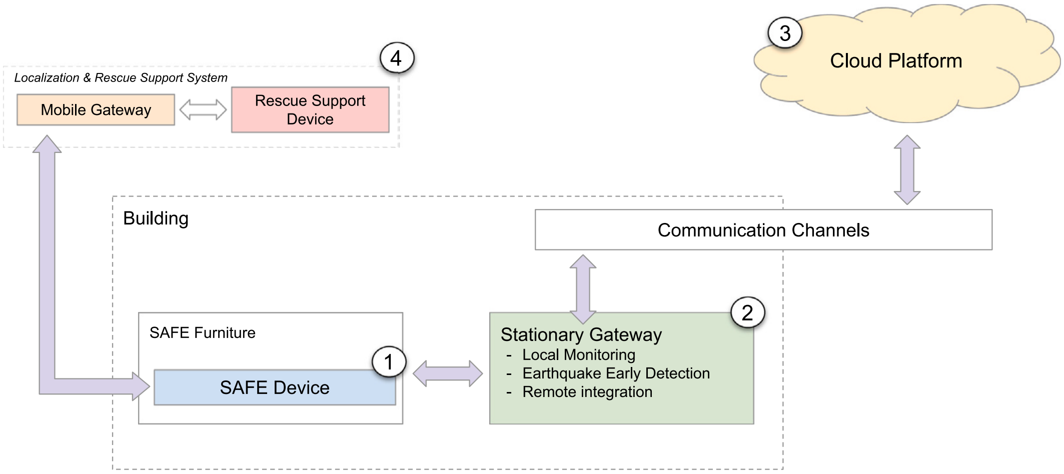


Fig. 1. SAFE ICT Platform conceptual model.

components employed in the response phase after an earthquake. The components of the conceptual model are described in the following.

The *SAFE devices* represent the IoT devices defined in the SAFE project, designed to integrate with SAFE furniture to enable the active protection system. Their primary objective is to detect the presence of people who have taken refuge under the SAFE furniture when an earthquake occurs and to transmit useful data to rescue teams for their localization. During peacetime, the SAFE devices conserve battery power by transmitting measurements and keep-alive messages to the gateway at extended intervals. Upon the occurrence of an earthquake, a SAFE device alters its operational mode. Specifically, it begins broadcasting messages if a person is detected, enabling their location using a mobile gateway. The characteristics of these devices are given in Section 6.1.

The *Stationary Gateway* executes the edge computing layer with the role of collecting, processing, and filtering data produced by the SAFE devices. The Stationary Gateway also connects local systems using open standard building automation protocols (e.g., Modbus, BACnet, KNX, etc.) [31] in order to support protective actions in case of an earthquake. For example, in the project, we connected the Stationary Gateway with a dedicated wireless accelerometer. In this way, the gateway is able to identify an imminent seismic event condition and send alarm commands to the SAFE devices. The Stationary Gateway communicates with the remote cloud platform to exchange local data as well as receive update commands. The characteristics of the Stationary Gateway are given in Section 6.3.

The *Cloud Platform* defines the storage and analysis layer on the remote data received by the Stationary Gateway. The primary role of the component is to provide management of the SAFE devices installed in the building. The component also leverages big data technologies to implement the data lake layer to persist historical data from the building. After the earthquake, the cloud platform aims to support location and rescue operations by providing analysis tools that leverage the data lake layer to make hypotheses about space occupancy in a building before the earthquake. The information can be useful to the rescue operations center to better organize the operations of the rescue teams. The characteristics of the cloud platform are given in Section 6.4.

The *Localization and Rescue Support System* consists of two components, namely a mobile gateway and a rescue support device. They are employed by the rescue teams to locate the SAFE devices that are signaling the presence of people protected by the SAFE furniture and waiting to be rescued. The role of the mobile gateway is to scan these signals over the disaster area. In our scenario, the mobile gateway is mounted on an unmanned vehicle system (e.g., drones) equipped with a GPS system, and it is used to scan the area to capture the radio messages along with the transmission power (i.e., the received signal strength indicator). The sampled georeferenced data is then passed to the rescue support device, which exploits algorithms and data analysis techniques to estimate the position of the devices and, therefore, of the people. The characteristics of the component are given in Section 6.5.

6. SAFE ICT platform design & implementation

In this section, we describe the design and implementation conceptual model depicted in Fig. 1. We used an agile methodology to develop incremental versions of the SAFE ICT Platform components evaluated during the project's meetings. The final result of this process is described in the following.

6.1. SAFE devices

The SAFE devices are designed to integrate with SAFE furniture, as shown in Fig. 2(a), and continue to operate even after the earthquake. They are capable of gathering information from the surrounding environment and maintaining communication, even when buried under rubble. Based on these assumptions, we defined the hardware characteristics of the SAFE devices depicted in

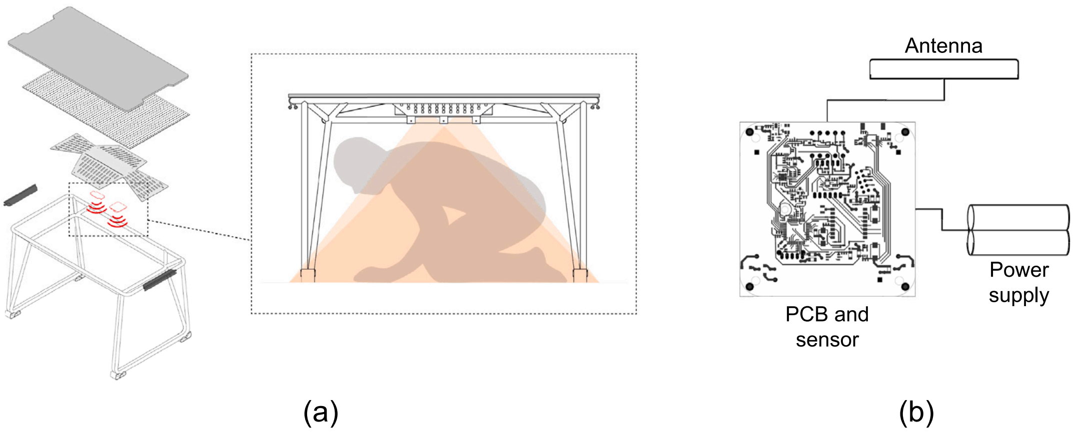


Fig. 2. An example of SAFE furniture showcasing a desk with an integrated SAFE device (a) and the reference design of a SAFE device comprising the set of decomposed components (b).

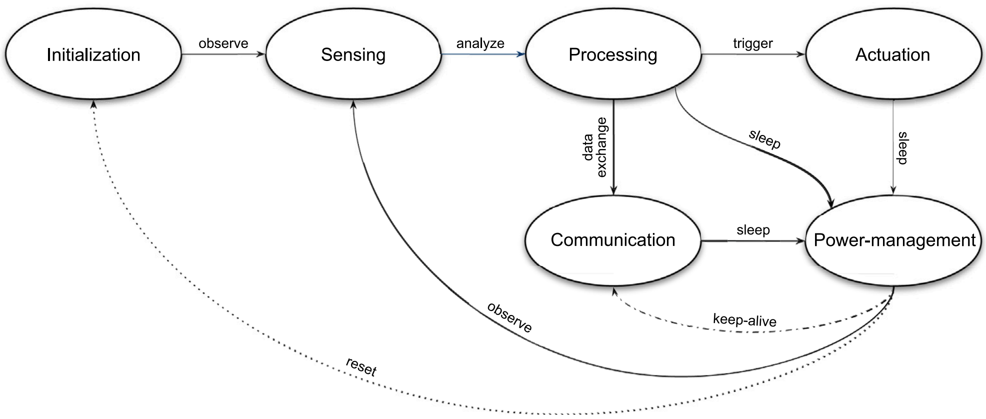


Fig. 3. Logical behavior of the SAFE devices. We distinguish the following states: *Initialization*: loading of the initial configuration to make the device up and running; *Sensing*: data collection from the local sensors; *Processing*: evaluation rules on the observed data and the device status; *Communication*: sending or receiving data using a given communication protocol. *Actuation*: triggering of actions on local systems; *Power management*: managing of the device's power usage.

Fig. 2(b). Specifically, they are battery-powered wireless devices designed to maximize energy efficiency. Even if a number of radio communication protocols exist [32], low-energy and long-range communication protocols are preferred, turning on the transmission system only when needed.

Beside the hardware characteristics, in Fig. 3 we modeled the behavior of the SAFE devices when interacting with the environment. Specifically, the SAFE device is capable of understanding the context (sensing and processing), exchanging data with a gateway (communication), possibly triggering actions on local systems (actuation), and preserving battery life (power management).

The SAFE device exhibits *dynamic behavior*, adapting its behavior in response to an earthquake. Specifically, during peacetime, a SAFE device optimizes the power consumption by minimizing the sensing activities, sending measurements occasionally (e.g., presence, air quality levels, etc.) along with diagnostic information (e.g., battery level, device temperature, etc.). This constitutes the baseline profile for SAFE devices, called *peace mode*.

When an earthquake occurs, the device switches its behavior to the *war mode*. In this mode, the SAFE device communicates only if the sensing phase detects a presence under the SAFE furniture. Upon detection, the SAFE device adjusts its power management system to prioritize message transmission (e.g., using a broadcast communication, increasing the number of messages generated, etc.) in order to make it possible to use the localization system described in Section 6.5. For earthquake detection, various strategies can be employed. For example, if the device is equipped with an accelerometer sensor, the sensing and processing phases can be used to analyze signal variations over time [33] and trigger the war mode. Additionally, profile switching can be initiated during the communication phase based on the alarm message received from the gateway or, alternatively, by interpreting a lack of communication with the gateway as an indication of an emergency condition.

Fig. 4. The SAFE PIR. From the commercial version of the SmartNetwork PIR device (a) we defined the prototype of the SAFE PIR (b). The prototype provides a new modular layout that improves the integration in the SAFE furniture.

6.2. SAFE PIR

An implementation of a SAFE device is the SAFE Passive InfraRed motion detector (SAFE PIR from now on). To implement such a device we started with an existing wireless sensor network technology called SmartNetwork[8] owned by the project's partner Filippetti. SmartNetwork is a non-timed asynchronous pervasive mesh network that consists of long-life battery-powered wireless devices (up to 10 years). The network infrastructure is made up of proprietary *multi-functional IoT devices* that communicate through different communication protocols, including a proprietary SmartNetwork protocol, Long Range (LoRa), Frequency-shift keying (FSK), Ultra-wideband (UWB).

In the project we considered the SmartNetwork PIR device (see Fig. 4(a)) which uses a PIR sensor to detect temperature variations in the form of electromagnetic radiation in the infrared spectrum (emitted by anybody at a temperature > 0° K). When a person moves, this radiation is picked up by the sensor, altering its normal state and activating the detection. When this condition occurs, the SAFE PIR device transmits a logical value of 1 to indicate a movement without reporting information that could be linked to personal data. We extended the SmartNetwork PIR to implement the SAFE PIR based on the characteristics defined in Section 6.1.

First of all, the commercial device has been revised in terms of physical layout to improve its integration into the SAFE furniture. In particular, we broke down the device into three modular parts (see Fig. 4(b)): (i) the Printed Circuit Board (PCB) that contains the electronic components as well as the PIR sensor; (ii) the communication antenna to send and receive the data packets; and (iii) the external battery pack. Regarding the communication protocol, we used LoRa which is considered a suitable solution for long-range and low-power applications, supporting data packet transmission over several kilometers [34]. Accordingly, we extended the capabilities of the device firmware to implement the dynamic behavior described in Section 6.1. Starting from the already available features (e.g., presence detection, keep-alive messages, etc.), we implemented the profile switching from peace to war mode and vice versa, considering two situations: (1) The device receives an explicit command from the gateway; (2) a timeout is reached in sending data from the device to the gateway. The latter situation relies on the feature of the SmartNetwork that supports acknowledgment (ACK) messages when the device communicates in unicast mode with another device. By adding a timeout parameter in the firmware, we can track if the gateway responds in a reasonable amount of time. If not, we can make some hypotheses about the gateway, such as its unavailability due to an earthquake.

6.3. Stationary gateway

The Stationary Gateway, reported in the left side of Fig. 5, is a standard Industrial IoT gateway available on the market that covers the computational layer within a building. The gateway is connected to the SAFE devices through a SmartNetwork USB dongle to exchange messages using the LoRa communication protocol. In addition, the gateway communicates with a local battery-powered wireless accelerometer from the University of L'Aquila [35] that we used for earthquake early detection. The accelerometer device, reported in the right side of Fig. 5, integrates a triaxial accelerometer Micro-Electro-Mechanical Systems (MEMS) sensor with high performance and low energy consumption, sending alert messages to the gateway communicating through the standard pWireless M-Bus protocol. The gateway executes the open source edge computing framework EdgeX Foundry[9] for the computational part and the software modules defined in the project to integrate the platform components. The resulting architecture is reported in Fig. 6 and described in the following.

EdgeX is a well-known enterprise edge computing framework that enables data collection from different data sources, local storage, real-time analytics, and trigger actuation on local systems through standard industrial protocols (e.g., Modbus, BACnet, EtherCAT). To integrate the external devices, we applied a message broker integration pattern [36] implemented with the MQTT message broker Mosquitto.[10] MQTT uses a simple and lightweight publish/subscribe mechanism for messaging since it is designed

[8] https://www.industrial-iot.it/smart-network/
[9] https://www.edgexfoundry.org/
[10] https://mosquitto.org/

Fig. 5. Stationary Gateway on the left and Wireless Accelerometer on the right.

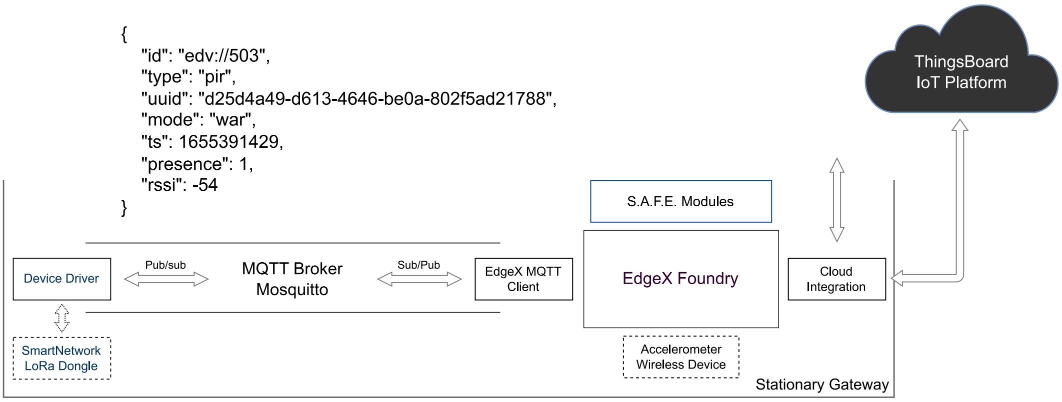


Fig. 6. Gateway architecture.

for constrained devices and low-bandwidth, high-latency, or unreliable networks. MQTT clients use channels (*topics*) to subscribe to get information or publish to send information; the broker manages the distribution of messages to decouple the publisher and the subscriber. In our architecture, we defined two main clients: (i) the device driver client, which publishes the SAFE device messages and subscribes for commands to forward back; and (ii) the EdgeX MQTT client, which collects the received data in the EdgeX and sends the configuration messages to the devices. We can distinguish the following types of messages exchanged between the components:

- *Measurement messages*. This is the data sent from the devices, processed locally in EdgeX, and forwarded to the cloud platform. The content of the message regards mainly the device information metadata, its status, the timestamp of the message, and a list of measures specific to the device.
- *Command messages*. This is the data sent from EdgeX, or forwarded from the cloud platform, to change a device's status. For example, to switch profile mode, update the polling time, etc. Similarly to a measurement message, the content consists of the data about the target device identifier, the list of updated parameters, etc.

We defined a plain text JSON notation to represent the messages exchanged between the components. An example of this notation is given in Fig. 6 about measurement messages from the SAFE PIR exchanged over the MQTT bus. The notation represents a generalization with respect to the specific protocol and device being used. This abstraction allows us to integrate generic devices within the platform in addition to the SAFE devices. The same JSON notation is used to exchange messages with the remote cloud platform, with a similar integration pattern adopted in the gateway.

Local processing about monitoring the devices and taking decisions in the building is part of the SAFE modules implemented over the EdgeX core services. The aim of these modules is to analyze the data from the connected data sources, detect conditions from the events being observed, and take the proper actions in terms of local action. For example, we used the EdgeX rule engine to define a dedicated rule to monitor the alarm messages from the wireless accelerometer raised due to a possible earthquake detection event. We primarily used the rule to send a command to the local SAFE devices to switch to the profile mode. We are aware that, in the worst-case scenario, after the earthquake, the above actions may not succeed due to the failure of the gateway. For this reason, we defined the SAFE devices capable of switching to the war profile in such a situation as described in Section 6.2.

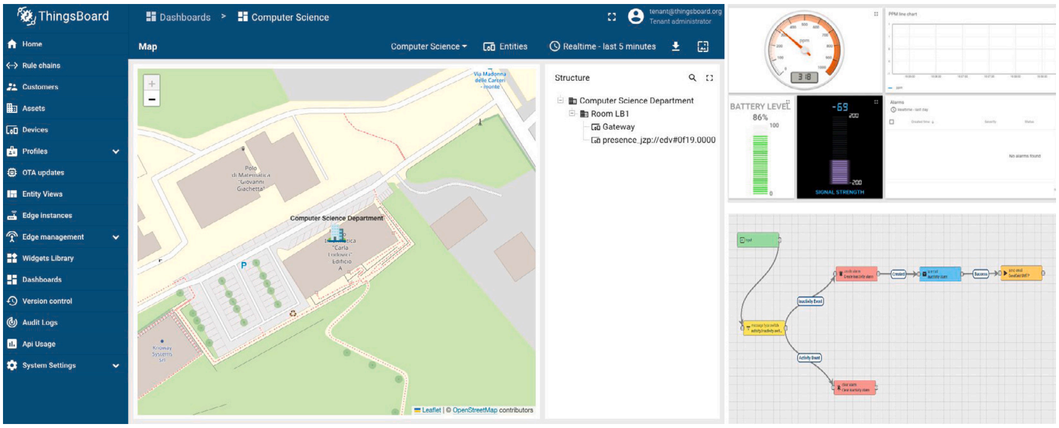


Fig. 7. The ThingsBoard IoT platform configured for the SAFE project.

6.4. Cloud platform

The characteristics of the cloud component are mainly related to the remote storage of device messages, the implementation of building monitoring, the analysis of hypotheses about the building after the earthquake to support rescue operations, and the remote management of the devices. Since these concepts are almost standard in modern IoT platforms, we used the well-known open-source IoT solution ThingsBoard[11] depicted in Fig. 7. ThingsBoard provides a wide range of out-of-the-box functionalities for IoT applications, such as device connectivity through standard IoT protocols (MQTT, CoAP, etc.), big data storage based on NoSQL databases (Cassandra, TimescaleDB), a rule engine to process the incoming messages from devices and trigger configurable actions, and management of the remote device. Moreover, it also supports the definition of a custom dashboard for managing IoT applications. The dashboards can be defined by adding widgets that support different kinds of visualizations, like charts about the data telemetry of the devices, geolocated maps, real-time alarms, etc.

We used the built-in MQTT broker exposed by Thingsboard to implement the remote storage service of the SAFE ICT Platform. The gateway connects to this broker to publish the messages on the remote cloud. A rule chain is then used to save the incoming data on a NoSQL database. The same MQTT broker is used for device management, sending back to the gateway the related configuration messages.

6.5. Localization and rescue support system

To locate the SAFE devices, and therefore the people, the SAFE ICT Platform defines two components that work in combination: a localization component that estimates the position of the SAFE devices based on the analysis of signals strength; and a rescue support system that uses the information from the localization component to provide visual indications to rescuers by means of geolocated maps and management tools to organize the rescue operations. The details about each component are given below.

The ***localization component*** aims at identifying the SAFE devices that are communicating messages about the presence of persons protected by the SAFE furniture to be rescued. To do so, the strategy we defined aims to exploit the information related to the Received Signal Strength Indication (RSSI) perceived by the observer that is able to detect these messages. Ideally, higher values of RSSI can indicate that the observer is closer to the device. Therefore, moving around the disaster area and registering the corresponding RSSI values of each message allows us to create a distribution map of the signal strength for each device. Finally, by analyzing this map, we can make hypotheses about the location of the devices. The analysis of signal strength has already been applied in other contexts for indoor and outdoor localization [37,38]. This technique is known to be affected by approximation errors. However, in the scenario we are considering, any reasonable information, although not extremely accurate, becomes important for the rescue teams if it allows them to get a more precise idea of where to search. This can streamline rescue operations and save valuable time.

The localization component implements the above strategy through the combination of SAFE devices, a mobile gateway, and a UAV system. The SAFE devices involved are those that communicate the presence of people to be rescued. The mobile gateway is a battery-powered device equipped with: (i) a radio antenna that receives the messages from which we can derive the corresponding RSSI values; (ii) a GPS module to associate each message with a corresponding position in terms of latitude and longitude. The UAV system is a drone equipped with a mobile gateway, shown in Fig. 8, that flies over the disaster area, collecting messages broadcast by SAFE devices. These elements are used in combination as follows. After the earthquake, the rescue team identifies the disaster area and creates the fly plan for the drone equipped with the mobile gateway. Ideally, the fly plan defines a bi-dimensional matrix

[11] https://thingsboard.io/

Fig. 8. The mobile gateway equipped on the DJI FX550 drone.

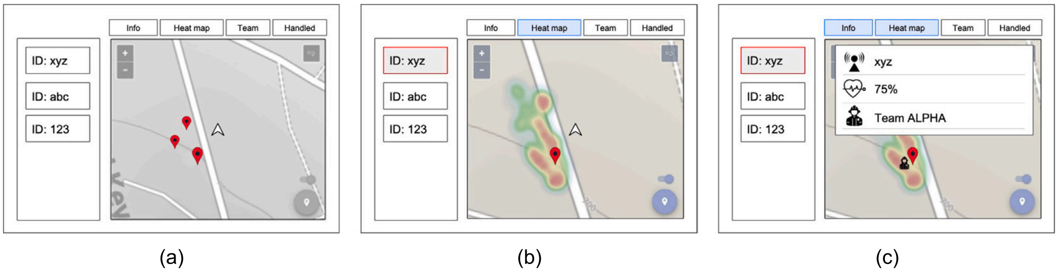


Fig. 9. Rescue Support System Mockup Interface.

over the area that should be covered. As a result of the execution of the fly plan, a geo-located dataset of the messages was obtained. Each message consists of: the device ID, the associated RSSI value, the time stamp of the observation, latitude, and longitude.

The ***rescue support system*** aims to support the rescue teams in locating and finding people through the SAFE devices. In particular, the rescue support system includes: (i) ***a** mobile device* (such as a rugged tablet) capable of running a standard mobile operating system (e.g., Android, iOS, etc.) and equipped with a local GPS system. The device is connected to the UAV system through standard interfaces (WI-FI, Bluetooth, SD card) to read the collected data. (ii) ***a** mobile app* that supports the management of the rescue operations by means of visual interfaces for the rescuers. A mockup of the app interface is reported in Fig. 9. The app, executed on a mobile device, does not require an Internet connection. The geolocation system uses locally downloaded maps of the surrounding area. There are different views about the devices, such as the estimated location area, heat maps of the signal strength distribution, etc. Markers are used to indicate both the estimated position of the devices as well as the position of the rescuer. In addition, the app can be used to manage a list of the rescue teams that will be assigned to a specific device.

The developed mobile app is compatible with standard Android tablets with built-in GPS modules. We relied on the open source UI framework toolkit Ionic.[12] The framework supports the definition of cross-platform web applications (Android, iOS) using standard web technologies (HTML, CSS, and JavaScript) and popular web frameworks (Angular, React, and Vue). In our case, we used Android as target systems and React framework for the UI. To implement the offline map rendering in the app, we used the open source library OpenLayers.[13] OpenLayers also supports offline maps rendering using the local map tiles stored on the device.

When rescuers arrive at the disaster area, they can use the pre-loaded maps on the device to visualize the area they are in and configure the localization component for the discovery of devices in emergency-mode. At the end of the scan, the data downloaded from the UAV system is analyzed to show the active devices detected and their estimated position on the map (Fig. 9(a)). To organize the rescue operations of a specific device, all the information collected is evaluated. In particular, since the position is estimated in a certain area, rescuers can view the signal power distribution map in order to better circumscribe the rescue operations (Fig. 9(b)). During the execution of the searches, rescuers can keep track of the status of each device by analyzing the information related to the acquired measurements and the rescue team that is managing it (Fig. 9(c)). This information can be updated over time through new acquisition campaigns in order to monitor, over time, the status of people still to be rescued.

12 https://ionicframework.com/

13 https://openlayers.org/

(a) (b) (c)

Fig. 10. Integration phases of the SAFE devices with the life-saving furniture desk.

7. Demonstration & evaluation

To demonstrate and evaluate the SAFE ICT Platform we set up a test environment at the Computer Science department at the University of Camerino in Italy. The objective was to observe the platform components in a real-life scenario and to validate the foundational ideas of the conceptual model described in Section 5.

The final output of the localization component is a list of the active SAFE devices, the estimation of their localization points based on the clusters, and the associated observed messages in the area along with the corresponding measurements. These details can be used to create a geo-located map of the device's position, and the signal distribution can be used to generate heatmaps that can guide rescuers to the estimated people location.

7.1. Setup of the environment

We set up a prototype of the SAFE desk furniture with an integrated SAFE PIR device. The prototype is depicted in Fig. 10(a). To accommodate the installation of the SAFE PIR, we devised a prototype enclosure situated under the desk's surface (see Fig. 10(b) and Fig. 10(c), respectively). This enclosure features small openings used to facilitate motion detection within the space beneath the desk. We placed the enclosure on the right side of the desk. In our assessments, this proved to be the most effective location for detecting individuals seeking shelter under the desk, ensuring minimal impact on the desk's typical usage. For the purpose of conducting the experiment, we placed the SAFE desk in our research laboratory.

Then we set up the Stationary Gateway close to the research laboratory. For the test, we used a Dell Edge Gateway 3003 equipped with the LoRa dongle to communicate with the SAFE PIR device. We also set up the wireless accelerometer that communicates with the Stationary Gateway. The Stationary Gateway exchanges the local messages acquired from the SAFE PIR with the remote ThingsBoard platform using the standard MQTT protocol.

Finally, we installed ThingsBoard Community Edition v3.4.4 on a dedicated Linux server of the Computer Science department. We exploited ThingsBoard to configure the user's dashboard to highlight information relevant to our test. In particular, we used the standard widgets to observe whether the device is in a state of peace or war, internal device parameters (e.g., battery level and device temperature), and the trend of historical data acquired during the test (e.g., presence events, RSSI values, etc.).

7.2. Device and communication tests

We configured the SAFE PIR device to communicate the keep-alive messages every 15-min. For the connection timeout with the gateway, we set a duration of 30 min. The war communication interval was configured to 10 s. To evaluate the test environment, we initially verified the correct behavior of the platform's components in peace mode (i.e., absence of earthquakes), as shown in Fig. 11. We used ThingsBoard to observe the regularity of the device's messages from the telemetry data reported in the user's dashboard. The messages we observed belong to two types: keep-alive messages and presence messages. While the keep-alive messages confirm that the SAFE PIR works properly, the presence messages provide information about the occupancy of the SAFE desk, as expected.

In the second part of the test, we evaluated the platform's components in war mode (i.e., during an earthquake event). The objective was to assess the dynamic behavior of the SAFE PIR device and its ability to switch from peace mode to war mode, as described in Section 6.1. To initiate the automatic profile switch, we first powered off the Stationary Gateway. After a 30-minute interval, according to the test configuration, we powered on the Stationary Gateway again to restore communication between the device and the gateway, as well as between the gateway and the cloud platform. As illustrated in Fig. 12, the user dashboard confirmed that the SAFE PIR device automatically switched to the war mode. We repeated the aforementioned test to further evaluate the profile switch triggered by the Stationary Gateway in response to an earthquake. For this purpose, we kept the gateway on, and simulated earthquake conditions by manipulating the accelerometer. This action generated an alarm message from the accelerometer to the Stationary Gateway and, subsequently, from the Stationary Gateway to the SAFE PIR device. Through the Thingsboard dashboard, we confirmed the successful adaptation of the SAFE PIR device.

In the final part of the test, we used the SAFE desk in order to trigger the presence sensor of the SAFE PIR device now operating in war mode. As expected from the behavior we described in Section 6.1, we observed through the user's dashboard that the SAFE

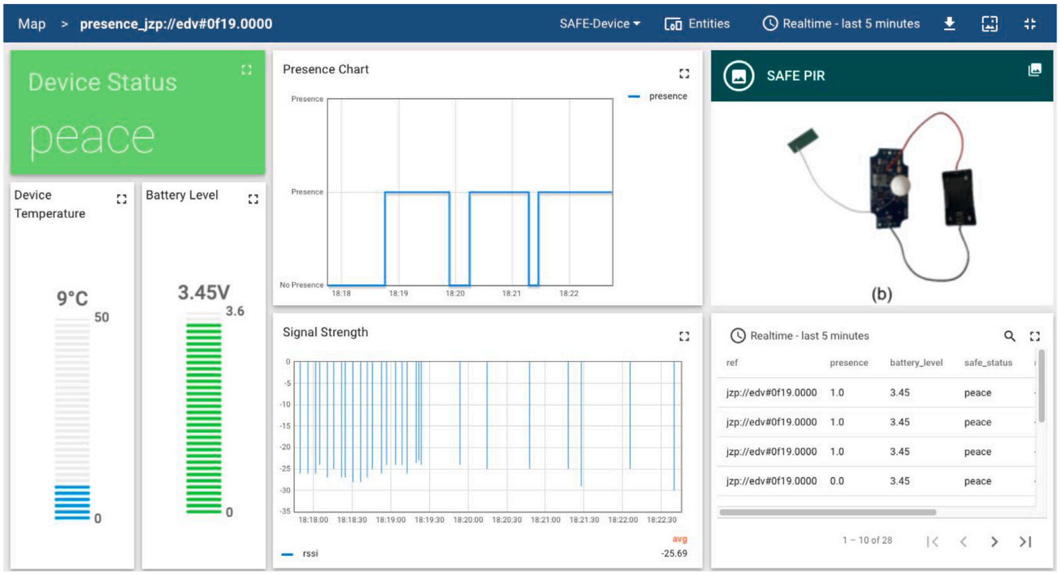


Fig. 11. Dashboard illustrating the SAFE PIR in Peace mode with its related measures.

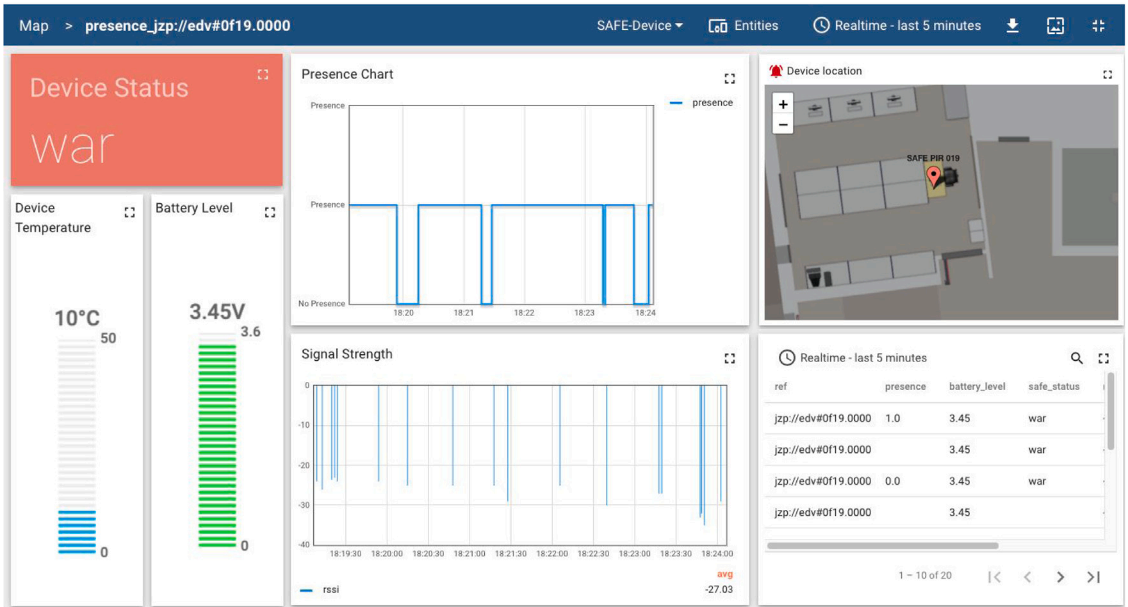


Fig. 12. Dashboard illustrating the SAFE PIR in War mode with its related measures.

PIR device started to send messages around every 10 s, closed to the war communication interval we configured at the beginning of the test. This performance demonstrates the sensor's capability to increase its communication frequency under predefined war mode conditions, as anticipated.

7.3. Localization and rescue support system test

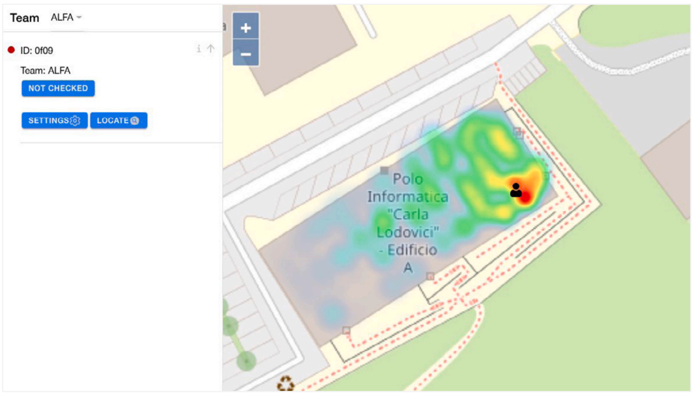
In this part of the evaluation we tested the localization system using the SAFE PIR device running in war mode. We also triggered the presence sensor in order to force the broadcasting of the message every 10 s according to the war communication interval we configured at beginning of the test.

To collect the messages and the corresponding RSSI values, we employed the DJI F550 drone introduced in Section 6.5. We equipped the drone with the mobile gateway consisting of a Raspberry Pi3 model B+ and an integrated GPS HAT module. We

Fig. 13. The Computer Science department at University of Camerino. The red marker indicates the location of the SAFE PIR device. The blue markers indicate the relevant data points we extracted from drone' observations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

DEVICE_ID	RSSI	LATITUDE	LONGITUDE
0f09	-50.25	43.13963935	13.0689233
0f09	-54.50	43.13967545	13.06884954
0f09	-51.50	43.13970321	13.0689223
0f09	-54.00	43.13961497	13.06875638
0f09	-65.25	43.13957138	13.06864622
0f09	-65.50	43.13953373	13.06853272
0f09	-69.75	43.1395393	13.06856419
0f09	-75.75	43.139552	13.06859874
0f09	-65.75	43.13946536	13.068583
0f09	-77.00	43.13949509	13.06863396
0f09	-55.00	43.13957795	13.06888193
0f09	-47.50	43.1396315	13.06888993
0f09	-61.25	43.13957186	13.06886012

(a)



(b)

Fig. 14. (a) An excerpt of the collected data resulting from the drone's flight and (b) the resulting mapping of such data on the map estimating the position of a person detected by the SAFE PIR. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

powered the Raspberry with a small 5 V power bank. We also connected the LoRa dongle to receive the broadcasted messages. On the Raspberry we also installed the software modules described in Section 6.5 to associate the observed messages with the related geographic coordinates using the GPS. Finally we equipped all the components on the drone to start the data acquisition campaign over the Computer Science department as illustrated in Fig. 13.

From the data acquisition campaign, we compiled the dataset stored internally in a CSV file on the mobile gateway. The dataset comprises a series of data points, a portion of which is presented in Fig. 14(a). Each data point includes the device identifier, the recorded RSSI value, and the associated geographic coordinates (latitude and longitude).

We used the dataset in the mobile app to render the heatmap about the RSSI signal distribution observed with the drone, from which we estimated the position of the SAFE PIR device. The result is shown in Fig. 14(b). The heatmap clearly shows the area covered by the drone, with a more intense red color highlighting the zone where the device was placed. Moreover, the app estimated the device position obtained by a localization algorithm. We then compared the estimated position with the actual location of the device in the building. The result of this comparison confirmed the app's capability to establish the device's position with a good degree of approximation.

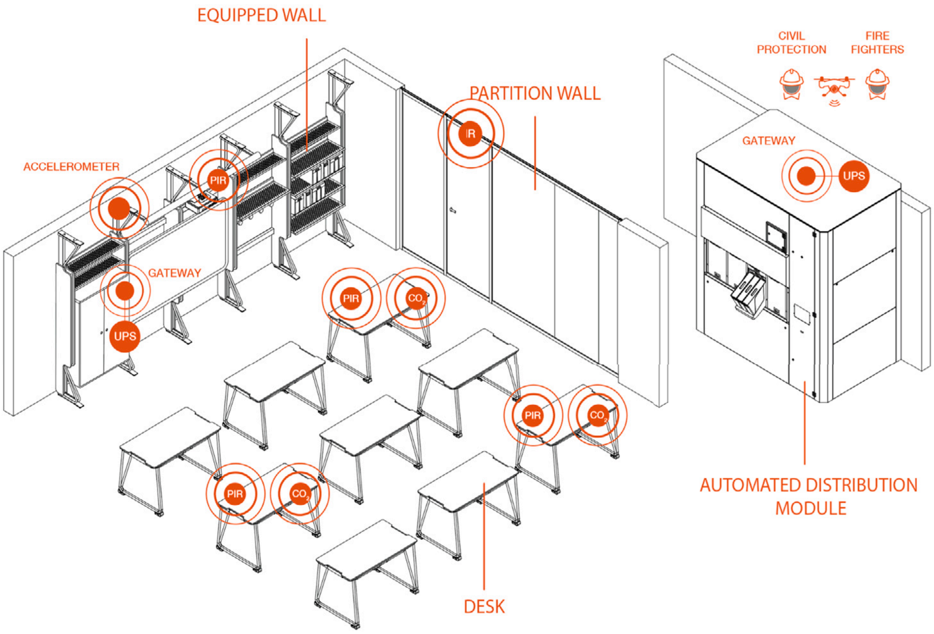


Fig. 15. Pre-Earthquake. A room equipped with SAFE furniture [7] and the SAFE devices.

Overall, the various tests confirmed that the system can provide valuable insights to the rescue teams in locating people under the rubble protected by the SAFE furniture.

8. The Safeville scenario

In this section, by means of a fictitious scenario, we describe the adoption of the SAFE furniture and the SAFE ICT Platform possible outcomes. The objective is to describe how the designed solutions make a significant contribution to mitigating the effects of an earthquake.

Safeville is a small historic town located in central Italy. Each building in this town has its own history: some date back to the Middle Ages, others to the Renaissance, and some to the post-war period. The region where this town was built is a seismic area where, statistically, a major earthquake occurs every twenty years, causing significant damage and potential fatalities. Like other buildings in Safeville, schools and public offices are not of recent construction, putting students, teachers, and public employees at potential risk whenever they go to schools, town halls, etc.

Regarding the high school, there is a new development in the town. Today, a news article appeared in the local newspaper discussing an agreement between the municipality, the University of Camerino, and ten other entities to install an experimental earthquake protection system called the Life-saving Furniture System in the school's classrooms. It seems to involve furniture (desks, lecterns, and shelves) incorporating IoT (Internet of Things) technology. Although these pieces of furniture appear similar to regular ones, the innovation is that they can protect people in the event of an earthquake. Moreover, the IoT devices should help rescuers locate people even if they are under debris. The news features an image of the system to be installed at the bottom of the page (see Fig. 15). The article concludes with a journalist's skepticism about the utility of the expenditure.

One day, a strong earthquake strikes in the midst of a class: some students calmly follow the procedures explained during emergency simulations, stating that during an earthquake, a person should seek shelter from falling objects under the desk or doorframe and orderly move to the safety area identified in the emergency plan. Other students, most of the class, remain motionless, paralyzed by fear in their desk chairs. Some instinctively seek shelter under the equipped wall, finding a refuge nearby. During this tragic event, the building collapses, trapping everyone inside. In Safeville, the alarm about the collapse of the high school building was raised by a citizen, Mr. Piero Rossi, who was walking on the street during the event and witnessed the disaster from the outside. Mr. Rossi tried several times to call the emergency number 115, but the phone lines were jammed, so he ran to the nearest safe area, where he found a Civil Protection volunteer and informed him about the school tragedy. The volunteer immediately contacts his supervisor with a walkie-talkie, who alerts a Fire Department rescue team to report the major emergency. Mr. Rossi and the volunteer see people arriving on foot after a while, carrying large backpacks. Eventually, it turns out they are a Urban Search and Rescue (USAR) team from a nearby region; they were stopped by debris on the road during the journey and had to proceed on foot, leaving some of them to clear the way. It's strange; the team moves swiftly towards the school building and appears well-organized. Yet none of them have been in these places before the earthquake. They take out strange objects from their backpacks, perhaps

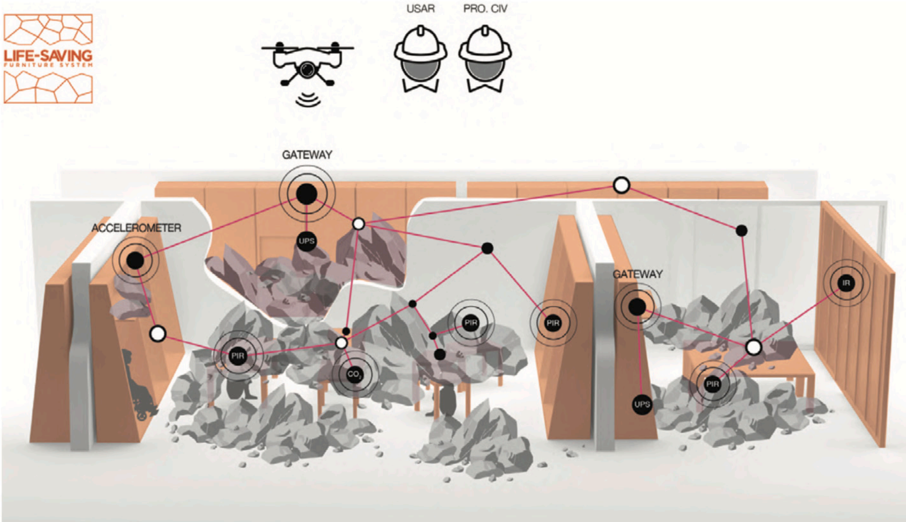


Fig. 16. Post SAFE ICT deploy [39].

familiar to someone. Intrigued, Mr. Rossi can only recognize a drone as he observes another pair of team members looking at a tablet and the collapsed building. Suddenly, a team member runs away from the building, taking the drone with them. Before he can turn around, Mr. Rossi sees the same drone flying high, describing seemingly regular trajectories, back and forth, each time more to the right. As soon as the drone stops flying, the team gathers and starts discussing while looking at the tablet. One of them, in particular, seems to be giving orders, pointing with their arm. Meanwhile, rescue vehicles and all the digging equipment arrive. Some groups are quickly formed, following the indications of the person with the tablet. It's even stranger for Mr. Rossi and the volunteer, who don't understand how these people know how to move in specific areas of the building, as if they already knew where to search. Other rescue teams, Civil Protection, and additional Firefighters arrive, starting to dig in the area alongside the USAR team. The same person with the tablet seems to provide information, hurrying to indicate specific areas of the building, observes Mr. Rossi, who by now wonders why most rescuers are focusing on the school building. It seems they already knew that there were many victims inside, almost as if they knew the number. Eventually, he learns that the building had been classified as "A" and it was already known that many people were inside when the earthquake occurred.

Several months have passed since the earthquake. Mr. Rossi buys one of the many national newspapers and stops at a particular article. It talks about his town, Safeville, and the use of the Life-saving Furniture System that allowed for the rescue of students and teachers trapped under the rubble of the collapsed high school during the earthquake. Mr. Rossi recalls seeing the same system in the local newspaper before the earthquake, to which he hadn't paid much attention. This time, Mr. Rossi reads the article carefully, describing in detail how the system works and how it contributes to saving lives. There is also a figure Fig. 16 illustrating the basic idea of the system during the rescue phase. Mr. Rossi now understands that the desks were not ordinary desks but solutions designed to create survival spaces in the event of an earthquake. He reads about IoT devices capable of reacting during earthquakes, monitoring the presence of people protected by the desk, and sending data collected by the drone that flew over the area. He remembers the tablet and why there was a person giving directions to the other rescuers. He discovers that the teams can use this app to see on a map where the devices located by the drone are, allowing them to reach them more quickly. Furthermore, the article mentions the cloud platform where the entire school, including plans and classrooms, was mapped, along with the position of IoT devices. Rescuers, the article reports, had estimates of how many people were in the school before the earthquake and their location relative to the building, thanks to platform data collected before the earthquake. This allowed them to organize rescues and identify the areas to dig in advance.

9. Related works

Disaster management is a relevant and complex topic that several other research works and projects addressed differently. In the following we report about related works that apply different approaches from ours, including a non-exhaustive list of European projects related to the SAFE project.

ICT related works. Information and Communication Technology (ICT) encompasses a diverse array of digital tools and resources utilized for communication, generation, dissemination, storage, and information management. The significance of ICT in disaster management has been affirmed, playing a crucial role in executing rescue, relief, and restoration efforts for community-wide disasters. Real-time information can be easily collected from various sources with the rapid advancement of information and communication technologies. A review of ICT usage in disaster management is provided in [40]. In [41] the authors focus on the importance of ICT for disaster management and how ICT can be helpful in disseminating earthquake alerts. They report on earthquake prediction methods and disaster management strategies using ICT and wireless sensor networks, supporting the argument that the implementation of wireless sensor networks in earthquake-prone areas and the application of ICT can prove to be very helpful in avoiding devastating situations during quakes and safeguarding people from heavy losses. In [42] authors propose an IoT architecture for Earthquake Early Warning (EEW), earthquake detection, localization, and event notification. The architecture has been designed, deployed, and tested on a standard cloud platform. A localization algorithm based on the hyperbola method is also proposed. The results show that the end-to-end architecture is able to provide a quick estimate of the earthquake epicenter location with acceptable errors for an EEW system scenario. Several works present an ad hoc architecture for supporting communication among emergency-response organizations that must collaborate to handle complex emergency scenarios. In [43], the Workpad architecture is presented. It consists of front-end emergency-management teams and back-end control rooms. Backend centers typically communicate directly with the team leader over available technologies, whereas team members communicate through a mobile ad hoc network (manet). At international level, the INSARAG Coordination and Management System (ICMS) [25] is the information sharing platform employed by the INSRAG organization and USAR teams for decision making during the disaster response phase. The ICMS platform consists of a suite of mobile phone and software applications aimed to the efficiency of rescue efforts. The platform support the functionalities to represents the disaster sites by means of geo-located maps, worksites and assigned teams to the rescue operations. Data can be collected using two key applications from the mobile devices, or online systems, and is then displayed on an operations dashboard.

Our contribution differs from the reported works since it focuses on providing an ICT platform that can be used during peacetime for monitoring the situation pre-event and for supporting localization and USAR's rescue operations after the seismic event occurs. The SAFE ICT Platform integrates IoT devices with anti-seismic furniture, the SAFE furnishings, to create active protection systems capable of detecting and localizing individuals during an earthquake, enhancing the effectiveness of rescue operations.

Related localization and rescue support systems. Immediately after a disaster, a key aspect is to detect and account for the victims trapped under the rubble, after which localization can be performed to further concentrate the efforts of the first responders [44]. Several techniques have been proposed for this task, such as: visual recognition with rescue dogs: (i) The traditional task of finding victims is usually performed either by direct observation or with the help of trained rescue dogs; (ii) human body image detection: when the victims are incapacitated, image recognition may help to find individuals that are on the surface; (iii) audio-processing-based human detection: when victims are trapped under rubble and there is no visual or imaging recognition, drones may integrate microphones to detect any distress calls and notify the rescue services; (iv) vital signs detection: Passive Infrared (PIR) sensor for detecting victims. Adoption of new techniques could reduce the chances of losing human lives as well as damage to large-scale infrastructure due to both natural and human-made disasters. IoT, which allows seamless interconnection among heterogeneous devices with diverse functionality, is a viable solution for disaster management. Since the impact of any disaster is enormous, the IoT-enabled disaster management system can be applied to find the victim and possible rescue operations [45]. In [20] an analysis of the impact of sensors on the disaster management process is reported. It highlights the types of sensors used in detecting the occurrence of these disasters or accidents and how sensors are used to detect the presence of living survivors and locate them. In [46] a discussion on key issues and inherent challenges facing localization approaches, techniques, and technology of localization in the Wireless Sensor Network (WSN) is reported. In [47] a SLR to examine the utilization of sensors in the IoT for urban catastrophe management is reported. The evaluation encompassed both the pre-disaster and post-disaster stages and analyzed a total of 72 publications. Modern life relies heavily on smartphones, in the event of disasters, individuals trapped in such situations are more likely to have their smartphones on them than other forms of technology. Researchers explore the adaptability of the existing search and rescue system to swiftly transform smartphones into location system [48]. However, leveraging these devices effectively in critical scenarios with restricted mobile Internet access poses challenges. In [49], the authors propose a phone-based Emergency Communication Systems (ECS) enabling long-range communication among survivors and rescue teams over critical environments where 3/4G cellular connectivity is not available and the traditional geolocalization technologies (e.g. the GPS) provide only partial coverage of the environment. The proposed system consists of a mobile application connected to a LoRa transceiver via Bluetooth Low Energy (BLE); through the app, users can send emergency requests that are re-broadcasted by other peers until reaching a rescue personnel who is able to handle the emergency. Locating things (objects or people) is an important issue in which UAVs can play an important and effective role. In [50] the role of WSNs and UAV systems is explored in the context of natural disaster management. In [51] the role of UAV systems and related technologies in disasters is explored. Localization can be implemented using sensors, RSSI, and RF emitter to measure distances from the source to the object, also auditory or sound sources can be used to estimate survivors' position, optimizing the intercommunication. Also sensing method between objects and base station is proposed in localization using UAV. The ICMS platform from INSARAG [25] also offers functionalities for managing rescue teams during the disaster response phase. Operators can represent worksites, associate USAR teams, and manage victims extrication. This information is intended to provide the ability to monitor and understand the overall status of the event as well as to plan possible rescue operations.

In our case, we designed wireless IoT devices that can adapt their behavior based on the occurrence of a seismic event, and we integrated them into seismic-resistant furniture. We do not require any active intervention from the people who only need to leverage the good practice of hiding under resistant furniture, in our case, SAFE furniture. In addition, we propose to use a UAV, especially a drone equipped with a LoRa gateway, to scan the surface of a disaster and collect data coming from the SAFE devices. The drone will be used in case an Internet connection is not available and the Stationary Gateway is not able to communicate with the IoT platform, delivering presence detection messages. In that case, the drone will collect messages from the SAFE PIR devices that are detecting the presence of people, and in combination with the SAFE rescue support system, represented by a developed mobile application, it will provide rescuers with indications on the current situation, helping to locate the presence of a person under the SAFE furniture.

Related projects. FASTER[14] addressed challenges faced by first responders in hazardous environments, deploying technologies such as UAVs, UGVs, resilient communications, companion K9 units, and AR tools. These technologies expanded responders' capabilities for enhanced situational awareness, communication, and safety during disasters. The LINKS[15] initiative delved into the intricate web of disaster governance in Europe, seeking to fortify the connections between technologies and society to bolster European resilience against calamities. Focused on the fusion of social media and crowdsourcing (SMCS) into disaster management, LINKS aims to generate sustainable advanced learning, fostering a more profound understanding of their impact. SGL for USaR[16] was specifically designed to address significant challenges arising from extensive structural collapses in urban areas. It focused on procedures and technology that facilitate secure and efficient responses. This comprehensive project aimed to integrate chemical and physical sensors while concurrently developing an open ICT platform. The primary objective was to meet the mobility and time-sensitive demands inherent in USAR operations. SECTOR[17] strives to lay the groundwork for future Common Cross-Border Crisis Management (CCM) Information Spaces by advancing the European scientific understanding of (cross-border) multi-agency CCM processes. The project addressed the challenges of establishing and designing cross-border supporting information systems for effective crisis management. RISKCOAST[18] a European initiative co-funded by the South-West European (SudOE) Interreg V program, was dedicated to the creation of tools for the prevention and mitigation of coastal geological risks associated with global warming. The project primarily addressed land movements and other phenomena, including changes in water tables. Its overarching objective was to investigate geological risks in coastal regions linked to climate change. The project placed a specific emphasis on enhancing the coordination and efficacy of preventive measures, disaster management, and the rehabilitation of disaster-stricken areas. The TURNkey[19] Project (Towards more Earthquake-resilient Urban Societies through a Multi-sensor-based Information System enabling Earthquake Forecasting, Early Warning, and Rapid Response Actions) had the primary objective of contributing to the reduction of earthquake risks through extensive scientific collaborations on both European and global scales. Overall, the project encompassed a wide range of research areas within earthquake engineering, aiming to enhance understanding, preparedness, and response capabilities in earthquake-prone regions.

Differently from the mentioned projects, the objective of the SAFE project was to create innovative furniture systems, called *SAFE furniture*, that are able to define a "passive" and "saving" intelligent protection systems for people in schools and offices in case of earthquake. Such smart furniture could be deployed in already available buildings that might have historical value and cannot undergo anti-seismic refactoring. Especially the SAFE project investigated the role of ICT in supporting localization and rescue operations in the event of an earthquake. It is important to emphasize that the originality of the results of the SAFE project has been demonstrated with a patent regarding the SAFE ICT Platform [9]. The patent highlights the novelty of the results obtained integrating anti-seismic furniture with IoT devices therefore transforming traditional furniture into life-saving protections systems capable of enhancing earthquake preparedness and response efforts.

10. Limitations

The SAFE ICT Platform represents a contribution to the advancing earthquake preparedness and response. By integrating IoT devices with anti-seismic furniture, it transforms traditional furniture into intelligent security systems capable of detecting seismic activity, localizing trapped individuals, and supporting rescue operations. Despite its potential, we acknowledge that the SAFE ICT Platform presents some limitations and challenges.

Potential challenges to consider include the optimal integration of the SAFE devices with the SAFE furniture and their placement. A careful design and actual development of the IoT integrated furniture must be carried out. The integration must be conducted in such a way that the SAFE devices are not obstructed by the furniture itself. They should be able to sense people and the environment, to properly communicate sensed data to the gateway, and to withstand impacts caused by the earthquake.

The main limitation related to the SAFE-devices that we recognize relates to the battery life of the device, which should last long enough to support rescue operations. A possible solution would be the implementation of predictive maintenance services added as a monitoring feature of the Cloud platform to replace the batteries timely. Another limitation concerns reliability of the Stationary Gateway which currently depends on electrical power. Using a low-powered gateway [52], for instance, would support the integration of batteries to ensure continuous operations after an earthquake, thereby improving the responsiveness of the SAFE devices during disasters. Another aspect to consider is the requirement of internet connectivity to manage and monitor SAFE devices remotely via the Cloud platform. In our envisioned application the local gateway is connected to the Internet and forwards the SAFE devices data to a cloud platform. We could think about relying on a LoRa-based communication to bring connectivity in area where the Internet is not available.

For what concerns the position estimation of the SAFE devices we currently rely on the collection and analysis of their signal strength. However, the performance of the localization algorithm based on signal strength analysis is highly dependent on the

14 https://www.faster-project.eu/
15 https://links-project.eu/project/
16 https://cordis.europa.eu/project/id/217967
17 https://cordis.europa.eu/project/id/607821
18 https://riskcoast.eu
19 https://cordis.europa.eu/project/id/821046

building characteristics and the consequences of the earthquake impact. It is in fact known that in obstructed conditions (e.g., devices covered by several layers of rubble or several building floors [53]) the signal propagation might be limited or inaccurate. Techniques based on AI and clustering could provide more accurate estimations based on RSSI analysis [54,55].

Some limitations of our solution concern the tests that have been conducted in simulated conditions at the Computer Science Department of the University of Camerino. Simulating an earthquake event is a non-trivial task, therefore we did not aim to simulate a realistic earthquake but just the effects that an earthquake could have on the SAFE ICT Platform. With respect to the test environments used, some open points still remain to be validated. We tested our solution in a limited amount of building of recent construction. The type of buildings could impact the radio performance of the SAFE devices and affect the localization and rescue system we have proposed. Tests that involve historical buildings should be conducted. Also tests under different weather conditions should be performed especially for validating the signal propagation and to what extent a flying drone could be used. Tests with the USAR teams to validate the effectiveness and usability of the proposed solution have still to be conducted. In the VITALITY project, we plan to install the SAFE ICT Platform in a real school in central Italy and involve the Italian National Fire and Rescue Service teams to validate the platform under various operational conditions.

11. Conclusion & future work

In this article we reported about the conceptualization, design, development and evaluation of the SAFE ICT Platform to support, in case of earthquake, the detection and localization of the individuals during the rescue operations.

The proposed SAFE ICT Platform works in combination with innovative anti-seismic furniture – named “SAFE furniture” – designed within the scope of the SAFE project [39]. Such furniture have been designed to resist to seismic events and to provide shelter to people allowing therefore to extend the time window necessary for rescuers to come and rescue people.

ICT technologies extend the capabilities of the SAFE furniture to signal the presence of individuals needing rescue though the integration of specific IoT devices, such as the SAFE PIR sensor, and a computer data management platform that transformed the furniture into smart systems. Together, they form the SAFE ICT Platform. Through the integration of life-saving SAFE furniture with dedicated IoT devices and a related ICT infrastructure, the SAFE project contributes to life protection and the location of people after an earthquake.

Among all the components that characterize the SAFE ICT platform two of them stand out: the monitoring and management system of devices executed in the cloud and based on the open-source platform Thingsboard, and the localization and rescue support system for the rescue of people detected by the SAFE device. These two components are complementary and functional to the requirements of understanding the situation after the event, supporting the organization and execution of the rescue. The localization and rescue system defines a new innovative tool that aims to increase the effectiveness and efficiency of the interventions by rescue teams after a seismic event. Specifically, the system is capable of providing geolocated information on the positions of the individuals to be rescued, starting from the detection of the radio signals from the SAFE devices acquired with autonomous flight systems, such as drones. This approach enhances the rapid identification and localization of people, significantly improving the speed and precision of rescue operations in the critical hours following an earthquake.

The relevance of the results obtained with the SAFE ICT Platform is demonstrated by the Italian patent [9].[20] The direct implications of our results can be translated into new regulations for the design of furniture in schools and public buildings. This includes updating the INSARAG guidelines and rescue practices for USAR teams in their search and rescue operations, and providing new equipment to rescue teams to leverage the presence of SAFE furniture and the functionalities of the SAFE ICT Platform.

To validate the hypotheses underlying the conceptual model we defined, we created a test environment at the Computer Science department at the University of Camerino, which allowed us to implement and test the entire system in a prototype. The demonstrator we set up provided us with significant elements that confirm how the ICT platform is effectively able to meet the requirements of the stakeholders. Given the promising results, an ongoing implementation of the SAFE system and its digital twin is under development within the project called VITALITY,[21] a research project founded by the National Recovery and Resilience Plan (Piano Nazionale di Ripresa e Resilienza, PNNR) in which the University of Camerino leads the activities about the innovation and safety of living environments in the digital transition era. Part of project’s activities are related to the exploitation of the SAFE project with the implementation of the SAFE life-saving furniture and the related SAFE ICT Platform to an actual classroom of a school in the Marche Region of Italy. The objective of the evaluation in a real operational environment is to reach a TRL 7 and subsequently develop a large-scale commercial version of the product. Furthermore, during the experimentation, a set of community engagement initiatives are planned to involve relevant stakeholders (e.g., students, teachers, local public administrations) to comprehensively evaluate the effectiveness, reliability, and usability of the SAFE ICT Platform. These initiatives aim to create awareness in local communities about appropriate behavior during an earthquake and how they can benefit from the SAFE life-saving protection system. For this purpose, we are creating a Digital Twin of the real scenario as mentioned in [9, 10] which could make people more aware of this topic and teach them good practices to adopt in case of an emergency.

As future works, on a device perspective we aim to enhance the furniture with additional sensors which could provide possible other values such as temperature, humidity, and the presence of hazardous substances. We want also to explore IoT-based prediction models that are being employed in the environmental context [56] and other mechanisms to identify the occurrence of an earthquake that might be mistaken with other external vibrational noises [57].

[20] https://arit.unicam.it/it/brevetti/piattaforma-hwsw-monitoraggio

[21] https://vitality-spoke6.unicam.it/en/

Regarding the management of IoT devices, the initial implementation of the SAFE ICT Platform has been achieved by utilizing the ThingsBoard open-source IoT platform. This adoption allows the platform to inherit all functionalities provided by ThingsBoard, such as data retrieval, manipulation, and visualization (e.g., through dashboards and widgets). The adoption of other IoT platforms could be investigated, or techniques could be employed to design and develop IoT applications that ensure portability across different platforms [58]. The localization system could be extended to integrate optimization logics tailored to the scenario [59]. The localization and rescue system could be enhanced to actively incorporate pre-event data from the cloud, obtaining an initial, albeit blurred, picture of individuals' locations before the event, thus providing rescuers with preliminary guidance. Additionally, we could empower USAR teams with a local mesh communication system among rescue devices for exchanging location data of the USAR teams and improve the coordination of the teams [43].

Other works focus on rethinking the way building are built so to incorporate IoT devices from the start [60]. Employing a Digital Twin of the building and furniture, which could leverage the role of Building Information Modeling (BIM) models [61], would enhance initially the prototyping of the solution and subsequently the monitoring of the current situation. Furthermore, it could simulate post-earthquake scenarios aiming to mirror the real consequences of the earthquake and assist in directing Urban Search and Rescue (USAR) teams to specific locations. This is a research direction that we have already started to explore [62,63].

CRediT authorship contribution statement

Massimo Callisto De Donato: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Flavio Corradini:** Supervision, Funding acquisition. **Fabrizio Fornari:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Barbara Re:** Visualization, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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