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Research Article

Mixed-reality for quadruped-robotic guidance in SAR tasks

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Abstract

In recent years, exploration tasks in disaster environments, victim localization and primary assistance have been the main focuses of Search and Rescue (SAR) Robotics. Developing new technologies in Mixed Reality (M-R) and legged robotics has taken a big step in developing robust field applications in the Robotics field. This article presents MR-RAS (Mixed-Reality for Robotic Assistance), which aims to assist rescuers and protect their integrity when exploring post-disaster areas (against collapse, electrical, and toxic risks) by facilitating the robot's gesture guidance and allowing them to manage interest visual information of the environment. Thus, ARTU-R (A1 Rescue Tasks UPM Robot) quadruped robot has been equipped with a sensory system (lidar, thermal, and RGB-D cameras) to validate this proof of concept. On the other hand, Human-Robot interaction is executed by using the Hololens glasses. This work's main contribution is the implementation and evaluation of a Mixed-Reality system based on a ROS-Unity solution, capable of managing at a high level the guidance of a complex legged robot through different interest zones (defined by a Neural Network and a vision system) of a post-disaster environment (PDE). The robot's main tasks at each point visited involve detecting victims through thermal, RGB imaging, and neural networks and assisting victims with medical equipment. Tests have been carried out in scenarios that recreate the conditions of PDE (debris, simulation of victims, etc.). An average efficiency improvement of 48% has been obtained when using the immersive interface and a time optimization of 21.4% compared to conventional interfaces. The proposed method has proven to improve rescuers' immersive experience of controlling a complex robotic system.

Keywords: robotics vision, quadruped robot, mixed reality, hololens, search and rescue

1 Introduction

Natural disasters (earthquakes, hurricanes, floods) or provoked ones (attacks) usually destroy buildings or cities. The consequences of these disasters result in the loss of human lives, many of which cannot be assisted in time because they are trapped in hard-to-reach areas. Post-disaster environments (PDE) are characterized by much debris and structures at risk of collapse, which hinder rescue brigades' inspection and displacement (Del Moral & Walker, 2007; Agarwal *et al.*, 2014; Times, 2016; BBC, 2016, 2021). One of the main goals that have motivated the constant growth of the search and rescue robotics line is to increase the rate of victims rescued or assisted in time (Tadokoro, 2009; Delmerico *et al.*, 2019).

Among the main tasks expected from Search and Rescue (SAR), Robots are: providing support to rescue teams through the transmission of audio-visual information, mapping, identification of victims, and assistance with first aid kits (Casper & Murphy, 2003; Kleiner & Dornhege, 2007).

Various interventions with robotic systems in real scenarios have been documented throughout the last decades, such as those in the United States (Twin Towers – 2001; Blackburn *et al.*, 2002), Japan (Fukushima – 2011; Spenko *et al.*, 2018), Italy (Amatrice – 2016; Kruijff *et al.*, 2016), and Mexico (Earthquake – 2017; Whitman *et al.*, 2018).

Technological development in sensors such as infrared cameras or laser (Gade & Moeslund, 2014; Krišto *et al.*, 2020), as well as mixed reality devices (Chakraborti *et al.*, 2018; Krupke *et al.*, 2018), have made it possible to capture and show information from the environment that is not perceptible to the rescuer but that it provides relevant information for the mission development. The main advantages of using these devices in SAR missions are their portability and allowing to provide high-level commands through gestures without dependence on a laptop.

On the other hand, quadruped robots have shown broad applicability in unstructured terrains with notable advantages over conventional locomotion systems such as wheels or tracks, as well as a faster response time and adaptability to different soil types such as sand, rocks, and debris (Catalano *et al.*, 2021). Recent developments have verified the functionality of quadrupedal robots on terrain with rough surfaces, debris and variable friction coefficients (Kumar *et al.*, 2021). These conditions are characteristic of PDE, so these robots are currently a great alternative to carrying out search and rescue tasks.

Most state-of-the-art developments focus on detecting people with RGB images (Cebollada *et al.*, 2021; Lygouras *et al.*, 2019). On the other hand, mixed reality focus on transmitting visual information to an operator (Llasag *et al.*, 2019; Sharma *et al.*, 2019). This article addresses the problem of high-level robotic control (guidance) through different interest zones of an environment (where there could be victims) considered risky for a rescuer.

Therefore, the main contribution of this work is focused on implementing a Mixed Reality system based on ROS-Unity capable of providing a rescuer with high-level control through gestures for guidance a legged robot, as well as suggesting to the rescuer through an image transmitted to their glasses, areas where there are potential victims.

The authors previously validated the victim's detection system, both for RGB (Cruz Ulloa *et al.*, 2021) and thermal images (Cruz

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Ulloa *et al.*, 2023), showing high efficiency in detecting potential victims (partially covered by materials or debris). This detection system informs the operator of the potential existence of victims.

The main functions of the robot in each area explored involve assistance to victims (delivery of first aid equipment and communicator) and inspection for additional victims occluded by debris.

The ARTU-R (A1 Rescue Tasks UPM Robot) robot has been used to validate this proof of concept. Thus, an A1 Unitree commercial robot has been equipped with sensors for harsh environments, an Optris-Pi640 thermal camera, an RPLidar laser and an RGB-D camera. The Leader rescuer uses the Hololens (first generation) to monitor the environment information and control the robot.

This development has been validated with a series of field experiments performed in reconstructed scenarios according to the NIST (National Institute of Standards and Technology) criteria (Jacoff *et al.*, 2001). The system has been validated regarding the successful completion rate of victim assistance and versatility of the M-R system management, which has been contrasted against conventional robot control interfaces.

The results show an improvement of 48% for immersive user experience and a 21.4% reduction in execution time of the SAR tasks when using MR-RAS (Mixed Reality for Robotic Assistance) against conventional interfaces. Moreover, average efficiency is over 90% in performing highly complex tasks (such as placing iterative way-points in strategic areas) concerning conventional interfaces.

This paper is structured as follows: Section 2 shows the most relevant state-of-the-art works, and Section 3 describes the proposed methods. Hardware, experimental fields, and algorithms are introduced in detail, followed by the Results and Discussion in Section 4. To conclude, Section 5 summarizes the main findings.

This work has been developed as part of the TASAR project (Team of Advanced Search And Rescue Robots), which is focused on using ground SAR-Robots for Humanitarian Assistance and Disaster Relief (Barrientos, 2021).

2 Related Works

2.1 Mixed reality for field robotics control

The interaction between mixed reality systems and robots is usually developed through Robot Operating System (ROS) due to Its versatility for node and topic management systems, allowing the combination of commercial software such as Unity or Unreal Engine with ROS development software (Wassermann *et al.*, 2018).

One of the most recent and relevant works in tele-operation using a mixed reality system shows a framework to control robots with Hololens. This work is limited to establishing an arbitrary point in laboratory conditions (Ostanin *et al.*, 2020). Other similar studies are Chakraborti *et al.* (2018), Krupke *et al.* (2018), Park *et al.* (2021), and Liang *et al.* (2019).

Other applications are focused on industry (Mourtzis, 2021; Adriana Cárdenas-Robledo *et al.*, 2022), also in simulation applied to manufacturing systems (Sha *et al.*, 2019; Mourtzis, 2020), which addresses the simulation part, considering the kinematic and dynamic parameters. Considering the mixed reality path planning area, the proposed methods develop visual interfaces on the Hololens that display information from 2D maps of the environment and trajectories without direct interaction with the robot (Wu *et al.*, 2018, 2020). There are few developments with direct interaction through the assignment of way points.

Some approaches have focused on the selective presentation of data to the operator to aim at facilitating the tele-operation of the robot (Livatino *et al.*, 2021). Still, they are limited to presenting RGB images (Kot *et al.*, 2018).

In these two works developed by the authors, the issue of teleoperation with the mixed reality of a 6DoF manipulator arm coupled to a quadruped robot is addressed, where the quadruped robot is teleoperated, and MR controls the arm. However, in these works, the robot is teleoperated, and constraints for virtual interaction, such as collisions with the physical environment, are not considered in this first approximation (Cruz Ulloa *et al.*, 2022; Cruz *et al.*, 2023a).

Currently, technologies such as Virtual Reality have been used in the same way to carry out field developments. One of its main advantages is keeping the operator in a safe area. However, in high-precision operations, execution times are usually higher due to the uncertainty generated in the operator by not being in the field of operation (Steffen *et al.*, 2019). From the point of view of SAR missions, the operator's sense of perception has a significant implication because the irregularity of the terrain can cause collisions in the robot. Hence, M-R technologies are the best alternative for on-site operations.

2.2 Vision systems applied to search and rescue

Most of the works described in the bibliography related to using RGB and thermal images involve drones for search and rescue tasks. The main developments with thermal imaging found are focused on surveillance (Königs & Schulz, 2012; Park *et al.*, 2020), people tracking with UAVs, object detection in different weather conditions (Krišto *et al.*, 2020), and face and emotion detection (Ilikci *et al.*, 2019). In the same way, it occurs with works focused on RGB images (Fung *et al.*, 2020; Katsamenis *et al.*, 2020)

Several works use low-resolution Thermal images to detect people (Gomez *et al.*, 2018; Cerutti *et al.*, 2019), analysing the feasibility and efficiency of using very low-resolution cameras, neural networks for systems with few resources, increasing the detection processing speed, and optimizing energy consumption.

In some works, optical sectioning techniques identify people with Thermal images (Schedl *et al.*, 2020). Whereas other methods use classical vision techniques (Doulamis *et al.*, 2017), optical sectioning initially shows good results. Still, it is not robust against heat or noisy sources, as usually happens in the case of fire.

The authors have made recent contributions to the state-of-the-art, which have been used as a basis for detecting victims through different infrared light spectra. This way, the use of RGB (Cruz Ulloa *et al.*, 2023), Thermal (Cruz Ulloa *et al.*, 2021), and Multispectral (Cruz *et al.*, 2023b) images for this purpose are highlighted. The first two have been used in this work since the third option does not work in real-time yet.

2.3 Quadruped robots for search and rescue applications

SAR environments' complex and unstructured conditions usually demand specific locomotion systems, including tracks, articulated wheels, or legs. The most versatile alternative of locomotion methods for executing explorations in unstructured terrain, due to their potential and great dynamism, is the quadruped robots (Biswal & Mohanty, 2021).

This type of robot is relatively new for search and rescue applications since most previous developments focused on low-level design, construction, and control (Cebe *et al.*, 2020; Liu *et al.*, 2020a; Shen *et al.*, 2020; Tan *et al.*, 2020; Xin *et al.*, 2020).

Main works focus on leader-Tracking by using lidar sensors (Fan *et al.*, 2020) or stereo cameras (Pang *et al.*, 2021) and mapping (Liu *et al.*, 2020b).

Figure 1: Identifications of the experimental Zones (Indoors–Outdoors) in ETSII-UPM. Source: Authors.

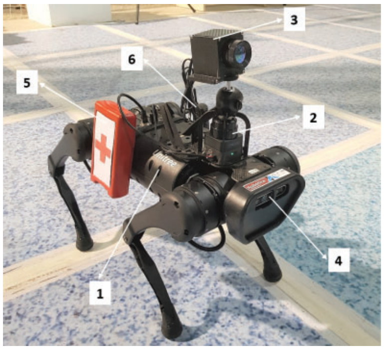


Figure 2: ARTHUR Robot (A1 Rescue Tasks UPM Robot) with sensory, communication, and medical equipment. Source: Authors.

One of the most relevant works within this context was developed by using the MIT Mini-Cheetah (Kim *et al.*, 2020), capable of generating interaction with the environment and avoiding obstacles on irregular terrain.

There are some comparisons between alternative locomotion systems and the one proposed; above all, some developments that seek to take advantage of each one (legged, tracked, wheeled) using convertible wheels (Zhou *et al.*, 2018; Mertyüz *et al.*, 2020). It is highlighted that one or the other turns out to be more practical depending on the terrain type. Moreover, legged locomotion systems have shown a significant advantage in overcoming obstacles and debris, conditions usually present in PDE. In contrast, tracked locomotion systems mainly stand out for steep slopes or slippery surfaces.

3 Material and Methods

3.1 Robotic system, instrumentation, and field experiments

PDE have been reconstructed according to the orange level conditions described by the National Institute of Standards and Technology (NIST; NIST, 2022). The experimental development of the tests to validate this work has been carried out in CAR-ARENA (Center for Automation and Robotics), located in (40°26′24.415″ N–3°41′21.553″ W). Figure 1 shows test Zones A outdoors (yellow) and B indoors (green).

The robotic system used for the experiment phase uses the ARTU-R robot shown in Fig. 2 and its sensory system to capture environmental information. The general dimensions of the robotic system are $0.5*0.3*0.6$ m, a weight of 14 kg, and a maximum speed of $3\ \mathrm{m\,s^{-1}}$. Table 1 shows the robot's sensory system and equipment.

Table 1: Sensory and medical equipment of ARTU-R.

Num	Component	Description
1	Robotic Unitree A1	Quadruped Robot
2	RPLidar S1	ToF 360° distance sensor
3	Thermal Camera O-PI640	640x480*px* [-20 2000]°C
4	RealSense D435i	RGB-D 1920× 1080*px*
5	First-aid kit	Medical equipment
6	Radio voice intercom	Communications equipment

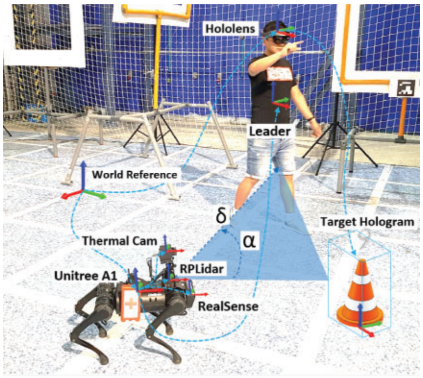


Figure 3: Variables and Coordinate reference systems between the World-Robot-Leader. Source: Authors.

The stage (Zone B) has been reconstructed to recreate a post-disaster scene, including obstacles, mannequins, and people who have pretended to be victims. The guidance method was tested in Zones A and B, while medical assistance to victims was only tested in zone B. The difference between the guidance and assistance to victims stands out in that in the latter, the robot must wait 10 seconds to capture more visual information of the area and for the victim to reach the required equipment (first-aid kit, communicator).

3.2 Mixed reality system

3.2.1 *Interaction between reference systems*

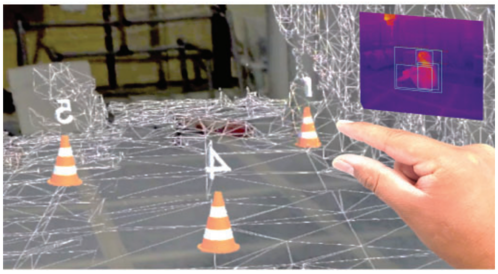
The Referential Systems (R-S) allow knowing the position and orientation of each element that interacts in the development of the experiments. These referential systems allow physical and virtual interactions (through holograms or augmented reality elements).

The physical R-S is allocated in ARTU-R according to, as well as in, Hololens. On the other hand, virtual R-S are World Referenced locations placed at fixed points of the environment, such as the initial position of the Leader at the beginning of the task, and the Holograms or interactive hand points (or way-points), which will be placed in Zones of interest in the environment by the Leader using the capture of his hand gestures.

Fig. 3 shows the different physical and virtual referential systems in an area of the test scenario. The Hololens and ARTU-R systems are taken from the World reference. The Leader places the Target Holograms to guide the robot to a target point. The figure also shows the δ and α variables corresponding to the distance and angle measured from the robot front to the Leader. The referential position of the targets (T) and the robot (R) concerning the world (W) implies a conversion between rotation and translation matrices and is given by equations (1) and (2).

$$ {}^{W}_{T}T ={}^{W}_{H} T.{}^{H}_{T}T \tag{1}$$

(a) **Visualization of the interface in first-person view.**



(b) **Way-point assignment by hand-gesture.**

Figure 4: Mixed reality interface implemented to develop assistance operations in SAR Tasks. Source: Authors.

$$ {}^{W}_{R}T = {}^{W}_{H}T . {}^{H}_{R}T \qquad (2) $$

3.2.2 *Mixed reality control interface*

Implementing a mixed reality interface seeks to improve the operator's confidence when assigning robot inspection destinations. The scenarios and situations where this interface is favourable are mainly in on-site operations and unstructured terrain, where the operator, from his perspective, can define the best inspection sites.

The R-M interface has been developed by using Unity (v2020.3). It uses the following tools: buttons, sliders, and checkboxes to develop the mission stages detailed in Fig. 4.

The R-M (Fig. 4a) contains the following elements:

- Checkbox START to initialize the robot movement.
- Toggle (1)*LeaderTracking*/(2)*VictimAssitance* to select one of the robot's operating modes. In the first case, the robot can track the rescuer to move to another place in the environment if necessary.
- Slider *UnitreeSpeedAdjust* to modify the overall robot speed.
- The button *ThermalVision*/*RGBVision* allows switching between the different vision systems. The image displayed in the upper right corner indicates if there is a victim inside it.
- Button *NewVictim* allows, if the operator wishes to incorporate another inspection point, it generates a new cone to be placed in the area to visit.
- Button *Data* > >*ROS* sends the data to the central system for path generation based on the different goals (cones).

Figure 4a shows the first-person view of the Hololens, the environment and, superimposed on it, the interactive interface. A box with the RGB image of the environment and a detected victim is shown in the upper right corner, marked with a red rectangle, which suggests the operator guides the robot towards that area to gather more information or assist the victim.

Figure 4b shows the placement of virtual cones in the environment, numbered according to the route order the robot must perform. The capture of thumb and index finger gestures, integrated by the Hololens, is used to place the virtual marks. The meshing of the environment to generate the depth is carried out thanks to the depth camera integrated into the glasses. The image also shows a victim detected in the upper right box.

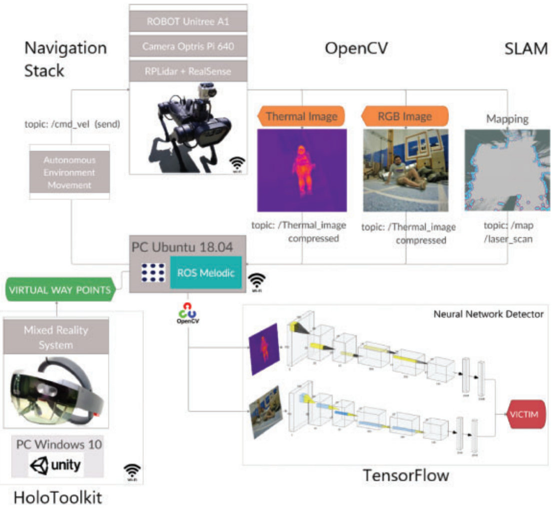


Figure 5: Connection diagram between the MR-RAS subsystems. The different variables (inputs-outputs) and their connections between Ubuntu (ROS) and Windows (Unity) are shown. Source: Authors.

3.2.3 *Connection between subsystems*

A system has been implemented for the high and low-level management of all the variables and subsystems. Two groups have been established, categorized mainly by the operating system (ROS Melodic-Ubuntu-18.04 and Unity-Windows) where the processes are executed. Figure 5 shows the general integration scheme between the subsystems and their wireless communication through a 5G network.

In the first group (Ubuntu), a computer (MSI i7-10th) is used as a command station, ARTU-R robot is equipped with an On-board Nvidia Jetson Xavier-NX. In the second group (Windows), a second computer (i7-7th) is used in the command station connected wirelessly to the Hololens glasses.

Jetson Xavier board is responsible for managing the robot's movement based on linear and angular speeds (*geometry_msgs/Twist*) through low-level control of the 12 robot actuators (gait patterns and stability), as well as the reading of the sensory variables: Thermal Image and RGB Image (*sensor_msgs/CompressedImage*) marked in orange output in Fig. 5 and Environment Mapping.

The Hololens glasses receive the image and position variables transmitted from the robot *geometry_msgs/Pose* (shown in orange in Fig. 5). At the same time, the published topics are *Topic/Leader_assistance*, which acts as a switch allowing selecting between the Leader-Tracking or victim assistance operation modes. *Topic/Virtual_way_points* sends the position of the interactive handle points to the scheduler to assist the victims and *Topic/speed_adjust* in regulating the global speed of the robot.

The command station receives the variables from both the robot in the field and those sent from the Mixed Reality system and manages the central nodes of robot control (planning-control). Hololens glasses use Mixed Reality Toolkit packages and a remote device holographic emulation tool at a bit rate (data-flow per second) of 99 999 (kbps).

RGB and Thermal images are processed using Convolutional Neural Networks for victim detection. This part of the work is better described in the works previously developed by the authors (Cruz Ulloa *et al.*, 2023) and (Cruz Ulloa *et al.*, 2021). In the case of the thermal camera, it captures the infrared emission of the bodies. This emission is greater or less depending on whether it is covered by some material. The camera cannot capture the thermal footprint if the material is thick. Some materials that adequately capture the thermal footprint are glass, plastics, fabric and polymers.

3.3 Algorithms and experiments

The experimentation phase was carried out in indoor and outdoor environments as shown in Fig. 1. Outdoor tests evaluate the guidance part of the method on unstructured terrain. Indoor tests evaluate both guided and victim assistance. These tests were conducted in a scenario with post-disaster conditions reconstructed by placing mannequins and people who simulated being victims (Fig. 1, Zone B).

3.3.1 *Robotic guidance through mixed reality*

The leader takes into account the victim's information coming from RGB and thermal images, in addition to his criteria, to place different points (virtual cones) through hand gestures towards zones of interest where potential victims are located.

Although the areas may be close, there could be high risk (collapse of structures, electrical shocks risk or gas leaks) for a rescuer in this scenario, so it is better to send the robot to gather more information.

Algorithm 1 M-R Robotic Guidance

```
Data:
$P[n] \Leftarrow$ Virtual Way-Points $size$ $[n]$
$map \Leftarrow$ Global costmap
$im_{th}, im_{rgb} \Leftarrow$ Thermal and RGB image size $[nxm]$
$R_{pose} \Leftarrow$ Robot pose
$[switch, n_{vict}, start] \Leftarrow$ M-R System Variables;
Initial Conditions:
$P[n] \Leftarrow P[x_{[1...n]}, y_{[1...n]}]$
$n_{vict} \Leftarrow 0$ Number of Victims
Result $[v_l, v_\alpha]$
if Class Detected in $im_{th}$ or $im_{rgb}$ is $victim$ then
    $Hololens \leftarrow suggest\ victim$
end if
if Leader $press$ New Victim then
    $M-R\ Interface \leftarrow new\ cone$ and $n_{vict}++$
end if
while $current\_vict <= n_{vict}$ and $switch$ is Start do
    if $map$ not None then
        $Find\ free\_collition\_path$ (RRT Path planner)
        $Q[x_{[n]}, y_{[n]}] \leftarrow$ from $R_{pose}$ to $P[n]$ in $map$
        $[v_l, v_\alpha] \leftarrow Vel\_Ctrl(R_{pose}, Q[x_{[n]}, y_{[n]}])$
        Publish $[v_l, v_\alpha]$
    end if
    if $error(R_{pose}, Q[x_{[n]}, y_{[n]}]) < safe\_zone$ then
        $wait[10s]$ for $data\_capture/assistance$
        $current\_victim+=1$
        $n \leftarrow current\_victim$
    end if
end while
```

Algorithm 1 details the pseudo-code implemented for guidance. This algorithm aims to move the robot towards each point of interest through a collision-free path obtained from a global scheduler based on the RRT algorithm. This planner considers the cost map generated by the advance, the different points of interest stored systematically, and the robot's position.

The robot's speed has been limited to 0.5 $\mathrm{m\,s^{-1}}$ and 0.9 $\mathrm{rad\,s^{-1}}$ (even though its maximum speed is around 3 $\mathrm{m\,s^{-1}}$) since the application to be executed includes collecting visual data. For this, oscillations should be avoided as far as possible.

4 Results and Discussion

4.1 Evaluation for victim assistance and mixed reality control

Figure 6 shows the result of an indoor test, where the robot is shown in different scenario positions, and the optimal trajectory is marked in blue. The environment has four victims, marked in red, one person, and three mannequins. Five operators conducted these tests with 10 repetitions to evaluate the system.

Four areas (Points 1, 2, 3, 4) of interest to inspect were defined. The recreated post-disaster area includes three mannequins, partially covered by debris (Points 1, 3, 4) and a seated person with acute pain and minor injuries (Point 2). The strategy implemented to carry out this mission was to reach an average approach distance of 1 m from each point and then stop and wait for 10 seconds to collect and transmit visual information and advance to the next point.

In the case of the victim at Point 2, this time was long enough to allow the victim extends her arm and take the first aid kit. Once the mission was finished, the robot had to return to the starting point (near the Leader). The average efficiency obtained for this mission was higher than 94%. It was measured according to equation (3). The efficiency is estimated based on the robot's final position in each of the four points and the destination position given by the leader through the Mixed Reality system for each of the four points. On the other hand, an average mission completion time of 78 s was obtained for this scenario, considering the 10 different iterations carried out by each operator.

$$eff = \frac{dist_{obj} - \sum_{i=1}^{n}(dist[P_{(x_{n[goal]};y_{n[goal]})}; P_{(x_{n[pose]};y_{n[pose]})}])}{n * dist_{obj}} * 100\% \qquad (3)$$

Figure 7 shows the execution of outdoor tests to verify the functionality of the interactive way-point definition in different zones. The robot arrives at the different interactive waypoints [1–5] placed by the leader. The trajectory performed to reach each point is shown in blue. Once the waypoints have been defined, the process starts according to the optimal route established by the scheduler, but in this case, the robot does not stop at each point, unlike the previous test.

Figure 7a corresponds to a sandy terrain, where the optimal average displacement speed was 0.4 $\mathrm{m\,s^{-1}}$, an effectiveness of 95%, and an average time of 21 s. Figure 7b corresponds to the robot on gravel terrain with light debris. The performance in this terrain type had an effectiveness greater than 92% with an approximate completion time of 25 s. Figure 7c shows the tests executed on a terrain with an approximate slope of 30°; the performance was higher than 93%, with an average completion time of 29 s.

Table 2 shows the average values of the variables measured during the tests carried out indoors and outdoors. Parameters such as time, distances travelled, number of way-points used and efficiency achieved in each scenario are evaluated.

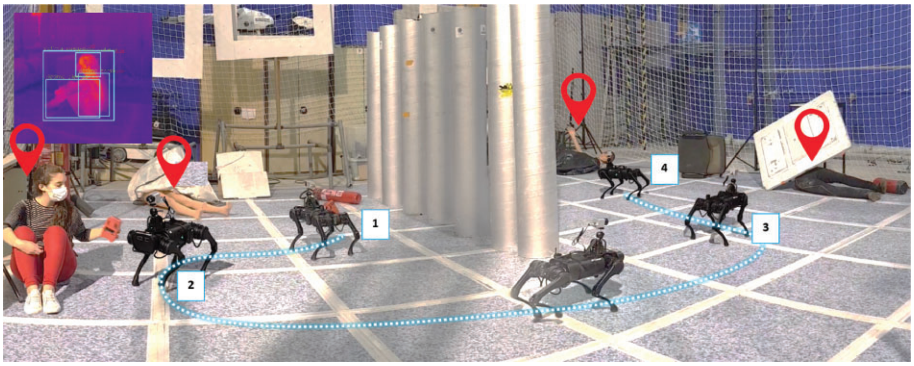


Figure 6: Assistance to a victim within the test environment. The figure shows in a representative way the trajectory covered by the robot in the four different points of the environment. The quadruped robot approaches the Way-points to collect thermal information and provide first aid equipment to victims. Source: Autors.

(a) **Displacement tests of the ARTU-R on a sandy ground, using M-R Interface.** (b) **Displacement tests of the ARTU-R on gravel terrain, using M-R Interface.**

(c) **Displacement tests on a grassy terrain (30 degrees slope).**

Figure 7: Robot displacement tests through the Mixed Reality System in different terrains. Source: Authors.

Table 2: Results and metrics of the MR-guided tests.

	Indoors		Outdoors	
	Reconstr. Env.	Sand	Gravel	Grass
Average time	78 s	21 s	25 s	29 s
eff	94%	92%	91%	93%
Number of tests	10	10	10	10
Traveled distance	16.3 m	18.6 m	8.9 m	19.5 m
Number of average way-points	4	5	5	5

4.2 Evaluation of suggestion system effectiveness

This subsection shows the system's effectiveness in suggesting zones to inspect based on victim detection in the scenario. These suggestions are displayed through a box at the top of the interface (Fig. 4), showing the zone where a victim may exist with a square on the image.

Table 3: Results of the victim detection tests in RGB and thermal images.

	Test										
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	e(%)
A	4	4	4	4	4	4	4	4	4	4	
B	4	4	5	3	4	4	4	3	4	4	7.5%
C	1	0	2	1	1	1	1	2	2	1	10%
S	4	4	5	4	4	4	5	3	4	4	

For this, the successful detections made by the neural network on the indoor test scenario will be evaluated. The four victims (one person and three mannequins) must be detected. In this case, the thermal system should suggest one victim, and the RGB system should suggest four. The RGB and thermal systems alert may come from the same site. In this case, the area to be inspected will be the same. However, if they appear in different locations, they will be considered independent areas to be inspected. In any case, the operator makes the final decision based on the number of suggestions detected.

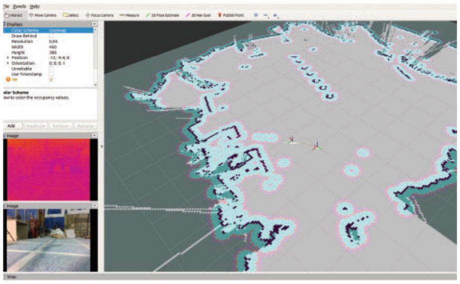
Table 3 shows the results for each test carried out and the error obtained based on equation (4). The nomenclature used in this table corresponds to:

- A: Number of victims within the scenario (real + mannequins).
- B: Number of victims in the environment detected by thermal imaging.
- C: Number of victims in the environment detected by RGB image.
- S: Total number of way-points placed by the operator based on the system suggestion.

$$error_{num-vict} = \frac{num - vict_{real} - num - vict_{detect}}{num - vict_{real}} * 100\% \tag{4}$$

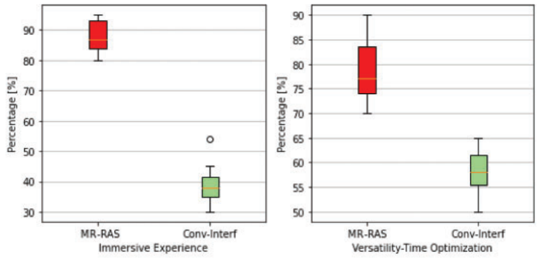
For critical missions which involve saving lives, it is better to have a false positive and inspect an area (which will require a minimum of time) than to stop doing it and ignore there is a person there.

(a) M-R interface view showing the thermal image and the robot's destination points.



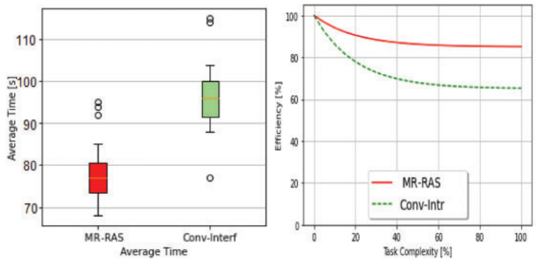
(b) Conventional RVIZ interface showing the map and images corresponding to the same mission

Figure 8: Comparative view of the conventional and immersive interfaces used. Source: Authors.



(a) Box plot for the evaluation of the immersive experience.

(b) Box plot for evaluating the versatility of the system.



(c) Box plot for the evaluation of average time.

(d) System efficiency curve vs task complexity.

Figure 9: Evaluation of MR-RAS against conventional interfaces for developing search and rescue tasks. Source: Authors.

4.3 System efficiency and versatility

The efficiency of MR-RAS (Fig. 8a) has been evaluated through the comparison against conventional interfaces such as those based on RVIZ (Fig. 8b), commonly used when working with ROS to show images and different variables when the operator is allocated in a remote area, monitoring or making decisions during of the mission execution through a monitor.

These interfaces have the same functionality as the proposed method, allowing remote image monitoring to high-level control of the quadruped robot.

Figure 9 shows the different metrics for both interfaces obtained from surveys applied to the operators after using both interfaces for the mission. Several of these metrics have been applied based on the NASA-TLX workload questionnaire, which is used in the context of robotic missions (Hart 2006).

The main results show a notable improvement in the Leader's experience in the execution of the mission. To obtain these results, the Leader has used both interfaces (Conventional and MR-RAS), repeating the mission execution under the same conditions to quantify the controlled variables accurately.

Figure 9 a shows the result of the immersive experience during the development of the missions. The diagram of boxes in red corresponding to MR-RAS has shown to provide a superior experience by 48%, concerning the diagram of Conventional interface boxes shown in green. This parameter indicates that using the M-R system allows the Leader to better interact with the environment, thanks to manipulating holographic objects and visualizing variables in mixed reality during the mission.

In Fig. 9b, the equipment portability and time optimization parameters are analysed when executing the different processes in Zones A and B, where the mission is carried out. MR-RAS shows an average percentage improvement of 20% value, which is significant when taking quick actions on the execution of the mission.

Figure 9c shows the average time the operator is required to carry out different missions with both interfaces. An average optimization of 25 s can be observed using M-R. During the tests, the leader required less time to make decisions thanks to the confidence provided by direct interaction with the physical environment.

Finally, the efficiency of the method has been evaluated against the complexity of the task within the mission, Fig. 9d, from easy tasks, such as exchanging between RGB-Thermal vision modes, regulating the general speed of movement of the robot to complex tasks, such as placing the iterative handle points in areas with high precision so that the robot moves with a safety margin when assisting victims.

Both interfaces showed high efficiencies for the execution of simple tasks; however, as the tasks become complex, the M-R method showed a higher percentage efficiency (by 21%) compared to conventional interfaces.

The results of the method implemented in this article are shown in the following video https://youtu.be/ZvhywpQzmOE.

4.4 Comparison with related works

This section compares the most notable works related to the proposed method. Table 4 shows the list of works related to the method proposed in this work, seven items related to the method proposed in this work have been taken into consideration, which allows us to know if the works within the state-of-the-art meet them or not (X shows if the criterion is met). These items, numbered from one to seven, are detailed in the following list.

- 1. RGB Image Transmision
- 2. Thermal Image Transmision
- 3. Use of Hololens Glasses
- 4. Multitarget
- 5. Robot type: (Q) quadruped, (W) wheeled, (M) Manipulator.
- 6. Comparison with conventional interfaces
- 7. Interaction of virtual objects with the environment.

Table 4: Comparison of the works related to the proposed method.

Work/item	1	2	3	4	5	6	7
Li *et al.* (2022)			X		W		
Gu *et al.* (2022)			X	X	W		
Leber & Dalm (2022)			X		W		
Park *et al.* (2021)			X		M		X
Wu *et al.* (2020)			X		W		X
Ostanin *et al.* (2019)			X		W		X
Liang *et al.* (2019)			X		M		X
Kästner & Lambrecht (2019)			X		W		X
Moezzi *et al.* (2019)			X		W		
Wu *et al.* (2018)			X		W		
Kot *et al.* (2018)	X		X		W		
Ostanin & Klimchik (2018)			X		W		X
Krupke *et al.* (2018)			X	X	M		X
Authors method	X	X	X	X	Q	X	X

Based on the criteria proposed for the analysis, Table 4 shows that most works focused on robot control using mixed reality lack several components relevant to the execution of applications in exploration missions.

The first component is the transmission of both RGB and thermal images; this information can be valuable for an operator in inspection missions. The second component is a multi-waypoint system, which allows the mission to expand towards different objective areas, and the last essential factor shows that the related works within the state-of-the-art do not compare their method against conventional interfaces (mouse, screen, and keyboard), a highly relevant criterion to validate this type of immersive technology.

5 Conclusions

This article presents MR-RAS, a proof-of-concept for Robotic Assistance in SAR tasks based on a complex integration of mixed reality systems and specific sensory systems for PDE. It uses algorithms based on computer vision-neural networks and a quadruped robot to assist rescuers and victims.

Mixed reality systems and their application in field robotics missions have proven to be a highly efficient alternative to conventional interfaces since they provide an immersive experience to the rescuer for monitoring missions and controlling highly complex robotic systems from Safe Zones.

The proposed method has shown an average efficiency higher by 21% concerning conventional interfaces for its application in complex high-level control tasks and a time optimization of 26% in the management and assignment of mission stages.

The use of RGB and Thermal images combined with CNN has shown high efficiency in detecting victims, being a helpful support system for the rescuer when detecting occluded victims or in precarious lighting conditions.

The high-level control strategies implemented through MR-RAS, such as the use of interactive handle points to define areas of interest for inspection or assistance to victims of the quadruped robot, have shown great versatility during tests carried out on different types of soil, such as sand, grass, or rocks with moderate obstacles size.

Regarding future works, the development of modular Mixed Reality systems is proposed, based on IOT, to provide remote assistance to operators in the field by external staff (doctors, firefighters).

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Conflict of interest statement

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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