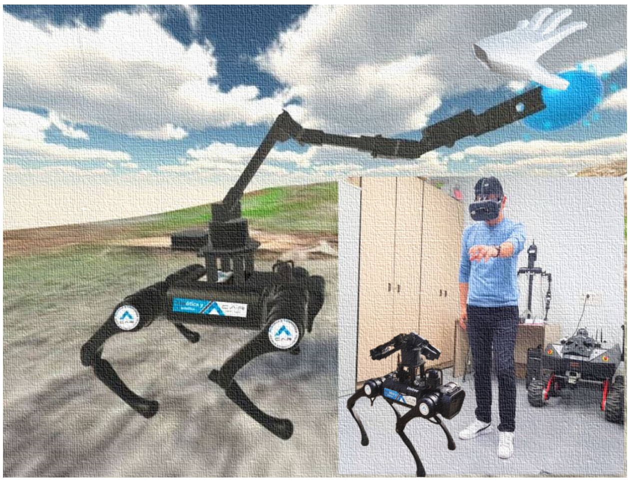
# Chapter 7

# Immersive Interfaces for High-level Teleoperation

*"The mind that opens to a new idea never returns to its original size."*

- Albert Einstein



*THIS chapter addresses victim assistance using quadrupedal robots equipped with medical equipment or communication systems, enhancing their capabilities through manipulation systems. Furthermore, it delves into the remote teleoperation of these robots through immersive interfaces, demonstrating how an operator from a secure location can effectively control a complex robotic system using gestures and virtual representations of the robots in the field, thereby enhancing the efficiency and safety of rescue operations.*

Scientific publications related to this chapter [1, 2, 3, 4].

## Preamble

The final chapter of this doctoral thesis focuses on addressing advanced methods for high-level teleoperation of quadrupedal robots in post-disaster scenarios. Up to this point, methods for managing their mobility through joysticks—where the operator has a direct line of view or through a screen using transmitted images and autonomous systems have been discussed. However, given the inherently complex and dynamic nature of a post-disaster environment, it is essential to have a high-level control method that enables executing operations requiring a high degree of precision.

Specifically, two recurring situations in Search and Rescue (SAR) missions have been addressed. On the one hand, the assisted guidance of the quadrupedal robot through the environment, and on the other hand, the second scenario involves manipulating elements. In the latter's case, a study, design, and implementation of a manipulation system integrated with the quadrupedal robot has been performed.

A study of immersive interfaces based on Virtual Reality (VR) and Mixed Reality (MR) has been conducted to address managing these situations. This study aims to provide the operator with technological tools that enable direct and indirect immersion into the scenario—via VR headsets (HTC Vive) and MR devices (Hololens). The operator can conduct missions by guiding the robot in the environment or manipulating interesting objects through gestures.

### Exploring Digital Worlds: Mixed and Virtual Reality.

Figure 7.1 illustrates the inflexion point between the transition from the real world to virtual environments. It aims to provide an applied perspective to the search and rescue research theme, taking one of the test environments as a reference, such as the real environment (RE). The second instance corresponds to mixed reality, characterized by the interaction of the RE with virtual objects through reference systems and adjacent surfaces (such as walls or floors).

Figure 7.1: General context of real and virtual environments.

In the provided exemplification, the superimposition of a virtual **legged-manipulator robot** in the real environment is shown for a manipulation task. One of the significant advantages of MR is that the user can recreate, anticipate, and program a sequence of manipulation, categorizing and correcting possible failures, as they are aware of the environment from their perspective.

On the other hand, virtual environments (VE) immerse the operator entirely in a recreated or reconstructed world. To generate situational awareness of what is happening in the VE, feedback from the environment in any form is necessary. This may include visual feedback through cameras and screens integrated into the VE and the interpretation of hand movements and gestures through sensors in the VR headset.

Both MR and VR have pros and cons that can be selectively chosen for teleoperation based on the specific situation. Among the most notable and qualitatively categorized aspects, specific criteria applicable to Search and Rescue (SAR) can be established, as shown in the following Table 7.1:

Table 7.1: Qualitative Consideration Criteria for MR-VR in SAR [253].

| Item | MR | VR |
|---|---|---|
| situational awareness of the environment | High | Medium<br>(depends of feedback) |
| operation from security zone | Low | High |
| visibility perspectives | High | Low |
| precision in decision-making | High | Medium |

One of the objectives of this chapter is to assess the effectiveness of this high-level teleoperation method in mission execution, compare it to conventional interfaces, and evaluate its impact on operators through specialized tests aimed at analyzing variables such as confidence levels, perceived user experience, method versatility, and other relevant factors.

This chapter is structured as follows: firstly, the MR-based method for assisted environmental guidance is discussed. Afterwards, the legged manipulation systems followed by their control through VR-MR are addressed. Finally, a comparative analysis between both methods is conducted.

## 7.1 Quadruped Robot Guidance using Mixed Reality

This subsection introduces the concept of assisted guidance for a quadrupedal robot through an environment utilizing Mixed Reality (**MR-RAS**) –**Mixed-Reality for Robotic Assistance**–, capitalizing on the heightened situational awareness engendered by this immersive technology. This innovative methodology showcases the potential for enhanced robotic locomotion and highlights the convergence of state-of-the-art robotic systems with the dynamic opportunities presented by immersive MR technologies.

This section is motivated by the applicability of the guided system for assisting victims and gathering environmental information at specific locations. In this way, ARTU-R has been equipped with additional instrumentation in both medical and communication domains (Figure 7.2), as depicted in Table 7.2. According to their judgment, the operator guides the robot through points considered of interest, enabling victims to access the communication or medical equipment anchored to the robot.

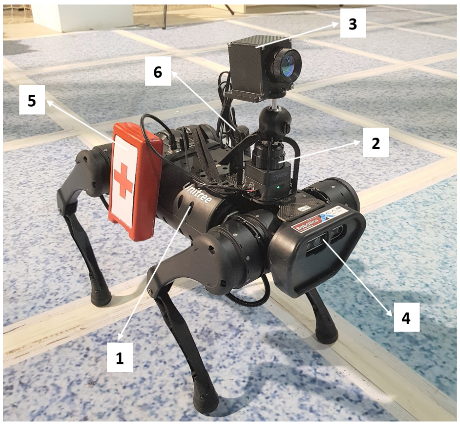


Figure 7.2: ARTU-R robot equipped with an array of sensory, communication, and medical instrumentation

Table 7.2: The sensory and medical equipment integrated into ARTU-R.

| Num | Component | Description |
|---|---|---|
| 1 | Robotic Unitree A1 | Quadruped legged Robot |
| 2 | RPLidar S1 | ToF 360° distance sensor |
| 3 | Thermal Camera O-PI640 | $640x480px$ [–20 2000] °C |
| 4 | RealSense D435i | RGB-D $1920\times1080px$ |
| 5 | First-aid kit | Medical equipment |
| 6 | Radio voice intercom | Communications equipment |

### 7.1.1 Mixed Reality System

#### Interaction of Reference Systems

Referential Systems (R-S) determine the spatial orientation and location of elements involved in experimental setups. These systems facilitate physical and virtual interactions.

The physical R-S is established within the framework of ARTU-R and Hololens. In contrast, virtual R-S comprises world-referenced positions strategically positioned within the environment. These positions include the initial location of the **Leader** at the commencement of the task and Holograms or interactive hand points (waypoints). The Leader deploys these virtual elements in designated zones of interest by utilizing hand gesture recognition [59].

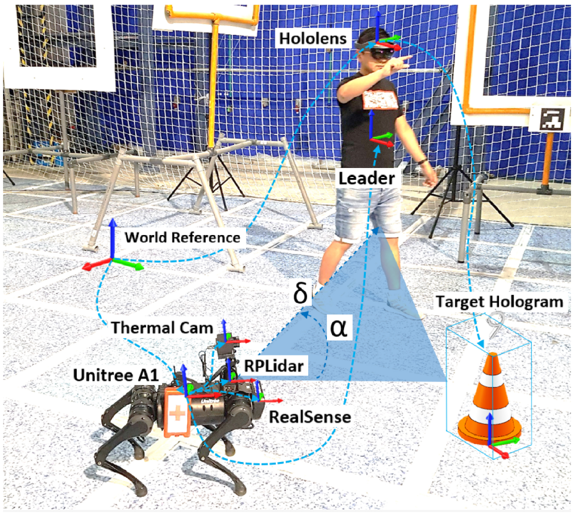


Figure 7.3: Variables and Coordinate Reference Systems in the Context of the World-Robot-Leader Interaction.

Figure 7.3 illustrates distinct physical and virtual referential systems within a specific region of the test scenario. Both the Hololens and ARTU-R systems are anchored to the World reference. The Leader uses Target Holograms to direct the robot towards a target point. Additionally, Figure 7.3 showcases the $\delta$ and $\alpha$ variables, representing the distance and angle measured from the robot's front to the Leader. Determining the referential positions of targets (T) and the robot (R) concerning the world (W) involves a conversion process between translation and rotation matrices, as described by equations 7.1 and 7.2.

$$ {}^{W}_{T}\mathrm{T} = {}^{W}_{H}\mathrm{T} \cdot {}^{H}_{T}\mathrm{T} \tag{7.1} $$

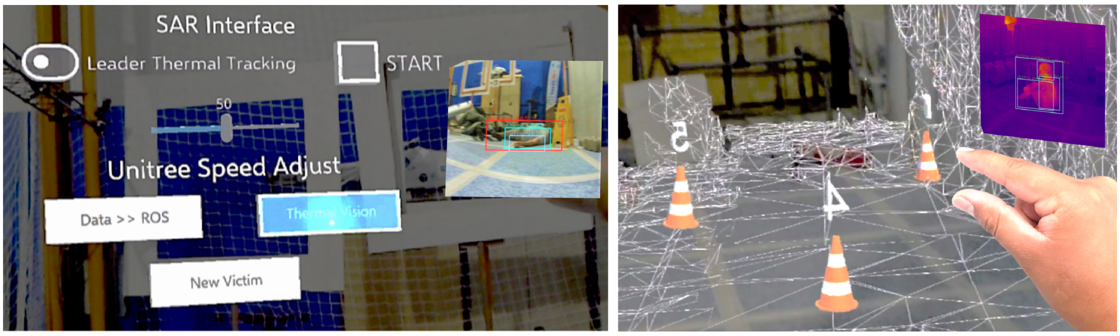
$$ {}^{W}_{R}\mathrm{T} = {}^{W}_{H}\mathrm{T} \cdot {}^{H}_{R}\mathrm{T} \tag{7.2} $$

### MR Control Inferface

The R-M interface has been implemented utilizing Unity. It employs a set of elements for the user interaction, such as buttons, sliders, and checkboxes, to construct the mission stages, as shown in Figure 7.4; specifically, it contains these elements:

- **START Checkbox**: This checkbox initiates robot movement.
- **Leader Tracking/Victim Assistance Toggle:** offers a choice between two operational modes for the robot. In the first mode, the robot can track the first-responder and relocate within the environment if necessary.

- **Unitree Speed Adjust Slider:** is employed to adjust the overall speed of the robot finely.
- **Thermal Vision/RGB Vision Button:** enables the seamless switch between different vision systems. The image displayed in the upper right corner serves as an indicator of the presence of victims within the field of view.
- **New Victim Button:** If the operator intends to add another inspection point, this button generates a new cone that can be placed in the desired area to visit.
- **Data>>ROS Button:** facilitates data transmission to the central system, which in turn uses it for path generation based on the various goals represented by the cones.



(a) View of the Interface from a First-Person Perspective. (b) Manual Gesture-Based Way-Point Assignment.

Figure 7.4: Implementation of a Mixed Reality Interface for Enhancing SAR Task Support.

Figure 4(a) provides a first-person perspective from the Hololens, showing the surrounding environment overlaid with an interactive interface. In the upper-right corner, an inset displays the RGB environment image featuring a detected victim highlighted by a red rectangle. This information could be used to suggest to the operator to guide the robot toward this region to collect additional information or assist the victim.

In contrast, Figure 4(b) showcases the process of inserting virtual cones into the environment, each numbered to indicate the sequence for the robot's navigation. Precision placement of these virtual markers is achieved through recognizing thumb and index finger gestures, seamlessly integrated within the Hololens. The depth of the environment is accurately mapped through the utilization of the glasses' integrated depth camera. Furthermore, the image presents a detected victim within the upper right box using the thermal method described in Section 5.2.

### Interconnection between Subsystems

An extensive system has been developed to manage various variables and subsystems at high and low levels. These subsystems are grouped into two categories based primarily on their operating systems: one operates within the ROS Melodic-Ubuntu-18.04 environment, and the other is in the Unity-Windows environment. These subsystems' integration and communication have been achieved through a 5G network, as depicted in Figure 7.5. In the first group, an MSI i7-10th generation computer (Ubuntu) is the command station, while the ARTU-R robot is equipped with an onboard Nvidia Jetson Xavier-NX.

The second group relies on another computer (Windows) with an i7-7th generation processor, functioning in the command station and wirelessly connected to the Hololens glasses. The Jetson Xavier board control the robot's movements, encompassing linear and angular speeds, low-level control of the robot's actuators, sensory data acquisition (including Thermal and RGB Images), and environment mapping.

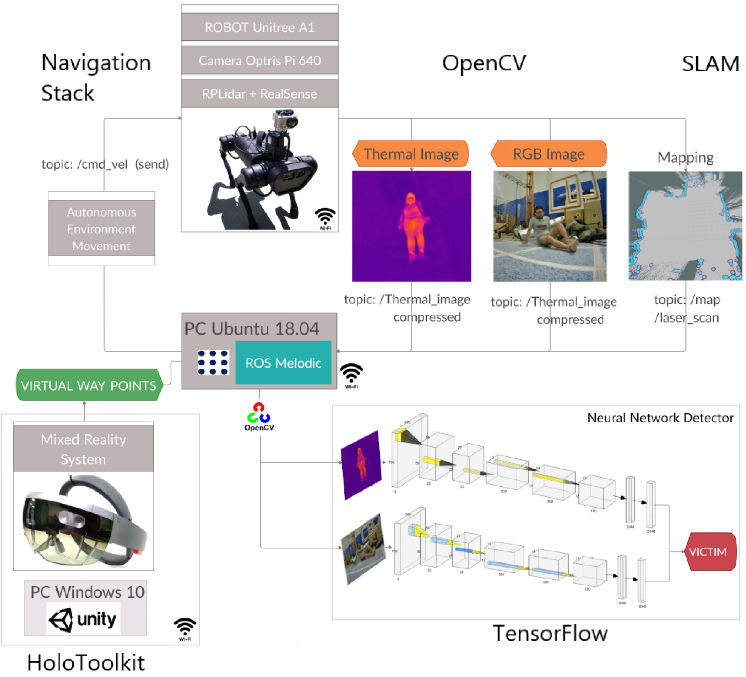


Figure 7.5: Diagram Illustrating the Interconnections Between Subsystems, Depicting Various Input-Output Variables and Their Linkages Between Windows (Unity) - Ubuntu (ROS).

The Hololens glasses receive image data and position variables transmitted from the robot in the $/geometry\_msgs/Pose$ format, as highlighted in orange in Figure 7.5. Concurrently, a published topic set is integral to the system's functionality. Notably, the Topic $/Leader\_assistance$ topic acts as a switch, enabling the selection between two critical operational modes: Leader-Tracking and victim assistance. Additionally, the Topic $/Virtual\_way\_points$ channel facilitates the communication of interactive handle point positions to the scheduler, thus aiding in victim assistance.

The command station serves as a pivotal hub, receiving data from both the robot in the field and the Mixed Reality system. A suite of Mixed Reality Toolkit packages enables the Hololens glasses' Mixed Reality functionality. Additionally, a remote device holographic emulation tool is utilized in Unity, operating at 99999 kbps to ensure seamless communication and real-time responsiveness.

### 7.1.2 Guidance Algorithms and Experiments

The leader in charge considers not only their judgment but also the information derived from RGB and thermal images when placing various points (virtual cones) in the environment using hand gestures. These cones are positioned in zones of interest where potential victims might be located.

Even though these areas may be in proximity, they could present significant risks to first-responders, such as structural collapse, electrical hazards, or potential gas leaks. Therefore, in such scenarios, it is often safer and more prudent to dispatch the robot to collect additional information, minimizing the risks to human first-responders.

Algorithm 9 provides a comprehensive pseudo-code representation of the implemented guidance system. Its primary objective is to navigate the robot towards designated points of interest while ensuring a collision-free path. This path is generated by a global scheduler employing the Rapidly-Exploring Random Trees (RRT) algorithm. The planner considers factors such as the cost map derived from previous robot movements, the systematic storage of various points of interest, and the robot's current position.

**Algorithm 9:** M-R Robotic Guidance

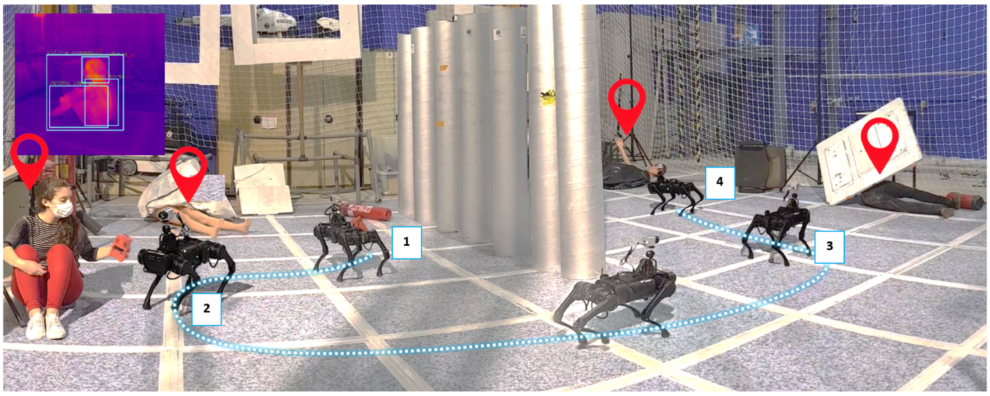
```
Data:;
$map \Leftarrow$ Global costmap;
$P[n] \Leftarrow$ Virtual Way-Points $size$ $[n]$;
$im_{RGB}, im_{TH} \Leftarrow$ RGB and Thermal image size $[nxm]$;
$[switch, start, n_{vict}] \Leftarrow$ M-R System Variables;
$R_{pose} \Leftarrow$ Robot pose;
Initial Conditions;
$n_{vict} \Leftarrow 0$ Number of Victims;
$P[n] \Leftarrow P[x_{[1...n]}, y_{[1...n]}]$;
Result $[v_l, v_\alpha]$;
if $Class\ Detected\ in\ im_{TH}\ or\ im_{RGB}\ is\ victim$ then
    $Hololens \leftarrow suggest\ victim$;
end
if $Leader\ press\ New\ Victim$ then
    $M - R\ Interface \leftarrow new\ cone$ and $n_{vict} + +$;
end
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 $error(R_{pose}, Q[x_{[n]}, y_{[n]}]) < safe\_zone$ then
        $wait[10s]$ for $data\_capture/assistance$;
        $current\_victim+ = 1$;
        $n \leftarrow current\_victim$;
    end
end
```

To ensure the safe execution of the application, the robot's speed has been deliberately restricted to 0.5 m/s for linear motion and 0.9 radians per second for angular motion despite its maximum capabilities of approximately three m/s. This limitation is enforced to minimize oscillations, essential in scenarios where collecting visual data is a primary objective.

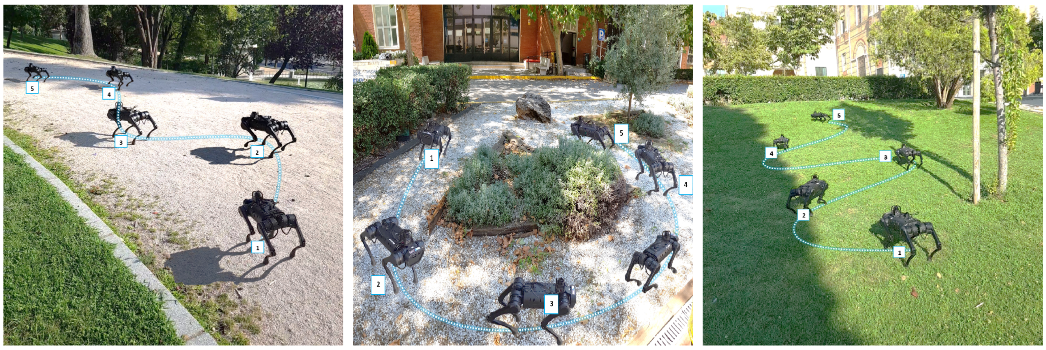
### 7.1.3 Results and Discussion

#### Assessment of Victim Assistance and MR Guidance.

Figure 7.6-a displays the outcomes of an indoor test, depicting various robot positions within different scenarios. The optimal trajectory is highlighted in blue. The test environment contains four victims, marked in red, comprising one real person and three mannequins. Five operators conducted these tests, each with ten repetitions, to thoroughly assess the system's performance.



(a) Assisting a Victim in the Test Environment: The figure provides a representative illustration of the robot's trajectory at four distinct points within the environment.



(b) Traversal across Sandy Terrain Through Five Designated Points.

(c) Traversal across Gravel Terrain Through Five Designated Points.

(d) Traversal across Grass Terrain Through Five Designated Points.

Figure 7.6: Test performed for guidance using the MR method.

In this experiment, four distinct inspection points (Points 1, 2, 3, and 4) were defined within a post-disaster simulation. The environment featured three mannequins partially concealed by debris (Points 1, 3, and 4) and a seated person with minor injuries and acute pain (Point 2). The mission strategy involved:

- Approaching each point to within an average distance of one meter.
- Pausing for ten seconds to gather and transmit visual information.
- Subsequently, moving on to the next designated point.

In the case involving Point 2, the mission allowed enough time for the victim to retrieve the first aid kit. The overall mission efficiency exceeded 94%, calculated according to

Equation 2, by comparing the robot's final positions at the four designated points to the destinations provided by the Leader through the Mixed Reality system. Additionally, the mission had an average completion time of approximately 78 seconds, with ten repetitions.

$$eff = \frac{dist_{obj} - \sum_{i=1}^{n}(dist[P_{(x_{n[goal]};y_{n[goal]})}; P_{(x_{n[pose]};y_{n[pose]})}])}{n * dist_{obj}} * 100\% \qquad (7.3)$$

Figures 7.6-b-c-d showcase outdoor tests evaluating interactive waypoint definition in different zones, where the robot navigates to waypoints [1-5] following optimal trajectories in blue without stopping at each point.

In the outdoor tests depicted in Figure 7.6-b, the sandy terrain yielded an optimal average displacement speed of 0.4 m/s, with an effectiveness of 95%, and an average mission completion time of 21 seconds. Similarly, Figure 7.6-c showcases the robot's performance on gravel terrain with light debris, achieving an effectiveness exceeding 92% and an approximate mission completion time of 25 seconds. Lastly, Figure 7.6-d illustrates tests conducted on terrain with an approximate 30-degree slope, demonstrating a performance surpassing 93% and an average mission completion time of 29 seconds.

Table 7.3 presents the average values of the measured variables obtained from the conducted tests, both indoors and outdoors. These parameters include time and distance travelled, the count of waypoints utilized, and the overall efficiency achieved in each scenario.

Table 7.3: Results and metrics obtained from the tests guided by Mixed Reality.

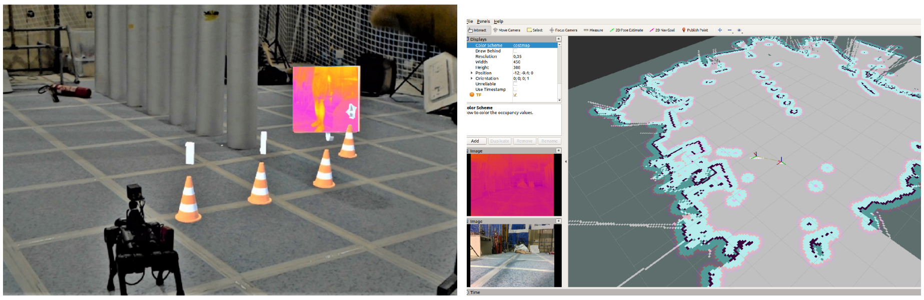
| | Indoors | Outdoors | | |
|---|---|---|---|---|
| | Reconstr. Env. | Sand | Gravel | Grass |
| Average time | 78 s | 21 s | 25 s | 29 s |
| eff | 94% | 92% | 91% | 93% |
| Number of Tests | 10 | 10 | 10 | 10 |
| Traveled Distance | 16.3 m | 18.6 m | 8.9 m | 19.5 m |
| Num of Average way-points | 4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

### System versatility and efficiency

The effectiveness of MR-RAS (as depicted in Figure 7.7-a) has been systematically assessed by conducting a comparative analysis with conventional interfaces, exemplified by those reliant on RVIZ (as illustrated in Figure 7.7-b). Such RVIZ-based interfaces are frequently employed within the context of ROS to facilitate the display of images and different variables. These interfaces find common usage in scenarios where the operator operates remotely, engaging in monitoring and decision-making activities during the execution of missions through a dedicated monitor.

Notably, these conventional interfaces offer comparable functionality to the proposed method, thereby enabling actions such as remote image monitoring and high-level quadruped robot management.

In Figure 7.8, a representation of various metrics of both interfaces is presented. After employing both interfaces during the mission, these metrics were derived from surveys administered to operators. A subset of these metrics has been applied following the **NASA-TLX workload questionnaire**, a tool commonly employed within robotic missions (as referenced in [114]).

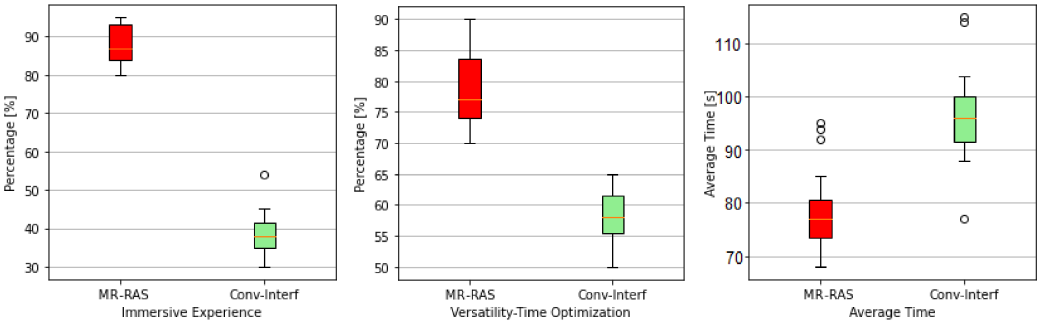


(a) View of the Mixed-Reality Interface Displaying Thermal Imaging and Robot Destination Points.

(b) Conventional RVIZ interface displaying the images and map associated with the mission.

Figure 7.7: A Comparative Analysis of Conventional and Immersive Interfaces Employed.

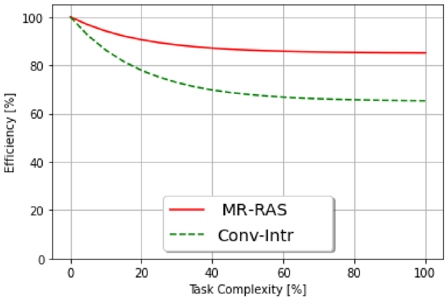
The primary findings from the study reveal a significant enhancement in the Leader's experience throughout the mission execution. To reach these results, the Leader used both Conventional and MR-RAS interfaces and executed the mission multiple times under identical conditions, ensuring precise quantification of the controlled variables.



(a) Box Plot Analysis to Assess the Inmersive Experience.

(b) Box Plot Analysis to Assess the System's Versatility.

(c) Box Plot Analysis to Assess the Average Time.



(d) System Efficiency Curve in Relation to Task Complexity.

Figure 7.8: Evaluation of MR Interface in Comparison to Conventional Interfaces for the Enhancement of Search and Rescue Task Capabilities.

The first test results, shown in Figure 7.8-a, illustrate the outcomes related to the immersive experience observed during mission development. The graph comprises red boxes representing MR-RAS and green boxes representing the Conventional interface. The MR-RAS method surpasses the Conventional interface by a significant margin of 48%. This metric signifies that using the Mixed Reality system enables the Leader to engage more effectively with the environment. This improvement is facilitated through manipulating holographic objects and visualising variables in a mixed reality context throughout the mission.

The second evaluation shown in Figure 7.8-b presents an analysis of parameters related to equipment portability and time optimization during the execution of various indoor and outdoor processes where the mission was conducted. MR-RAS exhibits an average improvement of 20%, a noteworthy enhancement that is especially valuable for expediting mission execution and facilitating fast decision-making actions.

The third Figure 7.8-c displays the average time necessary for the operator to complete various missions using both interfaces. A noticeable improvement in efficiency, with an average time reduction of 25 seconds, can be observed when employing the Mixed Reality interface. The tests showed that the leader could make decisions more swiftly due to the increased confidence derived from direct interaction with the physical environment.

The final metric evaluated was related to task complexity, as depicted in Figure 7.8-d. These tasks span a range of complexities, encompassing straightforward actions like switching between RGB and Thermal vision modes, as well as tasks of higher intricacy, such as precisely positioning iterative handle points in areas requiring a high degree of precision, ensuring the robot's movements maintain a security margin when aiding victims.

Both interfaces demonstrated high efficiency when it came to executing straightforward tasks. Nevertheless, as tasks increased in complexity, the Mixed Reality method exhibited a significantly higher efficiency, surpassing conventional interfaces by 21%. The video `https://youtu.be/ZvhywpQzm0E` shows a detailed demonstration of the results of the presented method.

### 7.1.4 Comparisson Against Works in the State-of-the-art

This Section provides a comparative analysis of the most significant works in the context of the proposed method. Table 7.4 enumerates the relevant works associated with the MR-guidance method introduced. Seven key aspects of the proposed method are considered in this comparative assessment. Each entry in the state-of-the-art table is annotated with an 'X' if it satisfies the specified criterion.

Following the specified analysis criteria, Table 7.4 demonstrates that a significant part of research in robot control using mixed reality technology lacks several essential components crucial for successfully executing applications in exploration missions.

The absence of both RGB and thermal image transmission represents a noticeable gap in these works, especially given the invaluable nature of this information for operators engaged in inspection missions.

Furthermore, the need for incorporating a multi-waypoint system is noteworthy. Such a system is essential for expanding mission objectives across diverse target areas, enhancing the versatility and adaptability of the robotic system.

Table 7.4: Comparison of the works related to the proposed method.

| Work | 1. Transmission of RGB Image | 2. Thermal Image Transmision | 3. Hololens Glasses | 4. Multitarget | 5. Robot: Quadruped, Wheeled, Manipulator. | 6. Conventional interfaces comparison | 7. Virtual objects interaction with the environment. |
|---|---|---|---|---|---|---|---|
| [176] | | | X | | W | | |
| [103] | | | X | X | W | | |
| [171] | | | X | | W | | |
| [232] | | | X | | M | | X |
| [305] | | | X | | W | | X |
| [225] | | | X | | W | | X |
| [177] | | | X | | M | | X |
| [143] | | | X | | W | | X |
| [197] | | | X | | W | | |
| [306] | | | X | | W | | |
| [161] | X | | X | | W | | |
| [224] | | | X | | W | | X |
| [167] | | | X | X | M | | X |
| **Proposed method** | X | X | X | X | Q | X | X |

Lastly, it is worth highlighting that related state-of-the-art works often fail to conduct comparative assessments against conventional interfaces, like mouse, screen, and keyboard. This omission is particularly pertinent as it serves as a fundamental criterion for validating the efficacy of immersive technology in these specialized contexts.

### 7.1.5 Conclusion

The application of mixed reality systems in field robotics missions has proven markedly efficient, serving as a compelling alternative to conventional interfaces. These systems offer an immersive experience to first-responders, facilitating mission monitoring and the control of complex robotic systems from closer zones.

The proposed method demonstrates an average efficiency improvement of 21% over conventional interfaces when applied to complex high-level control tasks. Additionally, it optimizes time management and mission stage allocation by 26%.

The integration of RGB and Thermal imaging, coupled with Convolutional Neural Networks (CNN), exhibits impressive efficiency in victim detection. This capability proves invaluable to first-responders, particularly in scenarios involving obscured victims or challenging lighting conditions.

Furthermore, MR-RAS's high-level guidance strategies show remarkable versatility, including interactive handle points for defining areas of interest during inspection or victim assistance by the quadruped robot. This versatility is evident in tests conducted on various terrains.

## 7.2 Legged-Manipulator robots

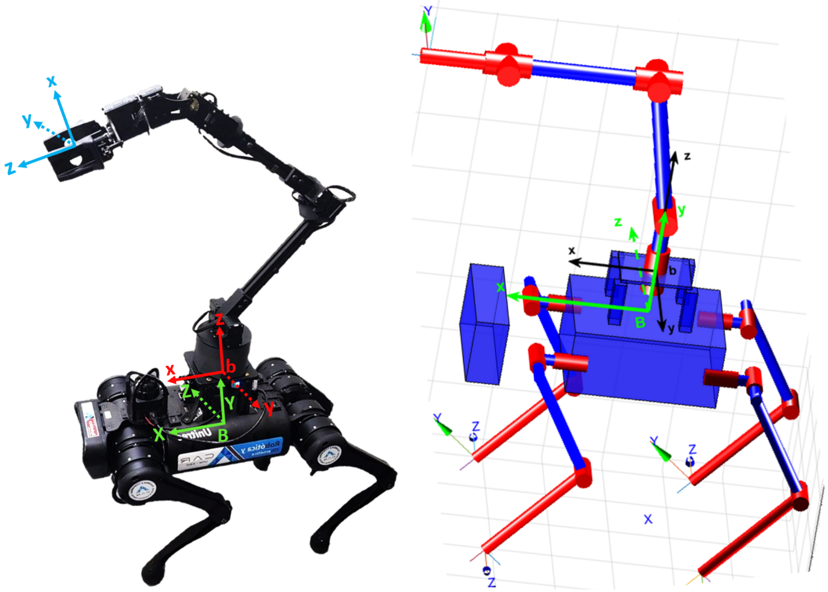
Following the establishment of an initial approach and strategic framework for facilitating the assisted movement of quadruped robots within disaster-stricken areas, with a primary focus on aiding victims and collecting important data as outlined in Section 7.1, our overarching objective is to enhance the research scope. This enhancement involves integrating a manipulation system to perform supplementary tasks directly on-site.

The expanded scope encompasses the robot's ability to assist and incorporates the capacity for on-the-spot execution of a set of tasks. Integrating this manipulation system enhances the robotic platform's overall versatility and utility. This section provides a comprehensive overview of the legged-manipulator robot's development. It begins with the initial phases of design and workspace calculation, where meticulous planning and engineering considerations are considered to ensure the robot's optimal functionality and range of motion.

Following this design phase, the robot's capabilities are rigorously tested and validated in a simulated ROS-Gazebo environment. This simulation phase serves as a step in refining the robot's performance and identifying potential issues or limitations before transitioning to real-world implementation. The culmination of this process involves implementing the robot into a cutting-edge hardware-software (HW-SW) system.

### 7.2.1 Kinematic Modelling

The legged mobile manipulator's model can be defined as a floating base denoted as B, to which limbs are affixed [175]. The fixed reference systems for the quadruped and the manipulator robots are shown in green and red in Figure 7.9-a.



(a) Assembling the legged-manipulator robot along with the reference systems. (b) Reference system **B** in green for the quadruped and **b** in black for the arm.

Figure 7.9: Assembled legged-manipulator Robot and Its Corresponding Kinematic Representation Using Matlab.

In the case of the quadruped, this system is located on the back (**B**), while for the robotic arm, the local system is fixed at the base, with the x-axis aligned with its counterpart on the quadruped, showing it is in the direction of the assembly's forward motion.

### Direct Kinematic Model (DKM)

The main objective of the direct kinematics study is to understand the workspace of the robotic assembly. In Section 4.1.1, the kinematic model of the quadruped robot has previously been studied independently. This section aims to integrate the robotic manipulator into its torso to define the optimal working areas.

The **Denavit-Hartenberg** (D-H) method is employed, utilizing a matrix transformation for each joint in the robot arm. Each matrix corresponds to a reference system that may not necessarily coincide in space with the joint itself. This method involves deriving D - H parameters, which indicate the base changes followed from the robot's fixed reference system to its considered end-effector. Furthermore, these parameters prove particularly valuable for toolboxes used in the Matlab environment, as explained in the upcoming Section 7.2.2.

The values of the link lengths of the manipulator are recorded in Table 7.5. The D - H parameters obtained for the arm are displayed in Table 7.6. Values calculated from equations 7.4 are useful for working with an idealized system that does not have an elbow-like geometry between joints 2 and 3 (refer to Figure 7.10).

Table 7.5: Values of the lengths of the bars of the wx250s in millimetres.

| L1 | L21 | L22 | L3 | L4 | L5 | L6 |
|---|---|---|---|---|---|---|
| 104.43 | 250 | 50 | 171.8 | 78.2 | 65 | 66 |

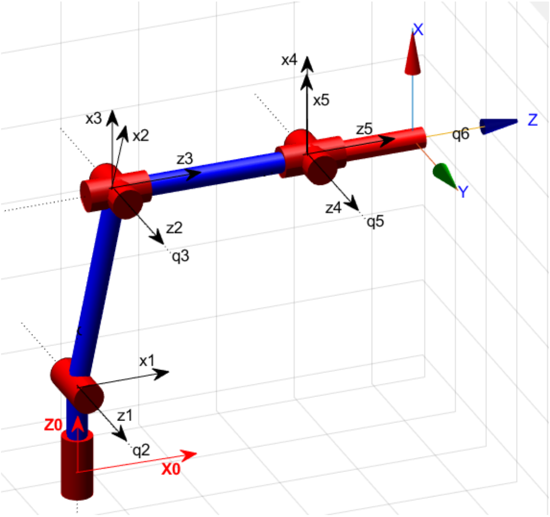


Figure 7.10: D-H Systems for the Manipulator. Fixed System in Red.

$$\begin{aligned} arc &= atan(L22/L21) \\ d &= sqrt(L21^2 + L22^2) \end{aligned} \tag{7.4}$$

Table 7.6: Denavit-Hartenberg parameters of the 6DOF manipulator.

| Theta($deg$) | d($mm$) | a($mm$) | Alpha($rad$) |
|---|---|---|---|
| q1 | L1 | 0 | $\pi/2$ |
| $\pi/2 - arc + q2$ | 0 | d | 0 |
| $arc + q3$ | 0 | 0 | $\pi/2$ |
| q4 | L3 + L4 | 0 | $-\pi/2$ |
| q5 | 0 | 200 | $\pi/2$ |
| q6 | L5 + L6 | 0 | 0 |

Based on the D-H parameter in Table7.6, 4x4 displacement matrices **A** are constructed, which are, in turn, homogeneous transformation matrices. As can be observed, the table contains variables $q_i$ corresponding to the angle associated with each degree of freedom $i$. The process begins with ${}^0\mathrm{A}_1$, representing the transformation from the fixed system 0 to system 1, and proceeds one by one for each reference system, corresponding to each row in the table: ${}^1\mathrm{A}_2$, ${}^2\mathrm{A}_3$, and so forth. Finally, when all the matrices ${}^i\mathrm{A}_j$ are obtained, they are multiplied to get **T** (equation 7.5), which represents the positioning of the robot's end effector relative to the fixed base 0.

$$T =^0 \mathrm{A}_1 \cdot^1 \mathrm{A}_2 \cdot^2 \mathrm{A}_3 \cdot^3 \mathrm{A}_4 \cdot^4 \mathrm{A}_5 \cdot^5 \mathrm{A}_6 \tag{7.5}$$

From Equation 7.5, the obtained matrix expression, its last column corresponds to the position vector *(x,y,z)* in the associated reference frame. In the case of T, this corresponds to the robot's end effector. This is how the equations 7.6 that provide the coordinates based on the values of the degrees of freedom angles are derived.

$$\begin{aligned}
x =& 50cos(q1)cos(q2) - 250cos(q1)sin(q2) + 131cos(q1)cos(q2)cos(q3)cos(q5) + \\
& 250cos(q1)cos(q2)cos(q3) - 250cos(q1)sin(q2)sin(q3) + 131sin(q1)sin(q4)sin(q5) \\
& - 131cos(q1)cos(q5)sin(q2)sin(q3) - 131cos(q1)cos(q2)cos(q4)sin(q3)sin(q5) - \\
& 131cos(q1)cos(q3)cos(q4)sin(q2)sin(q5) \\
y =& 50cos(q2)sin(q1) - 250sin(q1)sin(q2) - 250sin(q1)sin(q2)sin(q3) + \\
& 250cos(q2)cos(q3)sin(q1) - 131cos(q1)sin(q4)sin(q5) + \\
& 131cos(q2)cos(q3)cos(q5)sin(q1) - 131cos(q5)sin(q1)sin(q2)sin(q3) - \\
& 131cos(q2)cos(q4)sin(q1)sin(q3)sin(q5) - 131cos(q3)cos(q4)sin(q1)sin(q2)sin(q5) \\
z =& 250cos(q2) + 50sin(q2) + 250cos(q2)sin(q3) + 250cos(q3)sin(q2) + \\
& 131cos(q2)cos(q5)sin(q3) + 131cos(q3)cos(q5)sin(q2) \\
& + 131cos(q2)cos(q3)cos(q4)sin(q5) - 131cos(q4)sin(q2)sin(q3)sin(q5) + 104.43
\end{aligned} \tag{7.6}$$

Once the equations relating the manipulator's end effector (Equation 7.6) and the legs (Section 4.1.1) concerning the robot's body have been obtained, it becomes feasible to construct the workspace associated with the kinematic chain encompassing the entire robotic system, this entails systematically varying the distinct degrees of freedom while considering the diverse linkages in both the quadruped and the manipulator. The following Section 7.2.2 provides a detailed description of this process.

### Inverse Kinematic Model (IKM)

The inverse kinematic model has been independently developed for both the arm and the quadruped (as detailed in Section 4.1.1) due to their straightforward integrability using a transformation matrix for the arm's base system. It is important to emphasize that the arm and the quadruped are operated as distinct entities for teleoperation purposes in the next section.

Multiple methodologies have been employed to obtain the Inverse Kinematic Model (IKM). **Kinematic decoupling** has been utilized for the robotic arm, analyzing it as two independent problems. This approach takes advantage of the fact that the robotic arm model conforms to the characteristics of kinematic chains where a point (referred to as the **wrist** of the chain) remains invariant when modifying the last degrees of freedom. Consequently, the preceding joints position this wrist point, while the subsequent joints do not affect its position.

From a geometric perspective, This wrist point is located at the intersection of the rotational axes associated with the final degrees of freedom (*q4, q5, q6,* as seen in Figure 7.11). This property allows for the independent analysis of the degrees of freedom before and after the wrist point, with the understanding that the end-effector and the wrist are separated by a known distance in the direction of the gripper's approach, as illustrated in Figure 7.11.

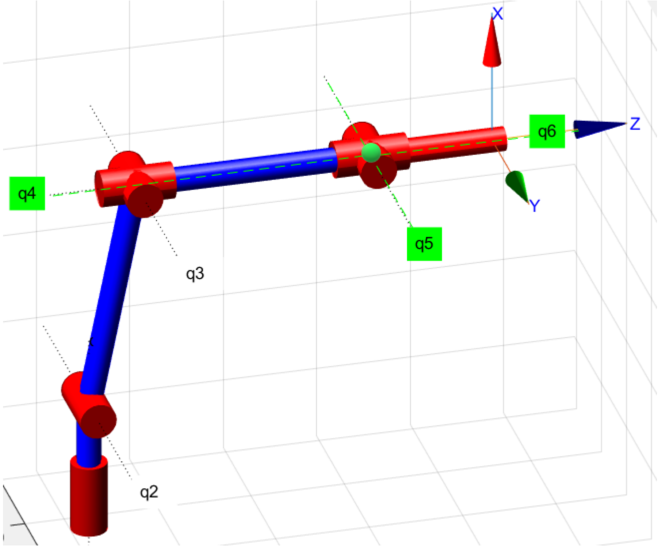


Figure 7.11: Location of the independent decoupling point of q4, q5 and q6.

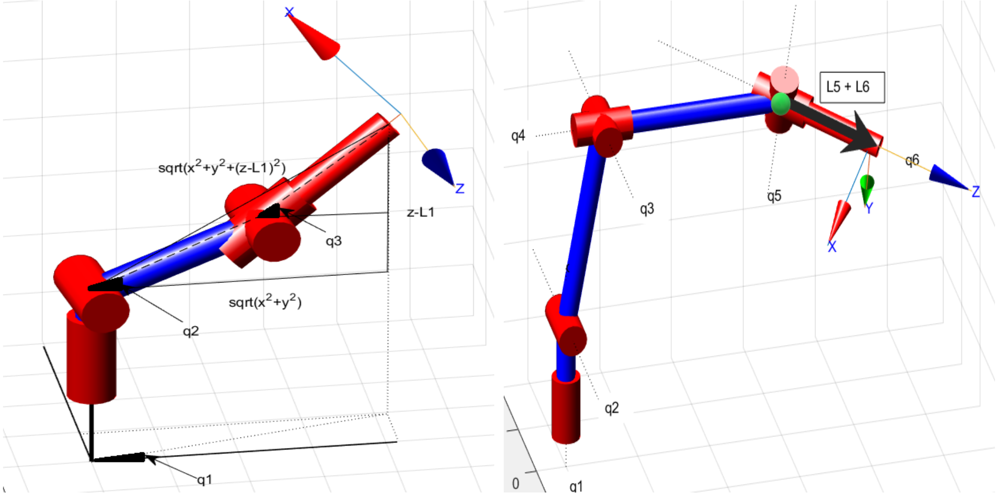
The 6-DoF manipulator's arm is divided into its first three DoFs, which position the wrist, and the last three DoFs, which orient the gripper. The methodology employed for joints 1, 2, and 3 involves a geometric analysis. Using the obtained values, joints 4, 5, and 6 are analyzed through the expressions derived from multiplying the rotation matrices associated with the rotations from the wrist to the robot's end effector, following equation 7.7.

$$^3\mathrm{R}_6 =^3 \mathrm{R}_4 \cdot^4 \mathrm{R}_5 \cdot^5 \mathrm{R}_6 \tag{7.7}$$

This approach is helpful because a displacement matrix $^5\mathrm{A}_6$, and therefore the rotation submatrix, will never depend on joint values higher than j, allowing for expressions to be easily derived as needed.

Regarding the quadruped, the legs are treated as kinematic chains with 3 DoF each (as analyzed in Section 4.1.1). The methodology applied to the first three joints of the manipulator can be fully adapted to the limbs. The position of the body of **ARTU-R** is entirely determined by the values obtained from the inverse model of each leg.

Following the kinematic decoupling method, Figure 7.12-a illustrates the placement of the wrist point at the end of the extremity. Additionally, it provides a visualization of the variables involved in deriving the inverse kinematic equations (following the geometric method) for the first three degrees of freedom, *q1, q2, and q3* (as shown in equation 7.8).



(a) Placement of the wrist point of q4, q5 and q6.

(b) Subtraction from end-effector to wrist. Negative in z6.

Figure 7.12: Matlab Representation of the Arm for Inverse Kinematics Definition.

$$\begin{aligned} q1 &= atan(\frac{y}{x}) \\ q2 &= atan(\frac{z-L1}{sqrt(x^2+y^2)}) + atan(\frac{sin(q3)L34}{L2+cos(q3)L34}) \\ q3 &= acos(\frac{x^2+y^2+(z-L1)^2-L2^2-L34^2}{2\cdot L2\cdot L34}) \end{aligned} \tag{7.8}$$

Afterwards, the coordinates of the decoupling point are determined by knowing the coordinates of the end effector, the dimensions of the connecting links, and the orientation of the gripper. Simply subtracting the lengths of the links in the direction of the z-axis (the direction of attack or operation) of the gripper is sufficient. This is illustrated in Figure 7.12-b.

Based on the premise that the three final degrees of freedom are intended for gripper orientation, the expression relating these parameters q4, q5, q6 (equation 7.9) is obtained from equation 7.10.

$$ {}^{3}\mathrm{R}_4^T \cdot {}^{3}\mathrm{R}_6 = {}^{4}\mathrm{R}_5 \cdot {}^{5}\mathrm{R}_6 \tag{7.9} $$

$$ {}^{0}\mathrm{R}_3 \cdot {}^{3}\mathrm{R}_6 = T(1:3,1:3) \tag{7.10} $$

In the final step, *q4, q5,* and *q6* were obtained using equation 7.11. On the right side of the equation, the element (3,3) was a constant, while on the left side of the equation, $R_34trans(3,1:3)\cdot R_36(1:3,3)$ depended only on *q4*. The equation was solved, and the value of q4 was recorded. Using the previously acquired values, the same methodology was applied to determine *q5* and *q6*.

$$ {}^{3}\mathrm{R}_4^T \cdot {}^{3}\mathrm{R}_6 = {}^{4}\mathrm{R}_5 \cdot {}^{5}\mathrm{R}_6 \tag{7.11} $$

As elucidated in this subsection, the direct and inverse kinematics are accessible within the GitHub repository maintained by ROBCOB. In this repository, you will discover comprehensive resources related to these kinematic concepts. One noteworthy resource is the interactive application designed for the legged-manipulator ensemble. This application has been crafted using the Matlab programming environment and is a valuable tool for visualizing the system's workspace (that will be described in the following subsection). It enables users to gain an intuitive understanding of how the robotic system's end effector moves within its operational envelope:

Legged-manipulator robot repository:

`https://github.com/Robcib-GIT/legged-manipulator/tree/main`

### 7.2.2 Definition of Articular Workspace

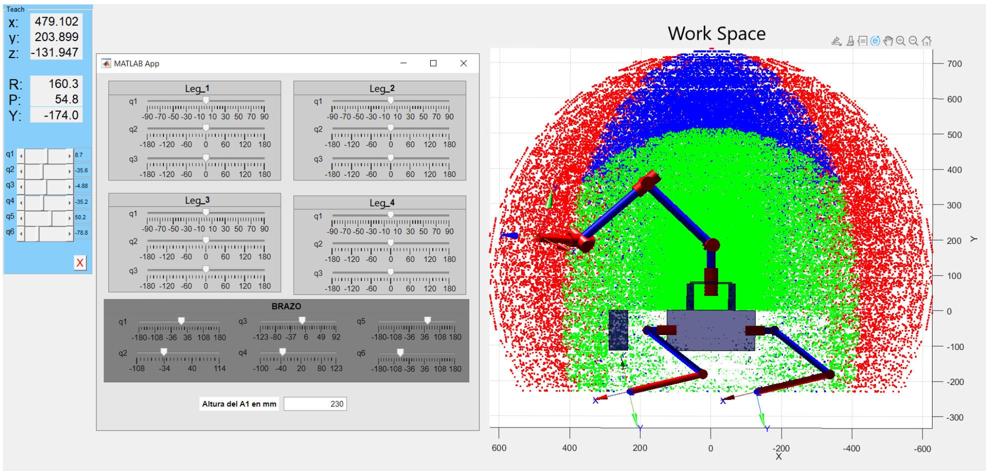
Based on the direct model, generating the **workspace** associated with the kinematic chain is possible, achieving its visualization as a pointcloud (as shown in Figure 7.13). Each point in space corresponds to one of the kinematically possible combinations when varying the different joints. This is achieved through knowledge of the limit values of each degree of freedom of the kinematic chain and creating an iterative and nested routine using Matlab.

The interface developed for visualization is shown in Figure 7.13-a. It comprises a graphical representation that integrates the assembly and associated workspace parameters, including ground clearance and manipulation area. It also incorporates an interactive panel for independently adjusting the values of the 18 degrees of freedom (18gdl).

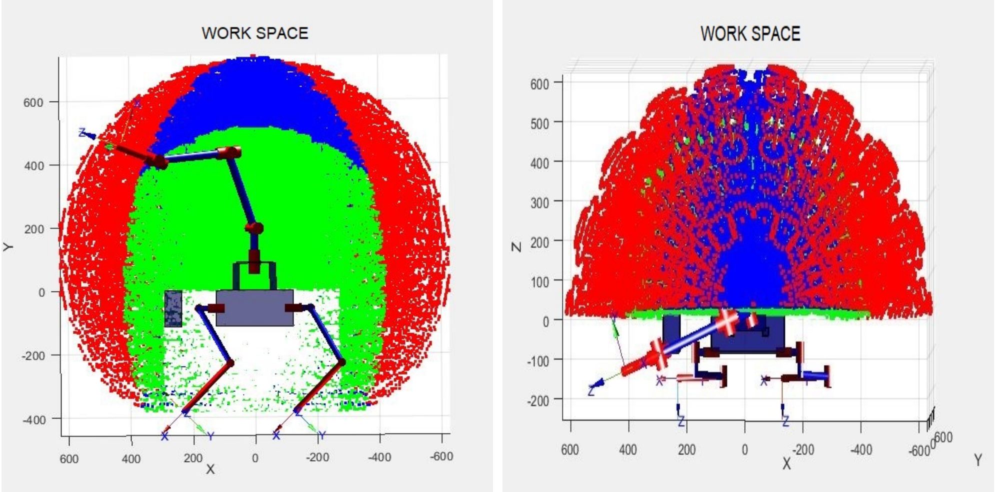
As depicted in Figure 7.13-a, the primary functionality involves inputting the desired operating height for the robot. Subsequently, the system generates the corresponding workspace based on this input.

The workspace of the wx250s is computed as manipulation operations are carried out with the static quadruped. Therefore, a kinematic chain with 6 degrees of freedom is used. The iteration step is set to a value of n = 0.35 rad, adequate to create a dense pointcloud without exceeding the computational cost. With these data, it is possible to calculate the kinematically accessible points, resulting in a sphere truncated at its lower pole due to self-collisions and the limits of joint rotations in the robot's servomotors.

Subsequently, two additional constraints had been applied. First, the manufacturer recommended that the wx250s operate within 70% of its kinematically feasible range to avoid singular points and undesirable torques. Second, for stability and operational reasons in the future legged-manipulator system, the arm was required to operate predominantly on the sides of the quadruped. For this purpose, an ellipsoid was defined with its longitudinal semi-axis shorter than the others. The vertical semi-axis allowed for a maximum reach of $740mm$, the transverse semi-axis reached the kinematic maximum of $636mm$, while the reduced semi-axis was set at $2/3 * 636mm$.


Teach
X: 479.102
Y: 203.899
Z: -131.947
R: 160.3
P: 54.8
Y: -174.0
q1 8.7
q2 -35.6
q3 -4.88
q4 -35.2
q5 50.2
q6 -78.8
Altura del A1 en mm 230

(a) A Matlab Interface Developed for Workspace Optimization: Depicting the Quadruped-Manipulator Robot in a Lowered Height Configuration.



(b) Side View of the Model's Workspace: The Reference System is Positioned at the Torso's Center.

(c) Top View of the Model's Workspace.

Figure 7.13: Matlab-Based Kinematic Model and Robotic Workspace Analysis.

Everything discussed is illustrated in Figures 7.13-b-c, two sections of the workspace (lateral and top view are shown) of the isolated robotic arm, where different colours represent:

- **Red**: Kinematically accessible points.

- **Blue**: Valid points while imposing the constraint that it mainly operates on the sides of the future assembly.
- **Green**: Valid points while adhering to the manufacturer's 70% of the red sphere constraint. These points satisfy the previous constraint and are the ideal operation points.

The kinematically reachable space had been stored in a variable $PointCloud_{XYZ}$, which had been analysed as a preliminary phase before executing a routine to verify when destination points had been sent.

### 7.2.3 ROS Simulation and Planning

Before the implementation phase, a comprehensive simulation phase of the legged - manipulator ensemble was executed. This phase served the dual purpose of verifying the overall functionality of the ensemble and facilitating the seamless integration of planning packages. Furthermore, it played a crucial role in the generation of collision-free trajectories.

The simulation phase involved subjecting the legged - manipulator ensemble to various scenarios and operational conditions to evaluate its performance thoroughly. This process not only ensured that all components of the ensemble functioned harmoniously but also allowed for the refinement of planning algorithms.

Gazebo and RVIZ tools were employed as the visualization platforms for this simulation stage. The ensemble was realized using the **xacro** language, seamlessly integrating the quadruped robot (available in `https://github.com/unitreerobotics/unitree_ros`), the robotic arm (available in `https://github.com/Interbotix/interbotix_ros_arms`), end-effector tool, perception system (RGB-D camera) and the rigid coupling between them. The TF - tree diagram in Figure 7.14 depicts a comprehensive structural description of all components integrated concerning the trunk(base).

With the assembled legged-manipulator set, the integration of the **MoveIt Motion Planning Framework** has been carried out to generate collision-free trajectories for the robotic arm, utilizing specified target points and RRT-based algorithms. Figure 7.15-a-b-c serves as an exemplification of the package's functionality. In the initial scene, the robot stands in a home position with the arm. The objective is to achieve the pose depicted in orange in the second scene, while the third scene exhibits the arm in its final position. During the planning phase, the quadruped body is considered a collision element, highlighted in red, to compute the trajectory.

Figure 7.15 corresponds to integrating the environment (as octomaps) through the RGB-D perception system. This allows these elements to be considered part of the collision-free trajectory generation process. It is utilized in a subsequent manipulation stage, where Figure 7.15-f illustrates the withdrawal position of the object once it has been picked up from the environment (Figure 7.15-e).

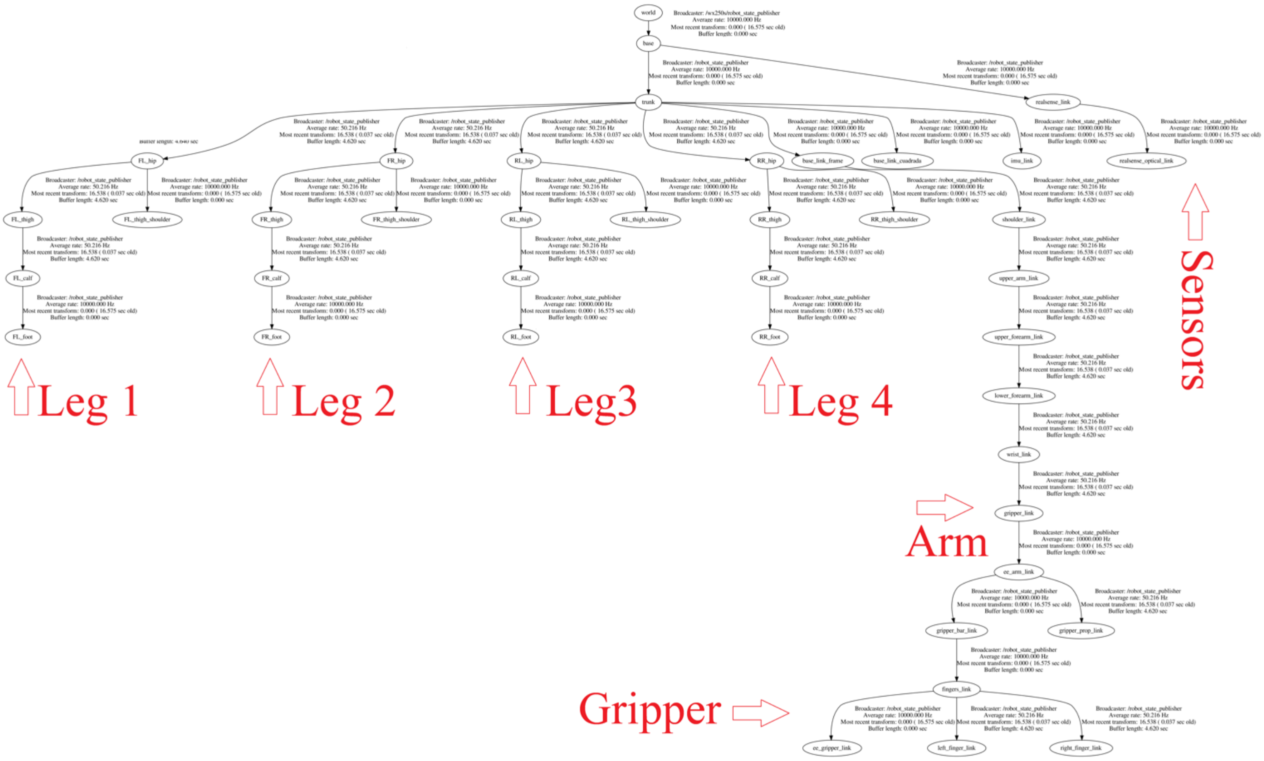
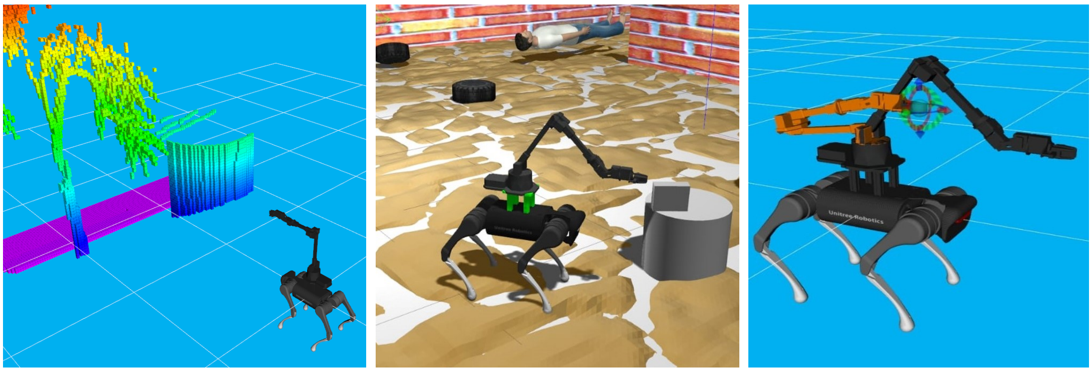


Figure 7.14: TF - tree connection for ARTU-R legged-manipulator robot.

(a) Legged-Manipulator Robot in Its Final Pose.

(b) Point-to-Point Destination Planning with MoveIt.

(c) Legged-Manipulator Robot in Its Initial Pose.



(d) Perception system integrated in simulation.

(e) Robot Approach for Object Pickup in a Simulated Environment.

(f) Motion Planning for Object Pickup.

Figure 7.15: Simulation and Motion Planning for Integrated Manipulator.

## 7.3 Teleoperation of Legged-Manipulator Robots Using MR-VR

After establishing the legged-manipulator robot type and conceiving an initial strategy for planning collision-free movements, certain deficiencies have become apparent in selecting destination points using the conventional interface (RVIZ). These deficiencies primarily stem from the conventional interface needing a more versatile perception of the surrounding environment. Consequently, significant complications emerge when determining destination points for manipulation tasks within a real-world setting.

In response to this challenge, and as discussed in Section 7.1, this section addresses immersive technologies **(MR-VR)** as a high-level control method for teleoperating legged-manipulator platforms. This exploration begins with the development of interfaces, the management of hardware-software communication, and a series of experiments to assess their significance in robot teleoperation, explicitly focusing on search and rescue operations.

### 7.3.1 Setup for Virtual and Mixed Reality

#### Interfaces for Virtual and Mixed Reality

The versatility of both immersive technologies has been evaluated using specific equipment (described in Table 7.7). The hardware system includes the HTC-Vive (RV) glasses and the Hololens2 (MR) glasses as integral components of human-robot interaction. The test robot used in the evaluation is ARTU-R, equipped with a 6 DoF manipulator.

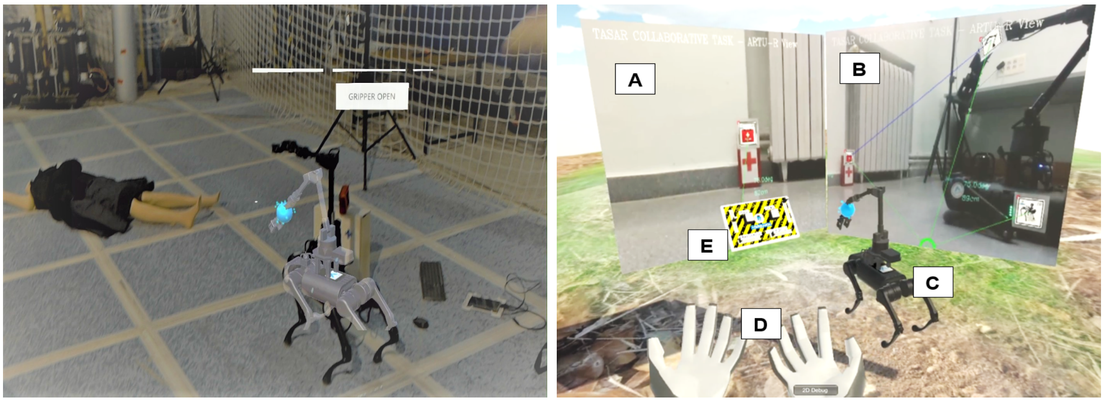
Table 7.7: Elements and robots used.

| Number | Component | Description |
|---|---|---|
| 1 | Hololens 2 | MR Classes |
| 2 | HTC-Vive | VR Glasses |
| 3 | Unitree A1 | Quadruped Robot |
| 4 | WX250S | 6DoF Robot Arm |
| 5 | Leap-Motion | Hands Detection Sensor |
| 6 | Wall-e | Tracked robot with an RGB-D sensor |
| 7 | Command station | Central Computer |

The development of interfaces (Figure 7.16) has been conducted by leveraging Unity3D software version 20.03, complemented by the integration of software packages such as HoloToolkit for Mixed Reality system support, SteamVR for Virtual Reality system compatibility, and the incorporation of RosBridge libraries to facilitate seamless communication with robotic systems.

The design process for both interfaces started by incorporating the simulated ARTU-R robot as a standard component. This deliberate choice ensures a unified user experience, allowing operators to become familiar with the virtual elements consistently. As a result, making meaningful comparisons under conditions that closely approximate one another in terms of interface-related factors becomes possible.

In this approach, the virtual robot governs the target positions of the physical robot by controlling its end effector. An interactive manipulation element (blue ball) has been



(a) First-Person Perspective in a Mixed Reality System: Assigning Destination Coordinates to the Robot Manipulator from the Virtual Model.

(b) Implementing Robotic Arm Manipulation in a Virtual Reality System with a First-Person Perspective.

Figure 7.16: Components and Interfaces Employed in the Teleoperation of the Robotic System.

integrated into the system to facilitate this control. The operator can manipulate and reposition this blue ball within the defined spatial constraints, which leads to the robotic arm's movement. These spatial manipulations are subject to the limitations imposed by the robot's kinematics and operational workspace.

In Figure 7.16-a, a first-person view was captured from the Hololens2 glasses within an indoor environment. In this representation, the physical robot, depicted in black, and its virtual recreation, superimposed in grey, are shown. Furthermore, virtual buttons for executing actions (such as open/close gripper or arm poses) and environment elements.

The second interface created for this study is illustrated in Figure 7.16-b, which displays the operator's perspective through the HTC-Vive glasses. This interface has been meticulously designed to furnish the operator with a comprehensive array of tools for teleoperation, including front screens for receiving visual feedback from the robotic systems. The VR interface comprises several key elements:

A. ARTU-R First-Person View Screen: This screen gives the operator a first-person perspective of the ARTU-R robot's surroundings.

B. External View of Wall-e Robot Screen: Here, operators can access an external view of the Wall-e robot, enhancing situational awareness from another perspective.

C. Virtual Model of ARTU-R: Within this component, a virtual representation of the ARTU-R robot is depicted, complete with a manipulator featuring the aforementioned blue ball at the end-effector. The operator can manipulate this ball to convey target positions to the real robot.

D. Virtual Hands: These virtual hands mirror the movements and actions of the operator's real hands, which are captured by the Leap Motion sensor affixed to the HTC-Vive glasses.

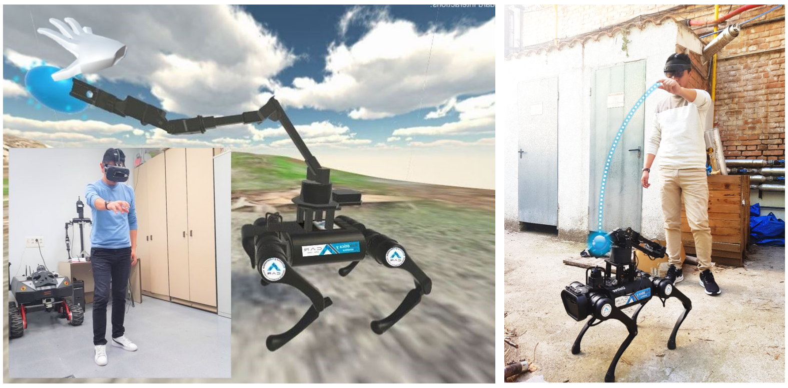
E. Virtual Control Panel: This panel is a user interface for executing various actions, such as controlling the gripper's opening and closing, setting predefined positions like "Home," and more.

#### Human-Robot Interaction Elements

The primary interaction systems involved in the teleoperation process are closely related to the operator's **visual sense** and **motion actions**, particularly the upper extremities. The transducer connecting the real and virtual worlds relies on the hand motion capture element, which replicates its virtual model, thereby enabling the manipulation of virtual elements through actions in the physical world.

Figure 7.17 depicts the operator in different scenarios. In the first case, as shown in Figure 7.17-a, a first-person perspective of the virtual model of the legged-manipulator robot within the environment is presented, with the operator's hand visible in the lower left corner, extended to execute manipulation tasks. Hand gesture is captured by the leap-motion sensor attached to the glasses.

Figure 7.17-b provides insight into the interaction between the operator's hand and the robotic arm's end-effector. Through the overlay of the virtual model onto the real environment, as illustrated in Figure 7.16-b, the operator's hand can control the position of the robot's end-effector. In this case, the hand gesture is captured by the Hololens depth camera.



(a) ARTU-R Robot and Operator with HTC-vive Glasses in indoors.

(b) ARTU-R Robot and Operator with Hololens 2 Glasses in Outdoors.

Figure 7.17: Operator Employing VR-MR Glasses and the ARTU-R legged-manipulator Robot.

### 7.3.2 Connection Layout

Figure 7.18 provides an illustrative connection diagram showcasing the interrelationships among different subsystems. This diagram serves to represent the distinct functional groups involved in teleoperation at a macro level, organized into three primary categories:

The **first group** encompasses both types of glasses, HTC-Vive and Hololens, which facilitate human-robot interaction. An interconnected switch symbolizes the data exchange between these devices for the teleoperation.

The **second group** is attributed to the command station, serving as the nexus that bridges the VR-MR environments developed on Windows with the control signals directed towards the robot. This pivotal role is fulfilled by a computer equipped with an MSI-Intel i7-10th operating on Windows 10 to support Unity 20.03.

The **third group** is dedicated to the robotic assembly, receiving position and speed commands essential for executing movements. This segment is controlled by an Nvidia Jetson Xavier-Nx card, running Ubuntu 18 alongside ROS Melodic.

Communication between the second and third groups is facilitated through RosBridge, which enables the seamless bidirectional flow of information between the Windows-based Unity environment and the Ubuntu-based ROS system.

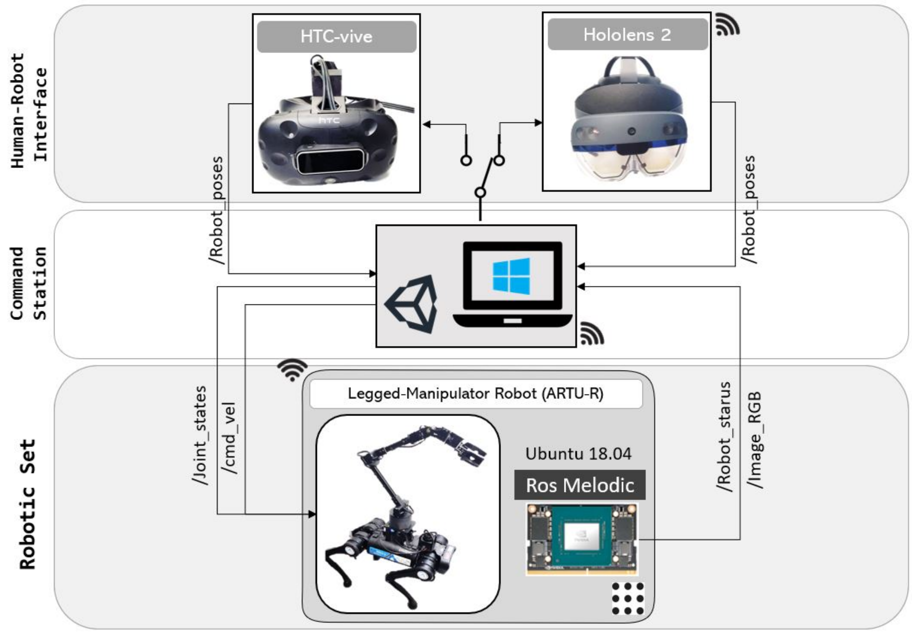


Figure 7.18: Connection Layout for legged-manipulator robot teleoperation.

### Action Control Loop

At the device control level, Figure 7.19 shows the block diagram utilized for controlling the robotic assembly. This diagram categorizes distinct systems with color-coded blocks. Referential inputs, extracted from the virtual model, are sourced from the Hololens after the operator moves to the virtual model. Different goal states are dispatched to collision-free planners tasked with generating both the trajectory for displacement and the manipulative arm movements.

For the quadruped robot, the variables denoting position and orientation encompass $x$, $y$, and $\theta$ for both goal and current positions. The trajectory global planner derives a discretized path $(x_{i...n}, y_{i...n})$ with $n$ goal points. Simultaneously, the control decision system computes the angular $(e_{ang})$ and distance $(e_{dist})$ errors between the current and goal positions. Subsequently, angular $(\omega)$ and linear $(v)$ velocities are transmitted to the robot until the trajectory is completed.

Conversely, the control of the robotic arm follows a similar pattern. The Collision-Free Planner receives current and target joint positions $(\theta_1,...,\theta_6)$, along with the present state of the quadruped robot. The planner calculates errors for each joint $(e_{\theta 1},...,e\theta 1)$, which serve as inputs for the controller. Finally, velocities $(\omega 1,...,\omega_6)$ are dispatched to the robot.

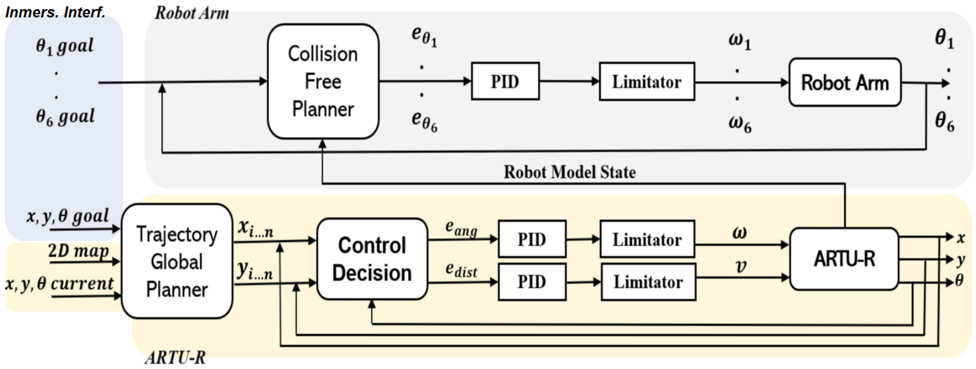


Figure 7.19: Structured Representation of the loop control for Robot Manipulator Teleoperation via Mixed-Reality.

### 7.3.3 Evaluation Test and Events Evolution

The experiment procedures centred on a pick-and-place task for a first aid team, involving the movement of the ARTU-R robot from point A to point B. This task was executed using the RM-RV interfaces as the teleoperation tool for the robot. The testing process comprised these pertinent stages:

1. Movement of the ARTU-R robot towards point A.
2. Manipulation of the robotic arm to grasp an object via the interface elements.
3. Displacement of the ARTU-R robot to a location near point B.
4. Placement of the object at point B.

Ten operators actively participated in the testing phase to ensure robust and reliable results. Each operator repeated the task fifteen times using each interface, providing data with high confidence. After conducting the tests, participants were asked to complete a survey in which they assigned ratings, on a scale from 0 to 10, to various variables (as described in the following section).

The group of participants had an average age of twenty-eight years. It consisted of male and female individuals who possessed knowledge and experience with both immersive interfaces and medium-sized robotic systems.

Figure 7.20 presents the dynamic progression of states and events throughout the performance of the task traced for the experiments.

The graphical evolution, depicted in both red and black, initiates when ARTU-R is initially positioned near the target object in Zone A and continues until the object has been successfully placed in Zone B.

Within Figure7.20, two distinct plots are straightforward. The red plot, scaled against the left vertical axis, illustrates the arm's proximity to the first aid object. In contrast, the black plot, scaled against the right vertical axis, tracks the robot's cumulative travel distance.

Significant events about interface interactions are denoted in blue, including pivotal instances such as the initiation of arm movement and the manipulation of the gripper's opening and closing actions. The time scale in this Figure7.20 corresponds to the average duration required for these events across both interfaces.

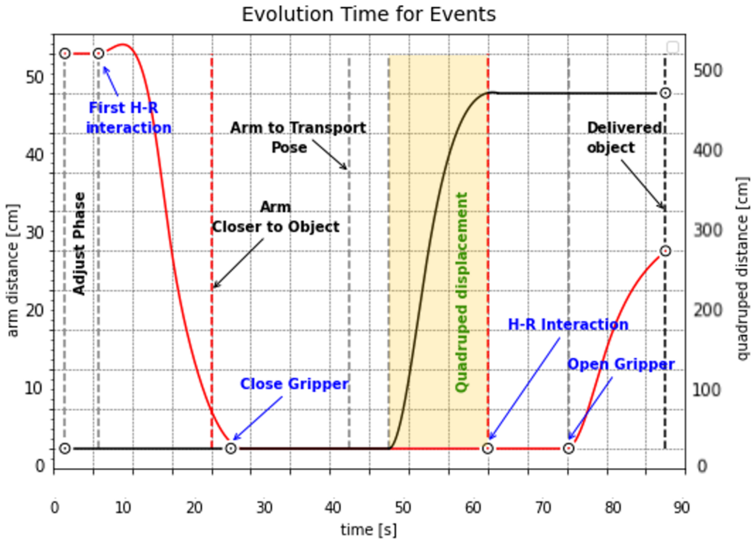


Figure 7.20: Chronological progression of stages involved in performing the task of managing and transporting an object.

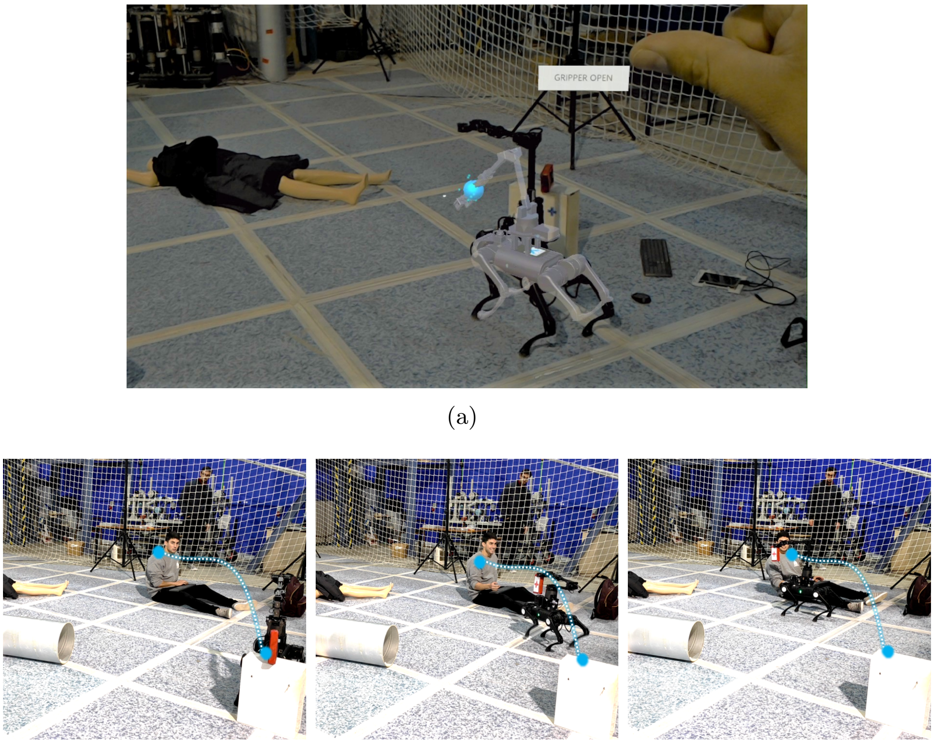
### 7.3.4 Mixed and Virtual Reality Test Execution

The complete experiments conducted can be examined in detail by referring to the following links:

- MR: `https://www.youtube.com/watch?v=_uN22XUTWjo&t`
- VR: `https://www.youtube.com/watch?v=IkBJ9LsFV0w`.

Figure 7.21 illustrates the sequence of events starting from manipulating the first aid kit, its transportation, and delivery to the victims, utilizing the MR interface. This interface can be observed from a first-person perspective in Figure 7.21-a, where the superimposition of the virtual robot over the real one is visible. Additionally, the operator's gesture for relocating the blue sphere that controls the end effector on the real robot can be observed [60].

In the second case (Figure 7.22), the collection stage of the first aid kit from an elevated area (approximately 700 mm) in an outdoor scenario is depicted. In contrast to the Mixed Reality (MR)-based interface, where the operator can directly perceive the entire environment and the robot in a first-person view, here, several occlusions exist. Initially, the front image captured by the robot becomes unusable for manipulation tasks due to these occlusions. Therefore, external perception from a second robot (Wall-e) becomes necessary. In this way, Figure 7.22-a displays the VR environment, the virtual robot in its current position, the operator's hand, and a screen in the background with the perspective provided by Wall-e. ArUcos have been placed both on Artur's body and manipulator arm to provide visual signals, particularly for distance estimation during manipulation tasks.



(a)

(b) (c) (d)

Figure 7.21: Manipulation tests for transporting objects (First kit aid), through MR (**a**) First view person. (**b**) Close the griper and capture the object. (**c**) Object transportation to the destination point. (**d**) Gripper opening to deposit the object.

(a)

(b) (c) (d)

Figure 7.22: Manipulation tests for transporting objects (First kit aid), through VR (**a**) First pose for payload manipulation. (**b**) Robot set grabbing payload. (**c**) Transport pose of the payload.

## 7.4 Comparative Analysis MR vs VR

### 7.4.1 Metrics for evaluation

Two evaluation types have been conducted: one focusing on operator performance and the other on interface performance. In the case of operator performance, variables related to the user experience during mission execution were assessed using metrics derived from the NASA-TLX workload questionnaire, a tool commonly employed in the context of robotic missions [114]. Conversely, evaluating interface performance involves quantifying aspects of their usage in percentage terms. The specific variables measured are detailed in Table 7.8.

Table 7.8: The variables used for analyzing both operator and interface performance are as follows:

| Operator Performance Variables | | Interface Incidence Variables | |
|---|---|---|---|
| $\alpha$ | Training evolution | $\alpha\prime$ | Low latency |
| $\beta$ | User preference | $\beta\prime$ | Interaction with virtual objects |
| $\gamma$ | Safety feeling | $\gamma\prime$ | Autonomy |
| $\delta$ | Confidence for decision-making | $\delta\prime$ | Equipment weight |
| $\epsilon$ | Inmersive experience | $\epsilon\prime$ | Space requiered |
| $\theta$ | Physical effort | $\theta\prime$ | Covered field of vision |
| $\phi$ | Frustration experienced | $\phi\prime$ | Security for operator |

The presented variables have been incorporated into the equations 7.12-7.13 formulated by the authors to assess operator performance, quantify the outcomes, and facilitate comparative analysis. Concurrently, the equations 7.14-7.15 proposed by the authors will be used to evaluate the performance scores attributed to the VR and MR interfaces, respectively. These diverse variables are denoted by sub-indexes 1 and 2, respectively, denoting their association with VR and MR.

In equations 7.12 and 7.13, all coefficients are scaled within the range of 0 to 100, except for $\alpha$, which quantifies the number of training sessions required to attain a task execution success rate exceeding 95%. Consequently, $\alpha$ is scaled by a factor of 10. As for the frustration parameter, $\phi$ is quantified as the complementary value relative to 100.

$$Score_{op}(VR) = \beta_1 + \gamma_1 + \delta_1 + \epsilon_1 + \theta_1 + (100 - \phi_1) - \alpha_1 * 10 \tag{7.12}$$

$$Score_{op}(MR) = \beta_2 + \gamma_2 + \delta_2 + \epsilon_2 + \theta_2 + (100 - \phi_2) - \alpha_2 * 10 \tag{7.13}$$

$$Score_{int}(VR) = \alpha\prime_1 + \beta\prime_1 + \gamma\prime_1 + \delta\prime_1 + \epsilon\prime_1 + \theta\prime_1 + \phi\prime_1 \tag{7.14}$$

$$Score_{int}(MR) = \alpha\prime_2 + \beta\prime_2 + \gamma\prime_2 + \delta\prime_2 + \epsilon\prime_2 + \theta\prime_2 + \phi\prime_2 \tag{7.15}$$

#### Analysis Proposed for Application in SAR Missions

In the preceding section, a general comparison of VR-MR interfaces was conducted. Nevertheless, assigning greater significance to variables directly impacting the operator's performance is necessary in scenarios demanding specificity, such as search and rescue operations. As a result, variables such as $\delta$ (Confidence in Decision-Making), $\gamma$ (Safety Perception), and $\theta$ (Physical Exertion) experience an augmented weighting in percentage terms. Conversely, variables like $\alpha$ (Training Progression) do not substantially influence such cases. In this context, we propose the introduction of new equations, denoted as 7.16 and 7.17, tailored for assessing operator performance within teleoperation tasks in search and rescue environments involving robotic systems.

$$Score_{SAR}(VR) = \beta_1 + 2 * \gamma_1 + 2 * \delta_1 + \epsilon_1 + 1.5 * \theta_1 + (100 - \phi_1) \tag{7.16}$$

$$Score_{SAR}(MR) = \beta_2 + 2 * \gamma_2 + 2 * \delta_2 + \epsilon_2 + 1.5 * \theta_2 + (100 - \phi_2) \tag{7.17}$$

### 7.4.2 Operator Evaluation

Figure 7.23 illustrates the training curve depicting the percentage of completed tasks versus the number of attempts made by operators for both interface types. As anticipated, when operators lack prior training, task completion does not reach 100%. However, as operators' skills develop, this percentage notably increases. It is important to note that this growth is not uniform across both cases. In the case of the VR interface, operators can achieve a task success rate exceeding 95% within an average of seven attempts, based on experiments. In contrast, achieving a similar level of proficiency with the MR interface requires a longer training period, averaging approximately eleven attempts.

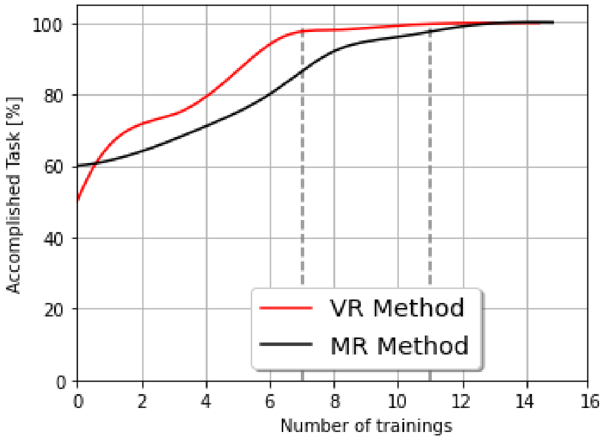
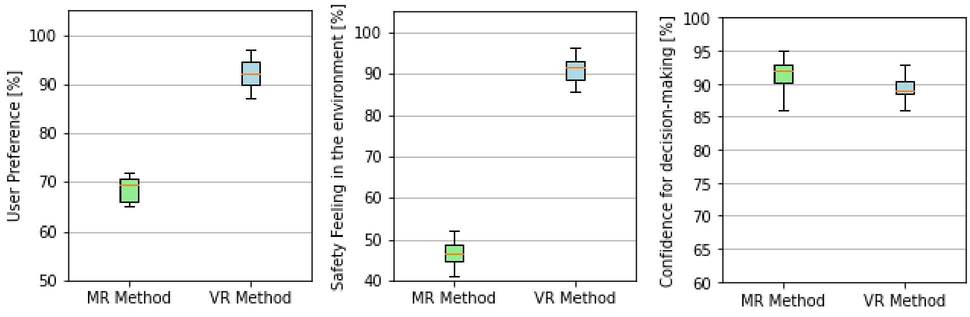


Figure 7.23: Analysis of the Progression of Task Completion Percentage concerning the Number of Operator Training Sessions.

Figure 7.24 displays boxplots illustrating an extensive analysis of variables used to assess operator performance during the legged-manipulator-type robot manipulation task. Notably, users exhibit a pronounced preference for the VR-based interface, marking a clear divergence from the MR alternative. This preference is primarily rooted in the immersive quality of the VR interface, which engenders a heightened sense of presence and engagement among operators.

Furthermore, the reduced frustration experienced by operators while utilizing the VR interface contributes to this preference. The immersive and intuitive design of the VR interface seems to mitigate user frustration during task execution, a crucial factor in achieving efficient and satisfactory performance. These findings emphasize immersive technologies' pivotal role in enhancing operator satisfaction and performance in legged-manipulator-type robot systems.

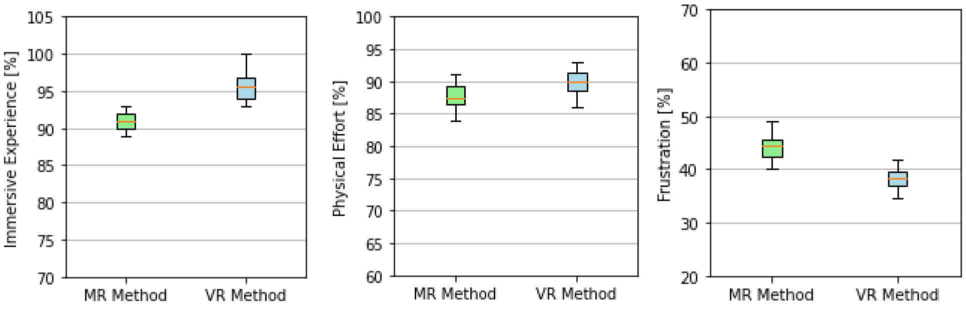
In both scenarios, the operators' perceived level of effort and confidence in decision-making are notably similar. However, a striking distinction arises when evaluating the sense of security provided by the VR interface, which places the operator in a safe virtual environment. This results in a substantial difference of approximately 44% compared to the MR interface.



(a) User Preferences.

(b) Safety Felling.

(c) Confidence in Decision-Making.



(d) Inmersive experience preference

(e) Physical Effort Analysis.

(f) Frustration Experienced.

Figure 7.24: Box Plots for Assessment of Operator Metrics in VR-MR Systems Through Experimental Methods.

The results obtained from the analysis of equations 7.12 and 7.13 demonstrate that the computed scores for operator performance are $Score_{op}(VR) = 450$ and $Score_{op}(MR) = 245$. These findings demonstrate that Virtual Reality-based interfaces outperform Mixed Reality-based interfaces for teleoperating this legged-manipulator robotic platform.

Moreover, when examining equations 7.16 and 7.17 in a more specialized Search and Rescue context, where the variables specifically address the preservation of the operator's well-being during robot teleoperation in post-disaster scenarios, the findings reveal $Score_{SAR}(VR) = 747.5$ and $Score_{SAR}(MR) = 624.5$ respectively. These outcomes underscore the pivotal role of prioritizing key factors, such as operator safety and decision-making confidence, contributing to enhanced task performance with the VR-based interface.

### 7.4.3 Evaluation of Interfaces

Figure 7.25 illustrates a radial diagram that analyses average values obtained for different established criteria ($\alpha\prime$, ..., $\phi\prime$, shown in Table 7.8) for evaluating the interfaces. Notably, the most significant criteria are those associated with non-in-situ operations, focusing on autonomy.

Specifically, the HTC-Vive glasses, owing to their direct electrical connection, exhibit a deficiency of usage limitations compared to the Hololens2 in terms of autonomy and restricted operational space. Moreover, they offer enhanced operator security during remote operations, which stands out. Conversely, latency and interaction with virtual objects display relatively similar performance levels across both interface types.

Following the equations 7.14 and 7.15, which were specifically formulated to get a relationship between these variables, the following scores were obtained: $Score_{int}(VR) = 645$ and $Score_{int}(MR) = 597$. These numerical results provided a quantitative insight into the performance of the respective virtual reality and mixed reality interfaces in the context of robotic manipulation tasks.

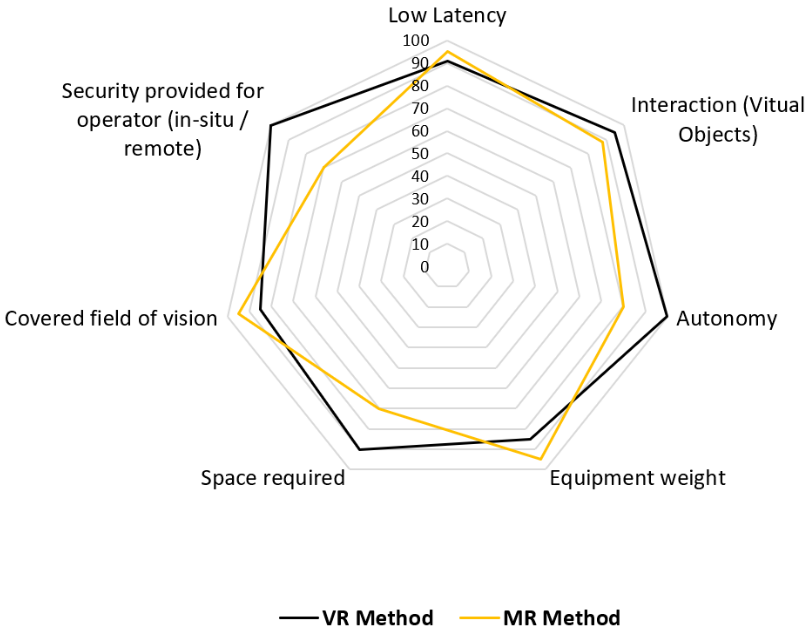


Figure 7.25: Comparing Parameters for System Performance in VR-MR Systems.

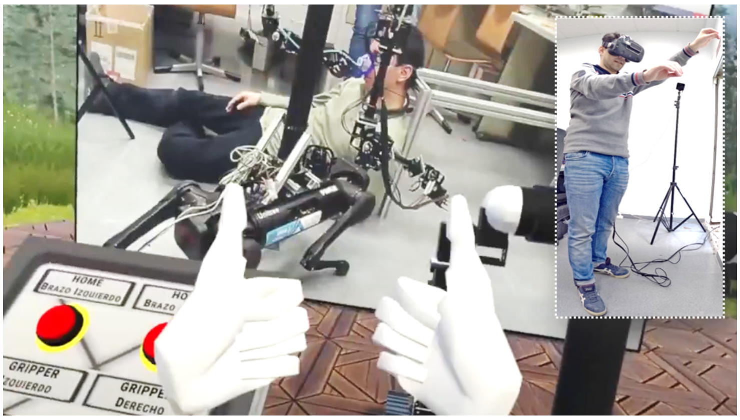
Notably, these scores propose a relatively minor difference between the two interface types, implying that both are proficient in efficiently facilitating the execution of robotic manipulation tasks. Nevertheless, a pivotal point of distinction emerges when considering remote operational scenarios. In such contexts, VR interfaces demonstrate a marked advantage, significantly enhancing MR interfaces. This observation underscores the potential superiority of VR-based solutions in remote teleoperation applications, a vital consideration for future developments in the field of human-robot interaction.

### 7.4.4 System Versatility

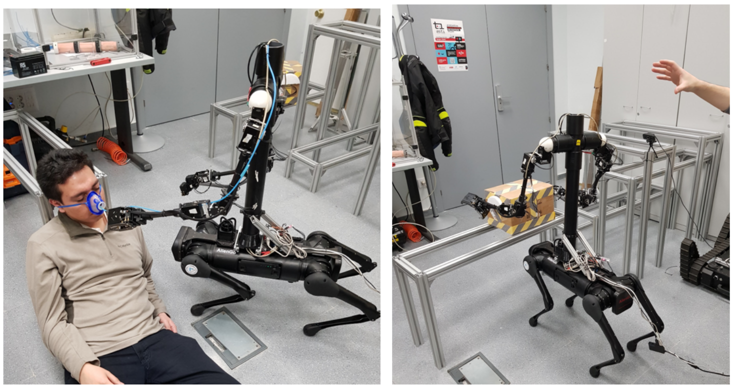
The system was complementarily evaluated by employing a dual-legged-manipulator type platform, which was teleoperated through the VR interface (Figure 7.26-c), incorporating the torso model with two robotic arms. The performed tasks involved the placement of an oxygen mask on an immobilized victim (Figure 7.26-a) and the lifting of a box (Figure 7.26-b). In both cases, the tests were completed with a success rate exceeding 95%. Each trial was repeated ten times.

Of particular note, especially in the first test, is the contribution of the quadruped robot in positioning the arm's end that holds the oxygen mask. This is achieved through its ability to **regulate both height and inclination** by adjusting its legs.

Videos about the experiments are accessible via the following link: `https://youtu.be/w70p0YqvgT0`.



(a) First view Perspective of the Dual Teleoperation Interface, displaying the image captured from a perspective of the robot, also the operator on the external side is shwon.



(b) Application of an Oxygen Mask to a Victim.

(c) Lifting of a 500-Gram Box.

Figure 7.26: Assistance provided by a dual-legged-manipulator type robot.

### 7.4.5 Lessons Learned

Given the challenging conditions and terrain uncertainties in post-disaster scenarios, teleoperating a complex legged-manipulator-type robotic setup emerges as the preferred option.

It has been demonstrated that immersive interfaces represent a viable and sufficiently mature alternative for controlling such robots. Drawing from the collective experience acquired through work involving these robots and interfaces, several salient points merit consideration, both for advancing the state-of-the-art and, more importantly, for mitigating risks to both humans and robots.

Foremost among these considerations is the need to avert collisions involving the robot. As depicted in Figure 7.27, the bar diagrams reveal that inexperienced operators generate a significant number of collisions, irrespective of the interface type in use. Consequently, it is advisable to establish a comprehensive simulation and mission environment, inclusive of a digital twin, to preempt collisions and consequent economic losses. Furthermore, Figure 7.27 also portrays a blue interlined curve denoting mission execution time, which is intrinsically linked to operator training.

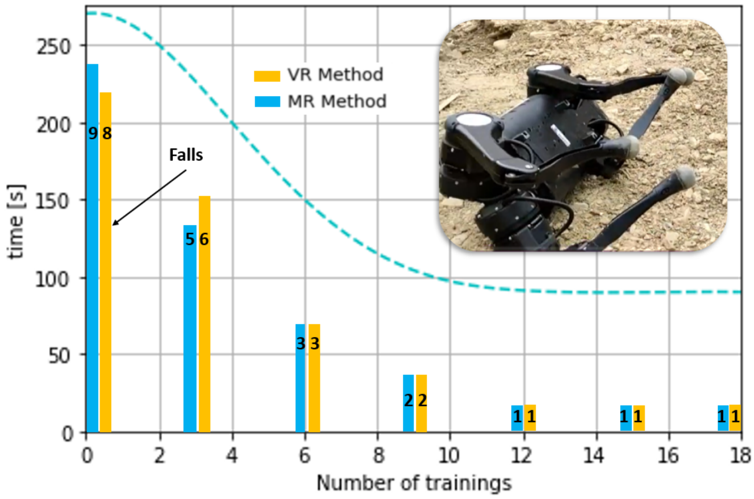


Figure 7.27: The correlation between the evolution of falls and the time needed to accomplish the task as influenced by the training undertaken.

Here are additional noteworthy considerations that can be outlined to ensure the mission's effective functionality:

- Execute soft-slow hand movements during teleoperation, moving the virtual model.
- Limiting the linear and angular velocities of the robotic assembly is a relatively simple solution to unforeseen sudden movements.
- The time autonomy in this quadruped robot is usually limited, even more so when a robotic arm is incorporated as payload; it is recommended to work until 25% of the battery charge.
- Train operators in mission simulation and recreation environments considering the most significant number of parameters or eventualities that can be had in a real situation.

## 7.5 Conclusion

In this chapter, it has been shown how immersive interfaces, specifically Mixed Reality (MR) and Virtual Reality (VR), were capable of maximizing an operator's mission management capacities. These immersive interfaces demonstrated superior performance and enhanced factors related to operator confidence compared to conventional interfaces like keyboard-screen-mouse setups, particularly during decision-making processes. While both types of interfaces exhibited adaptability in managing robotic systems, there are particular situations where one becomes more relevant according to the use case. Among the most noteworthy scenarios were:

One of the most significant impact variables taken into consideration by the operator is their safety in a post-disaster environment. The operator prioritizes remaining in a remote safe zone for the teleoperation of robots, although this negatively affects confidence levels in decision-making. Conversely, MR interfaces improve these confidence levels by providing direct visual contact with the operation but expose the operator to a certain level of risk in the area.

Regarding spatial considerations and portability, some VR glasses models need fixed-wired sources for communication and for determining the operator's position within the environment. In contrast, MR glasses require rapid recognition of the environmental structure to initiate the mission.

Robotic assistance systems employing quadrupedal robots without and with manipulation arms (legged-manipulator) have demonstrated high effectiveness in assisting victims with medical equipment and collecting environmental information. This effectiveness was achieved due to their versatility and integration with the implemented teleoperation MR-VR method.

The selection between one technology or another depends on the field of application. In this case, Mixed Reality demonstrates high performance in tasks requiring precision and environmental interaction (such as guidance or manipulation). In contrast, Virtual Reality is more suitable for remote operation tasks from safe zones.

# Chapter 8

# Conclusions

*"A ship is always safe at the shore, but that is not what it is built for."*

- Albert Einstein.

THIS *chapter focuses on synthesizing the main contributions of this doctoral thesis by presenting a series of conclusions while highlighting the advancements made in the state-of-the-art, along with the theses that have contributed directly or indirectly to this doctoral work.*

## 8.1 Conclusions

In this doctoral thesis, the focus has been on the problem of search and rescue robotics, utilizing quadruped robots as the protagonists for missions. The development explicitly undertaken emphasizes the relationship between perception systems and teleoperation with these robots, covering areas correlated with the missions and the challenges presented by each. In this context, the complete development illustrates a comprehensive sequence of search and rescue missions, from advancing through unstructured terrains to victim identification and assistance. The principal conclusions drawn from this thesis are summarized as follows:

1. Precise environment identification, quantifying its material composition and structural obstacles, has enabled the determination and regulation of optimal gait patterns for advancing a quadruped robot on the terrain. Further delving into environment perception, **probabilistic terrain characterization** generated based on stability criteria from a human perspective has proven to be a powerful tool for decision-making regarding the **foothold** points of the quadruped robot's legs during each step of advancement.

2. Different light spectra ranges have allowed for the generalization of victim detection in challenging conditions through specific **RGB, Thermal,** and **Multispectral** sensors. This detection has been automated to generate automatic detections in new scenarios using CNNs. Each light spectrum range has a differentiating characteristic that contributes to detection. In the first case, it leverages environmental colour and geometry differences; the second method demonstrates high efficiency for varying or null light conditions; and the third one, through operational spectrum band combinations, has allowed for robust detection in both indoor and outdoor settings.

3. Informed search criteria in unknown environments, generated from human consideration, have allowed the definition of how and in which direction to orient a victim search. This type of search was achieved by implementing an intelligent method that defines the **decision-making** process of the quadruped robot based on an **indirect search** that considers input from both random forest post-processing and spatial information obtained through LiDAR. The method has shown effectiveness in optimizing exploration times in the environment, as well as efficiency in finding victims in the test settings.

4. **Legged-manipulator robots** have demonstrated remarkable versatility, particularly in executing tasks that involve adjusting height and inclination in a static state to reach objects and assist victims, thanks to the flexibility of their legs.

5. Teleoperation systems, on the other hand, have proven to be a more highly regarded alternative than conventional interfaces, especially for tasks that require precision, from **guiding a robot** through an environment to remotely **teleoperating legged-manipulator** platforms. The additional advantages they offer are improved immersive experiences and increased operator confidence levels for decision-making.

## 8.2 Contributions

In this doctoral thesis, various contributions have been made, listed in this section. Figure 2 represents the axes around which the issue has been addressed, providing a more practical description of its relationship with quadruped robots and the detailed contributions in the Tables 8.1-8.2-8.3-8.4 within the field of search and rescue robotics.

Figure 8.1: Primary fields where contributions were made in this doctoral thesis.

### Quadrupedal Robots and Perception (Fields 1-2)

Table 8.1: Contributions about quadrupedal robots and perception.

| Contributions | |
|---|---|
| 1. Environment Perception | Primary identification and characterization of the environment for regulating gait patterns in quadrupedal robots. |
| 2. Probabilistic Analysis of the Environment | Generation of probabilistic terrains based on human stability criterion for the selection of the best support point for a quadrupedal robot. |
| 3. Multispectral Imagery | Formulation of new indices from multispectral images for victims identification. |
| 4. RGB Imagery | Development of convolutional neural network (CNN) models trained on synthetic, real, and combined data for victim identification. |
| 5. Thermal Imagery | Proposal of a real-time victim identification method using thermal images and trained CNNs. |
| 6. Active Search | Synergy of deep learning techniques (CNN+Random Forest) to create an intelligent system for active search for victims in unknown environments. |

### Quadrupedal Robots and Embedded System (Fields 1-4)

Table 8.2: Contributions about quadrupedal robots and embedded systems.

| Contributions | |
|---|---|
| 7. Modular Multi-Process System. | Distributed Modular Architecture for Real-Time Processing of Vision, Locomotion, Interface, and Manipulation Subsystems under ROS |

### Quadrupedal Robots and Mixed Reality Interfaces (Fields 1-3)

Table 8.3: Contributions about quadrupedal robots and Mixed Reality.

| Contributions | |
|---|---|
| 8. Mixed Reality Guidance | Assisted Guidance of Quadrupedal Robots through Unstructured Terrains using Mixed Reality and Gestures for victim assistance. |

### Legged-Manipulator Robots and Teleoperation (Fields 1-5-3)

Table 8.4: Contributions about quadrupedal robots and teleoperation.

| Contributions | |
|---|---|
| 9. Legged-Manipulator Robots | Kinematic Design, Workspace Analysis, Simulation, and Implementation. |
| 10. Mixed-Virtual Reality Teleoperation | Teleoperation and Comparative Analysis of MR-VR Systems Applied to High-Level Control of Legged-Manipulator Robots. |

## 8.3 Achievements

Thus far, the findings of the thesis have been documented in **seven** publications in Journals indexed in Jornal Citation Report (JCR) (Table 8.5), **four** in international conferences (Table 8.6), **one** ROSbook chapter (Table 8.7), **three** National Conferences (Table 8.8) and **four** articles under review submitted (Table 8.9) to top quartile journals.

### 8.3.1 Published Articles in JCR Journals

Table 8.5: Publications linked to the doctoral thesis published in JCR Journals.

| URL | Title | Authors | Journal | Year | Impact Factor | Quartile |
|---|---|---|---|---|---|---|
| 1 | Autonomous Victim Detection System based on Deep Learning and Multispectral Imagery. | **Cruz Ulloa, C.,** Garrido, L., del Cerro, J., Barrientos, A. | Machine Learning: Science and Technology. | 2023 | 6.8 | Q1 |
| 2 | Mixed-reality for quadruped-robotic guidance in SAR tasks | **Cruz Ulloa, C.,** del Cerro, J., Barrientos, A. | Journal of Computational Design and Engineering | 2023 | 4.9 | Q1 |
| 3 | Deep Learning Vision System for Quadruped Robot Gait Pattern Regulation. Biomimetics. | **Cruz Ulloa C,** Sánchez L, del Cerro J, Barrientos A. | Biomimetics | 2023 | 4.5 | Q1 |
| 4 | A Mixed-Reality Tele-Operation Method for High-Level Control of a Legged-Manipulator Robot. | **Cruz Ulloa, C.,** Domínguez, D., del Cerro, J., Barrientos, A. | Sensors | 2022 | 3.9 | Q2 |
| 5 | Autonomous thermal vision robotic system for victims recognition in search and rescue missions. | **Cruz Ulloa, C.,** Prieto Sánchez, G., Barrientos, A., del Cerro, J. | Sensors | 2021 | 3.9 | Q2 |
| 6 | Thermal, Multispectral and RGB Sensors: a comparison in SAR Robotics. | **Cruz Ulloa, C.;** Orbea, D.; del Cerro, J.; Barrientos, A. | Applied Sciences | 2024 | 2.7 | Q2 |
| 7 | RUDE-AL: Roped UGV Deployment Algorithm of an MCDPR for Sinkhole Exploration. | Orbea, D.; **Cruz Ulloa, C.;** del Cerro, J.; Barrientos, A. | Sensors | 2023 | 3.9 | Q2 |

### 8.3.2 International Conferences

Table 8.6: Publications associated with International Conferences related to the doctoral thesis.

| URL | Title | Authors | Conference | Year | Book |
|---|---|---|---|---|---|
| 1 | Design and Mixed-Reality Teleoperation of a Quadruped-Manipulator Robot for SAR Tasks. | **Cruz, C.**, Domínguez, D., Barrientos, A., del Cerro, J. | **CLAWAR2022** Robotics in Natural Settings | 2022 | Lecture Notes in Networks and Systems |
| 2 | Deep Learning for Victims Detection from Virtual and Real Search and Rescue Environments | **Cruz, C.**, García, M., Barrientos, A., del Cerro, J. | **ROBOT2022** Fifth Iberian Robotics Conference | 2022 | Lecture Notes in Networks and Systems |
| 3 | A Tracking-Guidance People Method using a Quadruped Robot and Artificial Vision | **Cruz, C.**, Orbea, D., del Cerro, J. Barrientos, A. | **ICARA2024** International Conference on Automation, Robotics and Applications | 2024 | Accepted and pending presentation and indexing in **IEEE** |
| 4 | Mobile CDPR system for robotic sinkhole exploration | Orbea, D., **Cruz, C.**, del Cerro, J. Barrientos, A. | **ICARA2024** International Conference on Automation, Robotics and Applications | 2024 | Accepted and pending presentation and indexing in **IEEE** |

### 8.3.3 ROSbook Chapter

Table 8.7: Chapter related to ROSBOOK VOL.7.

| URL | Title | Authors | Chapter | Year | Book |
|---|---|---|---|---|---|
| 1 | Autonomous 3D Thermal Mapping of Disaster Environments for Victims Detection | **Cruz, C.**,<br>Torres, G.,<br>Barrientos, A.,<br>del Cerro, J. | **ROSBOOK**<br>Robot Operating System | 2023 | Studies in Computational Intelligence |

### 8.3.4 National Conferences

Table 8.8: Publications associated with National Conferences related to the doctoral thesis.

| URL | Title | Authors | Conference | Location | Year |
|---|---|---|---|---|---|
| 1 | Sistema de realidad virtual para teleoperación de robots tipo centauro. | **Cruz, C.**,<br>Juez, J.,<br>del Cerro, J,<br>Barrientos, A. | XLIV Jornadas de Automática | Zaragoza | 2023 |
| 2 | Robótica colaborativa de búsqueda y rescate, una clasificación basada en interacción física. | **Cruz, C.**,<br>del Cerro, J.,<br>Barrientos, A. | XLIII Jornadas de Automática | Logroño | 2022 |
| 3 | Sistema robótico inteligente de exploración térmica para misiones de búsqueda y rescate. | **Cruz Ulloa, C.**,<br>Prieto Sánchez, G.,<br>Cerro Giner, J. D.,<br>Barrientos Cruz, A. | XII Jornadas Nacionales de Robótica | Málaga | 2022 |

### 8.3.5 Articles Under Review

Table 8.9: Publications linked to the doctoral thesis under review, sent to JCR Journals.

|  | Title | Authors | Journal | Year | Impact Factor | Quartile |
|---|---|---|---|---|---|---|
| 1 | Active Robotic Search for Victims using Ensemble Deep Learning Techniques. | García-Samartin J.,<br>**Cruz Ulloa, C.,**<br>del Cerro, J.,<br>Barrientos, A. | Machine Learning: Science and Technology. | 2023 | 6.8 | Q1 |
| 2 | MR-VR for Legged-Manipulator Robots Tele-operation: A Comparison and Lessons Learned | **Cruz Ulloa, C.,**<br>del Cerro, J.,<br>Barrientos, A. | Virtual Reality | 2023 | 4.2 | Q1 |
| 3 | Vision-based Collaborative Robots for Exploration in Uneven Terrains | **Cruz Ulloa, C.,**<br>A, Javier.,<br>del Cerro, J.,<br>Barrientos, A. | Mechatronics | 2023 | 3.3 | Q2 |
| 4 | A Portable Artificial Robotic-Nose for CO2 Concentration Monitoring | **Cruz Ulloa, C.,**<br>Orbea, D.,<br>del Cerro, J.,<br>Barrientos, A. | Machines | 2024 | 2.6 | Q2 |

### 8.3.6 BSc and MSc projects Supervision

In addition, 16 BSc(TFG) and MSc (TFM) were co-tutorized with Professor Antonio Barrientos, shown in Table 8.10.

Table 8.10: Co-tutorized BSc(TFG) and MSc (TFM) projects.

| Nº | Title | Author | Type | Year |
|---|---|---|---|---|
| 1 | Estudio, diseño e implementación de un sistema de locomoción basado en ruedas convertibles adaptativas | David de la Peña | TFG | 2021 |
| 2 | Reconstrucción de Entornos 3D e identifiacción de víctimas mediante Sistema Lidar | Javier Fadón | TFG | 2021 |
| 3 | Detección de Víctimas mediante Redes Neuronales e Imágenes Térmicas | Guillermo Prieto Sánchez | TFG | 2021 |
| 4 | Generación Automática de Mapas Térmicos 3-D e Identificación Inteligente de víctimas mediante Imágenes Térmicas en Entornos S.A.R. | Guido Rafael Torres Llerena | TFM | 2021 |
| 5 | Robot Delta para cultivo en hileras | Víctor Orihuel Arribas | TFG | 2021 |
| 6 | Sistema de exploración y asignación de recursos en equipos de robots heterogéneos | Javier Dávila | TFG | 2022 |
| 7 | Exploración activa en entornos de búsqueda y rescate utilizando un robot cuadrúpedo | Jorge García Samartín | TFM | 2022 |
| 8 | Detección de Víctimas en entornos SAR usando Redes Neuronales Convolucionales entrenadas a partir de modelos Reales y Simulados | Miguel Garcia | TFG | 2022 |
| 9 | Detección de víctimas en zonas de desastre mediante procesamiento de imágenes multiespectrales con redes neuronales | Luis Garrido | TFG | 2022 |
| 10 | Acoplamiento de un manipulador de 6dof a un robot cuadrúpedo | David Domínguez | TFG | 2022 |
| 11 | Aprendizaje autónomo de modos de marcha para robot hexápodo | Ricardo Serrano | TFG | 2023 |
| 12 | Tele-operación de un Robot Centauro mediante Realidad Virtual | Jorge Juez Alonso | TFG | 2023 |
| 13 | Entrenamiento de un sistema de conduccion autonoma mediante aprendizaje por refuerzo entrenado bajo simulación | Francisco Adrian Fernandez | TFG | 2023 |
| 14 | Generación de patrones de marcha para un robot cuadrúpedo en un terreno no estructurado | Lourdes Sánchez Losada | TFG | 2023 |
| 15 | Robots colaborativos para superacion de terrenos no estructurados | Javier Álvarez | TFG | 2023 |
| 16 | Sistema inteligente de percepción visual para caracterización de terrenos y ajuste de patrones de marcha en robots cuadrúpedos | Miguel Zaramalilea | TFG | 2023 |
| 17 | Reconstrucción y caracterización de entornos mediante sistema NERF | Javier Jiménez | TFG | 2023 |

### 8.3.7 International Stay and Scholarship

In addition, an international research stay at CTU in Prague (Czech Technical University in Prague) was realized during spring 2023 at Vision for Robotics and Autonomous Systems Research Group focused on Quadrupedal Robots. The author of this thesis was granted a scholarship (`https://www.upm.es/Investigacion/personal/Movilidad/programaPropio?id=d5a288f9933e5810VgnVCM10000009c7648a____&fmt=detail`) supported by Universidad Politecnica de Madrid to develop the stay in topics related to quadrupedal robots and perception in Prague (Table 8.11).

Table 8.11: Scholarship awarded for the development of an international stay.

| | Title | Beneficiary | Supervisors | University | Year |
|---|---|---|---|---|---|
| 1 | Convocatoria de ayudas dirigidas al personal investigador en formación predoctoral para realizar una estancia de investigación internacional igual o superior a tres meses | Christyan Cruz | Tomas Svoboda<br>Antonio Barrientos | Czech Technical University in Prague | 2023 |

This doctoral thesis had the financing of Spanish National projects, detailed in Table 8.13.

### 8.3.8 Journal Reviewer

During the Doctoral Thesis, contributions were made as a **reviewer** to the journals listed in Table 8.12.

Table 8.12: Journals with participation as a peer reviewer.

| | Journal | Year |
|---|---|---|
| 1 | IEEE/ASME Transactions on Mechatronics | 2023 |
| 2 | Revista Iberoamericana de Automática e Informática Industrial | 2022 |
| 3 | Applied Science | 2022 |
| 4 | Sensors | 2022 |
| 5 | Jornadas Nacionales de Automática | 2023 |

## 8.4 Repercussions

In a structured way, this doctoral thesis addresses approximately eighty per cent of the existing challenges in the field of search and rescue robotics, contributing significantly to each of the topics explored. The analysis of the implications of this thesis aligns with the United Nations' Sustainable Development Goals (**SDGs**), as depicted in Figure 8.2.

The primary focal point of the direct impact lies in using robotic technologies to safeguard human lives in the aftermath of disasters. This encompasses search, identification, and mitigating unnecessary risks to rescue personnel during early exploration phases. These endeavours align with **SDG-3**, which pertains to health and well-being.

From an economic standpoint, as indicated by **SDG-8**, the deployment of rescue robots undeniably incurs costs. Beyond the expenses associated with their acquisition and maintenance, there is a need for specialized programming and the hiring or training of operators to ensure the versatility and multifaceted applicability of these robots (**SDG-12**). It is essential to monitor the condition of the robots after arduous missions, as well as the possibility of malfunctions or damage.

However, it is crucial to consider, on the other side of the equation, that the value of each human life is immeasurable. Any imperfections, breakages, or mishaps occurring with the robot will always pale compared to the cost of a human life. The risk is inherent in search and rescue operations, with firefighters and law enforcement officers risking their lives yearly to save others. Systems like those described in this thesis can potentially reduce these numbers and promote collaborative efforts (**SDG-17**).

Figure 8.2: Sustainable Development Goals (SDGs) directly related to the impact of this doctoral thesis.

The integration of these advanced robotic systems raises important ethical and social considerations. While the automation of tasks can lead to workforce reductions, it is crucial to recognize that, in many cases, this transition is accompanied by improved safety standards in industrial settings, aligning with the objectives of sustainable development (**SDGs 9 and 11**). Much like the paradigm shift away from human labour in hazardous environments, the involvement of robots like ARTUR in rescue missions presents a positive step towards ensuring the safety and well-being of responders and those in need.

## 8.5 Founding

The development of this doctoral thesis has received funding from the projects detailed in Table 8.13.

Table 8.13: Projects that provided financing for this doctoral thesis.

| N$^{\text{o}}$ | Name of the project | Funding body | Code |
|---|---|---|---|
| 1 | GRob-UPM. RoboCity2030 Madrid Digital Innovation Hub | Comunity of Madrid | S2018/NMT-4331 |
| 2 | TASAR (Team of Advanced Search And Rescue Robots) | Ministerio de Ciencia e Innovación | PID2019-105808RB-I00 |

## 8.6 Future Research Lines

Throughout the development of this doctoral thesis, different aspects of the agents involved in search and rescue missions have been explored. While notable contributions have been made, there are opportunities for further research in foundational areas of this thesis. Some of these developments include:

- In the field of mobility through unstructured terrains, there is an open avenue for control based on black-box methods (reinforcement learning) to generate gait patterns on unstructured terrains.
- Within the domain of real-time processing for victim detection using multispectral images, current limitations revolve around data transmission because of the multiple channels (four) and high resolution, making streaming challenging. Additionally, there is potential for expanding to other fields of vision, such as polarization imaging.
- Coupled modelling of legged-manipulator systems and dynamic control for executing synchronous movements with systems that have a high number of degrees of freedom (e.g., “(n>18)”).
- Joint manipulation tasks offer another area with research potential, along with arm instrumentation, including proximity sensors for more precise manipulation.

# References

[1] A. L. Adams et al. "Search Is a Time-Critical Event: When Search and Rescue Missions May Become Futile". In: *Wilderness Environmental Medicine* 18.2 (2007), pp. 95–101. ISSN: 1080-6032. DOI: `https://doi.org/10.1580/06-WEME-OR-035R1.1`. URL: `https://www.sciencedirect.com/science/article/pii/S1080603207702181`.

[2] R. Agishev, T. Petříček, and K. Zimmermann. "Trajectory Optimization Using Learned Robot-Terrain Interaction Model in Exploration of Large Subterranean Environments". In: *IEEE Robotics and Automation Letters* 7.2 (2022), pp. 3365–3371. DOI: `10.1109/LRA.2022.3147332`.

[3] A. Agrawal, S. Chen, A. Rai, and K. Sreenath. "Vision-Aided Dynamic Quadrupedal Locomotion on Discrete Terrain Using Motion Libraries". In: *2022 International Conference on Robotics and Automation (ICRA)*. 2022, pp. 4708–4714. DOI: `10.1109/ICRA46639.2022.9811373`.

[4] M. S. Ahsan, H. Mobarak, and K. N. Chy. "Design and Construction of a Radio Controlled Floating Waste Collector Robot". In: *2020 11th International Conference on Electrical and Computer Engineering (ICECE)*. 2020, pp. 105–108. DOI: `10.1109/ICECE51571.2020.9393077`.

[5] A. Angelova, L. Matthies, D. Helmick, and P. Perona. "Fast Terrain Classification Using Variable-Length Representation for Autonomous Navigation". In: *2007 IEEE Conference on Computer Vision and Pattern Recognition*. 2007, pp. 1–8. DOI: `10.1109/CVPR.2007.383024`.

[6] M. Arduengo, C. Torras, and L. Sentis. "Robust and adaptive door operation with a mobile robot". In: *Intelligent Service Robotics* (2021). ISSN: 1861-2784. DOI: `10.1007/s11370-021-00366-7`. URL: `http://dx.doi.org/10.1007/s11370-021-00366-7`.

[7] P. Arm et al. "Scientific exploration of challenging planetary analog environments with a team of legged robots". In: *Science Robotics* 8.80 (2023), eade9548. DOI: `10.1126/scirobotics.ade9548`. eprint: `https://www.science.org/doi/pdf/10.1126/scirobotics.ade9548`. URL: `https://www.science.org/doi/abs/10.1126/scirobotics.ade9548`.

[8] R. Ashour, M. Abdelkader, J. Dias, N. I. Almoosa, and T. Taha. "Semantic Hazard Labelling and Risk Assessment Mapping During Robot Exploration". In: *IEEE Access* 10 (2022), pp. 16337–16349. DOI: `10.1109/ACCESS.2022.3148544`.

[9] U. Asif, M. Bennamoun, and F. A. Sohel. "RGB-D Object Recognition and Grasp Detection Using Hierarchical Cascaded Forests". In: *IEEE Transactions on Robotics* 33.3 (2017), pp. 547–564. DOI: `10.1109/TRO.2016.2638453`.

[10] C. G. Atkeson et al. "What Happened at the DARPA Robotics Challenge Finals". In: *The DARPA Robotics Challenge Finals: Humanoid Robots To The Rescue*. Ed. by M. Spenko, S. Buerger, and K. Iagnemma. Cham: Springer International Pub-

lishing, 2018, pp. 667–684. ISBN: 978-3-319-74666-1. DOI: `10.1007/978-3-319-74666-1_17`. URL: `https://doi.org/10.1007/978-3-319-74666-1_17`.

[11] J. S. Aware and A. Umbarkar. "Garbage Collecting Ship Robot Using Arduino Uno Microcontroller Based On Android Smartphone". In: *NeuroQuantology* 20.17 (2022), p. 1489.

[12] A. Aydemir, K. Sjöö, J. Folkesson, A. Pronobis, and P. Jensfelt. "Search in the real world: Active visual object search based on spatial relations". In: *2011 IEEE International Conference on Robotics and Automation*. 2011, pp. 2818–2824. DOI: `10.1109/ICRA.2011.5980495`.

[13] A. Aydemir, A. Pronobis, M. Göbelbecker, and P. Jensfelt. "Active Visual Object Search in Unknown Environments Using Uncertain Semantics". In: *IEEE Transactions on Robotics* 29.4 (2013), pp. 986–1002. DOI: `10.1109/TRO.2013.2256686`.

[14] S. Bansal et al. *AGDC: Automatic Garbage Detection and Collection*. 2019. arXiv: `1908.05849 [cs.RO]`.

[15] J. A. Barbera and A. Macintyre. "URBAN SEARCH AND RESCUE". In: *Emergency Medicine Clinics of North America* 14.2 (1996), pp. 399–412. ISSN: 0733-8627. DOI: `https://doi.org/10.1016/S0733-8627(05)70258-3`. URL: `https://www.sciencedirect.com/science/article/pii/S0733862705702583`.

[16] M. Barnes, H. R. Everett, and P. Rudakevych. "ThrowBot: design considerations for a man-portable throwable robot". In: *Unmanned Ground Vehicle Technology VII*. Ed. by G. R. Gerhart, C. M. Shoemaker, and D. W. Gage. Vol. 5804. International Society for Optics and Photonics. SPIE, 2005, pp. 511–520. DOI: `10.1117/12.604161`. URL: `https://doi.org/10.1117/12.604161`.

[17] A. Barrientos. *TASAR - Team of Advanced Search And Rescue Robots*. 2021. URL: `https://www.car.upm-csic.es/?portfolio=tasar`.

[18] A. Barrientos. *TASAR – Team of Advanced Search And Rescue Robot*. 2021. URL: `https://www.car.upm-csic.es/?portfolio=tasar` (visited on 09/06/2022).

[19] A. Barrientos. *Proyecto TASAR – Robots de Búsqueda y Rescate*. URL: `https://blogs.upm.es/tasar/`.

[20] A. Batinovic, A. Ivanovic, T. Petrovic, and S. Bogdan. "A Shadowcasting-Based Next-Best-View Planner for Autonomous 3D Exploration". In: *IEEE Robotics and Automation Letters* 7.2 (2022), pp. 2969–2976. ISSN: 23773766. DOI: `10.1109/LRA.2022.3146586`. arXiv: `2109.09323`.

[21] R. F. Battaglia. "Design of the SCOUT II Quadruped with Preliminary Stair-climbing". In: (1999).

[22] BBC. *Turkey earthquake: Deadly new tremor traps people under rubble*. Feb. 2023. URL: `https://www.bbc.com/news/world-europe-64711228`.

[23] BBC. *Ecuador volcano erupts.* URL: `https://www.bbc.com/news/av/world-latin-america-35714733`.

[24] G. Bellegarda, Y. Chen, Z. Liu, and Q. Nguyen. "Robust High-Speed Running for Quadruped Robots via Deep Reinforcement Learning". In: *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).* 2022, pp. 10364–10370. DOI: `10.1109/IROS47612.2022.9982132`.

[25] C. D. Bellicoso et al. "Advances in real-world applications for legged robots". In: *Journal of Field Robotics* 35.8 (2018), pp. 1311–1326.

[26] C. D. Bellicoso, F. Jenelten, C. Gehring, and M. Hutter. "Dynamic Locomotion Through Online Nonlinear Motion Optimization for Quadrupedal Robots". In: *IEEE Robotics and Automation Letters* 3.3 (2018), pp. 2261–2268. DOI: `10.1109/LRA.2018.2794620`.

[27] C. D. Bellicoso et al. "ALMA - Articulated Locomotion and Manipulation for a Torque-Controllable Robot". In: *2019 International Conference on Robotics and Automation (ICRA).* 2019, pp. 8477–8483. DOI: `10.1109/ICRA.2019.8794273`.

[28] K. Berns, A. Nezhadfard, M. Tosa, H. Balta, and G. D. Cubber. "Unmanned Ground Robots for Rescue Tasks". In: *Search and Rescue Robotics - From Theory to Practice.* InTech, Aug. 2017.

[29] C. L. Bethel. "Robots without faces: non-verbal social human-robot interaction". PhD thesis. University of South Florida, 2009.

[30] C. M. Biancardi and A. E. Minetti. "Biomechanical determinants of transverse and rotary gallop in cursorial mammals". In: *Journal of Experimental Biology* 215.23 (2012), pp. 4144–4156.

[31] A. Bircher, M. Kamel, K. Alexis, H. Oleynikova, and R. Siegwart. "Receding horizon next-best-view planner for 3D exploration". In: *Proceedings - IEEE International Conference on Robotics and Automation* 2016-June.January 2018 (2016), 1462-1468. ISSN: 10504729. DOI: `10.1109/ICRA.2016.7487281`.

[32] P. Biswal and P. K. Mohanty. "Development of quadruped walking robots: A review". In: *Ain Shams Engineering Journal* 12.2 (2021), pp. 2017–2031. ISSN: 2090-4479. DOI: `https://doi.org/10.1016/j.asej.2020.11.005`. URL: `https://www.sciencedirect.com/science/article/pii/S2090447920302501`.

[33] M. R. Blackburn, H. R. Everett, and R. T. Laird. *After Action Report to the Joint-Program Office: Center for the Robotic Assisted Search and Rescue (CRASAR) Related Efforts at the World Trade Center.* Tech. rep. SPACE and NAVAL WARFARE SYSTEMS CENTER SAN DIEGO CA, 2002.

[34] M. R. Blackburn, H. R. Everett, and R. T. Laird. *After Action Report to the Unmanned Ground Vehicles/Systems-Joint Program Office: Center for the Robotic Assisted Search and Rescue (CRASAR) Related Efforts at the World Trade Center.* Tech. rep. Office of the Secretary of Defense Joint Robotics Program, Aug. 2002.

[35] C. Bleiker. *Will robots replace dogs in earthquake rescue operations? DW 02/09/2023*. URL: `https://www.dw.com/en/will-robots-replace-dogs-in-earthquake-rescue-operations/a-64647765`.

[36] A. Bouman et al. "Autonomous Spot: Long-Range Autonomous Exploration of Extreme Environments with Legged Locomotion". In: *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2020, pp. 2518–2525. DOI: `10.1109/IROS45743.2020.9341361`.

[37] A. Bouman et al. "Autonomous spot: Long-range autonomous exploration of extreme environments with legged locomotion". In: *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE. 2020, pp. 2518–2525.

[38] M. Brandão, Y. M. Shiguematsu, K. Hashimoto, and A. Takanishi. "Material recognition CNNs and hierarchical planning for biped robot locomotion on slippery terrain". In: *2016 IEEE-RAS 16th International Conference on Humanoid Robots (Humanoids)*. 2016, pp. 81–88. DOI: `10.1109/HUMANOIDS.2016.7803258`.

[39] M. H. Bruch, R. T. Laird, and H. R. Everett. "Challenges for deploying man-portable robots into hostile environments". In: *Mobile Robots XV and Telemanipulator and Telepresence Technologies VII*. Ed. by M. R. Stein, H. M. Choset, D. W. Gage, and M. R. Stein. Vol. 4195. International Society for Optics and Photonics. SPIE, 2001, pp. 29–40. DOI: `10.1117/12.417321`. URL: `https://doi.org/10.1117/12.417321`.

[40] W. Burger and M. J. Burge. "Scale-Invariant Feature Transform (SIFT)". In: *Digital Image Processing: An Algorithmic Introduction*. Cham: Springer International Publishing, 2022, pp. 709–763. ISBN: 978-3-031-05744-1. DOI: `10.1007/978-3-031-05744-1_25`. URL: `https://doi.org/10.1007/978-3-031-05744-1_25`.

[41] Y. U. Cao, A. B. Kahng, and A. S. Fukunaga. "Cooperative mobile robotics: Antecedents and directions". In: *Robot colonies* (1997), pp. 7–27.

[42] CAR-UPM. *ROBOTICS & CYBERNETICS RESEARCH GROUP*. URL: `https://www.car.upm-csic.es/about-us/research-groups/robotics-cybernetics/`.

[43] M. Cardim Ferreira Lima et al. "Monitoring Plant Status and Fertilization Strategy through Multispectral Images". In: *Sensors* 20.2 (2020). ISSN: 1424-8220. DOI: `10.3390/s20020435`. URL: `https://www.mdpi.com/1424-8220/20/2/435`.

[44] J. Casper and R. R. Murphy. "Human-Robot Interactions During the Robot-Assisted Urban Search and Rescue Response at the World Trade Center". In: *IEEE Transactions on systems, man and cybernetics* (2003).

[45] J. L. Casper, M. Micire, and R. R. Murphy. "Issues in intelligent robots for search and rescue". In: *Unmanned ground vehicle technology II*. Vol. 4024. SPIE. 2000, pp. 292–302.

[46] CCHANG. *Garbage Classification*. 2018. DOI: `10.34740/KAGGLE/DS/81794`. URL: `https://www.kaggle.com/ds/81794`.

[47] G. Cerutti, R. Prasad, and E. Farella. “Convolutional neural network on embedded platform for people presence detection in low resolution thermal images”. In: *ICASSP 2019-2019 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*. IEEE. 2019.

[48] Z. Chang, L. Hao, H. Tan, and W. Li. “Design of mobile garbage collection robot based on visual recognition”. In: *2020 IEEE 3rd International Conference on Automation, Electronics and Electrical Engineering (AUTEEE)*. 2020, pp. 448–451. DOI: `10.1109/AUTEEE50969.2020.9315545`.

[49] E. Chao and R. Stickler. *Internal Review of MSHAs Actions at the Sago Mine Wolf Run Mining Company Sago, Upshur County, West Virginia.* Tech. rep. U.S. Department of Labor Mine Safety, Health Administration Program Evaluation, and Information Resources, June 2007.

[50] R. O. Chavez-Garcia, J. Guzzi, L. M. Gambardella, and A. Giusti. “Learning Ground Traversability From Simulations”. In: *IEEE Robotics and Automation Letters* 3.3 (2018), pp. 1695–1702. DOI: `10.1109/LRA.2018.2801794`.

[51] Y. Chen and H. Shin. “Multispectral image fusion based pedestrian detection using a multilayer fused deconvolutional single-shot detector”. In: *J. Opt. Soc. Am. A* 37.5 (May 2020), pp. 768–779. DOI: `10.1364/JOSAA.386410`. URL: `https://opg.optica.org/josaa/abstract.cfm?URI=josaa-37-5-768`.

[52] Z. Chen et al. “Towards hybrid gait obstacle avoidance for a six wheel-legged robot with payload transportation”. In: *Journal of Intelligent & Robotic Systems* 102.3 (2021), p. 60.

[53] S. Choi, J. Park, J. Byun, and W. Yu. “Robust ground plane detection from 3D point clouds”. In: *2014 14th International Conference on Control, Automation and Systems (ICCAS 2014)*. 2014, pp. 1076–1081. DOI: `10.1109/ICCAS.2014.6987936`.

[54] J.-W. Chung, I.-W. Park, and J.-H. Oh. “On the design and development of a quadruped robot platform”. In: *Advanced Robotics* 24.1-2 (2010). Cited by: 15, pp. 277–298. DOI: `10.1163/016918609X12586214966992`.

[55] L. T. by Content Engine. *Hurricane Ian leaves a trail of destruction in Florida.* Oct. 2022. URL: `https://search.proquest.com/docview/2720376485`.

[56] CRASAR. *THE CENTER FOR ROBOT-ASSISTED SEARCH AND RESCUE.* URL: `https://crasar.org/`.

[57] L. Crocco and V. Ferrara. “A review on ground penetrating radar technology for the detection of buried or trapped victims”. In: *2014 International Conference on Collaboration Technologies and Systems (CTS)*. 2014, pp. 535–540. DOI: `10.1109/CTS.2014.6867620`.

[58] N. Cross and E. Campbell. *This was Spain’s worst terrorist attack since trains were bombed in Madrid in 2004.* Aug. 2017. URL: `https://search.informit.org/documentSummary;res=TVNEWS;dn=TSM201708180217`.

[59] C. Cruz Ulloa, J. del Cerro, and A. Barrientos. “Mixed-reality for quadruped-robotic guidance in SAR tasks”. In: *Journal of Computational Design and Engineering* 10.4 (2023), pp. 1479–1489.

[60] C. Cruz Ulloa, D. Domínguez, J. Del Cerro, and A. Barrientos. “A Mixed-Reality Tele-Operation Method for High-Level Control of a Legged-Manipulator Robot”. In: *Sensors* 22.21 (2022). ISSN: 1424-8220. DOI: `10.3390/s22218146`. URL: `https://www.mdpi.com/1424-8220/22/21/8146`.

[61] C. Cruz Ulloa, G. Prieto Sánchez, A. Barrientos, and J. Del Cerro. “Autonomous Thermal Vision Robotic System for Victims Recognition in Search and Rescue Missions”. In: *Sensors* 21.21 (2021). ISSN: 1424-8220. DOI: `10.3390/s21217346`. URL: `https://www.mdpi.com/1424-8220/21/21/7346`.

[62] CTU. *DARPA Subterranean Challenge - CTU in Prague*. URL: `https://cyber.felk.cvut.cz/tag/darpa-subterranean-challenge/`.

[63] A. Cuddy. *Turkey earthquake: Being buried alive with my newborn son.* Feb. 2023. URL: `https://www.bbc.com/news/world-middle-east-64620357`.

[64] C. Dario Bellicoso et al. “Dynamic locomotion and whole-body control for quadrupedal robots”. In: *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2017, pp. 3359–3365. DOI: `10.1109/IROS.2017.8206174`.

[65] A. Davids. “Urban search and rescue robots: from tragedy to technology”. In: *IEEE Intelligent Systems* 17.2 (2002), pp. 81–83. DOI: `10.1109/MIS.2002.999224`.

[66] T. M. Dawdi, N. Abdalla, Y. M. Elkalyoubi, and B. Soudan. “Locating victims in hot environments using combined thermal and optical imaging”. In: *Computers & Electrical Engineering* 85 (2020), p. 106697. ISSN: 0045-7906. DOI: `https://doi.org/10.1016/j.compeleceng.2020.106697`. URL: `https://www.sciencedirect.com/science/article/pii/S0045790620305528`.

[67] P. De Petris et al. “Marsupial Walking-and-Flying Robotic Deployment for Collaborative Exploration of Unknown Environments”. In: *2022 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*. 2022, pp. 188–194. DOI: `10.1109/SSRR56537.2022.10018768`.

[68] P. G. De Santos, E. Garcia, and J. Estremera. *Quadrupedal locomotion: an introduction to the control of four-legged robots.* Vol. 1. Springer, 2006.

[69] J. Delmerico et al. “The current state and future outlook of rescue robotics”. In: *Journal of Field Robotics* 36.7 (2019), pp. 1171–1191. DOI: `https://doi.org/10.1002/rob.21887`. eprint: `https://onlinelibrary.wiley.com/doi/pdf/10.1002/rob.21887`. URL: `https://onlinelibrary.wiley.com/doi/abs/10.1002/rob.21887`.

[70] D. S. Dhande and S. S. Ohol. “Ground Traversability Estimation for Quadruped Robot with Modified DWA Algorithm”. In: *2022 International Conference on*

*Signal and Information Processing (IConSIP)*. 2022, pp. 1–5. DOI: 10.1109/ICoNSIP49665.2022.10007496.

[71] J. Di Carlo, P. M. Wensing, B. Katz, G. Bledt, and S. Kim. “Dynamic Locomotion in the MIT Cheetah 3 Through Convex Model-Predictive Control”. In: *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2018, pp. 1–9. DOI: 10.1109/IROS.2018.8594448.

[72] Y. Ding, A. Pandala, and H.-W. Park. “Real-time Model Predictive Control for Versatile Dynamic Motions in Quadrupedal Robots”. In: *2019 International Conference on Robotics and Automation (ICRA)*. 2019, pp. 8484–8490. DOI: 10.1109/ICRA.2019.8793669.

[73] P. Dong, X. Wang, H. Xing, Y. Liu, and M. Zhang. “Design and control of a tracked robot for search and rescue in nuclear power plant”. In: *2016 International Conference on Advanced Robotics and Mechatronics (ICARM)*. 2016, pp. 330–335. DOI: 10.1109/ICARM.2016.7606941.

[74] B. Douillard et al. “On the segmentation of 3D LIDAR point clouds”. In: *2011 IEEE International Conference on Robotics and Automation*. 2011, pp. 2798–2805. DOI: 10.1109/ICRA.2011.5979818.

[75] G. Dudek, M. R. Jenkin, E. Milios, and D. Wilkes. “A taxonomy for multi-agent robotics”. In: *Autonomous Robots* 3 (1996), pp. 375–397.

[76] T. Dudzik et al. “Robust Autonomous Navigation of a Small-Scale Quadruped Robot in Real-World Environments”. In: *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2020, pp. 3664–3671. DOI: 10.1109/IROS45743.2020.9340701.

[77] R. Eguchi, KenElwood, E. K. Lee, and M. Greene. *The 2010 Canterbury and 2011 Christchurch New Zealand Earthquakes and the 2011 Tohoku Japan Earthquake*. Tech. rep. Earthquake Engineering Research Institute, 2012.

[78] M. Eich, F. Grimminger, and F. Kirchner. “A Versatile Stair-Climbing Robot for Search and Rescue Applications”. In: *2008 IEEE International Workshop on Safety, Security and Rescue Robotics*. 2008, pp. 35–40. DOI: 10.1109/SSRR.2008.4745874.

[79] M. Eisenbach, D. Seichter, T. Wengefeld, and H.-M. Gross. “Cooperative multi-scale Convolutional Neural Networks for person detection”. In: *2016 International Joint Conference on Neural Networks (IJCNN)*. 2016, pp. 267–276. DOI: 10.1109/IJCNN.2016.7727208.

[80] P. Ewen et al. “Generating continuous motion and force plans in real-time for legged mobile manipulation”. In: *2021 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE. 2021, pp. 4933–4939.

[81] P. Fankhauser, M. Bjelonic, C. Dario Bellicoso, T. Miki, and M. Hutter. “Robust Rough-Terrain Locomotion with a Quadrupedal Robot”. In: *2018 IEEE International Conference on Robotics and Automation (ICRA)*. 2018, pp. 5761–5768. DOI: 10.1109/ICRA.2018.8460731.

[82] P. Fankhauser, M. Bloesch, C. Gehring, M. Hutter, and R. Siegwart. “Robot-centric elevation mapping with uncertainty estimates”. In: *Mobile Service Robotics*. World Scientific, 2014, pp. 433–440.

[83] P. Fankhauser and M. Hutter. “A Universal Grid Map Library: Implementation and Use Case for Rough Terrain Navigation”. In: vol. 625. Jan. 2016. ISBN: 978-3-319-26052-5. DOI: `10.1007/978-3-319-26054-9_5`.

[84] P. Fankhauser et al. “Collaborative navigation for flying and walking robots”. In: *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2016, pp. 2859–2866. DOI: `10.1109/IROS.2016.7759443`.

[85] A. Farinelli, L. Iocchi, and D. Nardi. “Multirobot systems: a classification focused on coordination”. In: *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)* 34.5 (2004), pp. 2015–2028. DOI: `10.1109/TSMCB.2004.832155`.

[86] J. Ferreira, A. P. Moreira, M. Silva, and F. Santos. “A survey on localization, mapping, and trajectory planning for quadruped robots in vineyards”. In: *2022 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC)*. 2022, pp. 237–242. DOI: `10.1109/ICARSC55462.2022.9784796`.

[87] G. Ferri et al. “DustCart, an autonomous robot for door-to-door garbage collection: From DustBot project to the experimentation in the small town of Peccioli”. In: *2011 IEEE International Conference on Robotics and Automation*. 2011, pp. 655–660. DOI: `10.1109/ICRA.2011.5980254`.

[88] H. Ferrolho, V. Ivan, W. Merkt, I. Havoutis, and S. Vijayakumar. “RoLoMa: Robust Loco-Manipulation for Quadruped Robots with Arms”. In: *arXiv preprint arXiv:2203.01446* (2022).

[89] P. Filitchkin and K. Byl. “Feature-based terrain classification for LittleDog”. In: *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2012, pp. 1387–1392. DOI: `10.1109/IROS.2012.6386042`.

[90] Fortin. *Papers with code - timberseg 1.0 dataset*. Mar. 2022. URL: `https://paperswithcode.com/dataset/timberseg-1-0`.

[91] T. Fukuda, Y. Hasegawa, K. Sekiyama, and T. Aoyama. *Multi-locomotion robotic systems: New concepts of bio-inspired robotics*. Vol. 81. springer, 2012.

[92] A. Fung, L. Y. Wang, K. Zhang, G. Nejat, and B. Benhabib. “Using deep learning to find victims in unknown cluttered urban search and rescue environments”. In: *Current Robotics Reports* 1 (2020), pp. 105–115.

[93] M. Gaertner, M. Bjelonic, F. Farshidian, and M. Hutter. “Collision-Free MPC for Legged Robots in Static and Dynamic Scenes”. In: *2021 IEEE International Conference on Robotics and Automation (ICRA)*. 2021, pp. 8266–8272. DOI: `10.1109/ICRA48506.2021.9561326`.

[94] R. Gallagher, B. Lizundia, and J. C. Barnes. *Building safety evaluation after the February 22, 2011 Christchurch, New Zealand earthquake: observations by the ATC reconnaissance team.* Tech. rep. Applied Technology Council, 2012.

[95] C. Gehring et al. “Control of dynamic gaits for a quadrupedal robot”. In: *2013 IEEE International Conference on Robotics and Automation.* 2013, pp. 3287–3292. DOI: `10.1109/ICRA.2013.6631035`.

[96] M. Geisert, T. Yates, A. Orgen, P. Fernbach, and I. Havoutis. “Contact Planning for the ANYmal Quadruped Robot Using an Acyclic Reachability-Based Planner”. In: *Towards Autonomous Robotic Systems.* Ed. by K. Althoefer, J. Konstantinova, and K. Zhang. Cham: Springer International Publishing, 2019, pp. 275–287. ISBN: 978-3-030-23807-0.

[97] T. George and T. Amudha. “Genetic Algorithm Based Multi-objective Optimization Framework to Solve Traveling Salesman Problem”. In: *Advances in Computing and Intelligent Systems.* Ed. by H. Sharma, K. Govindan, R. C. Poonia, S. Kumar, and W. M. El-Medany. Singapore: Springer Singapore, 2020, pp. 141–151. ISBN: 978-981-15-0222-4.

[98] A. Gomez, F. Conti, and L. Benini. “Thermal image-based CNN’s for ultra-low power people recognition”. In: *Proceedings of the 15th ACM International Conference on Computing Frontiers.* 2018, pp. 326–331.

[99] Z. Gong, Y. Zhang, D. Lu, and T. Wu. “Vision-Based Quadruped Pose Estimation and Gait Parameter Extraction Method”. In: *Electronics* 11.22 (2022). ISSN: 2079-9292. DOI: `10.3390/electronics11223702`. URL: `https://www.mdpi.com/2079-9292/11/22/3702`.

[100] I. Greatbatch, R. J. Gosling, and S. Allen. “Quantifying Search Dog Effectiveness in a Terrestrial Search and Rescue Environment”. In: *Wilderness and Environmental Medicine* 26.3 (2015), pp. 327–334. ISSN: 1080-6032. DOI: `https://doi.org/10.1016/j.wem.2015.02.009`. URL: `https://www.sciencedirect.com/science/article/pii/S1080603215001027`.

[101] F. Grimminger et al. “An Open Torque-Controlled Modular Robot Architecture for Legged Locomotion Research”. In: *IEEE Robotics and Automation Letters* 5.2 (2020), pp. 3650–3657. DOI: `10.1109/LRA.2020.2976639`.

[102] K. Grover, F. S. Barbosa, J. Tumova, and J. Kretinsky. “Semantic Abstraction-Guided Motion Planning for scLTL Missions in Unknown Environments.” In: *Robotics: Science and Systems.* 2021.

[103] M. Gu, E. Croft, and A. Cosgun. “AR Point &Click: An Interface for Setting Robot Navigation Goals”. In: *Social Robotics.* Ed. by F. Cavallo et al. Cham: Springer Nature Switzerland, 2022, pp. 38–49. ISBN: 978-3-031-24667-8. DOI: `10.1007/978-3-031-24667-8_4`.

[104] M. Guarnieri et al. “HELIOS system: A team of tracked robots for special urban search and rescue operations”. In: *2009 IEEE/RSJ International Conference on*

*Intelligent Robots and Systems*. 2009, pp. 2795–2800. DOI: `10.1109/IROS.2009.5354452`.

[105] S. Gupta, R. Girshick, P. Arbeláez, and J. Malik. "Learning Rich Features from RGB-D Images for Object Detection and Segmentation". In: *Computer Vision – ECCV 2014*. Ed. by D. Fleet, T. Pajdla, B. Schiele, and T. Tuytelaars. Cham: Springer International Publishing, 2014, pp. 345–360. ISBN: 978-3-319-10584-0.

[106] M. Gyarmati, M. O. Tătar, and C. Rusu. "Design and Development of a Search and Rescue Robot with TriSTAR Locomotion Units". In: *New Advances in Mechanisms, Mechanical Transmissions and Robotics*. Ed. by E.-C. Lovasz, I. Maniu, I. Doroftei, M. Ivanescu, and C.-M. Gruescu. Cham: Springer International Publishing, 2021, pp. 172–186. ISBN: 978-3-030-60076-1.

[107] S. Habibian et al. "Design and implementation of a maxi-sized mobile robot (Karo) for rescue missions". In: *Robomech Journal* 8.1 (2021), pp. 1–33.

[108] G. Haddeler et al. "Traversability analysis with vision and terrain probing for safe legged robot navigation". In: *Frontiers in Robotics and AI* 9 (2022), p. 887910.

[109] S. Halder et al. "Real-Time and Remote Construction Progress Monitoring with a Quadruped Robot Using Augmented Reality". In: *Buildings* 12.11 (2022). ISSN: 2075-5309. DOI: `10.3390/buildings12112027`. URL: `https://www.mdpi.com/2075-5309/12/11/2027`.

[110] W. Hamid, A. A. M. Faudzi, and K. B. Ismail. "Design and Analysis of an Articulated Tracked Robot for Search and Rescue Operations". In: *2022 IEEE 5th International Symposium in Robotics and Manufacturing Automation (ROMA)*. 2022, pp. 1–6. DOI: `10.1109/ROMA55875.2022.9915662`.

[111] Q. Hao, Z. Wang, J. Wang, and G. Chen. "Stability-Guaranteed and High Terrain Adaptability Static Gait for Quadruped Robots". In: *Sensors* 20.17 (2020). ISSN: 1424-8220. DOI: `10.3390/s20174911`. URL: `https://www.mdpi.com/1424-8220/20/17/4911`.

[112] H. Haq. *Three survivors pulled alive from earthquake rubble in Turkey, more than 248 hours after quake*. Feb. 2023. URL: `https://www.cnn.com/2023/02/16/europe/turkey-syria-earthquake-rescue-efforts-intl/index.html`.

[113] J. Harmsen, M. Willacy, and D. Stone. *Japan Earthquake Disaster Zone: Five days after the tsunami hit Japan's north east it is now clear there are tens of thousands of people dead or missing*. Mar. 2011. URL: `https://search.informit.org/documentSummary;res=TVNEWS;dn=TES20111101040`.

[114] S. G. Hart. "Nasa-Task Load Index (NASA-TLX); 20 Years Later". In: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 50.9 (2006), pp. 904–908. DOI: `10.1177/154193120605000909`. eprint: `https://doi.org/10.1177/154193120605000909`. URL: `https://doi.org/10.1177/154193120605000909`.

[115] D. R. Hartawan, T. W. Purboyo, and C. Setianingsih. “Disaster Victims Detection System Using Convolutional Neural Network (CNN) Method”. In: *2019 IEEE International Conference on Industry 4.0, Artificial Intelligence, and Communications Technology (IAICT).* 2019, pp. 105–111. DOI: `10.1109/ICIAICT.2019.8784782`.

[116] N. Hawes et al. “Dora The Explorer : A Motivated Robot”. In: *9th Int. Conf. on Autonomous Agents and Multiagent Sys- tems.* 2010.

[117] S. Hirose and K. Kato. “Study on quadruped walking robot in Tokyo Institute of Technology - past, present and future”. In: vol. 1. Cited by: 51. 2000, pp. 414–419. URL: `https://www.scopus.com/inward/record.uri?eid=2-s2.0-0033727412&partnerID=40&md5=2e5fe82cd8df76a08d2484457713b9cc`.

[118] S. Hirose, K. Yoneda, and H. Tsukagoshi. “TITAN VII: Quadruped walking and manipulating robot on a steep slope”. In: *Proceedings of International Conference on Robotics and Automation.* Vol. 1. IEEE. 1997, pp. 494–500.

[119] Y. Huang, Q. Wei, H. Ma, and H. An. “Motion Planning for a Bounding Quadruped Robot Using iLQG Based MPC”. In: *Journal of Physics: Conference Series* 1905.1 (May 2021), p. 012016. DOI: `10.1088/1742-6596/1905/1/012016`. URL: `https://dx.doi.org/10.1088/1742-6596/1905/1/012016`.

[120] A. Hutchinson. “Machines can walk”. In: *The Chartered Mechanical Engineer* 11 (1967). Cited by: 3, pp. 480–484. URL: `https://www.scopus.com/inward/record.uri?eid=2-s2.0-84995078932&partnerID=40&md5=ae0d42e9ac8ec09f1b406b0e169a5acc`.

[121] M. Hutter. “StarlETH Co.: Design and control of legged robots with compliant actuation”. PhD thesis. ETH Zurich, 2013.

[122] M. Hutter et al. “ANYmal - a highly mobile and dynamic quadrupedal robot”. In: *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).* 2016, pp. 38–44. DOI: `10.1109/IROS.2016.7758092`.

[123] M. Hutter et al. “Anymal-toward legged robots for harsh environments”. In: *Advanced Robotics* 31.17 (2017), pp. 918–931.

[124] J. Hutton, G. Lipa, D. Baustian, J. Sulik, and R. Bruce. “High accuracy direct georeferencing of the Altum multi-spectral UAV camera and its application to high throughput plant phenotyping”. In: *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* 43 (2020), pp. 451–456.

[125] D. J. Hyun, S. Seok, J. Lee, and S. Kim. “High speed trot-running: Implementation of a hierarchical controller using proprioceptive impedance control on the MIT Cheetah”. In: *The International Journal of Robotics Research* 33.11 (2014), pp. 1417–1445. DOI: `10.1177/0278364914532150`. eprint: `https://doi.org/10.1177/0278364914532150`. URL: `https://doi.org/10.1177/0278364914532150`.

[126] ICRA. *ICRA2023 Quadrupeds Challenge.* URL: `https://quadruped-robot-challenges.notion.site/ICRA-2023-Quadruped-Robot-Challenges`.

[127] W. Ilg, J. Albiez, H. Jedele, K. Berns, and R. Dillmann. “Adaptive periodic movement control for the four legged walking machine BISAM”. In: *Proceedings 1999 IEEE International Conference on Robotics and Automation (Cat. No. 99CH36288C)*. Vol. 3. IEEE. 1999, pp. 2354–2359.

[128] B. Ilikci, L. Chen, H. Cho, and Q. Liu. “Heat-Map Based Emotion and Face Recognition from Thermal Images”. In: *2019 Computing, Communications and IoT Applications (ComComAp)*. IEEE. 2019, pp. 449–453.

[129] *Infrared Thermography: Making the invisible visible.* es. `https://ebuilding.es/termografia-infrarroja/`. Acceso: 18 - 8 -2023. 2017.

[130] Institute for Economics & Peace. *Ecological Threat Report 2021: Understanding Ecological Threats, Resilience and Peace.* Tech. rep. Sidney, 2021. URL: `http://visionofhumanity.org/resources`.

[131] A. Jacoff, E. Messina, B. A. Weiss, S. Tadokoro, and Y. Nakagawa. “Test arenas and performance metrics for urban search and rescue robots”. In: *Proceedings 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2003)(Cat. No. 03CH37453)*. Vol. 4. IEEE. 2003, pp. 3396–3403.

[132] F. B. Jaradat and D. Valles. “A Victims Detection Approach for Burning Building Sites Using Convolutional Neural Networks”. In: *2020 10th Annual Computing and Communication Workshop and Conference (CCWC)*. 2020, pp. 0280–0286. DOI: `10.1109/CCWC47524.2020.9031275`.

[133] A. Jha et al. “Development of Autonomous Garbage Collector Robot”. In: *Proceedings of the Third International Conference on Microelectronics, Computing and Communication Systems*. Ed. by V. Nath and J. K. Mandal. Singapore: Springer Singapore, 2019, pp. 567–576. ISBN: 978-981-13-7091-5.

[134] Y. Ji, B. Zhang, and K. Sreenath. “Reinforcement Learning for Collaborative Quadrupedal Manipulation of a Payload over Challenging Terrain”. In: *2021 IEEE 17th International Conference on Automation Science and Engineering (CASE)*. 2021, pp. 899–904. DOI: `10.1109/CASE49439.2021.9551481`.

[135] Jiang. *Papers with code - rellis-3d dataset.* Nov. 2021. URL: `https://paperswithcode.com/dataset/rellis-3d`.

[136] G. Jocher. *YOLOv5.* 2020. URL: `https://github.com/ultralytics/yolov5` (visited on 02/23/2022).

[137] K. E. Jones, K. Dashfield, A. B. Downend, and C. M. Otto. “Search-and-rescue dogs: an overview for veterinarians”. In: *Journal of the American Veterinary Medical Association* 225.6 (2004), pp. 854–860.

[138] M. Kalakrishnan, J. Buchli, P. Pastor, M. Mistry, and S. Schaal. “Fast, robust quadruped locomotion over challenging terrain”. In: *2010 IEEE International Conference on Robotics and Automation.* 2010, pp. 2665–2670. DOI: `10.1109/ROBOT.2010.5509805`.

[139] N. A. S. Kamarudin et al. “Development of water surface mobile garbage collector robot”. In: *International Journal of Research in Engineering, Science and Management* 36.01 (2021).

[140] M. Kamezaki et al. “Design of four-arm four-crawler disaster response robot OCTOPUS”. In: *2016 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, May 2016.

[141] P. Kang et al. “Investigating Lushan Earthquake Victims’ Individual Behavior Response and Rescue Organization”. In: *International Journal of Environmental Research and Public Health* 14 (Dec. 2017), p. 1556. DOI: `10.3390/ijerph14121556`.

[142] T. Karakurt, A. Durdu, and E. H. Dursun. “Petri-net based control of six legged spider robot”. In: *2015 International Conference on Advanced Robotics (ICAR)*. 2015, pp. 117–122. DOI: `10.1109/ICAR.2015.7251443`.

[143] L. Kästner and J. Lambrecht. “Augmented-Reality-Based Visualization of Navigation Data of Mobile Robots on the Microsoft Hololens - Possibilities and Limitations”. In: *2019 IEEE International Conference on Cybernetics and Intelligent Systems (CIS) and IEEE Conference on Robotics, Automation and Mechatronics (RAM)*. 2019, pp. 344–349. DOI: `10.1109/CIS-RAM47153.2019.9095836`.

[144] K. Kato and S. Hirose. “Development of the quadruped walking robot,” TITAN-IX””. In: *2000 26th Annual Conference of the IEEE Industrial Electronics Society. IECON 2000. 2000 IEEE International Conference on Industrial Electronics, Control and Instrumentation. 21st Century Technologies*. Vol. 1. IEEE. 2000, pp. 40–45.

[145] I. Katsamenis, E. Protopapadakis, A. Voulodimos, D. Dres, and D. Drakoulis. “Man Overboard Event Detection from RGB and Thermal Imagery: Possibilities and Limitations”. In: *Proceedings of the 13th ACM International Conference on PErvasive Technologies Related to Assistive Environments*. PETRA ’20. Corfu, Greece: Association for Computing Machinery, 2020. ISBN: 9781450377737. DOI: `10.1145/3389189.3397998`. URL: `https://doi.org/10.1145/3389189.3397998`.

[146] B. Katz, J. D. Carlo, and S. Kim. “Mini Cheetah: A Platform for Pushing the Limits of Dynamic Quadruped Control”. In: *2019 International Conference on Robotics and Automation (ICRA)*. 2019, pp. 6295–6301. DOI: `10.1109/ICRA.2019.8793865`.

[147] S. Khandare, S. Badak, Y. Sawant, and S. Solkar. “Object detection based garbage collection robot (E-Swachh)”. In: *International Research Journal of Engineering and Technology (IRJET)* (2018).

[148] D. Kim et al. “Vision Aided Dynamic Exploration of Unstructured Terrain with a Small-Scale Quadruped Robot”. In: *2020 IEEE International Conference on Robotics and Automation (ICRA)*. 2020, pp. 2464–2470. DOI: `10.1109/ICRA40945.2020.9196777`.

[149] Y.-S. Kim, G.-P. Jung, H. Kim, K.-J. Cho, and C.-N. Chu. “Wheel Transformer: A Wheel-Leg Hybrid Robot With Passive Transformable Wheels”. In: *IEEE Transactions on Robotics* 30.6 (2014), pp. 1487–1498. DOI: `10.1109/TRO.2014.2365651`.

[150] H. Kimura and Y. Fukuoka. “Adaptive dynamic walking of the quadruped on irregular terrain-autonomous adaptation using neural system model”. In: *Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No.00CH37065)*. Vol. 1. 2000, 436–443 vol.1. DOI: `10.1109/ROBOT.2000.844094`.

[151] H. Kimura, I. Shimoyama, and H. Miura. “Dynamics in the dynamic walk of a quadruped robot”. In: *Advanced Robotics* 4.3 (1989), pp. 283–301.

[152] S. Kitano, S. Hirose, A. Horigome, and G. Endo. “TITAN-XIII: sprawling-type quadruped robot with ability of fast and energy-efficient walking”. In: *ROBOMECH Journal* 3.1 (2016). Cited by: 51; All Open Access, Gold Open Access. DOI: `10.1186/s40648-016-0047-1`. URL: `https://www.scopus.com/inward/record.uri?eid=2-s2.0-85042631292&doi=10.11862fs40648-016-0047-1&partnerID=40&md5=7592d6c71ebb0655e1a0adb1a2f1b06e`.

[153] D. Kırcalı and F. B. Tek. “Ground Plane Detection Using an RGB-D Sensor”. In: *Information Sciences and Systems 2014*. Ed. by T. Czachórski, E. Gelenbe, and R. Lent. Cham: Springer International Publishing, 2014, pp. 69–77. ISBN: 978-3-319-09465-6.

[154] T. Klamt and S. Behnke. “Anytime hybrid driving-stepping locomotion planning”. In: *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2017, pp. 4444–4451. DOI: `10.1109/IROS.2017.8206310`.

[155] T. Klamt et al. “Remote mobile manipulation with the centauro robot: Full-body telepresence and autonomous operator assistance”. In: *Journal of Field Robotics* 37.5 (2019), pp. 889–919. DOI: `10.1002/rob.21895`. URL: `https://onlinelibrary.wiley.com/doi/10.1002/rob.21895`.

[156] J. Z. Kolter, M. P. Rodgers, and A. Y. Ng. “A control architecture for quadruped locomotion over rough terrain”. In: *2008 IEEE International Conference on Robotics and Automation*. 2008, pp. 811–818. DOI: `10.1109/ROBOT.2008.4543305`.

[157] H. Komatsu et al. “Development of quadruped walking robot TITAN XII and its basic consideration on the control of large obstacle traversing motion”. In: *Transactions of the JSME (in Japanese)* 80.813 (2014).

[158] B. Kong. “Modeling and Algorithm Implementation of Free Gait Planning for Quadruped Robot Based on Machine Vision”. In: *2021 International Conference on Networking, Communications and Information Technology (NetCIT)*. 2021, pp. 196–199. DOI: `10.1109/NetCIT54147.2021.00047`.

[159] D. Konig et al. “Fully Convolutional Region Proposal Networks for Multispectral Person Detection”. In: *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR) Workshops*. July 2017, pp. 116–128.

[160] I. M. Koo et al. “Development of a quadruped walking robot AiDIN-III using biologically inspired kinematic analysis”. In: *International Journal of Control, Automation and Systems* 11 (2013), pp. 1276–1289.

[161] T. Kot, P. Novák, and J. Bajak. “Using HoloLens to create a virtual operator station for mobile robots”. In: *2018 19th International Carpathian Control Conference (ICCC)*. 2018, pp. 422–427. DOI: `10.1109/CarpathianCC.2018.8399667`.

[162] P. Kozlowski and K. Walas. “Deep neural networks for terrain recognition task”. In: *2018 Baltic URSI Symposium (URSI)*. 2018, pp. 283–286. DOI: `10.23919/URSI.2018.8406736`.

[163] M. Krišto, M. Ivasic-Kos, and M. Pobar. “Thermal Object Detection in Difficult Weather Conditions Using YOLO”. In: *IEEE Access* 8 (2020), pp. 125459–125476. DOI: `10.1109/ACCESS.2020.3007481`.

[164] E. Krotkov et al. “The DARPA Robotics Challenge Finals: Results and Perspectives”. In: *Journal of Field Robotics* 34 (2017), pp. 229–240.

[165] G. Kruijff et al. “Rescue Robots at Earthquake-Hit Mirandola, Italy: a Field Report”. In: Nov. 2012. DOI: `10.1109/SSRR.2012.6523866`.

[166] I. Kruijff et al. “Deployment of ground and aerial robots in earthquake-struck Amatrice in Italy (brief report)”. In: *2016 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*. Oct. 2016, pp. 278–279. DOI: `10.1109/SSRR.2016.7784314`.

[167] D. Krupke et al. “Comparison of Multimodal Heading and Pointing Gestures for Co-Located Mixed Reality Human-Robot Interaction”. In: *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2018, pp. 1–9. DOI: `10.1109/IROS.2018.8594043`.

[168] D. Labs. *Domestic Trash / Garbage Dataset*. Oct. 1, 2022. URL: `https://www.kaggle.com/datasets/dataclusterlabs/domestic-trash-garbage-dataset` (visited on 07/01/2023).

[169] Lambert. *Papers with code - MSEG dataset*. Dec. 2021. URL: `https://paperswithcode.com/dataset/mseg`.

[170] T. S. LANGDUN, M. OSWALD, T. STADELMANN, and P. SAGER. “Building a Vision-Based AI Demonstrator with Unitree A1 Quadruped Robot”. In: (2022).

[171] P. Leber and K. Dalm. “Using MR to Interact with a Mobile Robot Based on ROS”. In: *Available at SSRN 4074341* (2022). DOI: `10.2139/ssrn.4074341`.

[172] J. Lee, J. Hwangbo, L. Wellhausen, V. Koltun, and M. Hutter. “Learning quadrupedal locomotion over challenging terrain”. In: *Science Robotics* 5.47 (2020), eabc5986. DOI: `10.1126/scirobotics.abc5986`. eprint: `https://www.science.org/doi/pdf/10.1126/scirobotics.abc5986`. URL: `https://www.science.org/doi/abs/10.1126/scirobotics.abc5986`.

[173] S. Lee, D. Har, and D. Kum. “Drone-Assisted Disaster Management: Finding Victims via Infrared Camera and Lidar Sensor Fusion”. In: *2016 3rd Asia-Pacific World Congress on Computer Science and Engineering (APWC on CSE)*. 2016, pp. 84–89. DOI: `10.1109/APWC-on-CSE.2016.025`.

[174] J. D. Leon. "Definicion y analisis de los modos de marcha de un robot hexapodo para tareas de busqueda y rescate". MA thesis. Universidad Politecnica de Madrid, 2015.

[175] J. Li et al. "Whole-Body Control for a Torque-Controlled Legged Mobile Manipulator". In: *Actuators* 11.11 (2022). ISSN: 2076-0825. DOI: `10.3390/act11110304`. URL: `https://www.mdpi.com/2076-0825/11/11/304`.

[176] K. Li, R. Bacher, W. Leemans, and F. Steinicke. "Towards Robust Exocentric Mobile Robot Tele-Operation in Mixed Reality". In: *5th International Workshop on Virtual, Augmented, and Mixed Reality for HRI.* 2022. URL: `https://openreview.net/pdf?id=HYIes841hJc`.

[177] C. Liang, C. Liu, X. Liu, L. Cheng, and C. Yang. "Robot Teleoperation System Based on Mixed Reality". In: *2019 IEEE 4th International Conference on Advanced Robotics and Mechatronics (ICARM).* 2019, pp. 384–389. DOI: `10.1109/ICARM.2019.8834302`.

[178] T. Y. Lin et al. "Microsoft COCO: Common objects in context". In: *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* 8693 LNCS.PART 5 (2014), 740-755. ISSN: 16113349. DOI: `10.1007/978-3-319-10602-1_48`. arXiv: `1405.0312`.

[179] T. Linder et al. "Rescue robots at the collapse of the municipal archive of Cologne city: A field report". In: *Safety Security and Rescue Robotics (SSRR),* July 2010, pp. 1–6.

[180] B. Lindqvist et al. "Multimodality robotic systems: Integrated combined legged-aerial mobility for subterranean search-and-rescue". In: *Robotics and Autonomous Systems* 154 (2022), p. 104134. ISSN: 0921-8890. DOI: `https://doi.org/10.1016/j.robot.2022.104134`. URL: `https://www.sciencedirect.com/science/article/pii/S0921889022000756`.

[181] J. Liu, Y. Wang, S. Ma, and B. Li. "Analysis of stairs-climbing ability for a tracked reconfigurable modular robot". In: *IEEE International Safety, Security and Rescue Rototics, Workshop, 2005.* 2005, pp. 36–41. DOI: `10.1109/SSRR.2005.1501238`.

[182] W.-Y. G. Louie and G. Nejat. "A victim identification methodology for rescue robots operating in cluttered USAR environments". In: *Advanced Robotics* 27.5 (2013), pp. 373–384. DOI: `10.1080/01691864.2013.763743`. eprint: `https://doi.org/10.1080/01691864.2013.763743`. URL: `https://doi.org/10.1080/01691864.2013.763743`.

[183] Y. Ma, F. Farshidian, T. Miki, J. Lee, and M. Hutter. "Combining Learning-Based Locomotion Policy With Model-Based Manipulation for Legged Mobile Manipulators". In: *IEEE Robotics and Automation Letters* 7.2 (2022), pp. 2377–2384. DOI: `10.1109/LRA.2022.3143567`.

[184] M. Mahue-Giangreco, W. Mack, H. Seligson, and L. B. Bourque. "Risk Factors Associated with Moderate and Serious Injuries Attributable to the 1994 Northridge Earthquake, Los Angeles, California". In: *Annals of Epidemiology* 11.5 (2001),

pp. 347–357. ISSN: 1047-2797. DOI: `https://doi.org/10.1016/S1047-2797(01)00220-4`. URL: `https://www.sciencedirect.com/science/article/pii/S1047279701002204`.

[185] R. Manduchi, A. Castano, A. Talukder, and L. Matthies. “Obstacle detection and terrain classification for autonomous off-road navigation”. In: *Autonomous robots* 18 (2005), pp. 81–102.

[186] S. Marshall-Pescini, C. Passalacqua, S. Barnard, P. Valsecchi, and E. Prato-Previde. “Agility and search and rescue training differently affects pet dogs’ behaviour in socio-cognitive tasks”. In: *Behavioural Processes* 81.3 (2009). Canine Behaviour and Cognition, pp. 416–422. ISSN: 0376-6357. DOI: `https://doi.org/10.1016/j.beproc.2009.03.015`. URL: `https://www.sciencedirect.com/science/article/pii/S0376635709000989`.

[187] A. Martín-Barrio, J. J. Roldán-Gómez, I. Rodríguez, J. del Cerro, and A. Barrientos. “Design of a Hyper-Redundant Robot and Teleoperation Using Mixed Reality for Inspection Tasks”. In: *Sensors* 20.8 (2020). ISSN: 1424-8220. DOI: `10.3390/s20082181`. URL: `https://www.mdpi.com/1424-8220/20/8/2181`.

[188] T. Mathew, G. Knox, W. Fong, T. Booysen, and S. Marais. “The design of a rugged, low-cost, man-packable urban search and rescue robotic system”. In: *Proceedings of the robotics and mechatronics conference of South Africa, Cape Town, South Africa*. 2014, pp. 27–28.

[189] C. Mayorga et al. “GABOT: Garbage Autonomous Collector for Indoors at Low Cost”. In: *2019 International Conference on Mechatronics, Electronics and Automotive Engineering (ICMEAE)*. 2019, pp. 56–61. DOI: `10.1109/ICMEAE.2019.00018`.

[190] M. W. McDaniel, T. Nishihata, C. A. Brooks, and K. Iagnemma. “Ground plane identification using LIDAR in forested environments”. In: *2010 IEEE International Conference on Robotics and Automation*. 2010, pp. 3831–3836. DOI: `10.1109/ROBOT.2010.5509963`.

[191] X. Meng, S. Wang, Z. Cao, and L. Zhang. “A review of quadruped robots and environment perception”. In: *2016 35th Chinese Control Conference (CCC)*. 2016, pp. 6350–6356. DOI: `10.1109/ChiCC.2016.7554355`.

[192] Metzger. *Papers with code - tas500 dataset.* Mar. 2021. URL: `https://paperswithcode.com/dataset/tas500`.

[193] J. Meyer et al. “A semantic world model for urban search and rescue based on heterogeneous sensors”. In: *RoboCup 2010: Robot Soccer World Cup XIV 14*. Springer. 2011, pp. 180–193.

[194] M. Micire. “Analysis of the robotic-assisted search and rescue response to the World Trade Center disaster”. MA thesis. Collegeof Engineering, University of South-Florida, July 2002.

[195] I. D. Miller et al. “Mine Tunnel Exploration Using Multiple Quadrupedal Robots”. In: *IEEE Robotics and Automation Letters* 5.2 (2020), pp. 2840–2847. DOI: `10.1109/LRA.2020.2972872`.

[196] M. V. Minniti, R. Grandia, F. Farshidian, and M. Hutter. “Adaptive CLF-MPC With Application to Quadrupedal Robots”. In: *IEEE Robotics and Automation Letters* 7.1 (2022), pp. 565–572. DOI: `10.1109/LRA.2021.3128697`.

[197] R. Moezzi, D. Krcmarik, H. Bahri, and J. Hlava. “Autonomous Vehicle Control based on HoloLens Technology and Raspberry Pi Platform: an Educational Perspective”. In: *IFAC-PapersOnLine* 52.27 (2019). 16th IFAC Conference on Programmable Devices and Embedded Systems PDES 2019, pp. 80–85. ISSN: 2405-8963. DOI: `10.1016/j.ifacol.2019.12.737`. URL: `https://www.sciencedirect.com/science/article/pii/S2405896319326862`.

[198] L. Molyneaux. “Development of an Underground Mine Scout Robot”. MA thesis. Victoria Universit y of Wellington, 2016.

[199] F. L. Moro et al. “Horse-like walking, trotting, and galloping derived from kinematic Motion Primitives (kMPs) and their application to walk/trot transitions in a compliant quadruped robot”. In: *Biological cybernetics* 107 (2013), pp. 309–320.

[200] Mortimer. *Papers with code - TAS-nir dataset.* Dec. 2022. URL: `https://paperswithcode.com/dataset/tas-nir`.

[201] R. Mosher. “Test and evaluation of a versatile walking truck”. In: *Proceedings of Off-Road Mobility Research Symposium, Washington DC, 1968.* 1968, pp. 359–379.

[202] R. R. Murphy, J. Kravitz, S. L. Stover, and R. Shoureshi. “Mobile robots in mine rescue and recovery”. In: *IEEE Robotics Automation Magazine* 16.2 (June 2009), pp. 91–103. DOI: `10.1109/MRA.2009.932521`.

[203] R. Murphy. “Biomimetic search for urban search and rescue”. In: *Proceedings. 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2000) (Cat. No.00CH37113).* Vol. 3. 2000, 2073–2078 vol.3. DOI: `10.1109/IROS.2000.895276`.

[204] R. Murphy. “Navigational and Mission Usability in Rescue Robots”. In: *Journal of the Robotics Society of Japan* 28 (Jan. 2010), pp. 142–146. DOI: `10.7210/jrsj.28.142`.

[205] R. Murphy, J. Casper, J. Hyams, M. Micire, and B. Minten. “Mobility and sensing demands in USAR”. In: *2000 26th Annual Conference of the IEEE Industrial Electronics Society. IECON 2000. 2000 IEEE International Conference on Industrial Electronics, Control and Instrumentation. 21st Century Technologies.* Ed. by IEEE. Nagoya, Japan, 2000.

[206] R. R. Murphy. *Disaster robotics.* MIT press, 2014.

[207] R. R. Murphy. “A decade of rescue robots”. In: *IEEE/RSJ International Conference on Intelligent Robots and Systems* (Oct. 2012).

[208] R. R. Murphy and S. Stover. “Rescue robots for mudslides: A descriptive study of the 2005 La Conchita mudslide response”. In: *Journal of Field Robotics* 25 (2008), pp. 3–16.

[209] R. R. Murphy, S. Tadokoro, and A. Kleiner. “Disaster Robotics”. In: *Springer Handbook of Robotics*. Ed. by B. Siciliano and O. Khatib. Cham: Springer International Publishing, 2016, pp. 1577–1604. ISBN: 978-3-319-32552-1.

[210] R. R. Murphy et al. “Search and Rescue Robotics”. In: *Springer Handbook of Robotics*. Ed. by B. Siciliano and O. Khatib. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 1151–1173. ISBN: 978-3-540-30301-5.

[211] R. R. Murphy et al. “Robot-Assisted Bridge Inspection after Hurricane Ike”. In: *IEEE International Workshop on Safety, Security & Rescue Robotics* (Nov. 2009).

[212] R. R. Murphy20, J. Kravitz, K. Peligren, J. Milward, and J. Stanway. “Preliminary report: Rescue robot at Crandall Canyon, Utah, mine disaster”. In: *2008 IEEE International Conference on Robotics and Automation*. May 2008, pp. 2205–2206. DOI: `10.1109/ROBOT.2008.4543535`.

[213] M. Naazare, F. G. Rosas, and D. Schulz. “Online Next-Best-View Planner for 3D-Exploration and Inspection with a Mobile Manipulator Robot”. In: *IEEE Robotics and Automation Letters* 7.2 (2022), 3779-3786. ISSN: 23773766. DOI: `10.1109/LRA.2022.3146558`.

[214] J. Nataprawira, Y. Gu, I. Goncharenko, and S. Kamijo. “Pedestrian Detection Using Multispectral Images and a Deep Neural Network”. In: *Sensors* 21.7 (2021). ISSN: 1424-8220. DOI: `10.3390/s21072536`. URL: `https://www.mdpi.com/1424-8220/21/7/2536`.

[215] M. Neumann, T. Predki, L. Heckes, and P. Labenda. “Snake-like, tracked, mobile robot with active flippers for urban search-and-rescue tasks”. In: *Industrial Robot: An International Journal* (2013).

[216] M. K. ·. C. News. *Help from above: Canadian drones sent to Nepal for disaster relief effort — CBC News*. May 2015. URL: `https://www.cbc.ca/news/world/nepal-earthquake-drones-used-by-canadian-relief-team-1.3051106`.

[217] M. Ning et al. “Design and analysis for a multifunctional rescue robot with four-bar wheel-legged structure”. In: *Advances in Mechanical Engineering* 10.2 (2018), p. 1687814017747399. DOI: `10.1177/1687814017747399`.

[218] X. Ning, F. Li, G. Tian, and Y. Wang. “An efficient outlier removal method for scattered point cloud data”. In: *PloS one* 13.8 (2018), e0201280.

[219] NIST. *National Institute of Standards and Technology*. 2022. URL: `https://www.nist.gov/`.

[220] G. Nugroho, Z. Taha, T. Nugraha, and H. Hadsanggeni. “Development of a Fixed Wing Unmanned Aerial Vehicle (UAV) for Disaster Area Monitoring and Map-

ping". In: *Journal of Mechatronics, Electrical Power, and Vehicular Technology* 6 (Dec. 2015), p. 83. DOI: `10.14203/j.mev.2015.v6.83-88`.

[221] O. Nurlansa, D. A. Istiqomah, and M. A. S. Pawitra. "AGATOR (automatic garbage collector) as automatic garbage collector robot model". In: *International Journal of Future Computer and Communication* 3.5 (2014), p. 367.

[222] M. Oitzman. *DARPA Subterranean Challenge pushes AMRs deep into the earth.* 2021. URL: `https://mobilerobotguide.com/2021/09/20/darpa-subterranean-challenge-pushes-amrs-deep-into-the-earth/`.

[223] *ONU News: Pese al aumento de las amenazas de origen natural en el siglo XXI, los paises siguen "sembrando las semillas de su destruccion".* `https://news.un.org/es/story/2020/10/1482242`. Accessed: 2023-5-30. 2020.

[224] M. Ostanin and A. Klimchik. "Interactive Robot Programing Using Mixed Reality". In: *IFAC-PapersOnLine* 51.22 (2018). 12th IFAC Symposium on Robot Control SYROCO 2018, pp. 50–55. ISSN: 2405-8963. DOI: `10.1016/j.ifacol.2018.11.517`. URL: `https://www.sciencedirect.com/science/article/pii/S2405896318332233`.

[225] M. Ostanin, R. Yagfarov, and A. Klimchik. "Interactive Robots Control Using Mixed Reality **The work presented in this paper was supported by the grant of Russian Science Foundation 17-19-01740." In: *IFAC-PapersOnLine* 52.13 (2019). 9th IFAC Conference on Manufacturing Modelling, Management and Control MIM 2019, pp. 695–700. ISSN: 2405-8963. DOI: `10.1016/j.ifacol.2019.11.307`. URL: `https://www.sciencedirect.com/science/article/pii/S2405896319312613`.

[226] M. Ostanin, S. Mikhel, A. Evlampiev, V. Skvortsova, and A. Klimchik. "Human-robot interaction for robotic manipulator programming in Mixed Reality". In: *2020 IEEE International Conference on Robotics and Automation (ICRA)*. 2020, pp. 2805–2811. DOI: `10.1109/ICRA40945.2020.9196965`.

[227] G. Panckhurst, S. Bell, and D. Henry. *Royal Commission on the Pike River Coal Mine Tragedy. Volume 1.* Tech. rep. Royal Commission on the Pike River Coal Mine Tragedy, Oct. 2012.

[228] G. Panckhurst, S. Bell, and D. Henry. *Royal Commission on the Pike River Coal Mine Tragedy. Volume 2.* Tech. rep. Royal Commission on the Pike River Coal Mine Tragedy, Oct. 2012.

[229] H.-W. Park, S. Park, and S. Kim. "Variable-speed quadrupedal bounding using impulse planning: Untethered high-speed 3D Running of MIT Cheetah 2". In: *2015 IEEE International Conference on Robotics and Automation (ICRA)*. 2015, pp. 5163–5170. DOI: `10.1109/ICRA.2015.7139918`.

[230] H.-W. Park, P. M. Wensing, S. Kim, et al. "Online planning for autonomous running jumps over obstacles in high-speed quadrupeds". In: (2015).

[231] J. Park, J. Chen, Y. K. Cho, D. Y. Kang, and B. J. Son. “CNN-based person detection using infrared images for night-time intrusion warning systems”. In: *Sensors* 20.1 (2020), p. 34.

[232] K.-B. Park et al. “Hands-Free Human–Robot Interaction Using Multimodal Gestures and Deep Learning in Wearable Mixed Reality”. In: *IEEE Access* 9 (2021), pp. 55448–55464. DOI: `10.1109/ACCESS.2021.3071364`.

[233] L. Paya, A. Gil, and O. Reinoso. “A state-of-the-art review on mapping and localization of mobile robots using omnidirectional vision sensors”. In: *Journal of Sensors* 2017 (2017).

[234] L. Peppoloni, F. Brizzi, C. A. Avizzano, and E. Ruffaldi. “Immersive ROS-integrated framework for robot teleoperation”. In: *2015 IEEE Symposium on 3D User Interfaces (3DUI)*. 2015, pp. 177–178. DOI: `10.1109/3DUI.2015.7131758`.

[235] M. I. Perdana, A. Risnumawan, and I. A. Sulistijono. “Automatic Aerial Victim Detection on Low-Cost Thermal Camera Using Convolutional Neural Network”. In: *2020 International Symposium on Community-centric Systems (CcS)*. IEEE. 2020, pp. 1–5.

[236] A. Pomares et al. “Ground Extraction from 3D Lidar Point Clouds with the Classification Learner App”. In: *2018 26th Mediterranean Conference on Control and Automation (MED)*. 2018, pp. 1–9. DOI: `10.1109/MED.2018.8442569`.

[237] J. Portmann, S. Lynen, M. Chli, and R. Siegwart. “People detection and tracking from aerial thermal views”. In: *2014 IEEE International Conference on Robotics and Automation (ICRA)*. 2014, pp. 1794–1800. DOI: `10.1109/ICRA.2014.6907094`.

[238] C. in Prague. *Rescue robot goes to Italy*. Sept. 2016. URL: `https://cyber.felk.cvut.cz/news/rescue-robot-goes-to-italy/`.

[239] A. P. P. Prasetyo, Rendyansyah, S. D. Siswanti, S. Nurmaini, and Abdurahman. “Garbage Collector Robot (Gacobot) Design For Dry Waste Distribution”. In: *Journal of Physics: Conference Series* 1500.1 (Apr. 2020), p. 012103. DOI: `10.1088/1742-6596/1500/1/012103`. URL: `https://dx.doi.org/10.1088/1742-6596/1500/1/012103`.

[240] A. Pronobis and P. Jensfelt. “Large-scale semantic mapping and reasoning with heterogeneous modalities”. In: *Proceedings - IEEE International Conference on Robotics and Automation* (2012), 3515-3522. ISSN: 10504729. DOI: `10.1109/ICRA.2012.6224637`.

[241] J. P. Queralta et al. “Collaborative Multi-Robot Search and Rescue: Planning, Coordination, Perception, and Active Vision”. In: *IEEE Access* 8 (2020), pp. 191617–191643. DOI: `10.1109/ACCESS.2020.3030190`.

[242] P. Quin, D. D. K. Nguyen, T. L. Vu, A. Alempijevic, and G. Paul. “Approaches for Efficiently Detecting Frontier Cells in Robotics Exploration”. In: *Frontiers in Robotics and AI* 8.February (2021), pp. 1–15. ISSN: 22969144. DOI: `10.3389/frobt.2021.616470`.

[243] M. Raibert, K. Blankespoor, G. Nelson, and R. Playter. “BigDog, the Rough-Terrain Quadruped Robot”. In: *IFAC Proceedings Volumes* 41.2 (2008). 17th IFAC World Congress, pp. 10822–10825. ISSN: 1474-6670. DOI: `https://doi.org/10.3182/20080706-5-KR-1001.01833`. URL: `https://www.sciencedirect.com/science/article/pii/S1474667016407020`.

[244] M. H. Raibert. *Legged robots that balance.* MIT press, 1986.

[245] M. H. Raibert. “Hopping in legged systems — Modeling and simulation for the two-dimensional one-legged case”. In: *IEEE Transactions on Systems, Man, and Cybernetics* SMC-14.3 (1984), pp. 451–463. DOI: `10.1109/TSMC.1984.6313238`.

[246] M. H. Raibert. “Running With Symmetry”. In: *Autonomous Robot Vehicles.* Ed. by I. J. Cox and G. T. Wilfong. New York, NY: Springer New York, 1990, pp. 45–61. ISBN: 978-1-4613-8997-2. DOI: `10.1007/978-1-4613-8997-2_5`. URL: `https://doi.org/10.1007/978-1-4613-8997-2_5`.

[247] A. Rasouli, P. Lanillos, G. Cheng, and J. K. Tsotsos. “Attention-based active visual search for mobile robots”. In: *Autonomous Robots* 44.2 (2019), 131-146. ISSN: 15737527. DOI: `10.1007/s10514-019-09882-z`. arXiv: `1807.10744`. URL: `https://doi.org/10.1007/s10514-019-09882-z`.

[248] D. N. Rathee, S. Nagpal, A. Malik, and C. Khandelwal. “An Efficient Intelligent System for Data Communication Using LIFI Technology”. In: *INTERNATIONAL JOURNAL OF COMPUTERS TECHNOLOGY* 13.10 (Oct. 2014), pp. 5044–5050. DOI: `10.24297/ijct.v13i10.2326`. URL: `https://rajpub.com/index.php/ijct/article/view/2326`.

[249] R. Reni. *House Rooms Image Dataset.* 2020. URL: `https://www.kaggle.com/robinreni/house-rooms-image-dataset` (visited on 02/23/2022).

[250] H. Ritchie, P. Rosado, and M. Roser. “Natural Disasters”. In: *Our World in Data* (2022). https://ourworldindata.org/natural-disasters.

[251] J. J. Roldán et al. “Multi-Robot Interfaces and Operator Situational Awareness: Study of the Impact of Immersion and Prediction”. In: *Sensors* 17.8 (2017). ISSN: 1424-8220. DOI: `10.3390/s17081720`. URL: `https://www.mdpi.com/1424-8220/17/8/1720`.

[252] J. Roldán Gómez. “Adaptive and Immersive Interfaces to Improve Situational Awareness in Multi-Robot Missions”. PhD thesis. July 2018. DOI: `10.20868/UPM.thesis.52353`.

[253] J. J. Roldán Gómez. “Adaptive and immersive interfaces to improve situational awareness in multi-robot missions”. PhD thesis. Industriales, 2018.

[254] X. Rong, Q. Huang, and Y. Ren. “Experimental study on static and fatigue behaviors of stud connectors for composite beams after corrosion”. In: *Tumu Gongcheng Xuebao/China Civil Engineering Journal* 46.2 (2013). Cited by: 20, pp. 10–18. URL: `https://www.scopus.com/inward/record.uri?eid=2-s2.0-84875073144&partnerID=40&md5=88cb4fdaef52135d021efb471902357a`.

[255] T. Rouček et al. “DARPA Subterranean Challenge: Multi-robotic Exploration of Underground Environments”. In: *Modelling and Simulation for Autonomous Systems.* Ed. by J. Mazal, A. Fagiolini, and P. Vasik. Cham: Springer International Publishing, 2020, pp. 274–290. ISBN: 978-3-030-43890-6.

[256] R. Royo Pastor. “TERMOGRAFÍA INFRARROJA. FUNDAMENTOS, INVESTIGACIÓN Y APLICACIONES”. In: *Colección Manual de referencia* (2013).

[257] P. Rudol and P. Doherty. “Human Body Detection and Geolocalization for UAV Search and Rescue Missions Using Color and Thermal Imagery”. In: *2008 IEEE Aerospace Conference.* 2008, pp. 1–8. DOI: `10.1109/AERO.2008.4526559`.

[258] E. B. Salas. *Global number of natural disasters events 2000-2022.* Apr. 2023. URL: `https://www.statista.com/statistics/510959/number-of-natural-disasters-events-globally/`.

[259] S. Sambolek and M. Ivasic-Kos. “Automatic Person Detection in Search and Rescue Operations Using Deep CNN Detectors”. In: *IEEE Access* 9 (2021), pp. 37905–37922. DOI: `10.1109/ACCESS.2021.3063681`.

[260] J. Sandino, F. Maire, P. Caccetta, C. Sanderson, and F. Gonzalez. “Drone-based autonomous motion planning system for outdoor environments under object detection uncertainty”. In: *Remote Sensing* 13.21 (2021), pp. 1–30. ISSN: 20724292. DOI: `10.3390/rs13214481`.

[261] J. Sandino, F. Vanegas, F. Gonzalez, and F. Maire. “Autonomous UAV Navigation for Active Perception of Targets in Uncertain and Cluttered Environments”. In: *IEEE Aerospace Conference Proceedings* (2020). ISSN: 1095323X. DOI: `10.1109/AERO47225.2020.9172808`.

[262] J. F. Schmid, M. Lauri, and S. Frintrop. “Explore, Approach, and Terminate: Evaluating Subtasks in Active Visual Object Search Based on Deep Reinforcement Learning”. In: *IEEE International Conference on Intelligent Robots and Systems* (2019), pp. 5008–5013. ISSN: 21530866. DOI: `10.1109/IROS40897.2019.8967805`.

[263] G. Seeja, A. Arockia Selvakumar, and V. Berlin Hency. “A Novel Approach for Disaster Victim Detection Under Debris Environments Using Decision Tree Algorithms with Deep Learning Features”. In: *IEEE Access* (2023), pp. 1–1. DOI: `10.1109/ACCESS.2023.3281461`.

[264] M. Selin, M. Tiger, D. Duberg, F. Heintz, and P. Jensfelt. “Efficient autonomous exploration planning of large-scale 3-d environments”. In: *IEEE Robotics and Automation Letters* 4.2 (2019), 1699-1706. ISSN: 23773766. DOI: `10.1109/LRA.2019.2897343`.

[265] A. Serezhkin. *Drinking waste classification.* May 2020. URL: `https://www.kaggle.com/datasets/arkadiyhacks/drinking-waste-classification`.

[266] J. Shen et al. “Real-Time Superpixel Segmentation by DBSCAN Clustering Algorithm”. In: *IEEE Transactions on Image Processing* 25.12 (2016), pp. 5933–5942. DOI: `10.1109/TIP.2016.2616302`.

[267] A. Shukla and H. Karki. “Application of robotics in offshore oil and gas industry—A review Part II”. In: *Robotics and Autonomous Systems* 75 (2016), pp. 508–524. ISSN: 0921-8890. DOI: `https://doi.org/10.1016/j.robot.2015.09.013`. URL: `https://www.sciencedirect.com/science/article/pii/S0921889015002018`.

[268] A. Shukla and H. Karki. “Application of robotics in onshore oil and gas industry—A review Part I”. In: *Robotics and Autonomous Systems* 75 (2016), pp. 490–507. ISSN: 0921-8890. DOI: `https://doi.org/10.1016/j.robot.2015.09.012`. URL: `https://www.sciencedirect.com/science/article/pii/S0921889015002006`.

[269] K. Sjöö, A. Aydemir, and P. Jensfelt. “Topological spatial relations for active visual search”. In: *Robotics and Autonomous Systems* 60.9 (2012), pp. 1093–1107. ISSN: 0921-8890. DOI: `https://doi.org/10.1016/j.robot.2012.06.001`. URL: `https://www.sciencedirect.com/science/article/pii/S0921889012000851`.

[270] M. Sombolestan and Q. Nguyen. *Hierarchical Adaptive Control for Collaborative Manipulation of a Rigid Object by Quadrupedal Robots.* 2023. arXiv: `2303.06741 [cs.RO]`.

[271] *Standard on Operations and Training for Technical Search and Rescue Incidents.* 2017.

[272] J. H. Steffen, J. E. Gaskin, T. O. Meservy, J. L. Jenkins, and I. Wolman. “Framework of Affordances for Virtual Reality and Augmented Reality”. In: *Journal of Management Information Systems* 36.3 (2019), pp. 683–729. DOI: `10.1080/07421222.2019.1628877`. eprint: `https://doi.org/10.1080/07421222.2019.1628877`. URL: `https://doi.org/10.1080/07421222.2019.1628877`.

[273] I. A. Sulistijono et al. “Implementation of Victims Detection Framework on Post Disaster Scenario”. In: *2018 International Electronics Symposium on Engineering Technology and Applications (IES-ETA).* IEEE. 2018, pp. 253–259.

[274] K. Takumi et al. “Multispectral Object Detection for Autonomous Vehicles”. In: *Proceedings of the on Thematic Workshops of ACM Multimedia 2017.* Thematic Workshops '17. Mountain View, California, USA: Association for Computing Machinery, 2017, pp. 35–43. ISBN: 9781450354165. DOI: `10.1145/3126686.3126727`. URL: `https://doi.org/10.1145/3126686.3126727`.

[275] J. Tomlinson. “Multispectral and thermal surface imagery and surface elevation mosaics (camspec-air)”. In: (Apr. 2023). DOI: `10.5439/1894300`. URL: `https://www.osti.gov/biblio/1894300`.

[276] V. Tsounis, M. Alge, J. Lee, F. Farshidian, and M. Hutter. “DeepGait: Planning and Control of Quadrupedal Gaits Using Deep Reinforcement Learning”. In: *IEEE Robotics and Automation Letters* 5.2 (2020), pp. 3699–3706. DOI: `10.1109/LRA.2020.2979660`.

[277] C. C. Ulloa, L. Garrido, J. del Cerro, and A. Barrientos. “Autonomous victim detection system based on deep learning and multispectral imagery”. In: *Machine Learning: Science and Technology* 4.1 (Feb. 2023), p. 015018. DOI: `10.1088/2632-2153/acb6cf`. URL: `https://dx.doi.org/10.1088/2632-2153/acb6cf`.

[278] *UNDRR Home.* `https://www.undrr.org/`. Accessed: 2021-6-23.

[279] Unitree. *Unitree B1.* URL: `https://shop.unitree.com/products/unitree-b1`.

[280] Unitree. *Unitree Z1.* URL: `https://shop.unitree.com/products/unitree-z1`.

[281] *Unitree AlienGo - ROBOTDOGS — Unitree Official Shop — Unitree AlienGo.* URL: `https://unitreerobotics.net/robotdog/unitree-aliengo/`.

[282] B. Venkanna. *Fundamentals of heat and mass transfer.* PHI Learning Pvt. Ltd., 2010.

[283] R. Ventura and P. U. Lima. "Search and Rescue Robots: The Civil Protection Teams of the Future". In: *2012 Third International Conference on Emerging Security Technologies.* 2012, pp. 12–19. DOI: `10.1109/EST.2012.40`.

[284] R. Verbickas and A. Whitehead. "Sky and ground detection using convolutional neural networks". In: *International Conference on Machine Vision and Machine Learning (MVML).* Vol. 1. 2014.

[285] E. Vidal. "Online 3D view planning for autonomous underwater exploration". PhD. Thesis. Universitat de Girona., 2019. DOI: `10.1002/rob.21951`. URL: `https://www.tesisenred.net/handle/10803/668814#page=1%20https://www.youtube.com/watch?v=kSUP06aAv08`.

[286] F. Vidal-Verdú, M. J. Barquero, J. Serón, and A. García-Cerezo. "Large area smart tactile sensor for rescue robot". In: *2009 IEEE International Workshop on Robotic and Sensors Environments* (2009), pp. 6–10.

[287] V. Vijayan and P. Kp. "FLANN Based Matching with SIFT Descriptors for Drowsy Features Extraction". In: *2019 Fifth International Conference on Image Information Processing (ICIIP).* 2019, pp. 600–605. DOI: `10.1109/ICIIP47207.2019.8985924`.

[288] F. Voigtländer et al. "5G for Robotics: Ultra-Low Latency Control of Distributed Robotic Systems". In: *2017 International Symposium on Computer Science and Intelligent Controls (ISCSIC).* 2017, pp. 69–72. DOI: `10.1109/ISCSIC.2017.27`.

[289] F. Vulpi, A. Milella, R. Marani, and G. Reina. "Recurrent and convolutional neural networks for deep terrain classification by autonomous robots". In: *Journal of Terramechanics* 96 (2021), pp. 119–131. ISSN: 0022-4898. DOI: `https://doi.org/10.1016/j.jterra.2020.12.002`. URL: `https://www.sciencedirect.com/science/article/pii/S0022489820301117`.

[290] M. de Waard, M. Inja, and A. Visser. "Analysis of flat terrain for the atlas robot". In: *2013 3rd Joint Conference of AI & Robotics and 5th RoboCup Iran Open International Symposium* (2013), pp. 1–6.

[291] K. W. Wait and M. Goldfarb. "A pneumatically actuated quadrupedal walking robot". In: *IEEE/ASME Transactions on Mechatronics* 19.1 (2014). Cited by: 14, pp. 339–347. DOI: `10.1109/TMECH.2012.2235078`.

[292] K. Walas. “Terrain classification and negotiation with a walking robot”. In: *Journal of Intelligent & Robotic Systems* 78.3-4 (2015), pp. 401–423.

[293] D. Wallace, Y. H. He, J. Chagas Vaz, L. Georgescu, and P. Y. Oh. “Multi-modal Teleoperation of Heterogeneous Robots within a Construction Environment”. In: *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2020, pp. 2698–2705. DOI: `10.1109/IROS45743.2020.9340688`.

[294] T. R. Walter et al. “Late complex tensile fracturing interacts with topography at Cumbre Vieja, La Palma”. In: *Volcanica* 6.1 (Jan. 2023), pp. 1–17. DOI: `10.30909/vol.06.01.0117`. URL: `http://jvolcanica.org/ojs/index.php/volcanica/article/view/163`.

[295] C. Wang et al. “Autonomous Robotic Exploration by Incremental Road Map Construction”. In: *IEEE Transactions on Automation Science and Engineering* 16.4 (2019), 1-12.

[296] C.-Y. Wang, A. Bochkovskiy, and H.-Y. M. Liao. *YOLOv7: Trainable bag-of-freebies sets new state-of-the-art for real-time object detectors.* 2022. DOI: `10.48550/ARXIV.2207.02696`. URL: `https://arxiv.org/abs/2207.02696`.

[297] J. Wang et al. “A survey of the development of biomimetic intelligence and robotics”. In: *Biomimetic Intelligence and Robotics* 1 (2021), p. 100001. ISSN: 2667-3797. DOI: `https://doi.org/10.1016/j.birob.2021.100001`. URL: `https://www.sciencedirect.com/science/article/pii/S2667379721000012`.

[298] W. Wang et al. “A visual terrain classification method for mobile robots’ navigation based on convolutional neural network and support vector machine”. In: *Transactions of the Institute of Measurement and Control* 44.4 (2022), pp. 744–753. DOI: `10.1177/0142331220987917`. eprint: `https://doi.org/10.1177/0142331220987917`. URL: `https://doi.org/10.1177/0142331220987917`.

[299] Z. Wang, C. Sun, G. Deng, and A. Zhang. “Locomotion planning for quadruped robot over rough terrain”. In: *2017 Chinese Automation Congress (CAC)*. 2017, pp. 3170–3173. DOI: `10.1109/CAC.2017.8243321`.

[300] C. Wannous and G. Velasquez. “United Nations Office for Disaster Risk Reduction (UNISDR)—UNISDR’s Contribution to Science and Technology for Disaster Risk Reduction and the Role of the International Consortium on Landslides (ICL)”. In: *Advancing Culture of Living with Landslides.* Ed. by K. Sassa, M. Mikoš, and Y. Yin. Cham: Springer International Publishing, 2017, pp. 109–115. ISBN: 978-3-319-59469-9.

[301] M. Wermelinger et al. “Navigation planning for legged robots in challenging terrain”. In: *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2016, pp. 1184–1189. DOI: `10.1109/IROS.2016.7759199`.

[302] J. Whitman, N. Zevallos, M. Travers, and H. Choset. “Snake Robot Urban Search After the 2017 Mexico City Earthquake”. In: *2018 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*. 2018, pp. 1–6. DOI: `10.1109/SSRR.2018.8468633`.

[303] G. A. Wilde, R. R. Murphy, D. A. Shell, and C. M. Marianno. “A man-packable unmanned surface vehicle for radiation localization and forensics”. In: *2015 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*. 2015, pp. 1–6. DOI: `10.1109/SSRR.2015.7442944`.

[304] A. W. Winkler et al. “Planning and execution of dynamic whole-body locomotion for a hydraulic quadruped on challenging terrain”. In: *2015 IEEE International Conference on Robotics and Automation (ICRA)*. 2015, pp. 5148–5154. DOI: `10.1109/ICRA.2015.7139916`.

[305] M. Wu, S.-L. Dai, and C. Yang. “Mixed Reality Enhanced User Interactive Path Planning for Omnidirectional Mobile Robot”. In: *Applied Sciences* 10.3 (2020). ISSN: 2076-3417. DOI: `10.3390/app10031135`. URL: `https://www.mdpi.com/2076-3417/10/3/1135`.

[306] M. Wu, Y. Xu, C. Yang, and Y. Feng. “Omnidirectional Mobile Robot Control based on Mixed Reality and sEMG Signals”. In: *2018 Chinese Automation Congress (CAC)*. 2018, pp. 1867–1872. DOI: `10.1109/CAC.2018.8623114`.

[307] X. A. Wu, T. M. Huh, A. Sabin, S. A. Suresh, and M. R. Cutkosky. “Tactile Sensing and Terrain-Based Gait Control for Small Legged Robots”. In: *IEEE Transactions on Robotics* 36.1 (2020), pp. 15–27. DOI: `10.1109/TRO.2019.2935336`.

[308] N. Xu. “Active object searching on mobile robot using reinforcement learning”. In: *Proceedings - 2021 2nd International Conference on Computing and Data Science, CDS 2021* (2021), pp. 296–300. DOI: `10.1109/CDS52072.2021.00058`.

[309] B. Yamauchi. “All-weather perception for man-portable robots using ultra-wideband radar”. In: *2010 IEEE International Conference on Robotics and Automation*. 2010, pp. 3610–3615. DOI: `10.1109/ROBOT.2010.5509804`.

[310] Y. Yamazaki et al. “Victim Detection Using UAV with On-board Voice Recognition System”. In: *2019 Third IEEE International Conference on Robotic Computing (IRC)*. 2019, pp. 555–559. DOI: `10.1109/IRC.2019.00114`.

[311] C. Yang et al. “Collaborative Navigation and Manipulation of a Cable-Towed Load by Multiple Quadrupedal Robots”. In: *IEEE Robotics and Automation Letters* 7.4 (2022), pp. 10041–10048. DOI: `10.1109/LRA.2022.3191170`.

[312] Q. Yao et al. “Adaptive legged manipulation: Versatile disturbance predictive control for quadruped robots with robotic arms”. In: *Robotics and Autonomous Systems* (2023), p. 104468. ISSN: 0921-8890. DOI: `https://doi.org/10.1016/j.robot.2023.104468`. URL: `https://www.sciencedirect.com/science/article/pii/S0921889023001070`.

[313] X. Ye, J. Li, H. Huang, L. Du, and X. Zhang. “3D Recurrent Neural Networks with Context Fusion for Point Cloud Semantic Segmentation”. In: *Proceedings of the European Conference on Computer Vision (ECCV)*. Sept. 2018.

[314] L. Yu et al. “Inspection Robots in Oil and Gas Industry: a Review of Current Solutions and Future Trends”. In: *2019 25th International Conference on Automation and Computing (ICAC)*. 2019, pp. 1–6. DOI: `10.23919/IConAC.2019.8895089`.

[315] Zendel. *Papers with code - wilddash dataset.* Sept. 2018. URL: `https://paperswithcode.com/dataset/wilddash`.

[316] S. Zenker, E. E. Aksoy, D. Goldschmidt, F. Wörgötter, and P. Manoonpong. “Visual terrain classification for selecting energy efficient gaits of a hexapod robot”. In: *2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics.* 2013, pp. 577–584. DOI: `10.1109/AIM.2013.6584154`.

[317] F. Zha, C. Chen, W. Guo, P. Zheng, and J. Shi. “A free gait controller designed for a heavy load hexapod robot”. In: *Advances in Mechanical Engineering* 11.3 (2019), p. 1687814019838369.

[318] D. Zhang et al. “Development of a Hybrid Locomotion Robot for Earthquake Search and Rescue in Partially Collapsed Building”. In: *2019 IEEE International Conference on Mechatronics and Automation (ICMA).* 2019, pp. 2559–2564. DOI: `10.1109/ICMA.2019.8816327`.

[319] N. Zhang, F. Nex, G. Vosselman, and N. Kerle. “Training a Disaster Victim Detection Network for UAV Search and Rescue Using Harmonious Composite Images”. In: *Remote Sensing* 14.13 (2022). ISSN: 2072-4292. DOI: `10.3390/rs14132977`. URL: `https://www.mdpi.com/2072-4292/14/13/2977`.

[320] S. Zhang et al. “Static Gait Planning Method for Quadruped Robot Walking on Unknown Rough Terrain”. In: *IEEE Access* 7 (2019), pp. 177651–177660. DOI: `10.1109/ACCESS.2019.2958320`.

[321] W. Zhang, Q. Chen, W. Zhang, and X. He. “Long-range terrain perception using convolutional neural networks”. In: *Neurocomputing* 275 (2018), pp. 781–787. ISSN: 0925-2312. DOI: `https://doi.org/10.1016/j.neucom.2017.09.012`. URL: `https://www.sciencedirect.com/science/article/pii/S0925231217315060`.

[322] X. Zhao, Y. You, A. Laurenzi, N. Kashiri, and N. Tsagarakis. “Locomotion Adaptation in Heavy Payload Transportation Tasks with the Quadruped Robot CENTAURO”. In: *2021 IEEE International Conference on Robotics and Automation (ICRA).* 2021, pp. 5028–5034. DOI: `10.1109/ICRA48506.2021.9561720`.

[323] C. Zhou, C. Peers, Y. Wan, R. Richardson, and D. Kanoulas. *TeLeMan: Teleoperation for Legged Robot Loco-Manipulation using Wearable IMU-based Motion Capture.* 2022. arXiv: `2209.10314 [cs.RO]`.

[324] S. Zimmermann, R. Poranne, and S. Coros. “Go Fetch! - Dynamic Grasps using Boston Dynamics Spot with External Robotic Arm”. In: *2021 IEEE International Conference on Robotics and Automation (ICRA).* 2021, pp. 4488–4494. DOI: `10.1109/ICRA48506.2021.9561835`.