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Bringing Adaptive and Immersive Interfaces to Real-World Multi-Robot Scenarios: Application to Surveillance and Intervention in Infrastructures

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ABSTRACT Multiple robot missions imply a series of challenges for single human operators, such as managing high workloads or maintaining a correct level of situational awareness. Conventional interfaces are not prepared to face these challenges; however, new concepts have arisen to cover this need, such as adaptive and immersive interfaces. This paper reports the design and development of an adaptive and immersive interface, as well as a complete set of experiments carried out to establish comparisons with a conventional one. The interface object of study has been developed using virtual reality to bring operators into scenarios and allow an intuitive commanding of robots. Additionally, it is able to recognize the mission's state and show hints to the operators. The experiments were performed in both outdoor and indoor scenarios recreating an intervention after an accident in critical infrastructure. The results show the potential of adaptive and immersive interfaces in the improvement of workload, situational awareness and performance of operators in multi-robot missions.

INDEX TERMS Robotics, multi-robot systems, interfaces, virtual reality, surveillance.

I. INTRODUCTION

Robots are increasingly filling gaps in our lives. In a nutshell, they can carry out the jobs that we cannot or are not willing to do. This is especially interesting with hard or dangerous tasks. A type of missions where robots can be particularly helpful are interventions in disaster areas. Throughout the last decades, rescue teams have been integrating robots in their operations after natural or human-provoked disasters. They have used not only ground, aerial, surface or underwater robots, but also heterogeneous fleets that integrate multiple kinds of robots. Some examples of interventions are the World Trade Center attacks in 2001, the Katrina hurricane in 2005 and the Fukushima nuclear accident in 2011 [1].

Nevertheless, the use of robots in these kinds of missions presents a series of difficulties and, in fact, some of the reported experiences ended up being unsuccessful. Two causes of failure prevail among the rest: an inadequate application-oriented robot design, and problems related to human-robot interaction during missions. The first category takes place primarily with ground robots in complex environments (e.g., unstructured terrains or debris tunnels). The second one stands out when using different configurations of fleets and scenarios.

There are several key issues about human-robot interaction in real-world missions:

- Workload: It takes into account the amount of work, working time and experience of the operator [2]. There are six variables which influence workload: physical demand, mental demand, temporal demand, effort, performance and frustration [3]. A high workload can lead to a degraded performance, since it can increase robot waiting times and trigger wrong operator decisions [4]. According to the literature, an increase in the number of robots implies a significant rise of workload [5].
- Situational awareness: It is not only the perception of the robots and their environment in a volume of time and space, but also the comprehension of its meaning and its projection into the future [6]. There are six possible types of situational awareness according to the subject and object involved: human-human, human-robot, robot-human, robot-robot, human-mission (considered

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in [7]) and robot-mission (not considered by the authors, but equally important). A degraded situational awareness can produce mistakes that lead to inefficiencies and even accidents [8].

- Stress: This variable has to be controlled and kept within certain limits, since high values of stress can produce states of anxiety and low levels can induce situations of boredom, which generally decrease operator performance [9].
- Level of autonomy: Autonomy is the capability of systems to carry out tasks without human control [10]. The autonomy levels define the roles of systems and humans in missions. They vary from fully manual to fully autonomous through a wide range of intermediate states such as management by consent and exception [11]. The selection of an appropriate level of automation is fundamental not only for operator performance, but also for mission success.
- Trust in automation: Mission performance is affected not only by the level of automation of the system, but also by the operator's attitude towards it. It is important to avoid both mistrust, since it can lead the operator to reject the automation, increase workload and reduce performance; and overtrust, since the operator may stop paying attention and not detect automation failures [12].

Recent literature covers multiple proposals to address these issues. Workload can be reduced by increasing the level of fleet autonomy and transferring functions from operators to interfaces. Situational awareness can be improved by selecting the most relevant information and developing an immersive interface. Stress can be controlled by adjusting the level of autonomy and the amount of information. Finally, trust in automation can be improved by adjusting the level of autonomy and adequately training operators.

This paper tries to answer the following question: "Can adaptive and immersive interfaces lead to improvements in workload, situational awareness and performance of multi-robot operators?". For this purpose, it presents the development of an adaptive & immersive interface for monitoring and commanding multi-robot missions, as well as its validation with a set of missions emulating an intervention after a critical infrastructure accident. It collects the experiments of the PhD thesis of Juan Jesús Roldán [13].

The remainder of the paper is organized as follows: Section II reviews the state of the art regarding human-robot interfaces. Section III presents the scenarios considered in this work. Section IV describes the developed adaptive & immersive interface. Section V addresses the experiments performed to compare this interface to a state-of-the-art one. Section VI discusses the results of these experiments. Finally, Section VII summarizes the main conclusions of the work.

II. STATE OF THE ART

As mentioned in the previous section, multiple robot missions imply a series of challenges for single human operators, and conventional interfaces are not prepared to face these issues.

TABLE 1. A set of interfaces proposed in recent literature (GR: Ground Robot, AR: Aerial Robot, MR: Manipulator Robot, UR: Underwater Robot, S: Simulations, R: Real tests, Con: Conventional, Mul: Multimodal, Im: Immersive, and Adap: Adaptive).

Reference	Robots	Interface
[14]	1 AR (S)	Im
[15]	40 AR (S)	Mul
[16]	200 GR (S)	Con
[17]	250 AR (S)	Adap
[9]	4 AR (S)	Con
[18]	3 AR (S)	Adap
[19]	4 AR (S)	Con
[20]	1 GR (R)	Im
[21]	3 AR (S)	Im
[22]	1 UR (S)	Mul + Im
[23]	1 MR (R)	Mul + Im
[24]	1 GR + MR (S)	Mul + Im
[25]	1 GR + MR (R)	Im
[26]	10 AR (S)	Im
[27]	2 GR + 1 AR (R)	Con
[28]	1 MR (R)	Im
[29]	1 AR (S)	Im
[30]	1 GR (R)	Mul + Im
[31]	2 AR (R)	Mul + Im + Adap
[32]	1 GR + MR (R)	Im
[33]	1 MR (R)	Im
Here	1 GR, 2 AR, 1 MR (R)	Mul + Im + Adap

A set of interfaces proposed in recent literature has been collected in Table 1. These interfaces have been developed using different resources - multimodal interactions (Mul), immersive technologies (Im), and adaptive algorithms (Adap) - and validated with various numbers and types of robots - aerial (AR), ground (GR), underwater (UR) and manipulator ones (MR). All of them share the intention to evaluate and improve the impact of human factor issues such as workload and situational awareness.

The integration of multimodal interactions (e.g., sound and touch) can lead to improved performance in robot missions. There are two main uses for these interactions: to provide operators with information, and to allow them to command robots. In the first case, the use of haptic interactions (e.g., vibration of remote controllers) can be remarked as a way of giving feedback to operators when they are teleoperating robots [30]. Sounds can also be used to catch the attention of operators towards alarms. In the second case, voice [15] and gesture [22] commands are suitable alternatives to conventional teleoperation, as their intuitiveness favors workload reduction.

Immersive technologies allow to virtually introduce operators in scenarios and, therefore, improve their situational awareness. There are three main types of immersive resources: virtual reality (VR), which involves virtual scenarios and allows for virtual interactions; augmented reality (AR), which adds virtual elements to real scenarios and enables interactions with these elements; and mixed reality (MR), which combines virtual and real scenarios and includes interactions with both virtual and real elements.

Immersive technologies are used to train workers in the context of medicine [34], industry [35] and military missions [36]. Additionally, virtual reality systems allow to study human factor issues, such as ergonomics [37] and performance [38]. VR and AR technologies have been compared in the training of industrial operators for maintenance and assembly tasks [39]. In this study, AR provides better results than VR, both in terms of task performance and user experience. However, the VR system developed in that work used a screen instead of a head mounted device, which would be more immersive, intuitive, easy to use, interactive and easy to learn according to [40]. Finally, other works reveal several aspects of VR systems, such as the influence of a wide field of view on the spatial perception [41], and the importance of providing the operators with adequate feedback of their actions [42].

In the context of robot missions, there are two types of immersive interfaces based on AR and VR. AR-based interfaces provide video streams from multiple cameras and integrate information regarding robots, targets and scenarios. Some examples are collected in [14], [28], and [29]. VR-based interfaces include 3D models of robots and scenarios, allowing the operators to interact more naturally with them. Some examples are shown in [31], [32], and [33].

Finally, adaptive algorithms allow interfaces to change their information according to the mission's context and operator preferences. This strategy can address operator workload by reducing the amount of data, and control situational awareness by selecting relevant information. In some cases, the interface is able to guide the attention of operators to the areas where information is relevant or actions are required [18].

As it is shown in table 1, the interface developed in this work, together with the developed in the previous work [31], are the only ones that integrate immersion, adaptation and multimodal interactions. However, the new interface allows the operator to command the robots, whereas the previous one was just a monitoring interface. In fact, the interfaces currently used in search and rescue missions are much simpler, using traditional devices to display the information (screen) and command the robots (mouse, keyboard, remote controller and joypad). Further research works propose more diverse interfaces, but normally they focus on developing and testing specific components. To the best of our knowledge, none of the interfaces proposed in the recent literature reaches the complexity and versatility of the one presented in this work.

III. SCENARIOS

As stated above, the hypothesis of this work is "adaptive and immersive interfaces can lead to improvements in workload, situational awareness and performance of multi-robot operators". A set of multi-robot missions has been developed to validate this hypothesis comparing the proposed immersive & adaptive interface against a state-of-the-art one. The design of these missions took into account a set of requirements in order to obtain results as relevant as possible:

- Scenarios: The scenarios shall be as realistic as possible, even inspired by real-world robotics applications; and sufficiently diverse, including both outdoor and indoor locations. Therefore, they should be the result of a compromise between knowledge and uncertainty: i.e., some elements of the scenarios can be known prior to the missions, whereas some others should be discovered while the missions are taking place.
- Robots: A fleet with multiple robots shall be used to perform missions. The robots must be heterogeneous to extend the validity of the results: e.g., Unmanned Ground Vehicles (UGVs), Unmanned Aerial Vehicles (UAVs) and manipulators. Some robots should be used simultaneously in certain tasks to manage varying amounts operator workload, whereas others can be used separately in different tasks to determine the operator's performance.
- Operators: The operators shall perform the experiments one by one. They should be familiarized with the robots to be able to carry out the missions successfully, but they must not have experience using the interfaces to avoid biases in their evaluation.
- Other: The experiments with the interfaces must be relevant and reproducible. For this purpose, common hardware and software resources should be used and integrated with Robot Operating System (ROS) [43]. ROS is a well-known and widely used robotics middleware that organizes the processes in the form of graphs. These graphs have two main elements: nodes, which process data and perform actions, and topics, which manage the exchange of messages between the nodes.

In order to meet these requirements, the following scenario has been defined:

An accident has occurred in a chemical research center with both outdoor and indoor areas. A leakage has been reported inside the building, and there may be additional exterior damages. The area is dangerous for people because the spilled products are toxic. A team of robots has been deployed at the entrance of the plant. Their goal is to collect information and, if possible, to repair the damage. The team is formed by two UAVs and a UGV equipped with a manipulator. The mission can be divided into two phases:

- *Phase 1: The robots recognize the plant's exterior to evaluate damages caused by the accident. The UAVs can be used to quickly locate critical elements, whereas the UGV can be utilized to accurately inspect them. This phase ends when the UGV arrives to the entrance of the building.*
- *Phase 2: The ground robot equipped with the manipulator is operated to repair the damage. The UGV is driven through the building towards a control panel. Once there, the manipulator is used to close a valve, stopping the leakage and finishing the mission.*

As shown in Fig. 1, the scenario has been reproduced in the facilities of the Technical School of Industrial Engineering (ETSII) of the Technical University of Madrid (UPM). The two phases of the mission correspond to the two scenarios: the outdoor phase is explained in Section III-A, whereas the indoor phase is described in Section III-B.

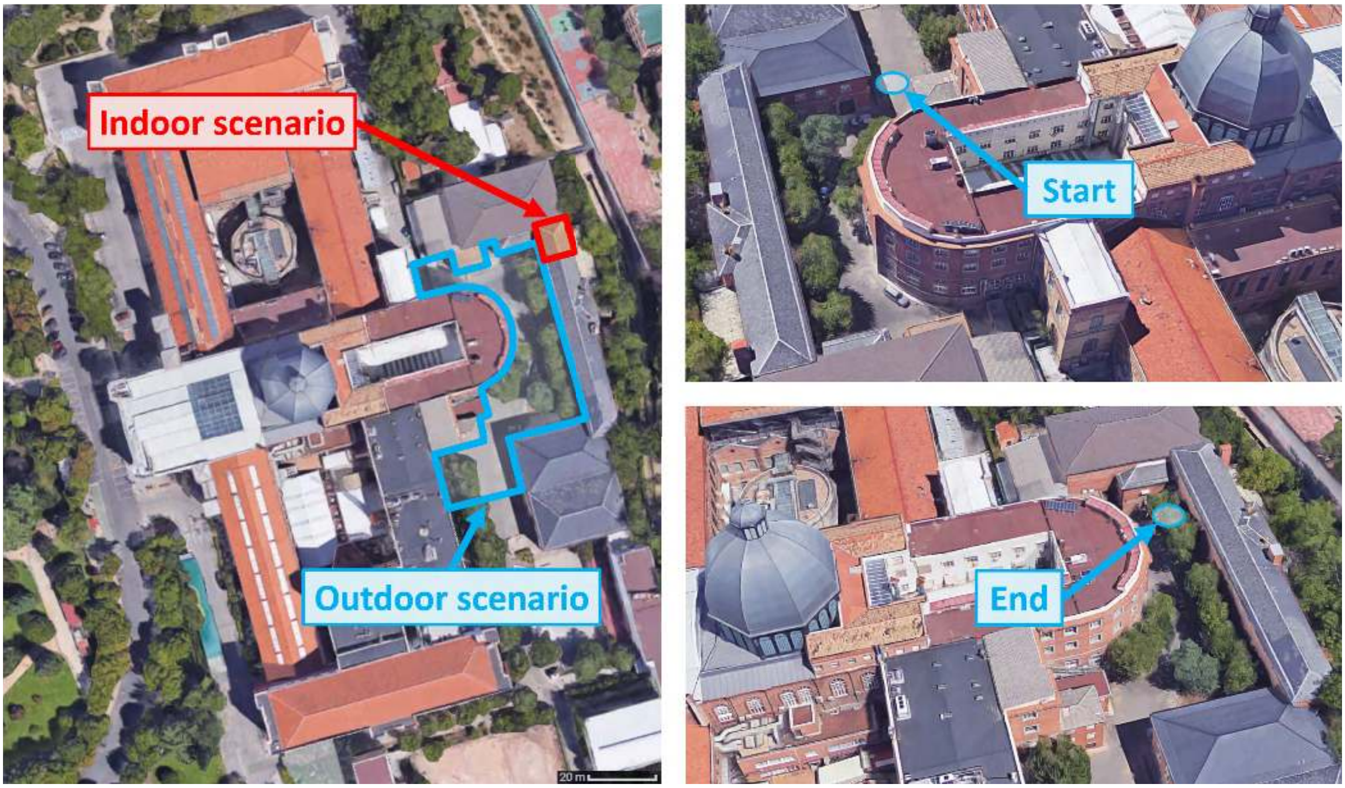


FIGURE 1. Scenarios considered for the experiments. Maps ©2018 Google and IGN España.

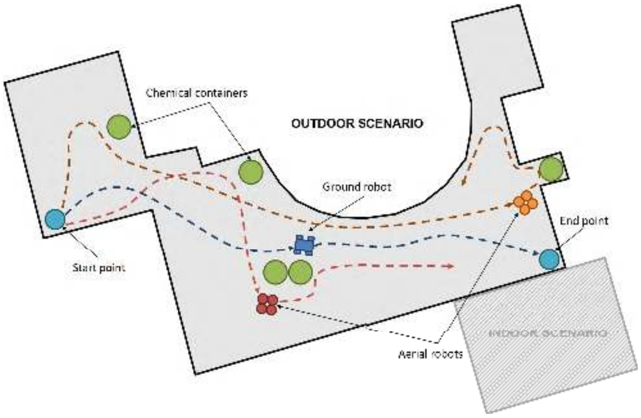


FIGURE 2. Mission in outdoor scenario.

A. OUTDOOR SCENARIO

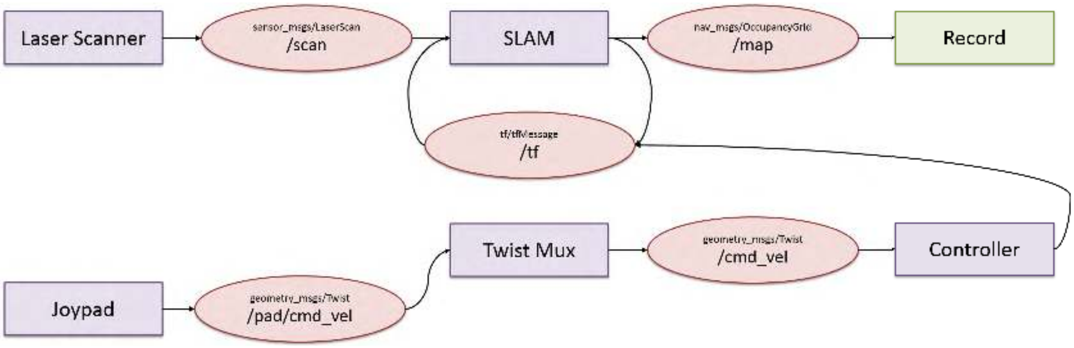
This scenario is located in one of the university's courtyards and reproduces the enclosure of a chemical research facility. It is an irregular area of 1,275 m^2 between various buildings, and it encloses parking spaces and green areas.

As already mentioned, a ground robot and two aerial robots are used in this scenario. These robots are deployed at the starting point and must go to the end point marked in Fig. 2. Along the way, they must search and inspect a series of chemical containers, checking if they are adequately closed or present leakages. Specifically, the aerial robots can perform a rapid exploration of the area with reduced risks and localize the containers, whereas the ground robot can be used to check the state of the containers and is necessary for the indoor scenario. The operator is free to use whichever robots to exploit their advantages.

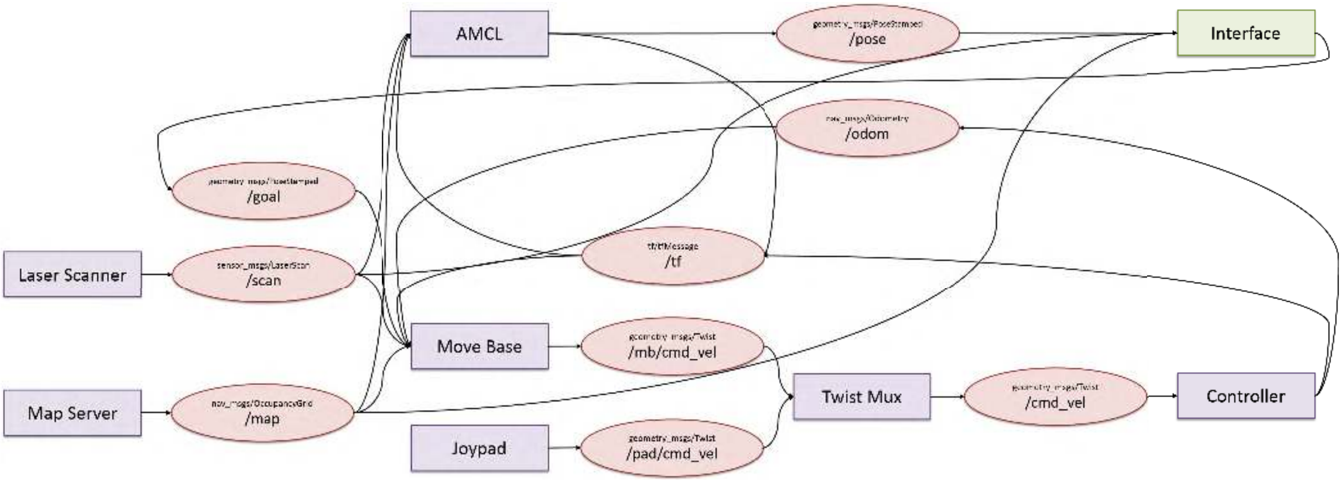
The goal of this phase is to check if the interfaces are appropriate to monitor and control multiple robots in an outdoor, irregular and partially unknown scenario. This scenario is expected to be a challenge for operators in terms of workload, due to the amount of information to analyze and the demand of fast and accurate decisions. More specifically, the operators must deal with the control of multiple robots at the same time (e.g. moving the UAVs to detect the containers, moving the UGV to inspect them, checking the containers in the camera images and taking the robots inside the building) and the management of the differences between mapped and actual scenarios. Finally, they have to perform the mission in the minimum time and avoiding any type of accident.

The ground robot is a *Robotnik Summit HL* [44], with a size of 722 × 613 × 416 mm, weight of 65 kg and load capacity of 65 kg. The battery duration ranges from 10 hours (continuous motion) to 40 hours (standard laboratory use), it has four wheels with four motors that allow it to rotate without translation, and its maximum speed is 3 m/s. It is controlled by an embedded computer with Linux and Robot Operating System (ROS).

The specific unit used in these experiments is equipped with the following sensors: a Hokuyo UTM-30LX laser scanner with a field of view of 270° and a range of [0.1 m, 30 m],



(a) Building the map.



(b) Navigating with the map.

FIGURE 3. Simplified ROS graphs of the ground robot. Squares represent nodes and ovals represent topics (i.e., the processes and exchanged data, respectively).

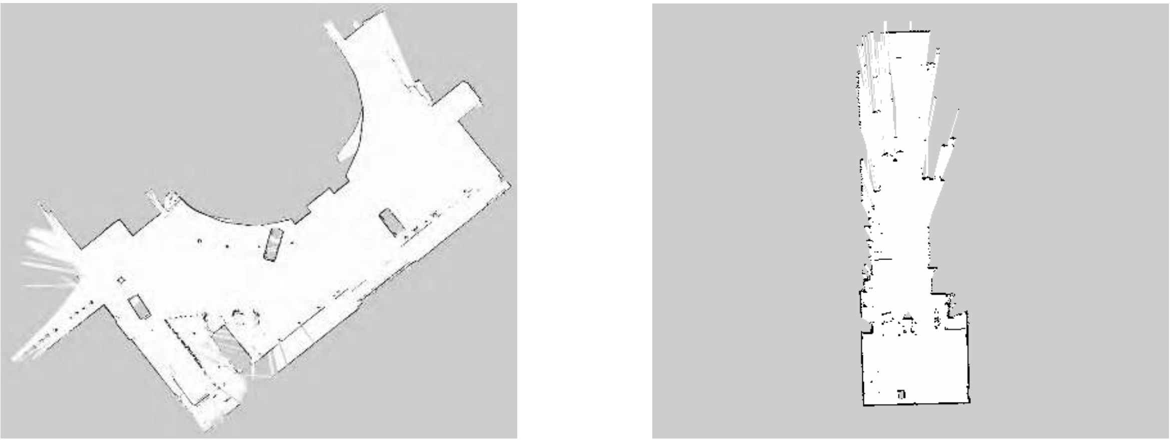
a Kinect 2.0 with a range of [0.5 m, 4.5 m] and a pan-tilt-zoom camera that can be used for inspection.

In this scenario, the *Robotnik Summit HL*'s mission is to go from the starting point to the end point and inspect the detected chemical containers. There were two alternatives to perform this navigation: the use of a Global Navigation Satellite System (GNSS) to determine its absolute position, and the use of a laser scanner to locate it in a previously known map. The first option was discarded because this system presents noise between the buildings of the city center. Therefore, the second option was chosen, as it is suitable for the experiments and is plausible for a real scenario. In fact, this technique only requires a previous map of the facilities and it is relatively robust to changes in layout. In this work, this necessary previous map is acquired by the robot.

Following the ROS computation graph shown in Fig. 3a, the robot was teleoperated to build a map of the environment. The Simultaneous Location And Mapping (SLAM) algorithm implemented in the ROS *gmapping* package of *slam_gmamping* stack was used for this purpose (more information can be found in [45] and [46]). This package uses the range measurements of a laser scanner to build a map and, while performing this task, to locate the robot in it with a high accuracy. Fig. 4a shows the map generated by this process, which reveals the outlines of buildings and some objects like cars or dumpsters. However, other elements in the scenario are not included in the map, as they should be placed dynamically during the course of the mission to reproduce the variability of a real-world scenario.

During the missions, the Augmented Monte Carlo Localization (AMCL) algorithm implemented in the *amcl* package of ROS *navigation* stack was used to locate the robot in the previously generated map. Additionally, the *move_base* package of the same stack was used to generate the speed commands required to arrive to the pose goals sent by operators. The ROS *navigation* stack manages both global and local costmaps that allow to simultaneously manage global and local plans, which is key for obstacle avoidance while navigating a partially unknown environment. Further information regarding this stack can be found in publications [47] and [48]. The ROS computation graph used for map navigation is shown in Fig. 3b.

On the other hand, the aerial robots are simulated because of the logistic and regulation problems associated to flying in the city center. However, they are implemented in the missions and integrated in the interfaces so that operators cannot know if there are physical platforms or just simulation models. In this scenario, there are two drones that can be



(a) Outdoor map.

(b) Indoor map.

FIGURE 4. Maps generated by SLAM algorithm.

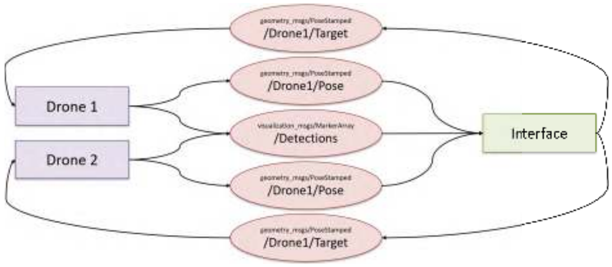


FIGURE 5. ROS graph to manage simulated drones. Squares represent nodes and ovals represent topics.

deployed to search for chemical containers. Their usefulness resides in their speed, as the aerial robots can find the targets faster. Once they have been pinpointed, the ground robot can approach these targets and extract more information about them.

In order to do this, a ROS node named *drone_simulator* has been developed, following the ROS graph shown in Fig. 5. This node receives the target positions for the drones and generates both their trajectories and detections.

The dynamics of the drones are described by (2), (3) and (3). The first one computes the velocity $\boldsymbol{v}(t_i)$ as the product of a module $v(t_i)$ and a unit vector $\boldsymbol{u}(t_i)$. The second one calculates the module of velocity at a certain time $v(t_i)$ through the commanded velocity at this time $v_c(t_i)$ and the actual velocity at the previous time $v(t_{i-1})$, in order to avoid abrupt changes in velocity and enable them to stop at the goal positions. Finally, the third one computes the unit vector that represents the direction $\boldsymbol{u}(t_i)$ as the difference between goal $\boldsymbol{g}(t_i)$ and current $\boldsymbol{p}(t_i)$ positions divided by the distance d.

$$\boldsymbol{v}(t_i) = v(t_i)\boldsymbol{u}(t_i) \tag{1}$$

$$v(t_i) = (1 - e^{\frac{-(t_i - t_{i-1})}{\tau}})(1 - e^{\frac{-d}{4}})v_c(t_i) + e^{\frac{-(t_i - t_{i-1})}{\tau}} v(t_{i-1}) \tag{2}$$

$$\boldsymbol{u}(t_i) = \frac{1}{d}(\boldsymbol{g}(t_i) - \boldsymbol{p}(t_i)) \tag{3}$$

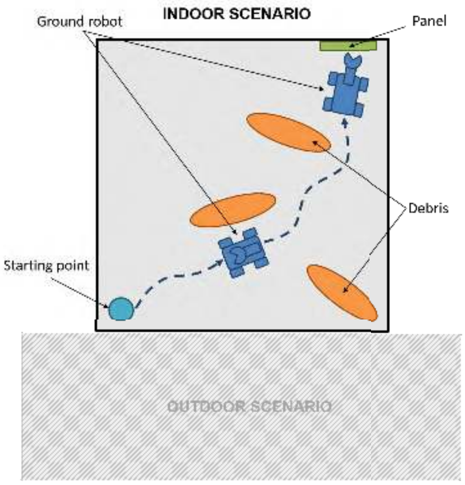


FIGURE 6. Mission in indoor scenario.

B. INDOOR SCENARIO

This scenario is located in one of the university's research laboratories, and it reproduces a control room of the chemical research center. It is assumed that a natural or human-provoked disaster has caused the gas leakage, as well as the presence of debris throughout the scenario. As shown in Fig. 6, it is a $5 \times 5 \times 3\ m$ room with a control panel in one of its corners. The control panel represented in the scenario consists of two tubes that join into one and three valves to control the three flow rates.

As already stated, the mission premise is that a ground robot with a manipulator has arrived to this room and it is at the starting point. The ground robot has to move throughout the room avoiding the debris to arrive at the control panel. Then, the manipulator has to close one of the valves to stop the leakage and finish the mission.

The goal of this phase is to test if the interfaces are appropriate to command a complex robot (mobile manipulator robot) performing a critical task (close a valve). This scenario tests the accuracy of operators in both perception and action, since they have to place the mobile manipulator close to the panel and its hand over the valve's handle. Both tasks are important for the success of the mission, since an adequate positioning of the mobile robot in front of the panel facilitates the deployment of the manipulator over the valve, taking into account the restrictions in the workspace, the reach of this robot and the requirements of the task.

In this scenario, the *Robotnik Summit HL* mobile robot had an integrated *Kinova Jaco*^{2} manipulator [49]. This manipulator has six articulations (shoulder, arm, forearm, wrist 1, wrist 2 and hand) and an effector with three fingers. Its total weight is 5.5 *kg*, it can reach a maximum distance of 984 *mm* and can manipulate a maximum payload of 2.4 *kg*.

Similarly to the previous scenario, the SLAM algorithm was used to build a map (shown in Fig. 4b and AMCL was implemented to locate the robot in the map. Contrary to the outdoor scenario, this time the robot was controlled using the *HTC Vive*'s touchpad or a joypad instead of commanded by sending goals. This fact is justified because the position of the ground robot must be accurate to facilitate the actions of the manipulator, and the way point commanding system implemented in this robot hinders this precision. In fact, some factors can affect the precision of the autonomous navigation in this scenario, such as the discrepancies between the map and the scenario, the features of the AMCL algorithm (update frequency of 1Hz) and the configuration of the navigation stack (precision of 0.20 meters and 15 degrees in the goals).

In the case of the manipulator, the desired positions and orientations of the gripper are sent to the controller node, which calls the services of *MoveIt!* to plan and execute the trajectories. *MoveIt!* is an application for robot planning and manipulation fully integrated with ROS [50].

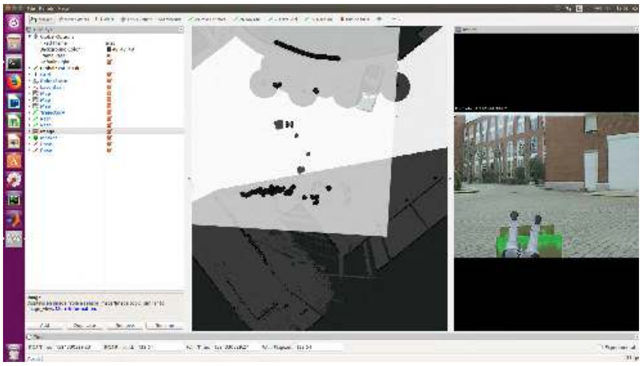
IV. INTERFACES

As already mentioned, two interfaces have been developed in this work: an adaptive & immersive interface and a state-of-the-art one. Both interfaces manage the same information about the mission, scenarios and robots, but they treat and show it in a different manner. Mainly, the proposed interface is focused on improving the operator immersion in mission, whereas the state-of-the-art interface does not consider operator immersion in any particular way. These interfaces are described in further detail in the following sections: the conventional one in Section IV-A and the adaptive & immersive one in Section IV-B.

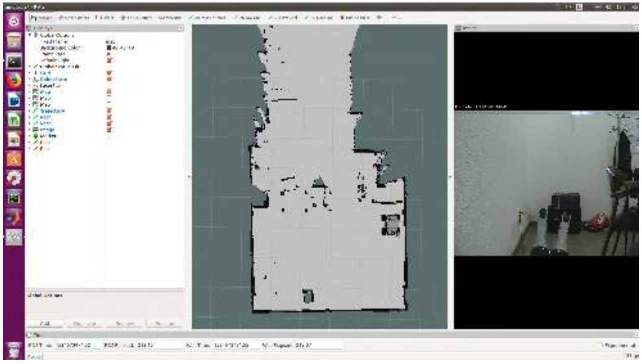
A. CONVENTIONAL INTERFACE

RViz is the most common 3D visualizer for Robot Operating System (ROS). It provides a set of displays and controls that allow to monitor and command a wide variety of robots. In fact, this tool has been used with mobile robots ([51]–[53]), drones ([54] and [55]), manipulators ([56] and [57]), mobile manipulators ([58] and [59]), humanoid robots ([60]–[63]) and multi-robot systems [27].

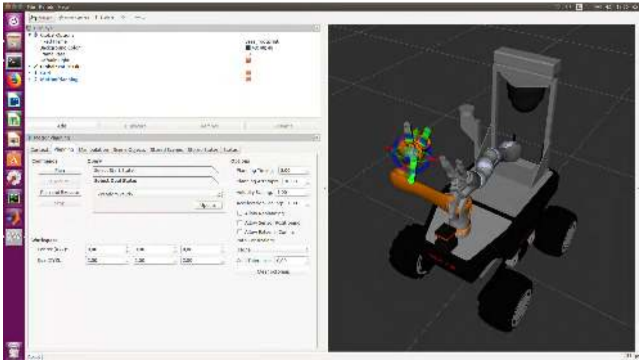
RViz was chosen to develop the conventional interface due to its simplicity and modularity. Two configurations were created: one for the outdoor scenario and another for the indoor scenario. Each configuration was designed taking into account the required tools for each specific mission.



(a) Outdoor configuration.



(b) Indoor configuration for ground robot.



(c) Indoor configuration for manipulator robot.

FIGURE 7. Screen captures of conventional interface.

The outdoor interface (shown in Fig. 7a integrates the ground robot model, three maps (one of the static scenario for localization, another of the permitted areas for planning and a third one with dynamic obstacles for navigation), long and short term trajectories, location of virtual drones and detection of boxes. Robot commanding in this scenario is performed by means of navigation goals. The operator just selects the robot to command and clicks the desired destination in the map.

The indoor interface (shown in Fig. 7b and Fig. 7c integrates elements for controlling both the ground robot and its manipulator. For the ground robot, it includes a model with laser scanner measurements and images of an axis camera, as well as two maps integrating the static scenario and dynamic obstacles to support the teleoperation. For the manipulator robot, it includes the complete model with its joints and end effector. In this interface, the operator controls the ground robot by using a joypad, since the scenario is smaller and the control must be finer. Nevertheless, the manipulator robot is controlled through VR using a sphere with three axes.

B. ADAPTIVE & IMMERSIVE INTERFACE

The adaptive & immersive interface was developed using the *Unity* game engine and the *SteamVR* plugin to be reproduced with an *HTC Vive* head mounted device. Similarly to the previous one, this interface has two configurations: one for the outdoor and another for the indoor scenario.

FIGURE 8. **Screen capture of adaptive & immersive interface in outdoor scenario.**

A screen capture of the interface configured for the outdoor scenario is shown in Fig. 8. Some of the interface elements can be seen in this image: a model of the real scenario, robot models, a cube with images from the camera and teleporting arc.

The main monitoring resources of this configuration are explained below:

- Scenario: The outdoor scenario is modeled in 3D in a state prior to the accident. This scenario represents the actual location of buildings, pavements and gardens, but some elements may have changed, such as the location of cars and containers.
- Robots: The UGV and UAV models are represented in the scenario, and their positions and orientations are continuously updated through telemetry.
- Camera: The images of the camera are shown on the faces of a cube, which can always be found over the UGV. This way, the operator can combine the perspective of virtual scenario with the images of real environment.
- Hints: The interface can highlight some robots and their potential destinations during the missions, in order to help the operator to efficiently use the resources and explore the map. In order to do this, the interface uses a search model with robots and manages a map with the explored and unknown areas.

The commanding resources used in this configuration are described below:

- Touchpad: For the outdoor scenario, the touchpad is used as a button. The operator has to press this button, point to a ground or aerial robot and release it to select the robot. Then, the operator must press again the button, point to the destination and release it to send the goal.
- Trigger: It is used to teleport the operator in the scene and control image transmission. For the first purpose, the operator has to press the button, point to the destination and release it to teleport to this location. For the second one, the controller should be hovered over the camera image cube and by pressing the trigger, the camera image can be activated or deactivated.

Fig. 9 shows a sequence of captures of the interface configured for the indoor scenario. These images show some of the elements of this configuration, such as the robot model, control panel, camera image cube and manipulator commanding method.

The main monitoring resources of this configuration are explained below:

- Scenario: The indoor scenario is modeled in an analogous way to the outdoor one. In this case, it represents the laboratory space and the location of the panel, but does not take into account the potential obstacles produced by the simulated accident.
- Robots: The model of the mobile manipulator is represented with its actual position and orientation in the scenario.
- Camera: The images of the camera are shown on the faces of a cube, which can always be found over the UGV. This way, the operator can combine the perspective of a virtual scenario with the images from the real environment.
- Hints: The interface can follow the development of the mission and support the operator in the control of the robot or the gripper.

Finally, the commanding resources applied in this configuration are described below:

- Touchpad: It is used to control the speed of the ground robot. The linear velocity can be modified by pressing the top or bottom sides of the touchpad, whereas the angular velocity can be controlled by pressing its right or left side. The magnitude varies from 0% (not touching the button) to 100% (touching the outer area of the button).
- Trigger: It is used to teleport the operator, control the manipulator robot and manage the image transmission. For the first purpose, the operator has to press the button, point to the destination and release it to teleport to this location. For the second one, the operator has to put the controller over the gripper, press the button to grab it, move to the desired destination and release the button to send the goal. For the third one, the operator has to hover the controller over the screen and press this button to activate or deactivate it.

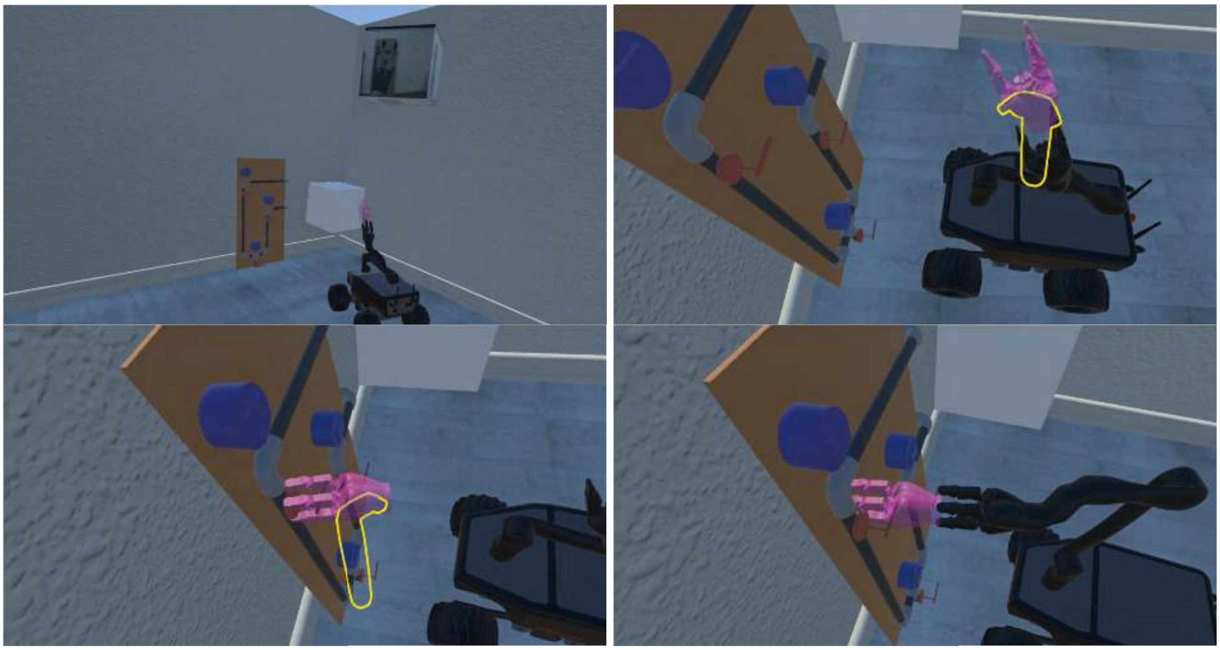


FIGURE 9. Captures of adaptive & immersive interface in indoor scenario.

- Gripper: It can be used to open and close the hand of the manipulator robot.

The transitions between outdoor and indoor scenario, as well as between the control of ground and manipulator robot, are made automatically by the interface. In order to do this, the interface manages a simple mission model, which was introduced manually, but can be improved through the experience. As proposed in previous works, the events performed by the robots, operator and interface are stored in logs, then process mining is applied to improve the previous model with the data logs, and finally the resultant model is integrated in the interface ([64] and [65]). In this work, the model is simple because the mission has not been repeated enough times, and this fact limits the adaptive functions of the interface. In following works, we are using a model enhanced by experience, so the interface will manage not only the changes of scenario and robot, but also the specific actions required to accomplish the mission.

Changes in the mission environment can be addressed in two ways. Some elements that were not considered in the 3D model of scenario can be recognized and included in the interface, such as the boxes located outside the plant. The rest of the unexpected elements can be detected by mean of the robots' cameras, whose images are integrated in the interface.

Finally, as it can be seen in Fig. 10, the adaptive & immersive interface uses the head mounted display and two controllers of the *HTC Vive* headset. The head mounted display allows to introduce the operator into virtual scenarios, whereas the controllers facilitate the command of robots. These two elements of the proposed interface perform the functions of the screens, keyboard and mouse of the conventional one. As also shown in Fig. 10, the main difference between the interfaces is that the operator is seated when working with the conventional interface, but he has to stand and move when using the adaptive & immersive one.

(a) Conventional interface.

(b) Adaptive & immersive interface.

FIGURE 10. An operator working with both interfaces.

V. EXPERIMENTS

Eight operators of different ages (from 21 to 32 years old), gender (5 men and 3 women) and studies (4 BSc and 4 PhD students) took part in the experiments. Each of them performed four missions: one for each combination of scenario and interface: outdoor with conventional interface (Out-CI), outdoor with adaptive & immersive interface (Out-A&II), indoor with conventional interface (In-CI) and indoor with adaptive & immersive interface (In-A&II). We chose this number of operators looking for a compromise between the feasibility of experiments and the significance of results. It should be noted that each experiment takes at least one hour (40 minutes for the four missions and 20 minutes for preparing and explaining them), but may require more time for preparing scenarios, charging robots and solving problems. The scenarios and interfaces were ordered as shown in Table 2, in order to compensate the influence of a learning curve on the results.

TABLE 2. **Design of experiments.**

Operator	A	B	C	D
1	Out-CI	Out-A&II	In-CI	In-A&II
2	Out-CI	Out-A&II	In-A&II	In-CI
3	Out-A&II	Out-CI	In-A&II	In-CI
4	Out-A&II	Out-CI	In-CI	In-A&II
5	In-CI	In-A&II	Out-CI	Out-A&II
6	In-CI	In-A&II	Out-A&II	Out-CI
7	In-A&II	In-CI	Out-A&II	Out-CI
8	In-A&II	In-CI	Out-CI	Out-A&II

The missions took place according to the following procedure:

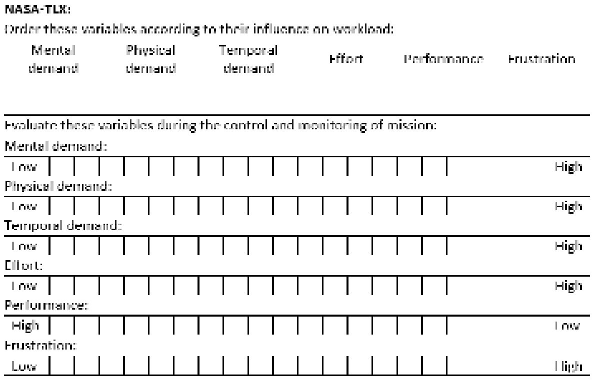
1) Explanation of the mission:
    - Outdoor: *In this mission you have to drive the ground robot from the starting point at the entrance of the plant to the end point at the entrance of the building. Along the way, you can use the aerial robots to search for boxes scattered through the scenario, and the ground robot to check if they are open or closed.*
    - Indoor: *In this mission you have to drive the ground robot through the room from the starting point to the control panel. Once in front of the panel, you have to place the manipulator's gripper over the valve's handle in order to stop the leakage.*
2) Explanation of the interface:
    - Conventional: Description of map, commanding methods (joypad for ground robot and sphere for manipulator in indoor scenario, and navigation goals for ground and aerial robots in outdoor scenario), potential detections and images of cameras.
    - Adaptive & immersive: Description of environment, commanding methods (speed commands for ground robot and goal commands for manipulator in indoor scenario, and navigation goals for all the robots in outdoor scenario), images of cameras and hints.
3) Annotation of user information: Age, gender, studies, experience with robots and experience with videogame
4) NASA-TLX questionnaire (weighing): Evaluation of six variables (mental demand, physical demand, temporal demand, effort, performance and frustration) according to their potential influence on workload.
5) Performance of mission.
6) Measurement of performance:
    - Outdoor: Annotation of time, detected and identified boxes and errors.
    - Indoor: Annotation of time, relative location of ground robot to panel, relative location of manipulator's gripper to valve and errors.
7) NASA-TLX questionnaire (scoring): Evaluation of the mission performed with a certain interface, taking into account six variables (mental demand, physical demand, temporal demand, effort, performance and frustration).
8) SAGAT questionnaire:
    - Outdoor: Draw in a map the paths of the robots, as well as the location and state of the boxes.
    - Indoor: Draw in a map the path of the ground robot, the state of the panel and the location of the gripper.
9) Observations: Comments about the interfaces.

As previously pointed out, NASA-TLX and SAGAT tests were used to estimate the workload and situational awareness of operators respectively. Fig. 11 shows the questionnaires that the operators had to fill after each of the missions. As shown, NASA-TLX allows to estimate the workload of operators using each interface, whereas SAGAT tests their knowledge about the mission, robots and targets.

Pictures of the missions being carried out can be seen in Fig. 12. The search for dangerous objects outside the plant is shown at the top of the figure, whereas the intervention inside the building is shown at the bottom of it.

The outdoor missions were evaluated considering performance, situational awareness and workload as explained below:

- Performance: This score takes into account both the mission time and operator actions and takes values between 0 (null performance) and 100 (perfect performance).
    - Time: 50% of the score is assigned according to the mission time, which varies from 0 points (600 seconds) to 100 points (0 seconds).
    - Actions: The remaining 50% of the score evaluates whether the operator has been able to go from the begin to the end point (10% of total score) and whether all boxes have been detected and identified (40% of total score).
    - Errors: Any type of collision of the robot against its environment is penalized by subtracting 10 points from the total performance score.
- Situational Awareness: This score is computed from the SAGAT questionnaire answers, and it includes the operator knowledge about the robot trajectories (50%) and the location and state of boxes (50%).



NASA-TLX:

Order these variables according to their influence on workload:

Mental demand · Physical demand · Temporal demand · Effort · Performance · Frustration

Evaluate these variables during the control and monitoring of mission:

Mental demand:

Low | | | | | | | | | | | | | | | | | High

Physical demand:

Low | | | | | | | | | | | | | | | | | High

Temporal demand:

Low | | | | | | | | | | | | | | | | | High

Effort:

Low | | | | | | | | | | | | | | | | | High

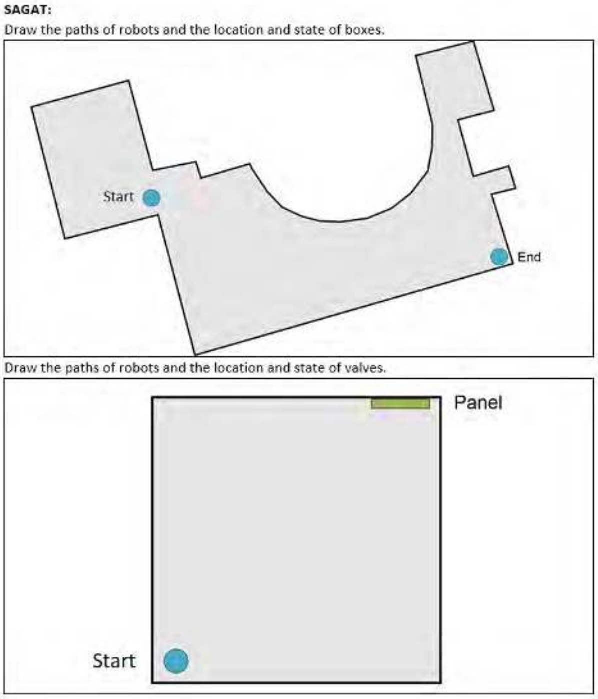
Performance:

High | | | | | | | | | | | | | | | | | Low

Frustration:

Low | | | | | | | | | | | | | | | | | High

(a) NASA-TLX workload test.



SAGAT:

Draw the paths of robots and the location and state of boxes.

Draw the paths of robots and the location and state of valves.

(b) SAGAT situational awareness test.

FIGURE 11. **Workload and situational awareness tests.**

- Workload: This score is calculated from the answers to the NASA-TLX questionnaire and computes the workload through the weighting and evaluation of the previously mentioned variables according to the operator's criteria.

In a similar manner, the indoor missions were evaluated taking into account the performance, situational awareness and workload as explained below:

- Performance: This score takes into account both the mission time and operator actions and takes values between 0 (null performance) and 100 (perfect performance).
  - Time: The time spent driving the robot from the starting point to the control panel counts 20% of the score, while the time required to place the manipulator over the valve sums another 20% of the score. Both variables are normalized so that 0 seconds mean 100 points and more than 240 seconds imply 0 points.
  - Location: The error in the relative location of the ground robot to the control panel counts 20% of the score. The optimal location would be the robot aligned with the center of panel and separated 200 *mm* from it (100 points), whereas the worse one considers a deviation of more than 400 *mm* (0 points). Additionally, the angle formed by the ground robot and control panel counts 10% of the score. An angle of 0° scores 100 points, whereas an angle of less than -45° or more than 45° scores 0 points. Finally, the error in the relative location of the manipulator's hand to the valve's handle counts 30% of the score. In this case, the optimal location considers a null distance between these elements (100 points), whereas the worst location considers a deviation of 400 *mm* (0 points).
  - Mistakes: Any type of collision of the robot against its environment is penalized by decreasing by 10 points the total score of performance.
- Situational Awareness: This score is computed from the answers to the SAGAT questionnaire and integrates the knowledge of the operator about the trajectory of the ground robot (33%), the location of the manipulator (33%) and the state of the valves (33%).
- Workload: This score is calculated from the answers to the NASA-TLX questionnaire and computes the workload through the weighting and evaluation of the previously mentioned variables according to the operator's criteria.

Finally, the implementation of experiments required the use of two computers: one with *Ubuntu 16.04* to launch the robots and execute the RViz interface, and another with *Windows 8* to execute the VR interface. The communications between robots and computers were performed through a wireless network generated by one router at the indoor scenario and three routers at the outdoor scenario.

VI. RESULTS

The main results of experiments are collected in Table 3. The workload, situational awareness and performance scores are normalized from 0 to 100. In the case of workload, the best score is the lowest one, whereas in the rest of variables, the best score is the highest one. As shown by this table, the adaptive & immersive interface (A&II) shows better results than the conventional one (CI) in terms of workload, situational awareness and performance in both scenarios. The figures in bold indicate that these results are statistically relevant, and the results are analyzed with more detail in the following sections.

A. WORKLOAD

The workload results from the outdoor scenario are collected in Fig. 13. As shown, the CI provides better results for mental and physical demand, but the A&II has better results in

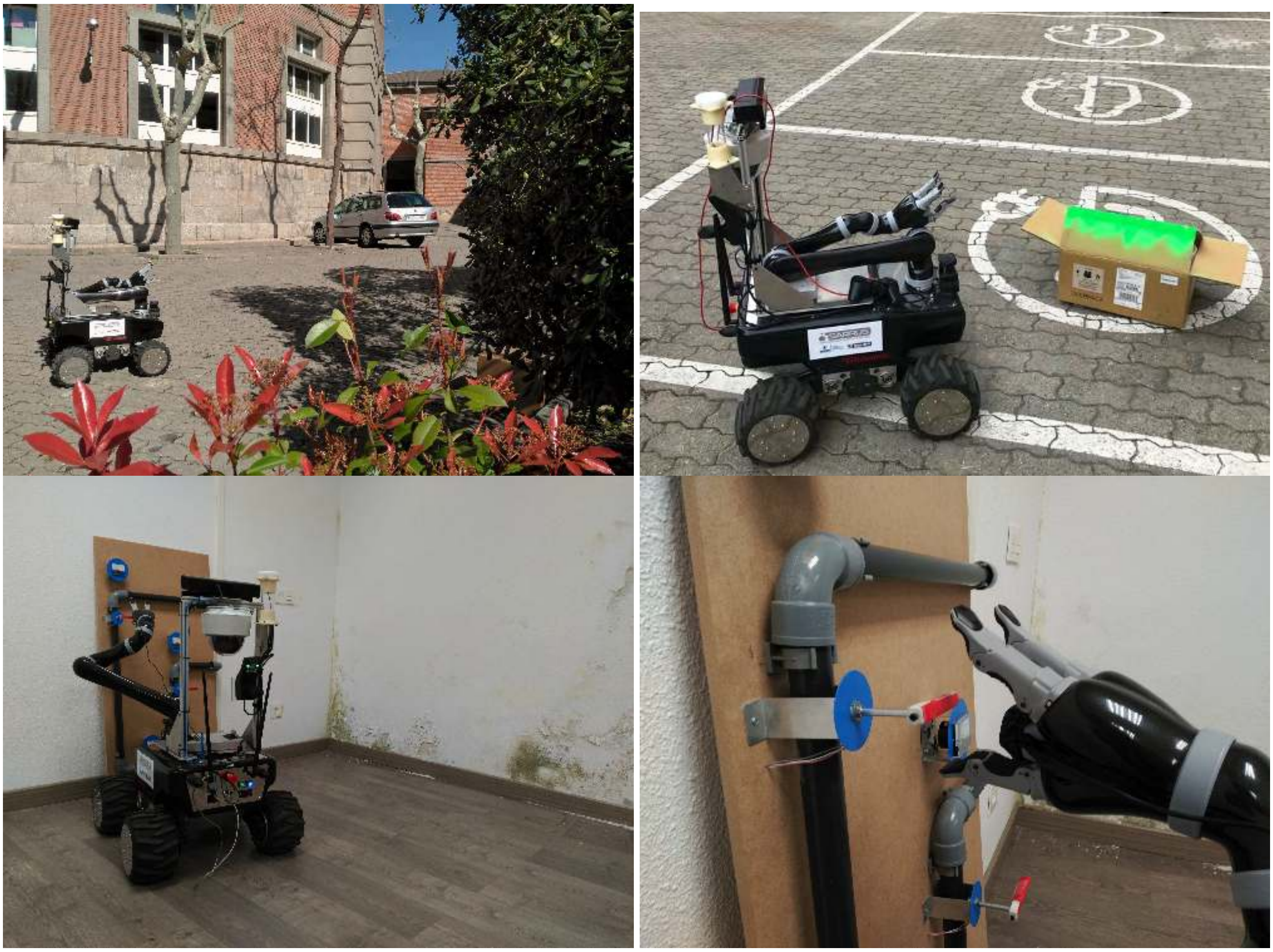


FIGURE 12. Pictures of outdoor and indoor missions.

TABLE 3. Summary of results.

Scenario	Interface	Workload (NASA-TLX)	S.A. (SAGAT)	Performance
Out	CI	45.04	77.91	60.53
Out	A&II	36.58	**89.79**	**74.16**
In	CI	54.33	62.90	51.25
In	A&II	**43.33**	63.74	**58.63**

temporal demand, effort, performance, frustration and total workload. A t-test with $\alpha = 0.05$ reveals these results are not statistically significant in this scenario. The results related to temporal demand ($p = 0.0732$) and performance ($p = 0.0719$) are the closest to be relevant.

The workload results from the indoor scenario are shown in Fig. 14. As it can be seen, the A&II provides better results for mental demand, temporal demand, effort, performance, frustration and total workload, whereas the CI only shows better results in physical demand. According to a t-test with $\alpha = 0.05$, the results related to mental demand ($p = 0.0142$), temporal demand ($p = 0.0093$), effort ($p = 0.0047$), frustration ($p = 0.0153$) and total workload ($p = 0.0015$) are significant in this scenario.

B. SITUATIONAL AWARENESS

The situational awareness results from the outdoor scenario are shown at the top of Fig. 15. In this case, the average result of A&II is clearly better than CI (89.78 vs 77.91) and a t-test with $\alpha = 0.05$ demonstrates this difference is significant ($p = 0.0228$).

The situational awareness results from the indoor scenario are shown at the bottom of Fig. 15. Although the result of A&II is also slightly better than CI in this scenario (63.74 vs 62.90), the t-test reveals this difference is not significant with $\alpha = 0.05$.

C. PERFORMANCE

The detailed results of performance for the outdoor scenario are collected in Table 4 and Fig. 16. As shown, A&II is better than CI, since the mission time is lower and completion and detection rates are achieved together with less errors. According to a t-test with $\alpha = 0.05$, these differences are significant in mission time and total score.

The detailed results of performance for the indoor scenario are collected in Table 5 and Fig. 17. The CI is better in terms of time and deviation in the control of the ground robot,

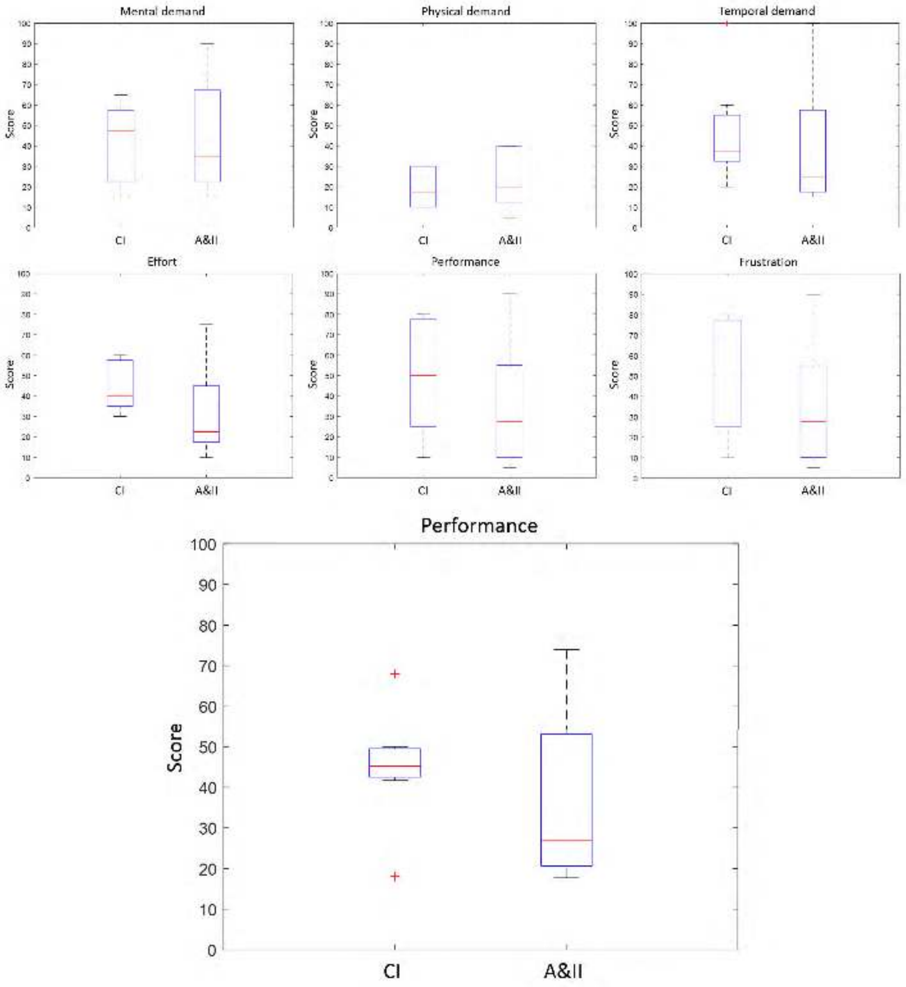


FIGURE 13. Box and whiskers diagrams for workload and its related variables in the outdoor scenario.

TABLE 4. Results of performance for outdoor scenario.

Interface	CI	A&II
Time	388 $secs$	307 $secs$
Completion	87.50%	100%
Detections	96.25%	100%
Errors	0.5	0.14
Total	60.53	74.16

TABLE 5. Results of performance for indoor scenario. GR means ground robot, whereas MR means manipulator robot.

Interface	CI	A&II
Time (GR)	70 $secs$	115 $secs$
Deviation (GR)	175 mm	193 mm
Errors (GR)	0.125	0
Time (MR)	171 $secs$	80 $secs$
Deviation (MR)	173 mm	157 mm
Errors (MR)	0.25	0
Total	51.24	58.63

whereas the A&II is better in terms of time and deviation in the control of the manipulator robot, produces less errors commanding both robots and has the best global score. However, the t-test with $\alpha = 0.05$ reveals these differences are only significant in mission times and global score.

D. COMMENTS FROM OPERATORS

As mentioned in Section V, operators not only performed the mission and answered to workload and situational awareness questionnaires, but also wrote their observations about the missions, robots and interfaces.

All the operators preferred the adaptive & immersive interface to the conventional one, regardless of their performance during the missions. Specifically, they reported the proposed interface provides better spatial perception of the agents involved in the mission (6) and understanding of the tasks that are being performed (3). In addition, most of the users remarked that the new interface is easier to use without prior experience (5), mentioning the intuitive way to get the information and control the robots (3).

The operators also made some proposals to improve the developed interface. Among these suggestions we can find simulation of robots' actions before their execution, several options to show, hide and resize the images of robots' cameras, and the possibility to change the method for commanding the robots during the mission (between way points and speed commands).

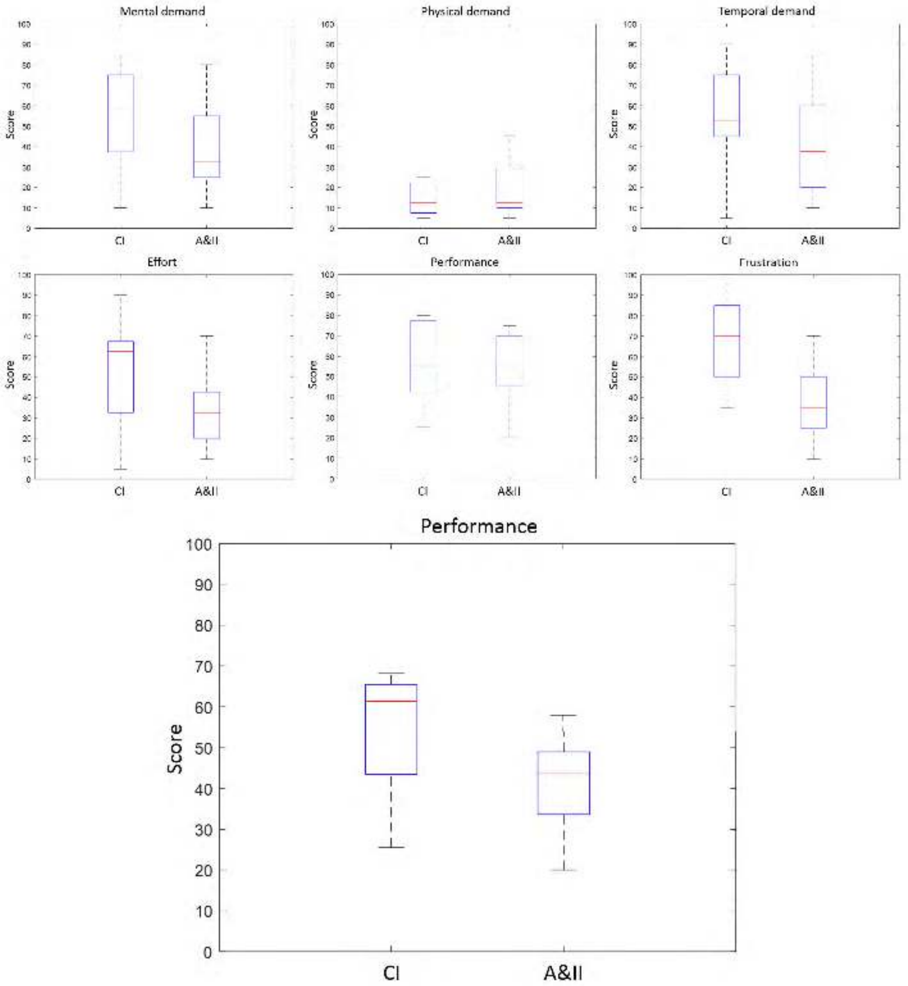
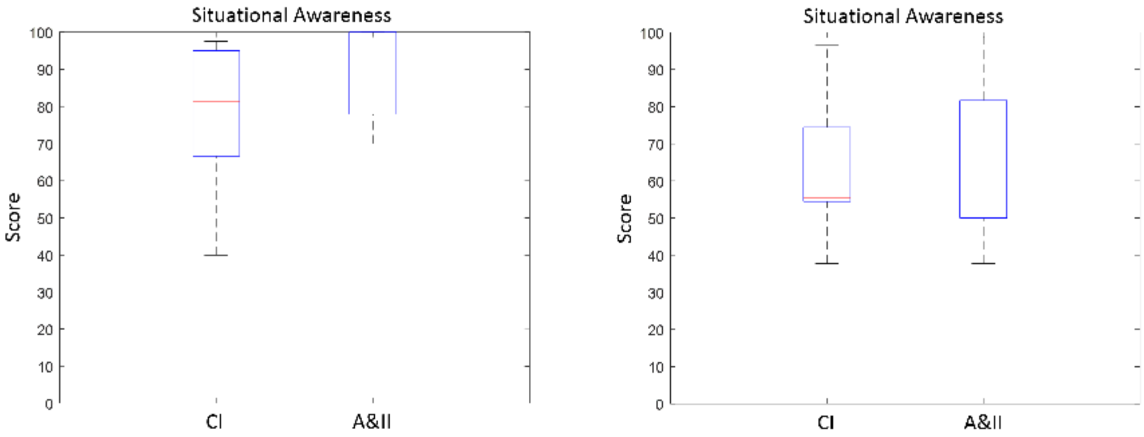


FIGURE 14. Box and whiskers diagrams for workload and its related variables in the indoor scenario.



(a) Outdoor scenario.

(b) Indoor scenario.

FIGURE 15. Box and whiskers diagrams for situational awareness.

Finally, one of the operators felt dizziness when performing the first phase of the mission. This is an already reported problem when the users are not familiar with the technology, the period of use is long or there are latency problems.

E. DISCUSSION

As mentioned in Section I, this work searches to answer the question: "Can adaptive and immersive interfaces lead to improvements in workload, situational awareness and

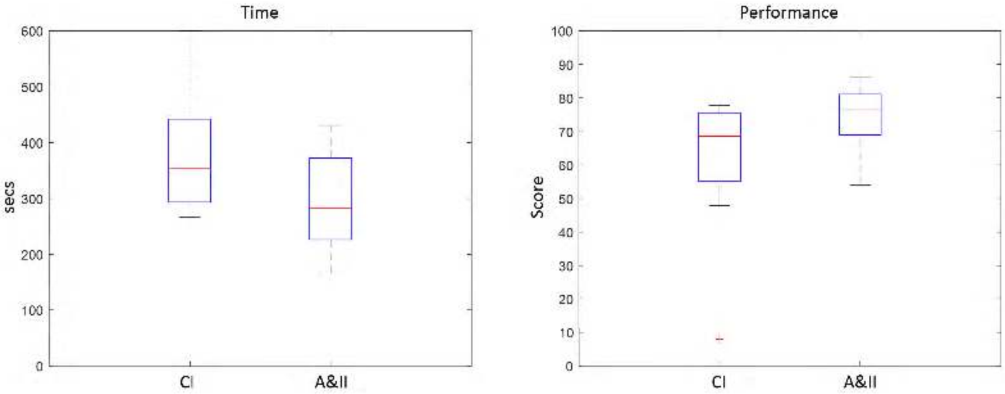


FIGURE 16. Box and whiskers diagrams for performance and its related variables in outdoor scenario.

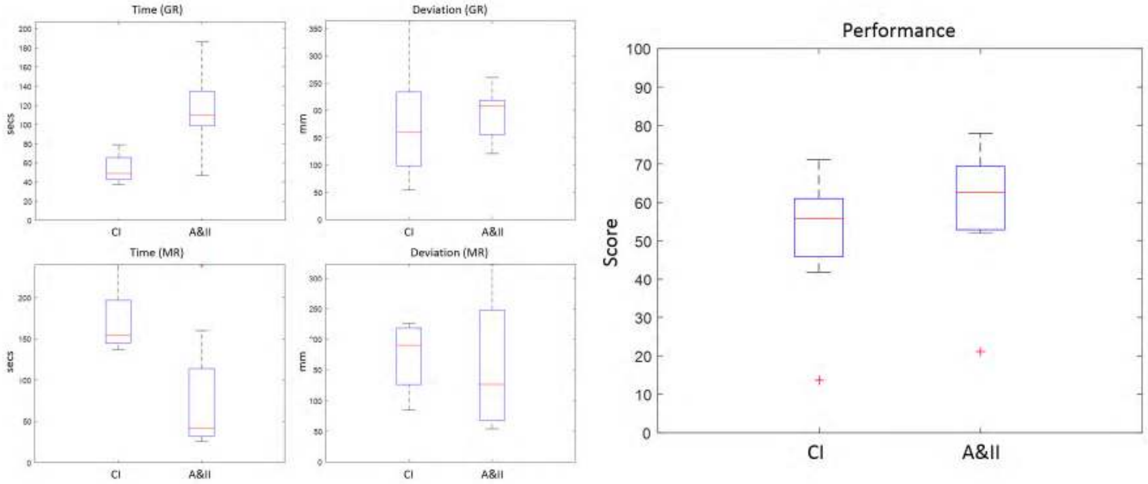


FIGURE 17. Box and whiskers diagrams for performance and its related variables in indoor scenario.

performance of multi-robot operators?''. In order to support or reject this hypothesis, experiments with two scenarios (outdoor and indoor), three types of robots (aerial, ground and manipulator), and two methods of commanding (speed and goals) have been performed.

In general, the results are better with the adaptive & immersive interface than with the conventional one. In terms of performance, this interface is significantly better to control all the robots in both scenarios, except when the ground robot is controlled by means of speed commands. We attribute this fact to the differences between the VR controller and joypad, instead of the visual part of the interfaces, since some operators expressed the difficulty of controlling the robot with the VR controller and no one with the joypad. The same occurs with workload at the indoor scenario (where operators have not only to perform a closer commanding of ground robot, but also need an accurate control of manipulator robot) and situational awareness at the outdoor scenario (where operators have to recognize, understand and remember the environment of robots). Additionally, the operators prefer the proposed interface against the conventional one, since they find it easier to use and better in terms of spatial perception and situational awareness.

All the above reasons show the potential of adaptive and immersive interfaces to address the human factor issues of multiple robots and single operator scenarios. The findings of this work open a pathway to the development of future prototypes of these interfaces and their application in a wide range of missions, scenarios and fleets.

One fact that should be discussed is the influence of mission length on interface performance. The missions performed in this work had an average length of 10 minutes, but the real missions usually imply more time. There are evidences to think that the adaptive & immersive interface will maintain its performance in longer missions. For instance, the enhancement in workload and situational awareness can lead to improvements in mission times, performance and errors. However, there are some challenges that should be addressed, such as the physical workload and the potential discomfort caused by working in VR for long periods of time.

VII. CONCLUSION

Multiple robot and single operator scenarios imply a series of human factor challenges, such as workload, situational awareness, stress, level of autonomy and trust in automation. Although conventional interfaces are not prepared to face these challenges, there are new concepts that can solve them in the future, such as adaptive and immersive interfaces.

This work develops an adaptive & immersive interface that uses virtual reality to introduce the operators in scenarios and allow an intuitive commanding of robots. This interface can be used to command multiple types of robots (ground, aerial and manipulator ones) in different kinds of scenarios (outdoor and indoor).

Additionally, a complete set of field experiments has been performed to compare the adaptive & immersive interface with a conventional one. The results show the potential of this kind of interface to address human factor challenges in multi-robot missions. Specifically, the adaptive & immersive interface provides significantly better results than the conventional one in terms of situational awareness (outdoor scenario), workload (indoor scenario) and performance (both scenarios). The remaining results are also favorable for this interface, but cannot be considered as relevant according to the statistical analyses.

To the best of our knowledge, this is the first work in which an adaptive & immersive interface is applied to control and monitor multi-robot missions in realistic scenarios. A video of these experiments can be found in [66].

In future works, the adaptive & immersive interface will be improved taking into account the suggestions of operators. In addition, the mission model managed by the interface will be enhanced with the experience of the reported experiments, which will allow new adaptive functions, such as the support to operators in the commanding of robots. Finally, the use of neural networks to adapt the interface's options to the operators' preferences will be studied. Further experiments will be performed in different environments to confirm and expand the conclusions of this work.

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