

# The Advantage of Mobility: Mobile Tele-operation for Mobile Robots

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**Abstract.** Intra-scenario operator mobility is claimed to be a strong advantage when acquiring situational awareness within a robot tele-operation. This factor should not be discounted when seeking to build more effective Human-Robot Interaction (HRI) systems. In this paper, on the basis of extensive experimentation comparing a desktop-based interface wrt. a PDA-based interface for remote control of mobile robots, we provide support (and also some confutation) of this claim. The experiments were performed in order to identify the most suitable operator interface for controlling a mobile robot depending on the task and mobility/visibility of the operator.

## 1 Introduction

Let's suppose a team of robots is deployed in a nuclear plant to execute scheduled operations of surveillance and security controls. A nuclear plant is characteristically divided into different security areas. As one gets closer to the reactor the radioactivity increases and so also the risk of contamination for humans. The advantage of using robots in such situations is to avoid undesirable risks for the workers while performing the inspection of the plant: robots go where humans fear to tread.

This working scenario would become critical if a nuclear accident, such as the explosion and subsequent fire of the Chernobyl Plant in the Soviet Union in 1986, were to occur. It is challenging for a first response team in accidents such as this to assess the extent of the damages and the associated risks. Emergency personnel deployed in a disaster zone normally cannot provide enough information about the state of the situation to the Center of Control and Operations (CCO) in order to plan the emergency response. The first responders who have reached the disaster zone usually are prevented from going beyond certain limits, due to high temperatures, radioactivity, or simply because they do not know the extent of the risks, being unable to assess the situation in its entirety. A robot team is again one solution in dealing with such hazardous scenarios, permitting the avoidance of unnecessary risks. Robots can be deployed to help the first responders to make a proper situation assessment. At the first moment operators would not have any visibility of the robot nor the scenario, as they cannot enter the disaster area. When an initial situation assessment is made, and areas safe for humans identified, responders

(carrying hand-held devices) can go into the affected zones, having partial visibility of the robots and scenario. Robots can even guide responders under low visibility conditions to desired target points through safe paths [11].

As seen in this scenario, operators or responders must remotely drive robots into areas which they might not be seeing and that could be partially destructed. Remote driving of a robot in such conditions is not a simple process, but a multicomponential one. A successful navigation in an information rich space requires human cognitive abilities such as orientation, wayfinding, visuospatial representation of environment, planning, etc. When a human operator drives a robot through a Graphical User Interface (GUI), he or she must have a proper Situational Awareness (SA). The SA provided by the interface has been considered in literature one of the measures for evaluating its usefulness [4][12][13][14].

We are working on the design and implementation of interfaces thought for this kind of missions. In disaster situations or scheduled operations the human team is composed of on-site operators, which can only wear hand-held devices, and remote operators, having access to wider computerized systems. Even if remote operators, using powerful workstations, can visualize and process a wider amount of data, responders carrying a PDA interface can boost the pervasiveness of robotic systems in mobile applications, where operators cannot be fixed to a particular place. Even if mobile devices are less powerful than desktop computers, they offer the operator the capacity to move, allowing him to partially view the actual scenario with the robot that he is controlling. The disadvantage related to the device limitations could be balanced by the advantage of mobility. Mobility could grant better situational awareness enhancing the control of the robot. First responders can control a robot team with a PDA interface while having a partial view of the environment, and thus obtain on-field information not retrievable by the robot sensors. This is the advantage of mobility, which will be studied in this paper.

Recently, a growing interest is emerging in how to develop human oriented robotic interfaces [7] [12] [19] [3]. Such interfaces do not require as extensive a knowledge of the robot system while they permit the operator to control and/or supervise a robot or team of robots. Certain guidelines for developing interfaces usable for humans have been reported in [1]. This paper presents the results of an experiment comparing the usefulness of a PDA with a desktop interface in order to determine the optimal way of distributing the control of a robot between a mobile operator using a hand-held device and a stationary operator using a desktop computer [17]. Particularly, the main purpose was to investigate which of the two interfaces is more effective both in navigation and/or in exploration tasks, depending on the different conditions of visibility, possibility of operator movement, and environmental spatial structures. Our research question is: *may the*

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*mobility of the operator inside the operating scenario counterbalance the disadvantages of a PDA device wrt. a desktop device?*, and, if yes: *how?*, *under which circumstances and/or tasks?*. The anticipated final result of our research is to identify the situations and tasks which can counterbalance the limitations of the devices required by mobile operators and the circumstances in which the desktop interface is preferred even if the operator using it is fixed remotely.

The work is organized into four main sections. We begin giving some theoretical foundations from *spatial cognition sciences* [Section 3] in order to justify the preliminary hypothesis of the experiments [Subsection 4.3]. We continue showing our two interface prototypes: a PDA-based interface and a desktop based interface (which were used in the experiments) [Section 3]. Then, we describe the experiments and how the data were analyzed [Section 4]. Finally, we present the results and discuss the contribution of this study [Section 5]. A final section closes the paper by outlining future work.

## 2 Situational Awareness and Spatial Cognition

The commonly accepted SA definition was given by Endsley [6] and adapted to HRI by Yanco, Drury and Scholtz as “*the understanding that the human has of the location, activities, status, and surroundings of the robot; and the knowledge that the robot has of the human’s commands necessary to direct its activities and the constraints under which it must operate*” [20]. This definition distinguishes three components within the concept of SA: human-robot SA, robot-human SA, and the human’s overall mission awareness [20]. Within the human-robot awareness two aspects are important for the purposes of this paper: location awareness, defined as a map-based concept, allowing the user to locate the robot in the scenario, and surroundings awareness pertaining to obstacle avoidance, allowing the user to recognize the immediate surroundings of the robot [4].

In order to better understand how the SA enhance the operator performance when he or she is driving a robot is useful to introduce two important concepts from human spatial-cognition: *route knowledge* and *survey knowledge*. The distinction between route and survey knowledge helps to understand the cognitive skills required by a human operator remotely controlling a robot. The route perspective is closely linked to perceptual experience: it occurs under the egocentric perspective in a “retinomorphous reference system”, that is, one is able to perceive himself in the space [9], with a special emphasis on spatial relations between objects composing the scene an agent is situated in. This is for example the case of an operator driving a robot with a tridimensional perspective on a screen, simulating the visual information that he or she would obtain by directly navigating in that environment (see Section 3.1, desktop interface 3-D viewer). Route-based information, from a ground perspective, is stored in memory to keep trace of turning points, distances and landmarks or relevant points of reference in the observed context. In contrast, survey perspective is characterized by an external and allocentric perspective, such as an aerial or map-like view, allowing direct access to the global spatial layout [2] as it would be if the operator had a device by which he or she can have a global, aerial view of environment and the robot inside it (see Section 3.2, PDA interface). Previous studies have shown that a navigator having access to both perspectives exhibit more accurate performances [9].

We can appreciate a relation between location awareness and survey knowledge, while surroundings awareness relates to route knowledge. Our case study consists of a human operator driving remotely a robot using a human-robot interface. When the operator is not physically in the navigation scenario, the interface must enhance his or her

spatial cognitive abilities by offering multilevel information about the environment (route and survey). Complex interfaces can provide different perspectives of the environment (bird’s eye view or first-person view). Such information allows an operator looking at a GUI (Graphical User Interface) to have more than one perspective at the same time. Contrarily, if the operator is in the scenario, part of the information can be acquired by direct observation, depending on the visibility the operator has. In such situations less information is required in the GUI.

These spatial-cognitive aspects should be taken in consideration when designing a human-robot interface for remote tele-operation. Unfortunately, HRI development tends to be an afterthought when designing robotic systems [1] and advances in AI, sensory fusion, path planning, autonomous navigation, image processing, etc. are not often integrated into proper interaction systems. Actually, most robot operation interfaces are system-oriented, permitting developers to have low level control of the system and facilitating the debug process but which are very difficult to operate for non-expert users.

## 3 Interface Prototypes

We have implemented two interface prototypes: one for desktop computers and one for PDA devices<sup>6</sup>. Both are based on the HRI interfaces discussed and analyzed by Yanco [4] and Nielsen [12]. Nevertheless, they only considered an egocentric point of view, either for video acquisition, either for map information. We associated to this approach an allocentric point of view, to enhance operator’s SA, as discussed in Section .

### 3.1 The Desktop Interface

Our desktop interface is designed for controlling robots in structured and partially unstructured environments. Its scope is to be able to control a robot dealing mainly with exploration, navigation and mapping issues. Its main purpose is to enhance the operator’s performance of complex tasks, with a comprehensive overview of the whole explored area, and supplying all the necessary tools to control the robot. The overall information is always visible on the screen while controlling the robot. The interface implements also the possibility to control a team of robots.

The interface shown in Figure 1 can be divided into two parts: the topmost panel is the *Active Robots Panel*, where the user can switch among the robots of the team, in order to directly interact with an individual unit. If a robot is added to the team, the operator can easily connect with it. The rest of the window contains all the information relative to the selected robot and the robot team:

**Navigation Panel.** It is localized in the central area of the window, it is composed of a *Local View of the Map* and a *Global View of the Map* giving a bird’s eye view of the zone. The map is constructed on-line from the robot laser range sensor and the odometry using SLAM (Simultaneous Localization and Mapping) techniques. The Local View can be zoomed in and out. The robot is located within the map by a rectangle-symbol containing a solid triangle that indicates its direction. The second component is the *3D Viewer*, which allows a more comfortable and realistic navigation in the tele-operation mode giving an egocentric perspective of the scenario. The pseudo-3D reconstruction may be based either on the laser range data or on the 2D map, by simply elevating the obstacles into 3D images. The laser view is more precise than the map view, but it only gives information of the obstacles in front of the robot, while the map view gives a

<sup>6</sup> They’re both available at <http://www.dis.uniroma1.it/~valero/sw/>.

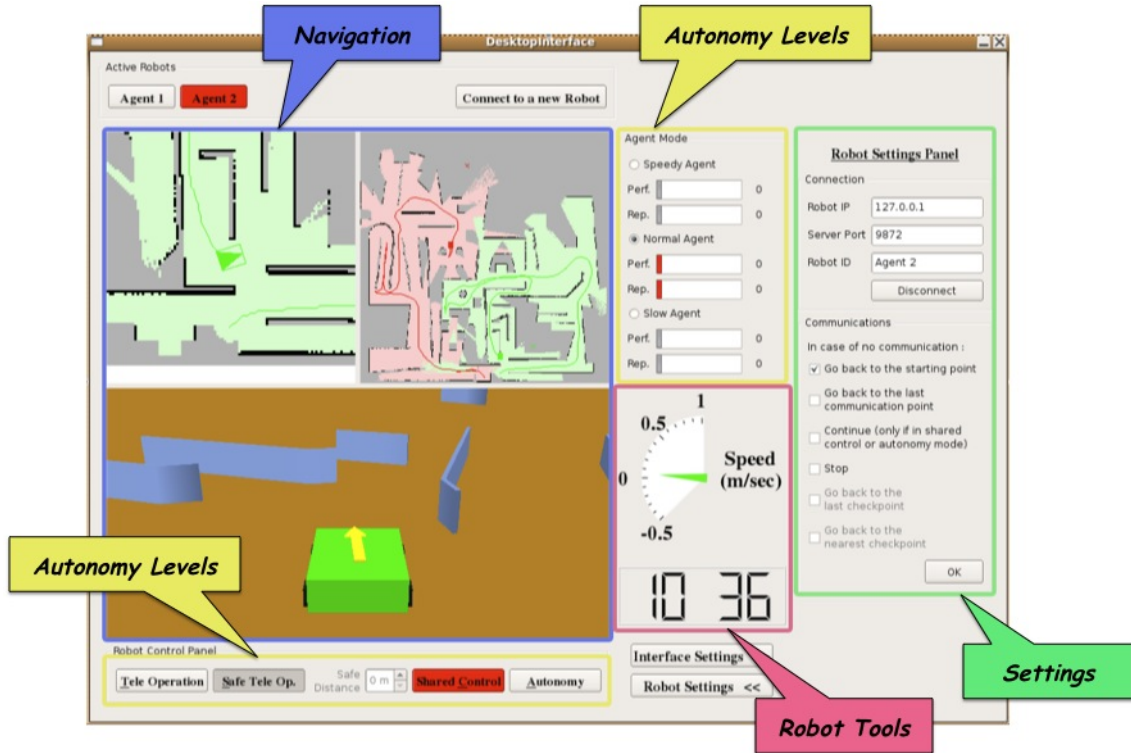


Figure 1. Desktop Interface

more global picture. The laser view is demonstrated to be more useful to drive the robot in narrow spaces in which the constructed map would not be adequately precise. The operator can manually switch from one to another as well as pan-tilt them.

**Autonomy Levels Panel.** It allows the operator to switch among four control modes: *tele-operation*, *safe tele-operation*, *shared control* and *autonomy*. In the safe tele-operation mode the system prevents the robot from colliding with obstacles. In the shared control mode the operator sets a target point for the robot by directly clicking on the map, which the robot tries to reach. When working in shared control or autonomy, the operator can select from three agents (*Agent Mode Panel*): *slow*, *normal* and *speedy*, which have different pre-set maximum velocities and use different heuristics to explore the environment.

**Robot Tools Panel.** This panel consists of several widgets to monitor the robot kinematics. There is a speedometer, a chronometer to keep track of the mission length, and a gyroscope directly embedded in the robot within the 3D View (yellow directional arrow).

**Settings Panel.** It is divided into two views and it consists of the *Interface Settings* and the *Robot Settings*.

### 3.2 The PDA Interface

Due to the reduced size of a PDA and its computational limitations, the display cannot present on-screen all the data provided by the HRI system. In order to keep the same functions offered by the desktop-based interface we implemented them using various simplified layouts. This underlines how critical it is to present the operator only the crucial data, as each layout change implies a longer interaction time with the device. Another critical point was to consider the slower

input capacities of the operator with a PDA, consisting of a touch screen and a four-way navigation joystick. Thus, it is important to minimize the number of interactive steps to change a setting or to command the robot.

The PDA has two kinds of 2D views, each selectable with its own tab. The first, egocentric, is the *Laser View* (Figure 2(a)). The second is the *Map View* (Figure 2(b)), equivalent to the *Global Map View* described in 3.1. A third tab (Figure 2(c)) is dedicated to the *Robot Control* functionalities, merging both the *Autonomy Levels Panel* and the *Agent Mode Panel* of the desktop version. The interface and robot settings can be modified by clicking the tab located at the bottom of the display.

## 4 Experimenting with the interfaces



Figure 3. The P2AT robot inside the indoor area during one of the experiment runs

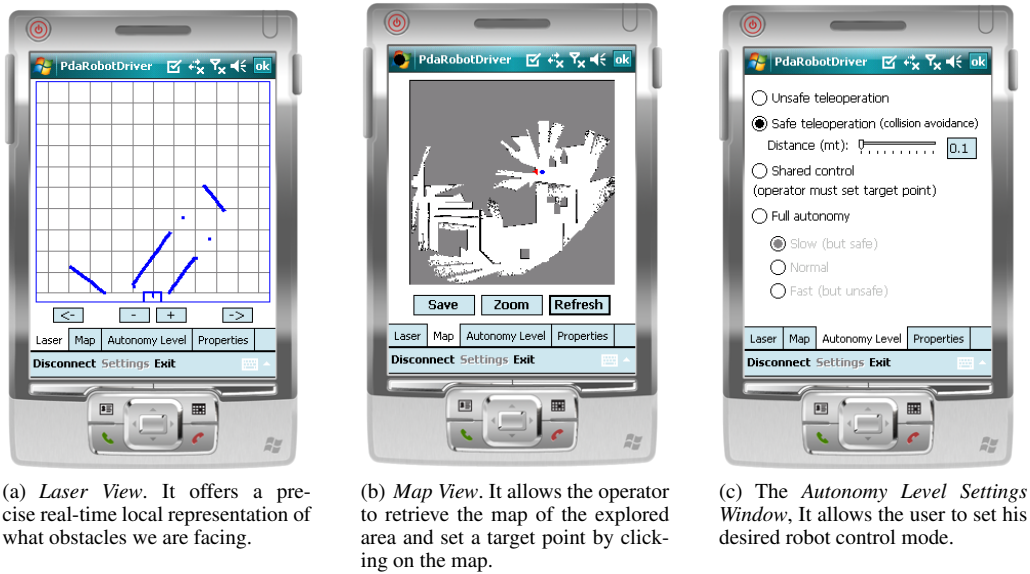


Figure 2. PDA Interface.

There have been studies done on how different designs of an interface and the interaction model can support the operator when operating and supervising a remote robot(s). These studies compare the usefulness of various desktop-based interfaces [5][4][12] or of various PDA-based interfaces [10][7]; however, very few studies compare desktop-based wrt. PDA-based interfaces for remote robot control. Our interest was to determine which are the main performance differences between a PDA and a desktop-based interface.

#### 4.1 Subjects

Twenty four subjects (four females and twenty males) ran the experiments, aged between 20 and 30, nineteen undergraduate and five PhD. candidates. The scenarios of the experiments were different and no participant had previous experience with any of the two interface prototypes. All of the participants completed the three experiments in the same order and so on no one had more experience than the others. We looked for a trade-off between people with experience in robotics and computer science and people with no experience.

#### 4.2 Experiment Design and Procedure

Three experiments were run. The whole experimental context was scheduled in five days. The subjects were splitted into two groups, one using the PDA interface, the other the desktop version. Every subject was trained for twenty minutes to acquire a basic knowledge of the functionalities provided by the interfaces. After the training, they ran the experiments in order. Each subject had a single trial.

**First experiment** The first experiment was run using Player/Stage [8] robotics simulator. Subjects were asked to explore a virtual unknown environment of 20 m x 20 m (Figure 5) using a mobile robot equipped with laser range scanner. Users were given twenty minutes of time to explore the maximum area without colliding. Each candidate was assigned a type of interface randomly and had a single

trial with it (twelve subjects drove the robot using the PDA and the other twelve the desktop interface). In order to “motivate” this task they were asked to look for “radioactive sources” distributed in the area. The sources were detected by a simulated sensor installed on the robot. During every run, the operator was supported and supervised by one assistant, who previously helped him or her in the training. Another person was in charge of supervising the correct-functioning of all the software. Returning to the scenario application given in the introduction, this experiment applies to the case in which responders must explore a disastred area in order to asses sthe extent of damages after a nuclear accident.

The independent variable was the *Interface Type*  $\in \{PDA\ interface, desktop\ interface\}$ , while the rest of the factors remained unchanged. The dependent variable was the covered area by the robot in square meters. An area was considered covered if it had been mapped.



Figure 4. Operator driving the robot with the PDA interface. The robot appears from a hidden area prior entering the building

**Second experiment** Subjects were asked to navigate with a real Pi-

oneer P2AT robot equipped with a SICK Laser Range Finder alongside a path composed by narrow spaces, cluttered areas and corridors (the path was about 15 meters long). Users did not need to find a way but just follow it from the beginning to the end. Subjects were not given a layout of the scenario and it was never visible to them. During every run, the operator was supported and supervised by three assistants: one who trained him or her for five minutes to use the real robots and recorded some data during the trial. The second person was the technical responsible of the robot and of the interface device, while the last controlled the robot during its motion and took care of its safety and of the scenario. This second experiment tries to reproduce the situation in which operators must drive remotely a robot to a target point, like in scheduled operations in nuclear plants.

The independent variable was the *Interface Type*. As for the dependent variable, we were interested in the *Navigation Time*, measured in seconds.

**Third experiment.** Subjects were asked to navigate again in a real scenario with the same P2AT robot. The environment consisted of an outdoor area in a courtyard, linked through a ramp to a corridor inside our department. The desired scenario recalls a disastere area and is composed by three different zones, all realized using reclining panels and cartons:

- *Maze*, with one entrance and one exit;
- *Narrow Spaces*, very tight areas where the robot can only pass through them, without any chosen direction;
- *Cluttered Areas*, contain several obstacles placed irregularly and isolated in the area, such that the robot can navigate through the area choosing more than one direction.

In this last experiment subjects using the PDA could move in the scenario, resulting in situations in which they could completely see the scenario and robot, and areas in which they could just see them partially. The outdoor area was visible to the operator while the robot was not always completely visible. Operator could not enter the *arena*. The indoor area was only partially visible through some windows located at the top of the indoor scenario and the robot was completely hidden at least half of the path. Outdoor and indoor areas were different and measured times cannot be compared among them. The operator was supported like in the previous experiment. This last experiments simulates a nuclear disaster after the initial situation assessment. Responders know where they can go without contamination risks, and thus, responders carrying a PDA can drive the robot partially seeing it. There will be some limits that responders will not be able to trespass, and thus, they will have to drive the robot with no visibility of it.

We used a 3x2x2 factor design, where the independent variables were: *Space Type*  $\in \{Maze, Narrow\ Spaces, Cluttered\ Areas\}$  for the part of the path, *Operator View Degree*  $\in \{Total\ Visibility, Partial\ Visibility\}$  which determines the operator direct view of the scenario and robot, and finally *Interface Type*. The first two were treated as “within-subjects” factors, while the last one as a “between-subject” factor. The measured variable was the time (in seconds) required to complete the path.

The scenario, the robot configuration, and the wireless signal strength were the same for all the subjects, to guarantee replicability.

### 4.3 Preliminary Hypothesis

The different technical features of the desktop and PDA interfaces are strictly connected with different ways of acquiring information

from the navigated space and consequently with different behavioral capacities to build a mental map of the environment depending on the scenario features. The laser and the map views, which are available in both desktop and PDA interfaces, represent respectively “route” and “survey” knowledge [15][16], as defined in the introduction.

These perspectives convey respectively to path-planning and survey knowledge. Path-planning, in order to avoid obstacles, depends on the operator surroundings awareness; spatial information is accessed sequentially, the number of paths emanating from each location is small, the information about the overall environment is rigid and poor, and an egocentric reference system is used to decide the direction of movement. On the contrary, survey knowledge, for wayfinding, depends on the operator location awareness, which is generally considered an integrated form of representation with fast and route independent access to selected locations, dynamic and overviewing information of the environment layout, and structured in an allocentric coordinate system [18].

Even if both interfaces provide both kinds of spatial knowledge, the PDA could result in less access to survey knowledge, due to the need to switch screen and the time consumption required to retrieve, process, and design the map. In the desktop interface the survey and route knowledge are always and contemporary available on the screen. Consequently, we hypothesized a better operator performance driving the robot with the desktop, in comparison with the PDA interface, in the scenario conditions which require dynamic environment orienting abilities (i.e maze). Contrarily, no meaningful performance differences were expected in the navigation situations in which no survey information is required and in which information obtained in the route perspective would be sufficient to accomplish the task (i.e narrow spaces). Besides, we expected a better general performance for PDA users in the full visibility condition, as the operator has the possibility to see the robot either represented on the PDA display either in the real environment. This could plausibly decrease the information accessibility disparities between the two interfaces and take advantage of a more salient route information access deriving from a direct environment experience. In any case, we did not know if communications latency and lower computational power associated with the PDA device would significantly influence the performance. The experiments were made in order to validate these hypothesis, and to test if the mobility advantage related to a PDA could counterbalance the disadvantages associated with the device limitations.

### 4.4 Data analysis

We used ANOVA (Analysis of Variance) to analyze the data and consider only significative values (with a significance level set at 0,05). Roughly speaking, a population of samples is significant when their variations are imputable only to intrinsic factors, and not to casual ones. In order to accept a statistical significance, the p-value returned by ANOVA must be lower than the set level. Within ANOVA, the F-test is used to compare the total deviations of the two components, returning the ratio of the two variances (F-value or F), that is usually reported with the p-value.

**First Experiment.** For the exploration task analysis we have subdivided an exploration time of 10 minutes in twenty discrete values (from 0.5 to 10); then a 2x20 ANOVA on the explored area (in  $m^2$ ) was carried on with the “between-participants” factor of Interface (Desktop and PDA) and the “within-participants” factor of Time (in

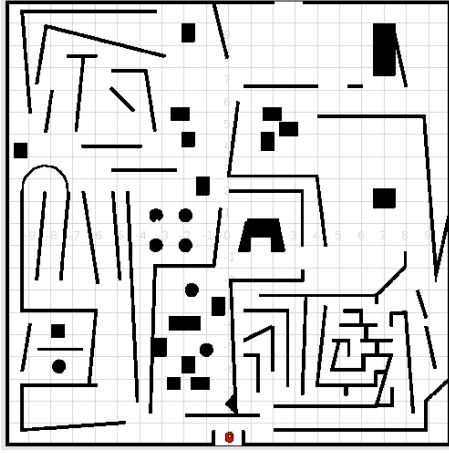


Figure 5. Virtual scenario for the first experiment

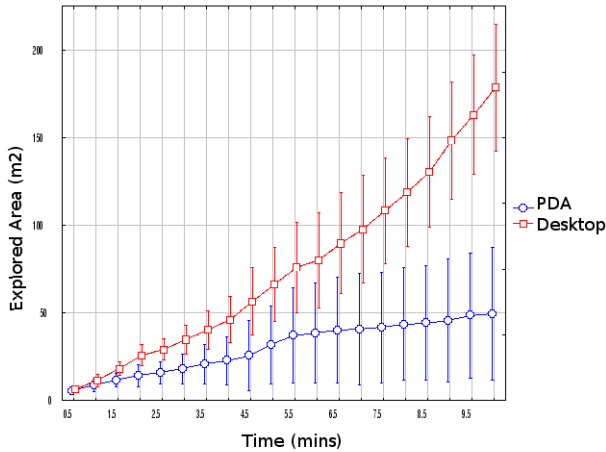


Figure 6. Covered area in square meters by the operator using the PDA (bottom curve) and the operator using the desktop interface

minutes from 0.5 to 10). The covered area was considered as a measure of the performance of the exploration.

**Second Experiment.** A one way ANOVA on navigation times was calculated to compare the interfaces in order to see if the differences under the PDA condition and the desktop condition had significant differences when the operator had to navigate without dealing with exploration (way finding).

**Third Experiment.** Two separated ANOVA's (since the visibility variable did not vary in the Desktop interface) on navigation times for each condition of PDA visibility: Total Visibility (TV) and Partial Visibility (PV), were carried out to study the PDA visibility effect on performance. For each of these analysis the design was a 2x3 with the Interface (Desktop and PDA) as a "between-participants" factor and Space Type (Maze, Narrow Spaces and Cluttered Area) as a "within-participants" factor. Three planned comparisons between Desktop and PDA for each space type were calculated afterwards to analyze the interface differences depending on the structural characteristics of the navigated space. Because the two analyzed populations can be characterized by a normal distribution, Student's t-test was used to verify a significant statistical difference between them..

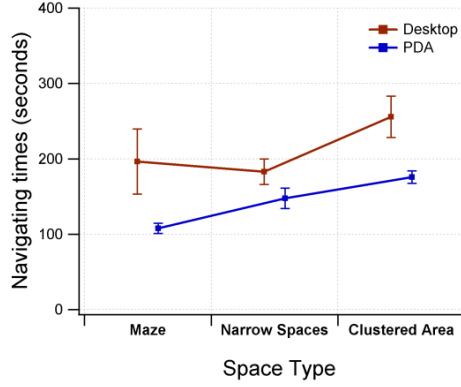
## 4.5 Results

**First Experiment.** Results are shown in Figure 6. A direct observation of the areas explored by the operator using the desktop and the operator using the PDA reveal that the former performs considerably better. The analysis showed a significant interaction between Interface and Time [ $F(19, 361) = 13.65, p < .00001$ ]. A planned comparison for each level of time was calculated, indicating that at minute 1.5 of exploration the difference between Desktop and PDA, in terms of explored area, is just significant [ $p < .05$ ]. Then it remains significant and grows at each level of Time.

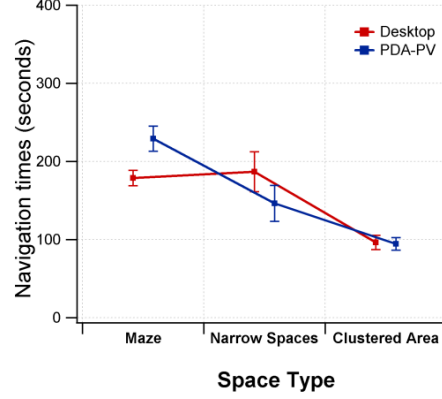
**Second Experiment.** The first ANOVA on navigation times resulted non significant [ $F < 1$ ] revealing no difference among the driving times between interfaces.

**Third Experiment.** Results are shown in Figures 7(a) and 7(b). The plain observation of the figures indicate that the operator using the PDA with full visibility drove the robot faster, while in the partial visibility it depends on the kind of *Space Type*. To study if these differences were significant we ran the ANOVA tests.

The first 2x3 ANOVA with the "between-factor" *Interface* (Desktop and PDA-TV) and the "within-factor" of *Space Type* (Maze, Narrow Spaces and Cluttered Area) revealed a non significant interaction between them [ $F(2, 32) = 1.43, p > .05$ ]; the main effects of *Interface* was instead significant [ $F(1, 16) = 6.67, p < .05$ ], revealing faster navigation times with the PDA interface in the total visibility condition in comparison with the desktop interface, independently from the *Space Type* (Figure 7(a)). The second analysis (partial visibility) showed a significant interaction between the *Interface* (Desktop and PDA-PV) and the *Space Type* [ $F(2, 32) = 4.41, p < .05$ ]. Consequently three planned comparisons between the desktop interface and the PDA interface with partial visibility (Figure 7(b)) for each condition of *Space Type* were calculated and revealed that in the Maze condition, the desktop interface drives to faster navigation times in comparison with the PDA interface under partial visibility [ $p < .05$ ]; no other significant differences were observed between the interfaces in the other *Space Type* conditions.



(a) Operator using PDA with full visibility of the scenario wrt. operator using desktop. Mean times and std. dev. are represented



(b) Operator using PDA with partial visibility of the scenario wrt. operator using desktop. Mean times and std. dev. are represented

From the t-test analysis a significant and a tendency to a significant difference between the desktop interface and the PDA interface was observed, respectively in the *Cluttered Area* [ $p < .05$ ] and *Narrow Spaces* [ $p < .06$ ]. We hypothesize that collected data was not significant due to the reduced number of subjects.

## 5 Discussion

The results of the experiments clearly indicate a difference between interfaces depending on the type of task. In Table 1 the different cases that were considered in the nuclear plant scenario are illustrated, indicating which interface would perform better. The exploration task corresponds to the case in which operators must assess the state of and unknown area. It applies to situations after a disaster, in which he or she must drive the robot throughout the area looking for victims, damages, etc. Navigating, instead applies to the case in which the operator must follow a path in which he or she must not find a way (corridor, tunnel, etc.), more typical of maintenance operations. For analyzing the data we have considered that finding a way through the maze consists of an exploration task, driving alongside narrow spaces of a navigation task, while driving in the cluttered area is a combination of both.

Both interfaces are practically identical in the navigation task under the same condition of visibility (second experiment), a highly relevant distinction between them could be stated for the exploration task (first experiment). Here the results evidenced that at just 1.5 minute of exploration the desktop exploration area was greater than the PDA one; moreover this difference gradually increased with time. This result was predicted and analyzed in the hypothesis section. The

| Exploration               | Expl./Nav.  | Navigation  |
|---------------------------|-------------|-------------|
| <b>Total Visibility</b>   |             |             |
| PDA                       |             |             |
| <b>Partial Visibility</b> |             |             |
| Desktop                   | Desktop/PDA | Desktop/PDA |
| <b>No Visibility</b>      |             |             |
| Desktop                   | Desktop/PDA |             |

**Table 1.** Best performance interface depending on the task and visibility

data analysis of the third experiment shows that in total visibility condition the PDA interface results in a general better performance in terms of navigation times than the desktop interface independently from the space type. That is, the information the operator receives through the PDA, completed with the information he receives directly from the operating scenario, provides him or her with a better robot situational awareness (location and surrounding awareness [20]) for driving the robot. This implies that a PDA permits a successful task accomplishment when the robot is monitored by using both screen given information and real environment cues. This different kind of information integration together with the interface simplicity allows the operator to overcome the device limitations.

Concerning the partial visibility condition results indicate that an operator driving the robot with our desktop interface in a maze-like space, brings to faster navigating times than the operator using our PDA interface. We hypothesize that this effect is due to the amount of information given by the two interfaces: while indeed in the desktop local and global (survey perspective - location awareness) and tridimensional (route - surrounding awareness) perspectives are simultaneously available, in the PDA only one of these views is shown and the operator must switch between tabs to change it, employing more time. Even more, switching the tab forces adds an ulterior latency time due to the computational time to render the selected visualization mode. This occurs mostly in mazes, presumably because in these kind of environments a global configuration of the spatial structure (survey perspective) is needed in order to find a way out. This explanation is also supported by the t-test results, which indicate a general better performance of our PDA interface wrt. the desktop interface in cluttered and narrow spaces, which likely do not necessarily require survey knowledge to successfully navigate through.

We finally hypothesize that the differences between tasks could derive from their different information requests. It is presumable that all the information given by the desktop (local, global and tridimensional perspectives) is not necessary in the navigation task but indispensable in the exploration task, in order to give the required location awareness.

## 6 Conclusion and further work

In this paper we have studied the influence of operator mobility and task when controlling a robot using a PDA interface wrt. controlling a robot with a desktop interface. Even if the results here analyzed only

apply to our interfaces, we believe that they can be generalized to the device and thus, our thesis is that similar results would be obtained if the same experiments were run with interfaces designed differently.

As a main conclusion we can state that the SA of the operator is smaller when using the PDA (mostly the location SA) due to the fact that the small size and low computation capacity of a PDA device does not allow to provide to the operator with the same amount of information that when using a desktop. *Nonetheless, the possibility of moving inside the operating scenario that permits a hand-held device can counterbalance this disadvantage, as proved from the results.* In the future we will work in finding ways of enhancing the survey knowledge (location awareness) through the PDA interface, in order to diminish this differences. In any case, *results demonstrated that when the operator does not need to find a way (exploration) but to follow a path, both interfaces were feasible enough to drive the robot obtaining the same performance.*

Furthermore, considering that our anticipated work consists of a team of operators controlling a team of robots, besides providing robot situational awareness, we must study how to provide them with team situational awareness, in order to coordinate the team activities, transfer the control of the robots and *intelligently* allocate the control of the robots among the operators. We are planning for the next year to make experiments in which operators do not control the robot independently, but in which the operator using the PDA and the operator using the desktop, control simultaneously a team of robots.

## ACKNOWLEDGEMENTS

We would like to thank the referees for their time and comments which helped to improve this paper.

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