TOURBOT and WebFAIR

Web-Operated Mobile Robots for Tele-Presence in Populated Exhibitions

BY PANOS TRAHANIAS, WOLFRAM BURGARD, ANTONIS ARGYROS, DIRK HÄHNEL, HARIS BALTZAKIS, PATRICK PFAFF, AND CYRILL STACHNISS

The design and development of mobile robots capable of operating and providing services in populated environments is an area that has attracted the interest of the scientific community throughout the last decade. Examples of such robots are deployed in hospitals, museums, trade fairs, office buildings, and department stores. In these environments, the mobile robots provide various services, including such tasks as delivering, educating, entertaining, or assisting people [5].

Two recent projects funded by the European Union (EU), TOURBOT (http://www.ics.forth.gr/tourbot) and WebFAIR (http://www.ics.forth.gr/webfair), address the development of mobile robots capable of operating in populated environments in order to provide alternative means of interaction with local and remote visitors, a field that is informally termed "robots in exhibitions." TOURBOT started in January 2000 and ended successfully in February 2002. This project pursued the development of an interactive tour-guide robot able to provide individual access to museums' exhibits over the Internet. The results of TOURBOT were demonstrated through the installation and operation of the system in three museums participating in the project as well as other interested organizations. WebFAIR (which began in December 2001 and ended in May 2004) was based on the TOURBOT results and extended relevant developments to the more demanding environment of trade shows. Additionally, WebFAIR introduced teleconferencing between the remote user and on-site attendants and employed a multirobot platform, thus facilitating simultaneous robot control by multiple users. Factual information about the two projects is summarized in Table 1.

In this article, we present selected techniques developed in these projects to cope with scientific challenges and technological requirements imposed by the specific application area. Among these are techniques for mapping large environments, an obstacle-avoidance technique that uses laser and vision information to detect objects invisible to the laser scanner, and an approach to filter out range measurements coming from moving persons during map construction.

A very important factor for the acceptance of a robotic tour guide by the broader public is the degree to which the system smoothly interacts with both Web and on-site visitors. For this reason, special emphasis was placed upon the development of appropriate robot-user interfaces in both projects. In this article, we also describe aspects of the developed interfaces, such as a speech interface for on-site users and a flexible Web interface with enhanced visualization capabilities for remote users.

An important aspect of EU-funded projects is that they do not only provide important technical developments but also permit the study of the maturity of technologies as well as the level of their acceptance by the broader public. Towards this end, extensive validation and demonstration trials have been performed within both projects. They have ascertained that the developed techniques have resulted in a considerable reduction of the system setup time compared to predecessor systems of lower complexity. Moreover, they have facilitated the assessment and validation of the robustness and effectiveness of the system under real conditions. Finally, they have provided useful data regarding public response and attitudes toward robotic tour guides. This article also reports on the experiences gained from these trials.

The TOURBOT-WebFAIR Approach

The goal of the TOURBOT project was the development of

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> ***The mobile robots can be operated over the Internet and provide telepresence to distant visitors.***

an interactive TOUr-guide RoBOT (TOURBOT) able to provide individual access to museums exhibits and cultural heritage over the Web. TOURBOT operates as the user's avatar in a museum, accepting commands over the Web that direct it to move in its workspace and visit specific exhibits. The imaged scene of the museum and exhibits is communicated over the Internet to a remote visitor. As a result, the user enjoys a personalized tele-presence in the museum, able to choose the exhibits to visit as well as the preferred viewing conditions (point of view, distance to the exhibit, and resolution). At the same time, TOURBOT can guide on-site museum visitors, providing either group or personalized tours.

The successful course of TOURBOT, and the vision to introduce similar services to the taxing case of trade fairs, resulted in the launch of the WebFAIR project. The latter was additionally endorsed by experts in the organization and promotion of large trade shows. Besides the TOURBOT functionality, which is now offered in a more demanding environment, WebFAIR introduced teleconferencing between the remote user and on-site attendants and employed a multirobot platform, facilitating simultaneous robot control by multiple users.

Focusing on the requirement for autonomous robot motion, both projects opted for the development of a safe and reliable navigation system. For this purpose, the robotic avatars are equipped with sensors such as laser range-scanners, sonars, and cameras. The navigation system uses this sensory information to adapt the robot's internal model of the environment in order to plan the robot actions.

In order to realize the TOURBOT and WebFAIR systems, the consortia developed a multimedia Web interface that allows individuals to interact with the tour-guide system over the Internet. Furthermore, an onboard interface for interaction with on-site visitors at the exhibition site has been developed. Using the Web interface, people are able to tele-control the robot and to specify target positions for the system. Camera controls are used to choose the part of the exhibition the user wants to observe in more detail. The robotic tour guide possesses a multimedia information base that provides a variety of information with respect to the exhibition at various levels of detail. Thus, the system serves as an interactive and remotely controllable tour guide that provides personalized access to exhibits with a large amount of additional information. Both the TOURBOT and WebFAIR systems use video streams to convey observed information to the user. Additionally, they provide online visualizations of their actions in a virtual three-dimensional (3-D) environment. This allows users to choose arbitrary viewpoints and leads to significant reductions of the required communication bandwidth.

The use of tour-guide robots has several advantages for the exhibition visitor as well as for the provider of such a service. First, TOURBOT and WebFAIR allow for a more

Table 1. Factual data of the TOURBOT and WebFAIR projects.

Project: TOURBOT, Contract: IST-1999-12643	
Funding: 5th Framework Programme, Information Society Technologies (IST)	
Start Date: 1 January 2000	End Date: 28 February 2002
Budget: €1,718,150	EU Contribution: €1,088,790
Consortium—Participant Roles	
Foundation for Research and Technology—Hellas (Greece)	Coordinator/Technology Provider
University of Freiburg (Germany)	Technology Provider
Foundation of the Hellenic World (Greece)	Technology Broker/End User
University of Bonn (Germany)	Technology Provider
THEON Robotic Systems (Greece)	Technology Provider
Deutsches Museum Bonn (Germany)	End User
Byzantine and Christian Museum of Athens (Greece)	End User
Project: WebFAIR, Contract: IST-2000-29456	
Funding: 5th Framework Programme, Information Society Technologies (IST)	
Start Date: 1 December 2001	End Date: 31 May 2004
Budget: €2,331,142	EU Contribution: €1,269,970
Consortium—Participant Roles	
ACTION Public Relations Hellas LTD (Greece)	Coordinator/End User
Foundation for Research and Technology—Hellas (Greece)	Scientific Coordinator / Technology Provider
RATIO Consulta SPA (Italy)	Technology Provider
IDEASIS Ltd (Greece)	Technology Provider
University of Freiburg (Germany)	Technology Provider
Polytechnic University of Madrid (Spain)	Technology Provider
Ente Fiere Castello di Belgioioso e Sartirana (Italy)	End User

effective use of exhibitions. A Web-based tour-guide robot can serve and educate people day and night since its operational time is not limited to the opening hours of an exhibition. Compared to static or even remotely controllable cameras for viewing parts of an exhibition, tour-guide robots can provide significantly more interaction capabilities. The mobility of the robots allows Web visitors to choose a wide variety of view-points and to get the feeling of "being present" in the exhibition. Moreover, increased interaction capabilities with the exhibits themselves can be offered to the user, which may be useful when visiting a science or technology museum. Therefore, a scenario such as "press the red button to watch . . ." and the corresponding service offered to the user can easily be implemented. In addition to this increased interactivity, the robotic agent can deliver high-resolution images over the Web, which is extremely beneficial to professionals and specialists.

The TOURBOT and WebFAIR concept provides visitors the ability to individually exploit the expertise stored in the tour-guide robot, which can react flexibly to the requirements of the visitors. It can, for example, offer dedicated tours on temporary focuses of the exhibition or, alternatively, give overview tours. Furthermore, robots improve the flexibility for the planning of tours, especially when more than one is deployed. This allows people, to be served individually even if they belong to a larger group. Additionally, robotic tour-guides contribute to the positive image of an exhibition since they emphasize state-of-the-art technology and future-orientation.

Table 2 summarizes a comparison of the main features of the proposed approach (within TOURBOT and WebFAIR) for accessing exhibition sites and trade fairs with traditional on-site visits and conventional Web presentations. As evidenced from this table, there is indeed grounds for pursuing the goals set forth in our projects.

Table 2. Access to exhibition sites and trade fairs.

	Access to Exhibition Sites and Trade Fairs		
Evaluation Feature	**On-Site Visit**	**Conventional Web Presentation**	**The TOURBOT and WebFAIR Approach**
Interaction	**High** The visitor is present at the exhibition site.	**Low** The presentation is static and preprogrammed. Remote visitors cannot interact with on-site people.	**Fair** The visitor is virtually present in the exhibition site through the robotic avatar and can observe and interact.
Quality of information	**High** The user sees the exhibits with his own eyes.	**Low** Storage and communication requirements trade off quality.	**Fair** The visitor can choose the optimal viewing parameters (viewpoint, resolution, etc.).
Accessing site information in a timely and comfortable manner	**Low** The visitor must travel to the exhibition premises and visit it during working days and hours.	**HIgh** The visitor can visit the exhibits from a computer at the comfort of his residence at any time.	**High** The visitor can visit the exhibits from a computer at the comfort of his residence at any time.
Adaptability to changes in content	**Fair** The visitor sees the current content of the exhibition site but should revisit it to see any changes.	**Low** Reorganization of the material is required, a costly procedure, especially for exhibitions with frequent changes in content.	**High** The visitor sees the current content of the site. Revisiting it has minimal additional cost.
Accessibility to visitors with special needs	**Low** Travel is required.	**High** Only the ability to interact with a computer is required.	**High** Only the ability to interact with a computer is required.
Savings in time for a typical visitor	**Low** A significant overhead is required for visiting a distant site.	**High** Almost instantaneous access to any exhibition site is given.	**High** Almost instantaneous access to any exhibition site is given.
Financial savings for a typical visitor	**Low** This is the standard model of operation.	**Fair** The exhibition site is advertised through the availability of Web presentations.	**High** The robotic avatar becomes an exhibit by itself. The site offers an extra service to both exhibitors and visitors.

Figure 1 provides a conceptual overview of the TOURBOT and WebFAIR systems. A detailed description of the developed systems is beyond the scope of this article. Instead, we emphasize specific techniques developed in the context of the TOURBOT and WebFAIR projects for solving important scientific and technological problems for the realization of the corresponding robotic systems. We specifically report on techniques for environment mapping, obstacle avoidance, and an approach to filter out range measurements coming from moving persons in the process of map construction. We also present important aspects of the user interfaces of the developed systems.

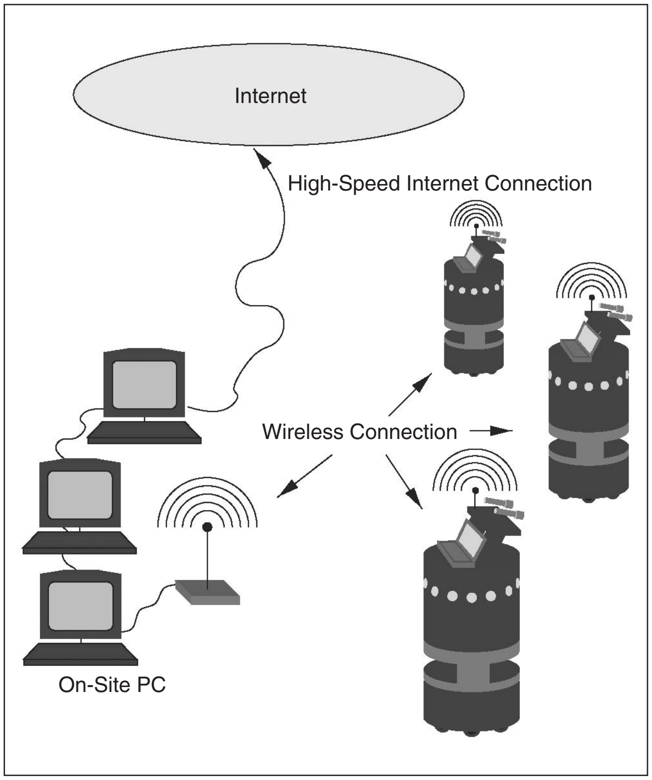


Figure 1. Conceptual overview of the TOURBOT and WebFAIR systems.

Mapping

In order to navigate safely and reliably, mobile robots must be able to build suitable representations of the environment. Maps are also necessary for human-robot interaction since they allow users to direct the robot to specific locations in the environment. Our current robotic systems use two different mapping techniques, depending on the characteristics of the environment in which the robot is deployed. In environments with a complex shape, our systems employ dense grid maps and operate according to a discrete hidden Markov model. The model is very efficient in terms of computational performance, has been proven quite robust with respect to range measurement errors, and can operate regardless of the structure of the workspace. Its main drawback lies in the achieved localization accuracy, which depends on the resolution of the grid. In order to overcome this limitation, an alternative localization method has been developed that involves a hybrid model, i.e., a combination of a discrete (hidden Markov) model and a continuous (Kalman filter) model [3]. This combination enables the use of Markovian dynamics for global localization and Kalman filter-based tracking for achieving increased accuracy.

Grid-Based Mapping

This grid-based mapping technique employs occupancy grid maps. In probabilistic terms, the goal of map learning is to find the map and the robot positions that yield the best interpretation of the data d_t gathered by the robot. Here the data $d_t = \{u_{0:t-1}, z_{1:t}\}$ consists of a stream of odometry measurements $u_{0:t-1}$ and perceptions of the environment $z_{1:t}$. The mapping problem can be phrased as recursive Bayesian filtering for estimating the robot positions together with a map of the environment

$$\begin{aligned} & p(x_{1:t}, m \mid z_{1:t}, u_{0:t-1}) \\ & = \alpha \cdot p(z_t \mid x_t, m) \cdot \int p(x_t \mid x_{t-1}, u_{t-1}) \\ & \cdot p(x_{1:t-1}, m \mid z_{1:t-1}, u_{0:t-2})\, dx_{1:t-1}. \end{aligned} \tag{1}$$

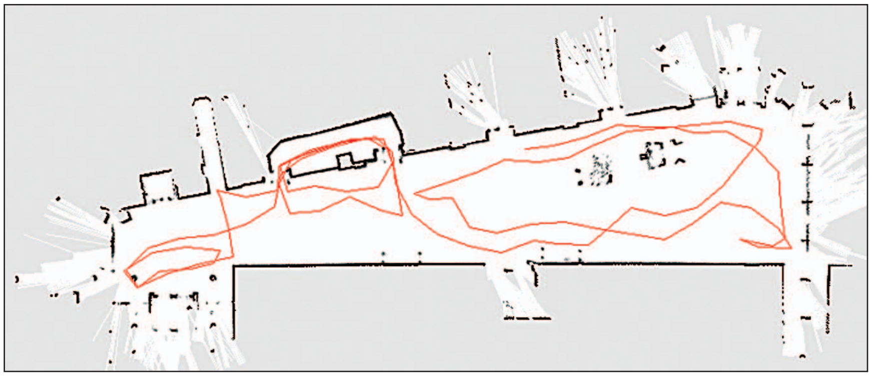


Figure 2. Map generated using our Rao-Blackwellized mapping algorithm. The size of the environment is 18 × 51 m. The robot had to close several loops during the mapping process.

In probabilistic mapping and localization, it is typically assumed that the odometry measurements are governed by a probabilistic motion model $p(x_t | x_{t-1} u_{t-1})$, which specifies the likelihood that the robot is at state x_t, given that it previously was at state x_{t-1} and the motion u_{t-1} was measured. On the other hand, the observations follow the observation model $p(z_t | x_t, m)$, which defines the likelihood of the observation z_t given the map m for every possible location x_t in the environment.

The systems described in this article apply a Rao-Blackwellized particle filter

[13] to estimate a posterior of the path of the robot. The key concept in Rao-Blackwellized mapping is to use a particle filter in order to represent potential robot trajectories $x_{1:t}$. Each sample of the particle filter possesses its own map, which is conditioned on the trajectory of that particle. The importance weights of the samples are computed according to the likelihoods of the observations in the maximum likelihood map constructed using exactly the positions taken by this particular particle. The key advantage of this approach is that the samples approximate the full posterior over robot poses and maps at every point in time.

Our approach differs from previous techniques in that it transforms sequences of laser range scans into odometry measurements using range-scan registration techniques [10]. The highly accurate odometry data is then used as input to the particle filter. Since the scan matching yields odometry estimates that are an order of magnitude more accurate than the raw wheel encoder data, our algorithm requires fewer particles than the original approach. Simultaneously, the transformation of sequences of scans into odometry measurements reduces the well-known particle deprivation problem [18] since the number of resampling operations is also reduced. In several experiments [8], it has been demonstrated that our approach results in an improved ability to map large environments.

Figure 2 depicts a map of the entrance hall of the computer science building at the University of Freiburg, Germany. The trajectory of the robot is also shown. Although the mapped area was large (18 m × 51 m) and the robot had to close several loops during the mapping process, the resulting map is highly accurate.

Feature-Based Mapping

In the case of structured environments, localization accuracy can be increased by constructing and employing feature-based maps of the environment, namely maps of line segments and corner points [2]. In contrast to most existing feature mapping approaches, our approach avoids the explicit storage and manipulation of feature-to-feature and feature-to-pose covariance information by treating map features as parameters of a dynamical system according to which the robot state evolves. This results in a learning problem that is solved via a variant of the expectation maximization (EM) algorithm. The proposed EM algorithm (see Figure 3) iterates a Kalman smoother-localization step (E-step) and a map recalculation step (M-step) until the overall process has converged or until a certain number of iterations have been carried out.

To detect and correctly close loops during mapping, our algorithm relies on the global localization capabilities of a

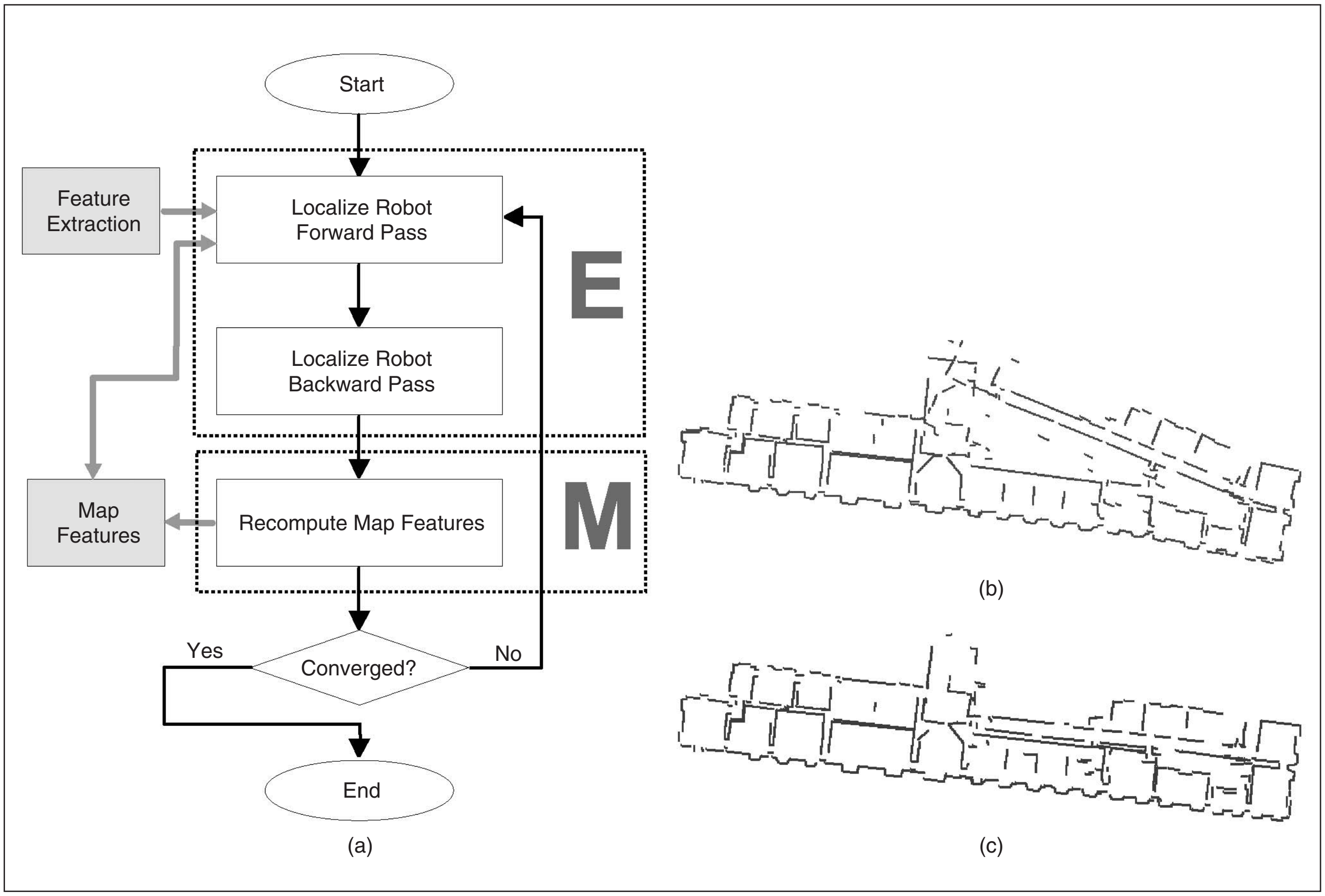


Figure 3. Feature-based mapping, including (a) a block diagram of the algorithm and (b)–(c) line feature maps of an exhibition site: (b) original data and (c) and map generated by our algorithm.

hybrid method based on a switching state-space model [3]. This approach applies multiple Kalman trackers assigned to multiple hypotheses concerning the robot's state. It handles the probabilistic relations among these hypotheses using discrete Markovian dynamics. Hypotheses are dynamically generated by matching corner points extracted from measurements with corner points contained in the map. Hypotheses that cannot be verified by observations or sequences of observations become less likely and usually disappear quickly. The resulting map always corresponds to the most likely hypothesis.

Figure 3(c) shows a typical map of an exhibition site resulting from this process; the map corresponding to the input data is shown in Figure 3(b).

Mapping in Dynamic Environments

Whereas most contemporary mapping methods are able to deal with noise in the odometry and the sensor data, these methods assume that the environment is static during mapping. However, in public spaces such as museums or trade fairs, the environment cannot be regarded as static during the robot installation time. The systems described in this article address this issue through an approach that employs an EM-technique. In the E-step, we compute a probabilistic estimate regarding measurements that correspond to static objects. In the M-step, we use these estimates to determine the position of the robot and the map. Experimental results provided evidence that the resulting maps are more accurate than maps constructed without considering dynamic beams.

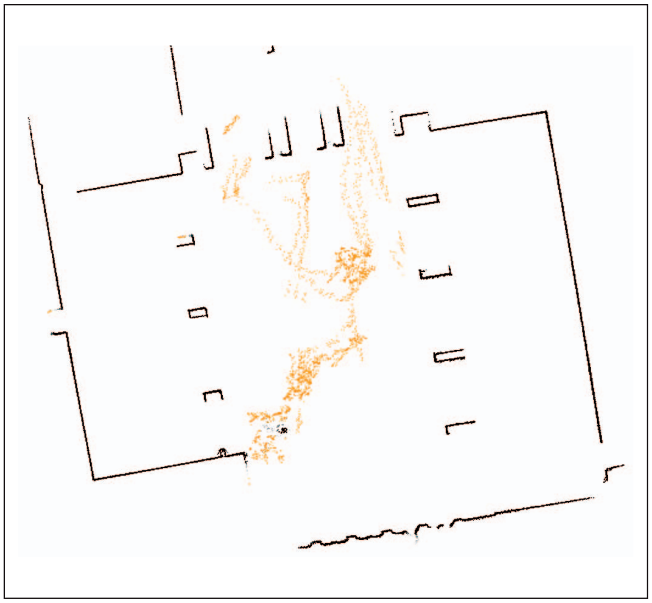


Figure 4. *Map of the populated exhibition hall of the Byzantine Museum in Athens. Measurements labeled as belonging to dynamic objects are shown in orange/gray.*

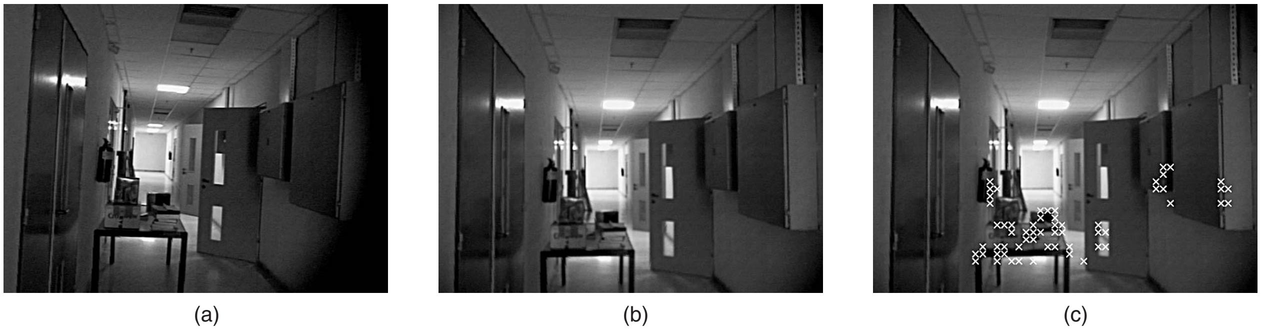
Figure 4 shows an application of this approach to data acquired by a mobile robot in the Byzantine Museum in Athens, Greece. Structures identified by the algorithm as static are shown in black; the ones belonging to dynamic objects are shown in orange/gray.

Fusion of Laser and Visual Data

The ability to correctly identify objects in the vicinity of the robot is particularly important for robots in real-world environments such as exhibitions; it is a basic precondition for the safety of the robot and the exhibits. A common problem is that various objects, such as chairs, tables, and shelves, are not correctly represented in the two-dimensional (2-D) laser range scans used for navigation. To overcome this problem, our systems additionally use visual information.

According to the employed method [1], the 2-D structure acquired with the laser-range scanner is used to compute a 2.5-D representation of the environment by assuming vertical planar walls for all obstacles in the 2-D map. We then exploit camera information to a) validate the correctness of the constructed model and b) qualitatively and quantitatively characterize inconsistencies between laser and visual data wherever such inconsistencies are detected. The inconsistencies between the laser and visual data are converted to real-world coordinates and accumulated in a 2-D occupancy map.

Figures 5 and 6 illustrate a typical application example in a corridor environment at the Institute of Computer Science (ICS) of the Foundation for Research and Technology–Hellas (FORTH). In this case, the robot travels along a corridor with several objects that are invisible to the laser scanner, such as



(a) (b) (c)

Figure 5. *(a)–(b) Images acquired at successive points in time and (c) results of obstacle detection superimposed on the image shown in (b).*

tables, fire extinguishers, and a wall cabinet. Figure 5(a) and (b) shows the images grabbed by the robot at two consecutive moments in time. Figure 5(c) shows the results of obstacle detection. Regions with inconsistencies are marked with crosses. It can be seen that objects that cannot be detected with only the range finder are successfully detected with the proposed technique. Finally, Figure 6 shows the occupancy grid maps obtained without considering visual information [Figure 6(a)] and after fusing vision and laser information [Figure 6(b)]. The map generated by our algorithm provides a more accurate representation of the environment, which can be used to prevent the robot from colliding with obstacles not visible in the range scans.

Interfaces

Robots in museums and exhibitions should be able to interact with on-site visitors in a natural way and allow distant visitors to feel like they are present at the site. Thus, the employment of intuitive human-robot interfaces is of paramount importance to the acceptance and success of the overall system. The interfaces should be tailored to the type of user; clearly there are similarities as well as important differences between distant and on-site users.

Web Interface

A variety of Web-based tele-operation interfaces for robots have been developed over the last several years, including the Mercury Project [6], the "Telerobot on the Web" [7], and Tele-Garden [16]. The mobile robotic platforms Xavier, Rhino, and Minerva [4], [15], [17] could also be operated over the Web. Their interfaces relied on client-pull and server-push techniques to provide visual feedback of the robot's movements; this includes images taken by the robot as well as a Java-animated map indicating the robot's current position. However, their interfaces do not provide any means to reflect changes in the environment. Three-dimensional graphics visualizations for remote robot control have already been suggested by Hirukawa et al. and Marin et al. [11], [12], allowing remote users to carry out manipulation tasks with a mobile robot by controlling a 3-D graphics simulation of the robot.

The Web interface developed within TOURBOT and WebFAIR has been designed to provide enhanced functionality and ease of use. Besides providing live streaming video from the exhibition site, the interface also allows personalized control of the robot(s), a feature that was not provided in the interfaces of previous systems such as Xavier, Rhino, and Minerva [14]. Remote users can control the robot exclusively for a fixed amount of time, which is generally set to ten minutes per session. During this time, the user can direct the robot to any desired location in the exhibition. The user can also select from

> ***A very important factor for the acceptance of a robotic tour guide by the broader public is the degree to which the system smoothly interacts with both Web- and on-site visitors.***

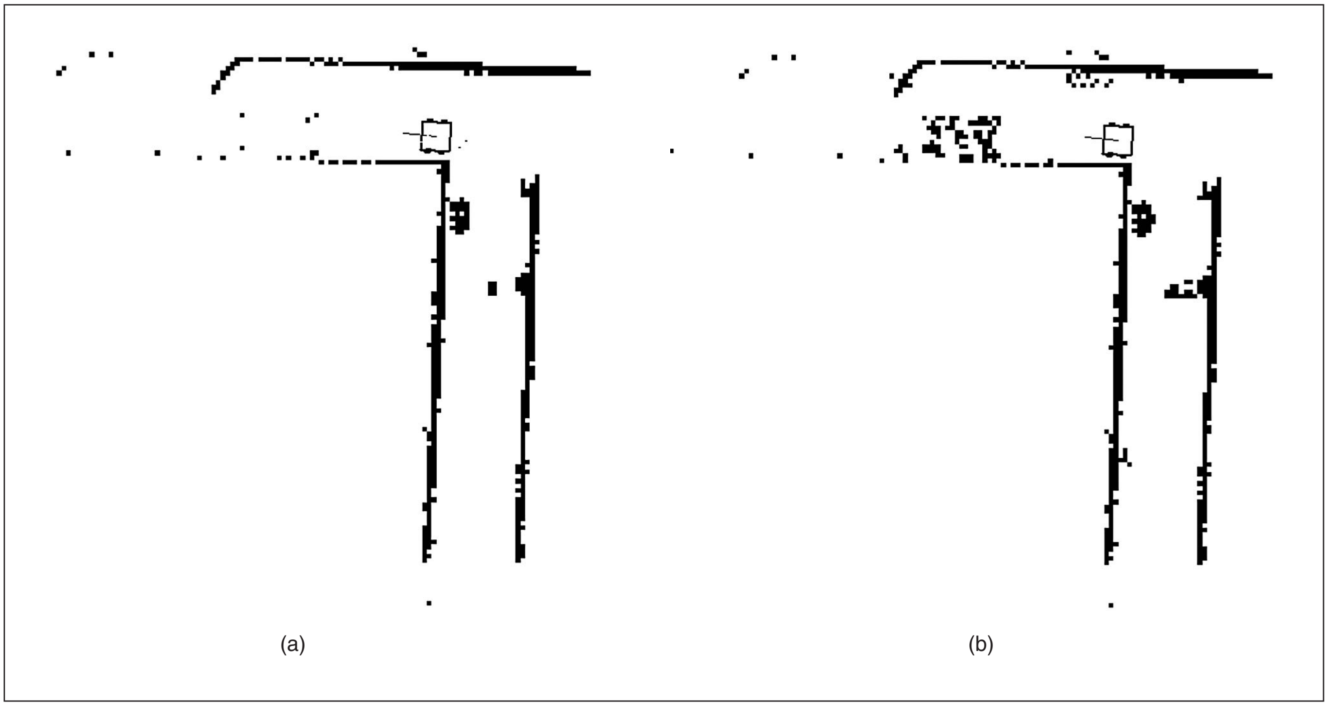
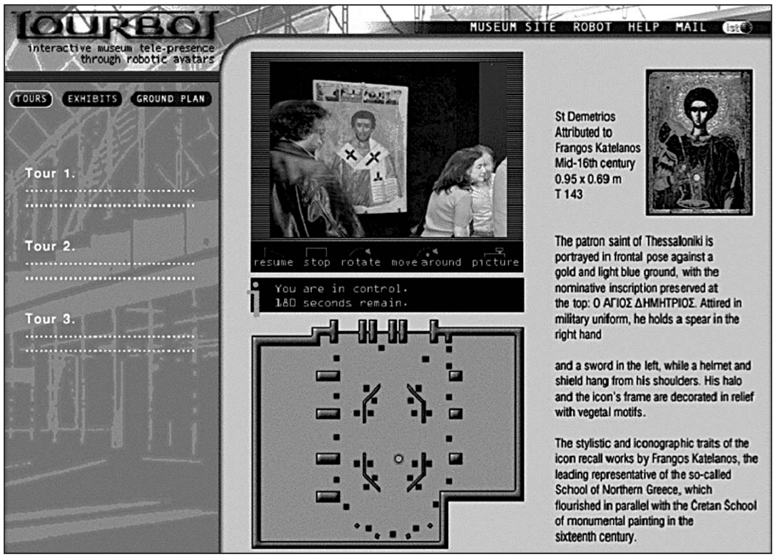


Figure 6. *Occupancy grid maps computed based on the fusion of vision and laser data: (a) the map computed from the laser-range data and (b) the map after combining vision and laser data.*

a list of predefined guided tours or direct the robot to visit particular exhibits or locations in the exhibition. Furthermore, the user can control the pantilt unit of the robot to request the robot to move around an exhibit in order to view it from various directions and to grab high-resolution images.



You are in control.
180 seconds remain.

St Demetrios
Attributed to
Frangos Katelanos
Mid-16th century
0.95 x 0.69 m
T 143

The patron saint of Thessaloniki is portrayed in frontal pose against a gold and light blue ground, with the nominative inscription preserved at the top: Ο ΑΓΙΟΣ ΔΗΜΗΤΡΙΟΣ. Attired in military uniform, he holds a spear in the right hand

and a sword in the left, while a helmet and shield hang from his shoulders. His halo and the icon's frame are decorated in relief with vegetal motifs.

The stylistic and iconographic traits of the icon recall works by Frangos Katelanos, the leading representative of the so-called School of Northern Greece, which flourished in parallel with the Cretan School of monumental painting in the sixteenth century.

Figure 7. *Web interface of the TOURBOT system for exclusive control over the robot.*

A screenshot of the Web interface is shown in Figure 7. The left side contains the list of exhibits and predefined tours offered to the user. Live streaming video as well as a Java applet animating the robot in a 2-D floor plan (map) are shown in the center of the screen. This floor plan can also be used to directly move the robot to an exhibit or to an arbitrary location in the exhibition. Between the map and the live video stream, the interface includes control buttons as well as a message window displaying system status messages. The right part of the interface is used to display multimedia information regarding visited exhibits and to provide links to relevant background information.

Enhanced Visualizations

Web users strongly depend on the accurate visualization of the robot's environment and the moving people therein to grasp what is going on at the exhibition site and understand why the robot is carrying out its current actions. For this purpose, we also developed a control interface that provides the user with a virtual reality visualization of the environment, including the robot and the people in its vicinity. Depending on the level of detail of the virtual reality models used, Internet users can obtain visualizations

(a) (b) (c) (d)

Figure 8. *The enhanced 3-D visualization allows arbitrary viewpoints: (a) the real and (b) the virtual view through the robot's cameras and (c) the robot guiding three people through the museum and (d) a bird's eye view of the scene.*

with quality comparable to video streams, yet at much lower bandwidths. As an example, consider Figure 8, which shows two sequences of visualizations provided during the operation of the system in the Deutsches Museum Bonn, Germany, in November 2001 along with images recorded with a video camera and with the robot's onboard camera. As can be verified, the visualization is almost photo-realistic and the animated avatars capture the behavior of the people in the scene quite well.

Onboard Interface

In addition to interacting with remote users, robots should interact with on-site visitors as well. For this purpose, a properly enhanced version of the Web interface is displayed in a touchscreen mounted at the rear side of the robot.

Video streams and enhanced visualizations are not provided to on-site visitors since they are not actually required. Instead, the onboard interface makes extensive use of speech synthesis and commercial speech recognition software capable of understanding sets of simple phrases; this set varies depending on the task at hand. Figure 9 shows a scene in which a person interacts with the robot Albert during the Hannover trade fair in 2001 in Germany. Here the person asked several questions of the robot (Who are you? Where are you from? What are you doing here?) and requested information about the time. Depending on the input of the user, the robot can dynamically generate speech output.

Another very important aspect of robotic systems is their ability to alter the facial expressions of their mechanical heads based on their internal status. Currently, there are three different facial expressions, namely "happy," "neutral," and "angry." These facial expressions are implemented by modifying the shape of the eyebrows and the mouth. Combined with a variety of voice messages, the robots use these expressions to inform the on-site visitors regarding their internal status. For example, if the paths of the robots are not obstructed by the on-site visitors, the robots appear happy. In the opposite case, "mood" changes progressively in time. Moreover, the head of the robot is controlled so that it looks towards the direction of intended motion.

Figure 9. *Person interacting with Albert during a Hannover trade fair demonstration.*

(a)

(b)

(c)

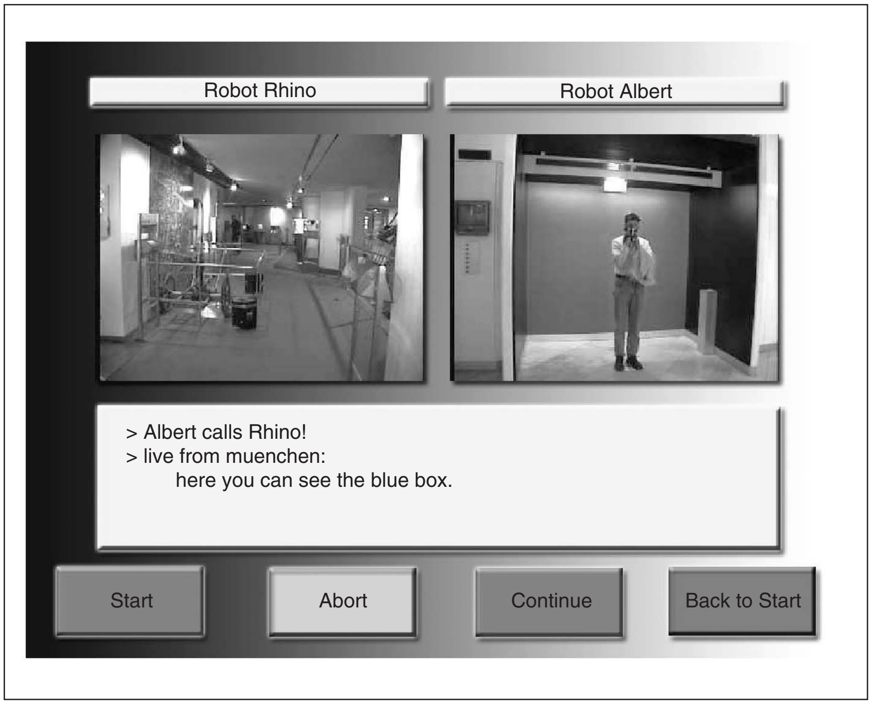
(d)

Figure 10. *(a) Robot Lefkos operating in the exhibition of the Foundation of the Helenic World. (b) Robot Rhino operating in the Deutsches Museum Bonn. (c) Robot Lefkos operating in the Byzantine and Christian Museum. (d) Robot Albert operating in the Belgioioso Exhibition Center in Italy.*

System Installation and Demonstration

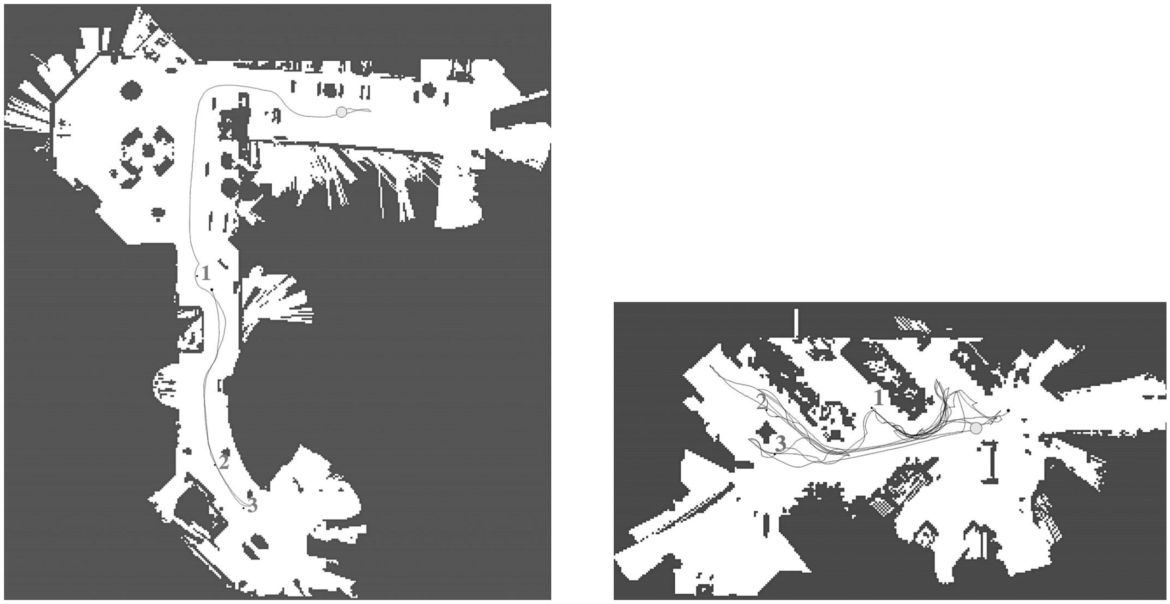
In the framework of the TOURBOT project, a number of demonstration trials were undertaken on the premises of the participating museums. Factual information on these events is as follows:

- Foundation of the Hellenic World, Athens, Greece, 28 May–2 June, 2001. Exhibition: "Crossia, Chitones, Doulamades, Velades—4,000 Years of Hellenic Costume." The exhibition area comprised 2,000 m^2. During the trial, the robot operated approximately 60 h, covering a distance of 14 km. More than 1,200 Web users observed the exhibition through TOURBOT. A typical situation, in which the robot Lefkos guides visitors through the museum, is shown in Figure 10(a).
- Deutsches Museum Bonn, Bonn, Germany, 6–11 November 2001 [see Figure 10(b)]. Exhibition: "Part of the permanent exhibition, highlighting scientific achievements that were awarded the Nobel Prize." The exhibition area in which the robot moved comprised about 200 m^2. The system operated about 60 h, covering a distance of 10 km. Approximately 1,900 Web visitors had a look around the museum via the robot.
- Byzantine and Christian Museum, Athens, Greece, 3–7 December 2001 [see Figure 10(c)]. Exhibition: "Byzantium Through the Eyes of a Robot." The exhibition area was about 330 m^2. During the trial, the robot operated 40 h, covering a distance of 5.3 km. The number of Web users was small in this trial, due to the volume of on-site visitors. Since the first day of the trial at the Byzantine and Christian Museum, a large number of (on-site) visitors were coming to the exhibition. This



> Albert calls Rhino!
> live from muenchen:
here you can see the blue box.

Figure 11. Screen shot from the GUI for the RoboTalk event.



(a) (b)

Figure 12. Synchronization of the tours given by Rhino and Albert in the Deutsches Museum Bonn and the Deutsches Museum Munich.

forced the TOURBOT team to make the decision to devote significantly more system time to on-site visitors as opposed to Web visitors.

Additionally, TOURBOT was installed and operated for a longer period of time (October 2001–February 2002) at the Heinz Nixdorf MuseumsForum (HNF) in Paderborn, Germany. This was in the framework of the special exhibition "Computer.Gehirn" (Computer.Brain) with a focus on the comparison of the capabilities of computers/robots and human beings. In June 2002, TOURBOT was introduced for one week in the Museum of Natural History of the University of Crete, Heraklion, Greece.

Within the WebFAIR project, a prototype event called RoboTalk aimed to coordinate two robots installed in two different exhibitions. The event lasted four days (19–22 June 2003), during which the mobile robots Rhino and Albert were installed in the Deutsches Museum Bonn and the Deutsches Museum in Munich, respectively.

Both robots were connected via the Internet so that visitors in one exhibition could participate in the tours given by the other robot. Whenever one robot arrived at an exhibit, it communicated this to the other robot. The latter would stop and provide the video and audio data received from the other robot. In this way, visitors of one museum could also see exhibits presented by the other robot at the remote site. Figure 11 shows the user interface of the robots during this event. In addition to information about the exhibition, this interface includes a window showing the video stream obtained by the other robot. Figure 12 shows two particular trajectories of Rhino and Albert during the event. While Figure 12(a) shows the trajectory taken by Rhino in Bonn, Figure 12(b) depicts the path of Albert in Munich. The points in space where the two robots were synchronized are labeled by the numbers in the figure.

In April 2004, another event was organized within the WebFAIR project at Belgioioso Exhibition Center, Italy. During this event (which lasted two days, spanning an annually organized vintage fashion exhibition), robot Albert traveled a distance of about 2 km during 10 h of operation in an environment that was very challenging for robot navigation. At the same time, Albert provided teleconferencing capabilities to remote users [Figure 10(d)].

Installation Time

The large number of test installations of the TOURBOT and WebFAIR systems required the development of sophisticated tools for the set-up of the overall system. The most crucial part of the overall procedure is the generation of the navigation map. However, based on the techniques described earlier in this article, the overall mapping process could in all cases be accomplished within several hours.

Another time-consuming process is the generation of the multimedia content that is presented to the users and the definition of task-specific information (e.g., location within the map of designated exhibits, definition of tours, etc.) For this purpose, the TOURBOT and WebFAIR systems include multimedia databases containing site-specific HTML pages, images, audio, video sequences, and other material. Most of the multimedia information pertinent to the exhibits can be obtained directly from the exhibition sites since pictures, text, and other relevant material are often already packaged in existing Web presentations.

TOURBOT operates as the user's avatar in a museum, accepting commands over the Web that direct it to move in its workspace and visit specific exhibits.

The whole setup can therefore be accomplished in less than two days. This is an enormous speedup compared to previous tour-guide systems. Figure 13 shows the time required to install the Rhino and Minerva systems [4], [17] in comparison to that of the TOURBOT system. As can be seen, the TOURBOT system requires significantly less time to set up than Rhino and Minerva. Our experience with tour-guide robots in exhibition sites suggests that 3-D models of exhibitions' premises are generally not available. The automatic generation of such models with the mobile robot itself is a subject of ongoing research [9].

Reactions of the Public

An interesting study was carried out in the context of the above trials regarding the visitor-robot interaction patterns. This study was planned and executed during the trial in the Byzantine and Christian Museum, Athens, Greece. Based on the observations during the previous trials, the human-robot-interaction was qualitatively classified into four behaviors: watching the robot, moving towards the robot, touching the robot, and using the touchscreen. The frequency of the occurrence of these behaviors for the cases of adults and children is

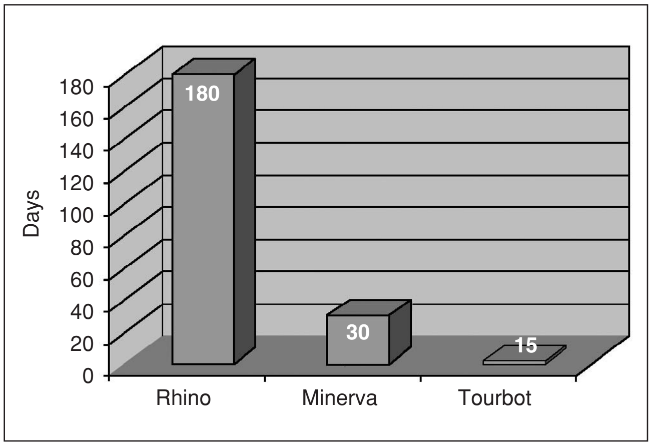


Figure 13. *Time required to install the different tour-guide systems Rhino, Minerva, and TOURBOT.*

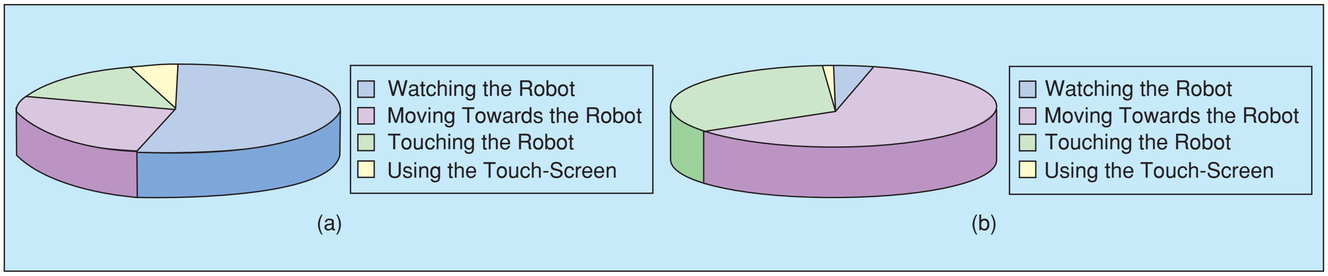


Figure 14. *The reactions of visitors to the robotic tour guide: (a) adult visitors and (b) children.*

summarized in Figure 14.

Considering these results, one may come to some preliminary conclusions regarding the human-robot-interaction. Most visitors turn/move to the robot when they see it, whether immediately or after watching it for a time. This indicates that the robotic platforms attract the interest of the visitors. The smaller counts that were observed in the fourth behavior (using the touchscreen) are mostly due to only one person being able to use the touchscreen at any point in time. Comparing adults and children, it can be stated that children are uninhibited and natural in their behavior. Significantly more counts relate to the behavior "moving towards the robot" than to "watching it." On the contrary, adults tend to exhibit a more "reserved" behavior towards the robot. The performance in the correct use of the robot is better in adults than in children.

Conclusions

In this article, we presented a number of techniques that are needed for realizing Web-operated mobile robots. These techniques include effective map-building capabilities, a method for obstacle avoidance based on a combination of range and visual information, and advanced Web and onboard robot interfaces. In addition to video streams, our systems provide high-resolution virtual reality visualizations that also include the people in the vicinity of the robot. This increases the flexibility of the interface and simultaneously allows a user to understand the navigation actions of the robot.

The techniques described in this article have been successfully deployed within the EU-funded projects TOURBOT and WebFAIR, which aimed to develop interactive tour-guide robots able to serve Web- as well as on-site visitors. Technical developments in the framework of these projects have resulted in robust and reliable systems that have been demonstrated and validated in real-world conditions. Equally important, the system setup time has been drastically reduced, facilitating its porting to new environments.

Our current research extends the navigation capabilities of the robotic systems by further enhancing existing competences and introducing novel ones. Specific capabilities that are studied include obstacle avoidance in the cases of objects that are not visible by the laser scanner, 3-D mapping, mapping in dynamic environments, predictive navigation, and multirobot coordination [5]. Moreover, in the context of the above projects, additional issues have been addressed, such as a) how to adapt this technology in order to fit the long-term operational needs of an exhibition site, b) how to evaluate the robotic system in terms of its impact to the main function and objectives of the exhibition site (financial impact, accessibility, marketing and promotion, and impact on visitor demographic), and c) how to evaluate the content and educational added value to museum and exhibition visitors and generate a feedback to the technology developers in order to improve the robotic avatars and further adapt to the needs of the users.

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Keywords

Web-operated robots, robots in exhibitions, navigation competences, remote visualization.

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