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TOOMAS: Interactive Shopping Guide Robots in Everyday Use - Final Implementation and Experiences from Long-term Field Trials

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Abstract— **The paper gives a comprehensive overview of our** *Shopping Guide* **project, which aims at the development of interactive mobile shopping companion robots for everyday use in challenging operating environments such as home improvement stores. It is spanning an arc from the expectations and requirements of store owners and customers, via the challenges of the shopping scenario and the operating environment, the implemented functionality of the shopping guide robots, up to the results of long-term field trials. The field trials started in April 2008 and still ongoing aim at studying whether and how a group of interactive mobile shopping guide robots can operate completely autonomously in such everyday environments and how they are accepted by uninstructed customers. In these field trials, where nine robotic shopping guides traveled together 2187 kilometers in three different home improvement stores in Germany, more than 8,600 customers were successfully guided to the locations of their products of choice. With the successful development of these shopping guide robots, a further important step towards assistive robotics for daily use has been done.**

I. INTRODUCTION

More and more shopping centers are looking for new ways to make shopping an experience for the customers. Improving the shopping quality and the service offers is an interesting way of ensuring customers returning to the shop. Assistive mobile robots offering a spectrum of novel on-site services, e.g. an interactive article search, a smart guiding function, or an individual counseling by highly skilled and omnipresent expert staff per video link can play an important role in this process. Also for the shop owners such assistive robots are of great interest, because they disburden the expert staff from less challenging, trivial routine tasks, like guiding customers to the products of their choice or informing them about prices, and allow them to focus on their main task - detailed customer counseling.

Against this background, in continuation of [1] this paper gives a comprehensive overview of our *Shopping Guide* project. This project started in 2000 [2] aims at the development of interactive shopping guide robots for use in spacious and populated public environments under everyday conditions such as shopping centers or home improvement stores.

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Fig. 1. Interactive mobile shopping assistant TOOMAS guiding a customer together with his shopping trolley to the location of the product of his choice in a typical home improvement store.

Our robotic shopping guides are supposed to autonomously contact potential users, intuitively interact with them, and adequately offer their services. Service tasks tackled in this project are to autonomously navigate through the market and guide the customers to the products of their choice, and to accompany them during the whole purchase as mobile shopping companions offering a set of further functionalities, like video connection to a salesperson, infotainment, or executing composite purchases (Fig. 1). Because our project is primarily focused on interaction and guidance functionality, a shopping cart function allowing to carry the chosen goods by the robot has been excluded explicitly from the beginning for various reasons. For example, this would have required a completely different platform design and engineering, and many other constraints would have had to be taken into consideration, e.g. the payload and therewith the spectrum of goods that can be chosen by the customer. Instead of that, customers use the standard shopping carts available in the store for carrying the chosen goods when employing a robot as shopping guide (see Fig. 1).

Unlike our previous publications dealing with more methodologically oriented aspects of our *Shopping Guide* project, like e.g. self-localization and map building [3], [4], [5] or human-robot interaction [6], this paper is giving a summarizing overview of the project. For this purpose, it is covering a broad range from the expectations and requirements of the store owners and customers, via the challenges of the shopping scenario and the operating environment, the robot hardware and the functionality implemented of the shopping guide, the integration of the components into a smoothly working interactive system, up to the results of long-term field trials, which have been conducted with nine robotic shopping guides in three different home improvement

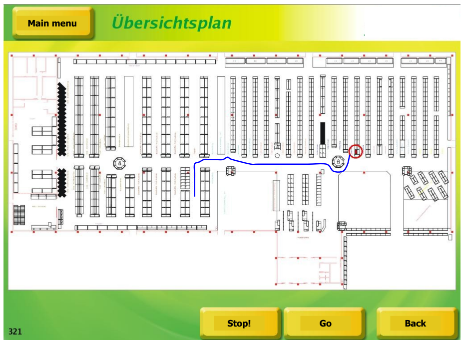

Fig. 2. Part of the interactive menu on the touch screen of the shopping assistant. Here, the map of the store is shown, in which the current position of the robot, the position of the article in the store (red circle), and the suggested path planned by the robot (blue line) are drawn in.

stores in Germany since April 2008. The main objective of the still ongoing field trials is a long-term evaluation of the technical performance of the shopping robots and their in principle acceptance by uninstructed customers, while a systematic evaluation study of the interaction, the user experiences, and the usability will be done in the near future.

II. Challenges, Constraints and Requirements of the Shopping Robot Scenario

In this section, the key insights we gained from (i) requirement specifications of the store owners and managers, (ii) own experimental experiences achieved in the different home stores used as test environments since 2000, but also from (iii) surveys of the market staff and customers are summarized. The aim of this compilation is to support other projects doing similar robotics research in avoiding dead-ends, making the same mistakes, or putting envisaged technical solutions on unrealistic assumptions. These requirements pose great challenges to the navigation, interaction and service components of each mobile robot assistant.

A. Challenges & Requirements to Navigation & Integration

Complexity of the environment: A home improvement store is a very complex, maze-like indoor environment with a very high structuring (see Fig. 2). It consists of a set of parallel, long hallways or corridors separated by shelves, corridors connected to alleys, a network of alleys, connected to the main store entrance and to the checkout counters. Typically, the area has a size of 5,000 to 15,000 square meters. The environment is highly dynamic due to moving people (customers, staff) or other moving objects, like shopping carts or pallet transporters. Moreover, a home store is a very evolutive environment regarding the filling of the shelves, or the placement of special offers at the head sides of the shelves (product heaps, sales, etc.).

Plug & Play solutions vs. installations: The embedding of mobile service systems in a market should be doable without cost- and time-expensive modifications of the market or its technical infrastructure. For most store owners we discussed with, it was unacceptable to retrofit the whole operation area (all shelves and corridors) with a dense net of RFID tags to allow a robust navigation. This also applies to a retrofitting of the store with Indoor-GPS techniques based on laser or other active components. The best would be a simple plug & play solution using only the robot's on-board sensors and advanced navigation techniques. Also required is a simple integration in the existing infrastructure (wi-fi, merchandize management system, etc.). Only that way, a high flexibility of the robotic solution regarding reconfigurations of the store, task changes, and new requirements can be guaranteed.

Another key problem is the question of how to accomplish an automatic labeling of the navigation map with the positions of all products, because a manual labeling of all goods locations is impossible. The reason is that for large hardware stores up to 60,000 different products have to be placed in the map used for navigation. Here an automatic mapping between this map and the places of the goods within the shelves (stored in the merchandize management system of the store) is required.

B. Requirements to Human-Robot Interaction

Speech-based dialog and article search: It rapidly turned out that speech recognition features a significantly higher complexity compared to other typical HCI application scenarios due to (i) the extreme background noise in home stores, (ii) distracting public address announcements, (iii) the large diversity of descriptions for the same article, and (iv) the use of common speech and dialects, unclear articulation, and pronunciation. Against this background, it proved to be an unrealistic requirement to recognize the desired goods by speech - also due to the huge spectrum of different articles in a home store and the necessary speaker-independence. Therefore, we agreed to abstain from a speech-based article selection and decided in favor of a pure menu-based selection on the touch screen using established methods of keyword or product group search.

Getting and staying in contact with customers: The getting in contact and the interactive dialog have to be intuitively understandable, so that the customers don't have to be briefed before using a shopping robot. From our own experience we know that customers often are restrained and incommunicative or even anxious if confronted with this kind of technology. They don't know if and how the robot can communicate by speech or other modalities. Therefore, in 90% of all interactions they waited in the vicinity of the robot to be addressed by it - an unexpected experience which was of immediate importance for the dialog design, particularly for the question how to take the initiative by the robot while getting in contact. Moreover, RFID proved as a not-practicable technology for user detection and tracking, because most customers are not willing to wear RFID tags. Many of them try to kid or even mislead the robot e.g. by putting down the tags into the shelves. Speech-based user tracking is also unsuitable because single users typically don't speak along their paths, and background noise is significantly higher than the voice of a person in a distance of several meters. So, only vision in combination with distance measuring sensors proved to be suitable for robust user detection and tracking.

III. Related Work

A comprehensive overview of the employment of mobile robots as tour guides in expositions, museums, or other places open to the public is given in [7]. Among them are such well known robots like Rhino, Minerva, and Sage, the exposition guide RoboX, or the robots Mona/Oskar at the Opel sales center at Berlin. Usually, these robots guide visitors to a set of predefined exhibits following a planned path while offering exhibition-related information. They navigate in populated, structured, but completely known operation areas as they are typical for expositions - in the most cases limited to a few hundred square meters. By contrast, the shopping robot scenario and the operational environments in shopping centers make still more challenging demands.

So far, there are only a few approaches known that have tried to tackle the challenging requirements of the shopping scenario. RoboCart [8], [9], a robotic shopping assistant for the visually impaired, or the approaches of [10] and [11] belong to this. However, these systems don't operate autonomously as it is required for a realistic application as shopping assistant. Moreover, most of them require customized, engineered stores with shelves or hallways equipped with RFID-tags for self-localization of the robots. Other robots are completely remote-controlled from a user outside the store, like the robot *Luk* from *NTTcom* and *tmsuk*, or the robot of the Tsukuba University (Japan) that allows a user a tele-operated grasping of fruit during a remote-controlled shopping tour [11].

Another interesting approach dealing with an assistive and highly interactive shopping cart robot for supermarkets is being developed in the ongoing project CommRob [12], [13]. High-level human-machine communication and user acceptance aspects are of particular interest in this project. At the end of the project in 2010, the prototype of a shopping cart robot is supposed to operate and interact with humans in an environment modeled after a real supermarket.

Most recently, Kanda et al. from ATR presented an affective guide robot [14], an interactive system that can explain the way to the shops in a mall by means of speech and gestures. From mobile robotics point of view this approach, however, is only a stationary interactive system that does not move and guide the customers to the locations of the shops. Moreover, its speech recognition and decision making is partially controlled by a human operator to cope with the challenges of a real environment and to handle unexpected situations. For estimation of the customers' positions during interaction, floor sensors covering a local area around the robot and RFID tags worn by the customers are used.

All the approaches introduced here are either proof-of-concept prototypes only or just design concepts not yet ready for autonomous operation in real shopping environments. Most of them show very limited functionality regarding an autonomous guidance behavior and require instructed or even technically equipped users and the presence of roboticists or human operators during their operation to guarantee the safety of the users and to handle unexpected situations. Either they do not emphasize the interaction or autonomous navigation part enough, or they rely on techniques and requirements which are very questionable in that specific application field, e.g. they require controlled uncluttered environments, clothes with specific appearance to be worn by the users, RFID tagging of the operation area or the users, Indoor-GPS for localization, or floor sensors for user detection. Having true autonomy in mind, none of the aforementioned systems can already be considered as autonomous shopping robot. Moreover, none of these systems has continuously been involved in shopping tasks over longer periods of time, or was subject of long-term field trials during routine operation of the store. Therefore, all these systems are not yet suitable for autonomous operation in unengineered environments and for everyday use. Both features are, however, the essential prerequisites for a serious acceptance of mobile service robots both by customers and the owners of a store.

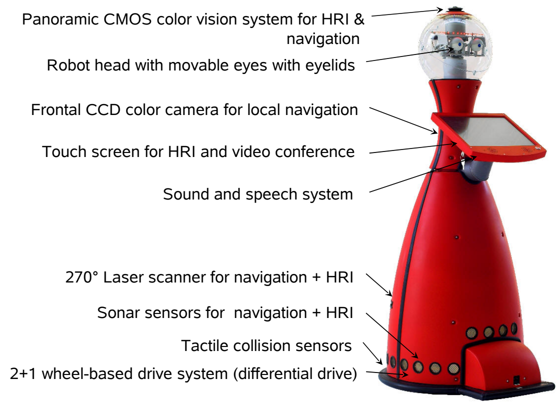

Fig. 3. Interactive mobile shopping assistant TOOMAS based on a SCITOS A5 (developed by MetraLabs GmbH Ilmenau, Germany,) with its main equipment for environment perception, navigation, and human-machine interaction.

IV. Mobile Shopping Robot TOOMAS

The robot TOOMAS we developed for the application as mobile shopping companion is based on a SCITOS [saitoz] A5 shown in Fig. 3. With a height of 1.5 m the robot is comparable with the size of a 14 years old child. Its size is optimized for a friendly appearance and an ergonomic operation. The drive system of the robot consists of a differential drive and a castor on the rear. This gives TOOMAS a good maneuverability and stability in spite of its height and weight of 75 kg, and allows a max. driving speed of up to 1.4 m/s.

Sensor equipment: For navigation, HRI and safety, the system is equipped with various sensor systems. First, there is an omnidirectional camera mounted on the top of the head. Due to the integrated hardware transformation, the camera delivers both a panoramic image (720x150 pixels) and a high resolution frontal image (720x362 pixels), which can be panned around 360^o. Besides this main sensor, the robot is equipped with a set of 24 sonar sensors at the bottom, which are used for obstacle detection, map building, localization and person tracking. They cover the whole 360^o around the robot. Contrary to our original planning but required by safety regulations of the German Technical Inspection Agency (TUV), a laser range finder (SICK S300) had to be added and mounted in front direction at a height of 35cm.

Human-robot interaction: For interaction with the customers TOOMAS is equipped with an integrated touch display (see Fig. 3), a sound system, and a 6 DOF RoboHead. The touch screen is the central communication interface to the robot. A set of stereo loudspeakers and two omnidirectional condenser microphones are integrated in the screen device. The head with several degrees of freedom gives the robot a smart but still technical appearance, which encourages users to interact with it.

Hardware: SCITOS A5 is controlled by an Embedded PC with an Intel Core 2 Duo processor and a multitude of small hardware units which monitor several functions of the robot [15]. The hierarchical energy-saving concept in conjunction with the energy-saving units enables a long run-time. Based on two lead-acid gel batteries with an overall charge of 38 Ah, a SCITOS A5 autonomously operates about 8-12 hours until it needs a break for recharging. Easily connected to main supply or its self-charging station, it can be recharged by the integrated charging system in about 10-12 hours. The safety system of the robot involves a closed bumper with tactile sensors for the detection of possible collisions. In combination with additional sensors, like the vision system, the laser range finder and the sonar sensors, SCITOS has a safety approval of the German TUV that was given after a number of challenging safety tests.

Integration: TOOMAS is getting the required data about the article information, product groups, price information and current promotions from the market server, an off-board PC in the market which it is linked with via WiFi. However, it does not rely on this connection because it is always running from its on-board computer in fully autonomous mode. Other PCs in the market can be connected to this market server to be used as info and video-link terminals for the staff. This allows to display the current positions and their current status of all robots operating within the store.

V. Realized Service Functionality

Before the control architecture and techniques for robust HRI and navigation implemented in the current version of the shopping guide will be presented in the following sections, a brief overview of the already realized service functionality is to be given. With the objective of finding people who might need assistance, the shopping guides move around in the store and patrol between particular points of interest which can be set by the store management. If one of the robots detects a potentially interested customer during its tour by means of the techniques presented in Section VII, it stops and offers its service by using a short voice output like "Hello! May I help you to find an article?". In situations with more than one user in the local vicinity of the robot, the robot selects that person of the group with the lowest distance to the robot, if that person is facing the robot which is interpreted as interest in assistance. If the customer is interested, s/he starts the communication with the robot by pressing the "Start" button on the touch screen. To that purpose, the robot is turning to the customer presenting its touch screen and giving instructions by synthesized speech. Because the head can be rotated completely, the robot is facing the user during interaction.

Then, the menu for selecting the several modes for goods search (keyword or product group search) are displayed and also verbally explained. If the customer has found the requested article in the database, a map of the store is shown (see Fig. 2), in which the current position, the position of the article in the store, and the suggested path planned by the robot are drawn in. If the customer presses the button "Go", the robot moves along its planned path to the requested article while the customer is following the robot during this guided tour. The speed of the robot during guiding the customer is controlled in dependence of the speed of the person, i.e. the distance between robot and user during the tour. In straight hallways, a pleasant walking speed of 1.0 m/s can be reached. At the arrival point, the robot steps aside, so that the customer has enough space for choosing the preferred article, and offers additional services like a video conference to a salesperson, a price scanning, or a new search. If the customer wants to bring the assisted shopping process to an end, s/he can finally press a "Good bye" button.

It should be stressed, that users don't need to be briefed before using the robot. As described above, the robot is autonomously making contact to the user by active user search, and all activities to be done by the user (e.g. pressing buttons) are explained by speech output during the greeting and article search phase. The dialog is self-explanatory and assisted by the robot, and nearly all users confirm its simplicity and intuitiveness.

VI. Robot Control Architecture

A. Layers and Main Components

To guarantee the main requirements to a modern robot control architecture, like modularity, extensibility, efficiency, customizability, reusability, and rapid application development [16], we decided to separate the robot-specific methods and skills from the application itself resulting in a flexible three-layered control architecture (Fig. 4). The layer L_0 (*Hardware Layer*) encloses the robot hardware (sensors and actuators), the operating system, and the low-level interface to the hardware. The low-level sensor information is processed in the next higher level to provide different skills, which then will be executed in L_0. In the next layer L_1 (*Skill Layer*) all required classical robotic-specific methods are located. Typically, these are modules for collision avoidance, localization and navigation, speech recognition, speech synthesis, people tracking and so on. These different robot-specific skills are reusable for various applications. The highest layer L_2 (*Application Layer*) provides elements, which are required for a specific application of a mobile interactive robot. An important fact is, that all layers are

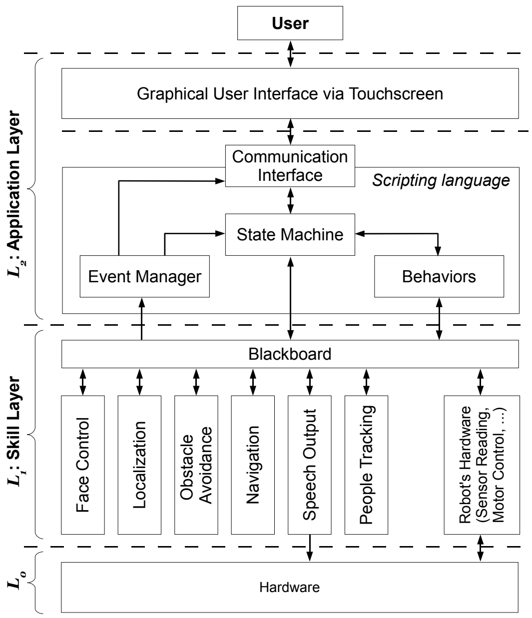

Fig. 4. The main components of our universal robot control architecture: the *Hardware Layer*, the *Skill Layer* with robot-specific methods and skills, and the *Application Layer* for hardware-independent applications.

only communicating with their immediate neighbors. This guarantees the transparency between the different layers. By using this strict separation, for a new application or for the usage of an alternative robot system only the *Application Layer* L_2 has to be changed rather than the whole system. The *Skill Layer* L_1 (Fig. 4) consists of two main components: the robot-specific and application-independent skills and a *Blackboard System*. The Blackboard can be considered as general shared data memory allowing to share all required information between the different skills. This makes it easy for the programmers to integrate new modules or to make modifications on existing modules.

The *Application Layer* L_2 combines the different skills and capabilities of the robot into a complete application. The main components of this layer are a *State Machine*, an *Event Manager* and a set of *Behaviors*. Additionally, the *Communication Interface* provides a coupling to the Graphical User Interface (GUI). The *Event Manager* listens on the Blackboard for specific events or changes in the robot's environment, like the detection of a new user, the arrival at the target position, or a collision with an obstacle. Based on these events and other information from the Blackboard, a finite *State Machine* controls the application. Further, each defined state also represents a principle behavior which will be executed if the system is in this specific state. Typical behaviors are "Explore & search user" or "Guide user to target position". The different behaviors use the skills of Layer L_1 to realize the desired functionality. Each state is connected with at least one other state. These connections define specific conditions that have to be fulfilled to transfer into a state. The whole *Application Layer* is realized in a script language, which allows an easy programming of the behaviors and the *State Machine*.

B. The State Machine

Fig. 5 shows the *State Machine* of the shopping robot application. Our *State Machine* uses hierarchical states, which means that there exist both *high level* as well as *low level* states. The low level states inherit all features from the corresponding high level state. That means, that all state transitions of a high level state are also active in the respective low level state. For example, the high level state *RobotMoving*, which contains all low level states where the robot is moving autonomously (*Explore*, *Guide user*, etc.), has a transition to the *Bumper* state, which is activated by a bumper signal or event. In this way, the *State Machine* becomes much simpler than a non-hierarchical one. For our mobile shopping robot we use a *State Machine* with four nested high level states (dashed gray lines in Fig. 5). The highest ranked state is *RemoteMaintenanceAllowed*. In this state, remote administrative commands are allowed. In our case, all other states are sub-states of *RemoteMaintenanceAllowed*. The next high level state is *AdminAllowed*. In this state, the *AdminMode* can be activated (using a special RFID key) by the personnel of the shopping store. An other high level state is *CallRobotAllowed*, which allows the employees of the store to call the robot to an information desk. The innermost high level state is *RobotMoving*, which handles the *BumperState* as explained above.

During a typically operating day, the robot boots up in the morning automatically and starts in the *Init* state. In this state, the robots waits for the activation by a responsible employee of the store. After the activation, the robot is in the *Admin* state, where some adminstrative functions are available. After that, the robots waits in the state *Wait on charging station* until the configured operating time has been reached. Before the robot can begin its operation, it is necessary to go to the state *Undock from the charging station*. After a successful undock process, the robot is in the *Explore/Search user* state, in which the robot explores between specific locations (like the entrance area and the main information desk) and searches for users. After a user pressed the "Start" button on the touchscreen, the state *Dialog* is active. Now the user can search for articles, product groups or special services of the store. After a selection, the state *Guide User* is activated, in which the robot guides the customer to the location of the product of choice in the store. After the destination is reached (state *Goal Reached*), the robots moves a little bit further (state *Step aside*) not to block the product shelves. After that, the user can continue the shopping tour with the robot, or the robot goes back to the state *Explore/Search user* and looks for a new customer. When the operating time is over, or the batteries become empty, the robot enters the state *Drive to charging station*, where the robot autonomously drives to the charging station. After the dock process (state *Dock on charging station*), the robot waits in the state *Wait on charging station* until the batteries are recharged.

VII. INTERACTION AND NAVIGATION METHODS

HRI and robust user localization and tracking: At first, people, who seem to need assistance have to be found,

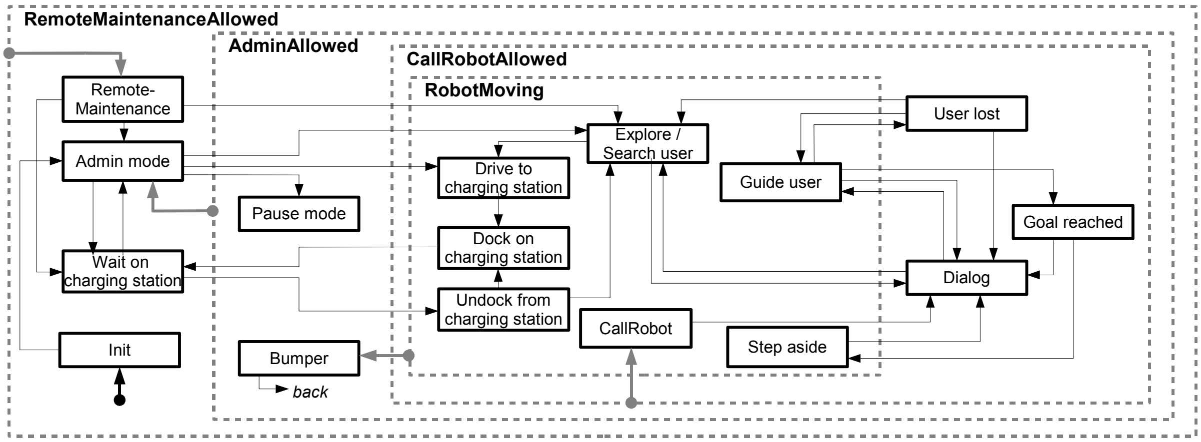

Fig. 5. Hierarchical State Machine consisting of high level states (boxes marked by dashed gray lines) and low level states (small thick line boxes).

while the robot is patrolling through the operational area. Indications for the interest of customers to interact with the robot are given, when a person is standing still or approaching and facing the robot for a while. During the guided tour, the robot has to continuously observe the user to detect, if the person keeps on following the robot. Thereto, we developed a probabilistic approach for detection and tracking of (potential) users in the local vicinity of the robot. The main sources of information are the images of the frontal and panoramic cameras and the occupancy map of the local environment, integrating all the range information from sonar and laser. All sensory cues are chosen to complement each other. As visual cues *skin color* is used in combination with *motion* (only if the robot is not moving) and *face detection*. Face detection gives a further hint, that the person did notice the robot, because only frontal faces can be found. All sensory observations are fused in a probabilistic user model to estimate the users' positions and further behavior-relevant properties, like the estimated need for interaction, or the probability of being the current dialog partner. The latter is a key value for controlling the robot's interaction behavior. Because the user's presence is of primary interest during a guiding tour, a particular region behind the robot dependent on the robot's movements is defined. If a user hypothesis is inside this region, the probability of being the current dialog partner is increased for that hypothesis, while it is decreased outside. Based on both periodically updated probability values, the robot can select its interaction and navigation behavior appropriately. For example, if the robot is not yet involved in a dialog or a guidance tour, and a new strong user hypothesis is developing in the user model because of an approaching person, the robot turns to the potential user and offers its service by audiovisual output. Details of the sensor cues and the probabilistic user model are given in [6].

Autonomous Navigation: In addition to the capability of smart HRI, robust autonomous navigation is a fundamental base for the operation of the mobile shopping robot. Important navigation skills (see Fig. 4) are self-localization, path planning, and motion control with collision avoidance. Within the scope of the shopping guide project, a method for Simultaneous Localization and Mapping (SLAM) has been developed, which is suitable for both high-precision laser range scanners and low-cost sonar sensors. The resulting Map-Match-SLAM algorithm published in [4], [5] is based on the well known Rao-Blackwellized Particle Filter (RBPF) [17]. By adding a memory-efficient global map representation [4] and dynamic adaptation of the number of particles, an on-line learning of the environment map by joysticking the robot through the operation area was possible. Fig. 6 shows an example of an occupancy map of a home improvement store which was built by means of our Map-Match-SLAM approach.

After completing the on-line mapping of the whole store, the global map of the best matching particle is stored to be used later on in the routine operation as global map for self-localization by MCL [18], and path planning to the article locations. Beforehand, however, this global map had to be labeled with the locations of all articles (about 60,000) available in the store. As specified in Section II-A, this can be done semi-automatically, because all article locations are stored in the merchandize management system of the store with an exact reference to the shelf number and the position within the shelf. It is an essential advantage of our approach and the used metric representation that the built global gridmap can easily be made fitting with the metric CAD map of the goods shelves in the marked by a simple manual map transformation (see Fig. 2 and 6).

Path planning is done by the utilization of standard graph search algorithms (A* algorithm) taking the specifics of the operation area into consideration. Motion control and *collision avoidance* use an enhancement of the well known Vector Field Histogram (VFH) approach [19] in combination with a new vision-based approach for monocular scene reconstruction and local map building. Our approach is able to detect obstacles that cannot be robustly observed by distance measuring sensors (e.g. empty Euro-pallets, ladders, shopping carts, shelves that extend into the scene, etc.). In

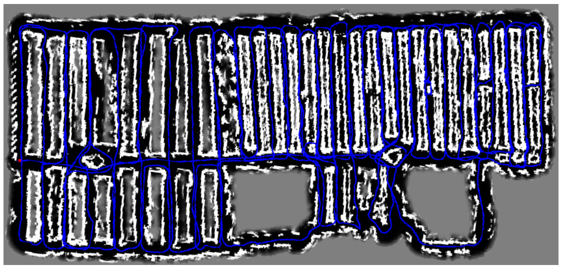

Fig. 6. Occupancy map of a home improvement store built by means of our online Map-Match-SLAM approach presented in [4], [5]. The store has a size of $120m \times 60m$ and consists of 29 parallel hallways. The entire path driven to built the map by joysticking (shown as blue line) has a length of about 2,300 meters and consists of more than 40 individual loops. The figure shows the map that belongs to the best matching particle of about 1,500 particles used in this RBPF-SLAM experiment.

[20] we show that this visual obstacle detection combined with a laser-range-finder can increase the detection rate of critical obstacles considerably, allowing the autonomous use of mobile robots also in complex environments.

VIII. Results of Long-term Field Trials

Our long-term field trials started in April 2008 and still ongoing (in July 2009) aim at studying whether and how a group of interactive mobile shopping robots can operate completely autonomously without any assistance by roboticists in an ordinary home improvement store, and how they are accepted by non-briefed customers. To this purpose as a first step, a home store with a size of about 7,000 square meters situated in Bavaria was equipped with 3 robotic shopping guides. With the objective of finding people who might need assistance, the robots move around in the store and patrol between particular points of interest. If one of the robots detects a potentially interested customer during its tour, it stops and the dialog and guidance functions are activated. To get an impression whether the customers are pleased with the robots as shopping guides or not, we inserted two dichotomous questions on the last screen page appearing after the guidance tour: First, the robot asks if the customer was satisfied, and then, if they would use the shopping robot again in the future.

Period I: During the first five months (April - August 2008) of this field test, there were about 210 kilometers traveled by each of the first three robots on average. The run-time was limited by the battery capacity and the decision to use no more than two robots at the same time in the store. With a full battery charge, the robots were running between 6 and 8 hours. The mean daily run time was 4.1 hours a day. All in all, 3,764 customers were in dialog with the robots. 5,781 times a guiding tour was started, which is 1.53 tours per customer in average. If we adjust this figure by subtracting the events when the customer had manually stopped the guidance process, we get 2,799 successfully finished guidance tours. In the other 2,982 cases, the customers did not complete the tour, for example, because they found a similar article along the tour elsewhere, or they were distracted by special offers, family members, etc. and left the robot alone for a longer time causing an automatic end of the dialog. In 83,7% of the guidance tours that had not been interrupted by the user, the robots reached their target points successfully. In 16.3%, they did not reach their targets, because, e.g. hallways were blocked by groups of customers or other dynamic obstacles, but also because the robots sometimes lost their position hypotheses (see Sec. IX) due to unusable measurements, e.g. in over-crowded hallways. The results from the simple survey at the end of the interaction were promising, however, we are aware that they are questionable because of the missing evaluations from those customers who did not complete their tour. About one fifth of the users who completed their tour has taken an interest in giving a feedback. 93.4% of them are contented with the shopping robot, and 92% would use the robot again.

Period II: In November 2008, two further home improvement stores (near Cologne) with a size of about 8,000 and 10,000 square meters were equipped with 6 more robots. So, in three home stores 9 mobile robots have been used in field experiments. Table I presents the results achieved in all three home improvement stores in the period from November 2008 until February 2009. For the example of store 1, the table is to interpret as follows: in the respective period 4,691 customers used one of the three shopping guides installed in the store. 4,606 employed the keyword search for finding a product, while 1,798 made use of the product group search, many of them used both possibilities. About 8% of the customers were interested in a price info by the on-board bar-code scanner. The 4,691 users employed the shopping guides in 6,924 guided tours to desired products, that means each user did start 1.48 tours in average. From these guided tours, about 40% (2,775) reached the target position of the product of choice. 2,298 tours (33%) were actively stopped by the customers by pressing the "Stop" button for various reasons (loss of interest, similar product found elsewhere in the store, unexpected interruptions by other events, etc.). In 1,851 cases (27% of all tours) the robots did not reach their targets because of the aforementioned reasons (blocked hallways, uncooperative customers, loss of position hypotheses, etc.). This result is not yet satisfying, therefore we are currently re-working the localization system to reduce the number of position losses due to unusable sensor measurements (see above), and implement a kind of autonomous local exploration behavior in case of losing the global position

TABLE I

Results of the field tests (Nov. 2008-Feb. 2009)

	Store 1	Store 2	Store 3
User logins	4691	1477	3347
Keyword search	4605	1304	2923
Product group search	1798	722	1427
Price info	582	179	411
Start guide tour	6924	1996	5768
Tour stopped by user	2298	648	2060
Goals reached	2775	899	2143
Searches per user	1.36	1.37	1.30
Started tours per user	1.48	1.35	1.72
Survey: Contented?	88.2%	87.5%	87.7%
Survey: Use again?	89.4%	88.1%	87.3%

that can be self-activated by the robots.

It is obvious, that the results in the three stores are different. Especially, the absolute numbers of user actions (login and menu actions) and reached goal positions differ significantly. The computed relative numbers based on the user logins are, however, in a similar range. The reason for the differences between the stores is, that the employees in the stores are responsible for activating the robot. Normally, the robot should be activated already in morning, when the store opens, but sometimes this is not done before noon. For this reason, the operating hours and also the absolute numbers of users vary from store to store. All in all, the nine shopping guides together traveled 2,187 kilometers between April 2008 and February 2009 and successfully guided more than 8,600 customers to the locations of their products of choice.

During the field trials we made the experience that the *patrol mode* is indeed a good choice to advise the customers to the shopping robot, but there are times, where it does not make sense. During rush hour it is sometimes so overcrowded that the robots are not able to move along the planned path. Then, they had to be taken out by the market staff and placed in their resting area, to avoid a frustration of the customers by shopping robots not operating as expected.

It shouldn't be forgotten to remark that robotic experts had to be present in the stores only one day per week in average to adjust the navigation and HRI software and to incorporate the hints and feedback of the market staff. During the other time, the robots operated completely autonomously and required only assistance by the store staff during power-up and shut-off in the morning and evening respectively.

Based on [21], a more detailed evaluation of the interaction and user experiences is planned for the near future. In particular, the utility, enjoyment and acceptance of the shopping guides will be analyzed by means of covered field observations and oral interviews.

IX. Summary and Outlook

With this successful development of the first shopping guide robots which are suitable for everyday and long-term use, a further important step towards assistive robotics for daily use has been done. In long-term field trials running since April 2008 in one and since November 2008 in three home improvement stores in Germany, the robots could demonstrate their suitability for a challenging real-world application, as well as a first positive user feedback. The high complexity of acting as a robotic guide in a real shopping environment, the practical utility of the developed shopping robots, their suitability for everyday use demonstrated in long-term field trials with more than 13,000 uninstructed customers (in both periods), and the fully autonomous navigation and interaction of the employed nine shopping robots make this project an important step in mobile robotics research. Our long-term field trials were successful in two main dimensions. First, they demonstrated the robustness of the hardware and the software architecture with the various probabilistic navigation and HRI techniques in a challenging real-world scenario. Second, they provided some evidence towards the feasibility of using mobile robots as assistants to people without any background knowledge in robotics.

Despite the encouraging results of the field trials, there is still potential for improving the existing solutions. For example, we are currently reworking (i) the localization system to reduce the number of position losses, (ii) the person tracker to allow detecting humans as potential users at distances greater than 2-3 meters and (iii) to integrate a video-based re-identification of the user if she was lost from view.

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