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A mobile robot platform for socially assistive home-care applications

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Abstract

The increasing number of elderly people with cognitive disabilities creates higher efforts and costs for care providers and family members. Assistive robot systems could accompany elderly people and help keeping the elderly longer at home to increase their quality of life and to save costs. However, current robot systems fail to deliver an adequate support of elderly people at acceptable costs. This paper presents a mobile robot platform for socially assistive care applications that was developed under consideration of functionalities, user acceptance, and costs.

1 Introduction

The increasing life expectancy leads to an increasing number of elderly people with cognitive disabilities. At the same time, the costs for the care systems increase, which results in an overall assistance restricted to people with advanced disabilities. Further, the changed structure of nowadays families and personal living conditions complicate a comprehensive private care by family members.

To compensate this leak of personal care, assistive robots could be used to support elderly or mildly disabled persons in their homely environments. So far, several robot systems are available, e.g., the telepresence robots Giraff [1] and VGo [2]. These systems can be remotely controlled by family members or care givers to interact with elderlies. A more complex example is the Care-O-Bot 3 robot, developed by the Fraunhofer IPA [3], that is able to autonomously move inside a house and to manipulate objects using a robot arm. However, up to now all available systems were unable to enter the market for assistive care in homely environments. The reasons are unsatisfactory functionalities, an excessive system complexity, or inadequate production costs.

This paper presents the technical realization of a novel robot platform for socially assistive home-care applications developed within the European FP7 project CompanionAble [4]. This platform was developed considering three aspects: the realization of a set of mandatory functionalities to support care recipients and care givers, a strict design and usability driven realization to increase the acceptance of the robot, and the development and component selection considering production and operational costs. The successful technical realization of the robot platform is described in the following sections. Based on the aspired robot application and the required functionalities (see [5]), technical requirements to the robot platform are derived. The realization of the robot (including embedded systems, sensor systems, battery technologies, and the mechanical integration) is discussed and important components are described. Finally, an outlook is given to the verification process of the developed robot platform.

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2 Requirements

The requirements specification for the assistive robot is based on a set of surveys and studies that were carried out during the first year of the CompanionAble project [6]. In these surveys, more than 250 end-users (care recipients, their relatives, caregivers, and care professionals in Austria, Belgium, Great Britain, France, Netherlands, and Spain) have been interviewed about their individual needs and priorities in assistive smart home technologies and services that could be provided by home robot companions. As a result of these end-user studies, the following categories of system requirements could be identified [7]:

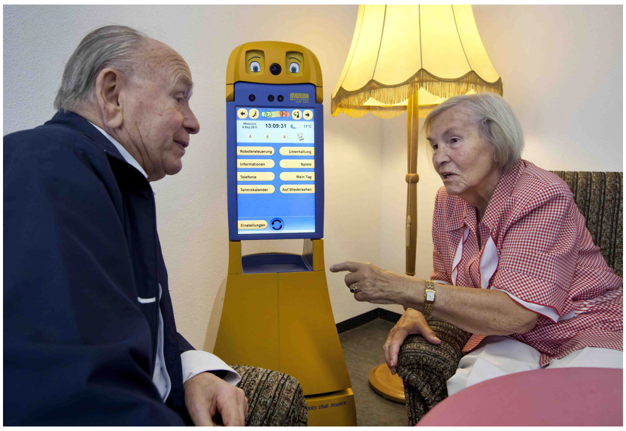

Figure 1: Elderly people in a homely environment interacting with the assistive robot developed in the CompanionAble project [4].

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- Communication: functions that allow keeping in touch with family members, friends, or care professionals, e.g., by video-telephony or telepresence

- Safety: functions that increase the safeness of the CR, e.g., user monitoring, fall detection, emergency call functionality, and remote-control of the robot to allow a care giver to evaluate critical situations quickly at any location in the home of the CR

- Services and assistive functions: functions that allow the CR to organize daily activities, e.g., by reminding taking medication, daytime management, suggestion of clothing based on weather forecasts, keeping and dispensing personal items of the CR, entertainment and interactive media access

- Therapy: functions that are intended to improve the CR's state of health, e.g., cognitive training exercises or stimulating games

- Smart situation awareness: the ability of the robot companion to collect information about the CR and to adapt its behavior to the exact preferences of the CR.

For the realization of these functionalities, the technology of the robot platform should include high performance computational units for the execution of software algorithms, adequate interaction systems for elderly people, and multiple sensor systems to analyze to robot's environment. The system design has to consider that the robot has to move in narrow home environments. Further, the variety of objects, which can also be displaced, has to be taken into account (e.g., glass tables, opened drawers).
The following requirements for the technical realization of the robot platform were derived: a) driving with moving speeds up to 0.6 m/s, b) passing of barrier heights up to 1.0 cm, c) avoiding of contusions through the drive systems (wheels have to be covered), and d) a secure shutoff of the motors in case of a collision. For the battery and energy management system, the following requirements were identified: a) operating times of more than ten hours, b) autonomous recharging of the batteries, c) reduction of energy consumption during charging to fasten the recharge process, and d) implementation of persistent battery technologies. The sensor configuration of the robot must allow: a) the detection of obstacles at different heights, b) a secure detection of a collision at the outline of the robot's footprint, c) the detection of different kind of surfaces, and d) the identification of the position of persons. For the user interaction, the platform must provide: a) a large touch screen for the presentation of information and the input of user data, b) the possibility to use the robot in a standing and a sitting position, c) high-quality and high-performance loudspeakers, d) directional microphones to detect speech and sound sources, e) a pleasant appearance, f) the possibility to express emotions to the CR, and g) a tray for carrying important personal objects (e.g., keys, wallets, or spectacle cases).

3 Implementation

The concept of a service robot realization can follow different technological approaches, e.g., the movement of the robot based on wheels or legs. Different solutions might allow for the fulfillment of all requirements, however, the outcome would differ regarding complexity, costs, or stability. Therefore, additional aspects must be considered to maximize the later success of a robot platform. In addition to a convincing set of functionalities and a pleasant design, we have considered later production and operating costs and the longevity of system components during the development process. This led to the technical implementation decisions, described in the following sections.

3.1 System Architecture

The system architecture of the robot platform (Figure 2) consists of several control modules that include embedded system units, specifically developed for this platform (marked by an *E*), and off-the-shelf products by external suppliers (marked by an *X*).

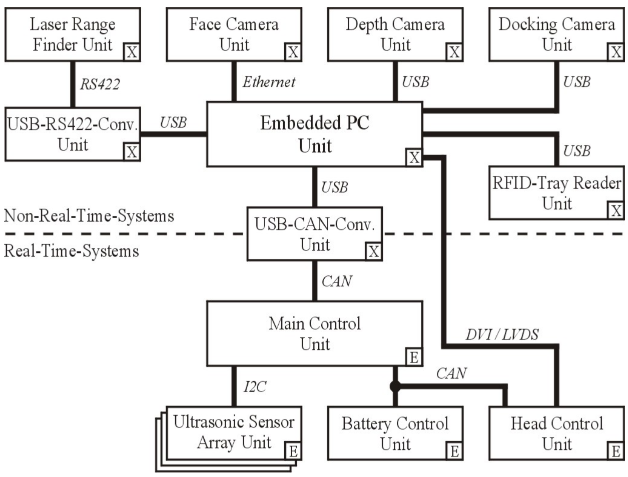

Figure 2: System architecture including real-time systems for robot control and non-real-time systems for user interaction and obstacle detection. Embedded systems units are marked by an E; off-the-shelf components by external suppliers are marked by an X.

Two units are of most relevance for the control of the robot: an Embedded PC Unit and a system specific Main Control Unit. The Embedded PC Unit is equipped with an Intel i7-620M quad core processor and computes high-performance algorithms (e.g., for navigation, localization, or interaction). It communicates with other units based on standard PC interfaces like USB or Ethernet. The Main

Control Unit (Figure 3) is responsible for low-level control tasks that require fast and determined system reaction times, e.g., the control of the motors or the communication to sensors. The diversity of signals that need to be handled by this unit (e.g., analog measurements of voltage and current levels, communication interfaces to other modules, or Pulse-Width Modulation (PWM) signals for controlling the motor speed) required the integration of a microcontroller and a Field Programmable Gate Array (FPGA) into the Main Control Unit. The communication to other low-level system modules is usually realized based on the Controller Area Network (CAN) bus. For the communication of the Main Control Unit to the Embedded PC, an USB-CAN-Converter was integrated.

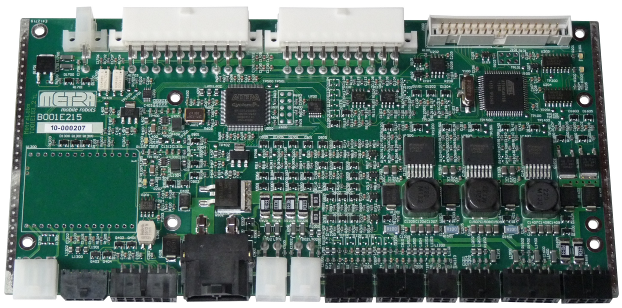

Figure 3: Main Control Unit of the robot platform. This module, in addition to other units, was designed within the CompanionAble project by the project partner MetraLabs. It is responsible, e.g., for the control of the motors, the power supply of several other units, or the communication to the ultrasonic sensors.

The two described modules are responsible for the control of real-time tasks (Main Control Unit) and non-real-time tasks (Embedded PC Unit). For the detection of the robot's environment, the interaction with users, and the movement of the robot system, further units had to be included into the system architecture. The Laser Range Finder Unit is responsible for the detection of obstacles and the calculation of the robot's position. This unit is connected to the Embedded PC by an USB-RS422-Converter Unit. Furthermore, three camera systems are connected to the Embedded PC Unit to detect obstacles, persons, or the charging station during the docking process. The RFID-Tray Reader Unit detects labeled objects located in the tray. Real-time systems include an array of ultrasonic sensors for the detection of obstacles that are not visible for the laser range finder. The Battery Control Unit monitors the current state of the battery and controls the charging process. The Head Control Unit is connected to several interaction components like the touch display, loudspeakers, or the eyes. Further details of these units and the connected elements can be found in the following sections.
The system architecture, we integrated into this robot, allows for adequate production costs by adapting the control units to the tasks of the robot system. In particular, the Main Control Unit is highly specialized to the usage of the robot and the integrated components. Redundancy, e.g., by the separate Battery Control Unit was limited to functions that are of relevance for the safeness of the system. As a consequence, the implemented system architecture is significant less flexible compared to other service robots' system architectures (e.g., [8]).

3.2 Platform Design and Drive System

With a height of 120 cm, the robot platform is comparable to the size of an eight years old child. The size is optimized for an ergonomic operability by a standing or sitting user. The design of the robot should suggest a cartoon like appearance instead of human like look. This should clarify that the robot does not have a similar intelligence like a human.
The drive system of the robot consists of two driven wheels combined with one castor wheel on the rear side. The two driven wheels are placed outside the centerline of the robot to avoid the need of a spring-mounted second castor wheel. This reduces the complexity and costs of the platform and increases the stability. The roundish form of the robot's rear side still allows for a good maneuverability of the platform. The robot has a footprint of about 50 x 50 cm^2 and a weight of ca. 50 kg.

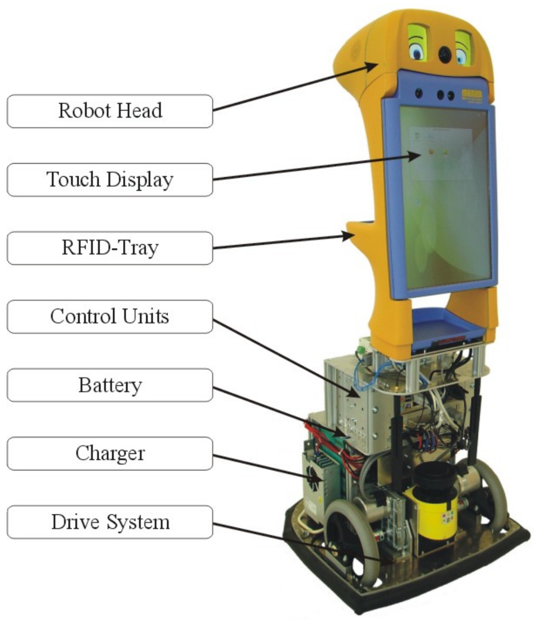

Figure 4: Placement of system components. The usability of the robot required the integration of interactive components at the front side of the robot. Therefore, heavy system components like the battery or the charger were placed at very low positions at the backside of the robot.

The design of the robot was optimized for a good usability of the robot. Therefore, display and the head were inte-

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grated at the front side of the robot to be easily accessible by the users. For a high stability of the platform and the generation of an optimal center of gravity of the platform, heavy components, like the battery, were placed at the lowest possible positions at the back side of the robot (Figure 4).

3.3 Power Supply and Charging

To be able to operate the robot for more than ten hours, the battery capacity and the overall power consumption had to be optimized. For the storage of the required energy, we have equipped the robot platform with a $LiFePO_4$ battery with about 1000 Wh. Compared to other lithium battery technologies (e.g., lithium polymer), this battery has a lower energy density. However, we decided to apply this technology, because of the significantly lower costs per watt-hour compared to other technologies and because of the outstanding safety characteristics of this system.
The voltage levels of all battery cells are controlled by the Battery Control Unit (Figure 5). In case of unbalanced cell voltages, this module is able to balance all cells by discharging specific cells. Furthermore, this unit is responsible to monitor inappropriate battery conditions like overvoltage, under-voltage, or over-current. In case of critical failures, it stops the charging process or turns off the whole robot to protect the battery from damage. In addition to safety tasks and the control of the charging process, this module is also responsible for other low-level functions of the robot, e.g., the control of the robot's sleep mode.
For the charging of the battery, two solutions are available: a standard power plug and an autonomous charging plug. The standard power plug can be used to charge the robot at any place with line voltage and a standard power cable. The integrated power supply unit is able to fully charge the robot within four hours. For an autonomous recharging of the battery, a new docking concept was developed and integrated. The concept of this autonomous charging system was to enable low cost space saving charging stations. Therefore, all complex and bulky components (power supplies and control systems) were placed inside the robot. The autonomous recharging technology allows for a direct connection of the robot to line voltage without user interference. Inspired by the connector concept known from water boilers used in millions of households, a safe version of an autonomous line voltage connector has been developed. We have integrated the socket at the robot platform and designed a spring loaded plug at the charging station. A small camera is located above the socket to detect synthetic markers that are used for the autonomous docking process. Based on this concept, we realized a reliable, safe and cost-effective docking system, which is an important prerequisite for autonomous recharging and long-term applicability of the robot companion.
The power consumption of the robot was reduced by optimizing the robot's electronic modules (primarily the co-controller) and by the selection of an embedded PC with adequate energy consumption. Further, we implemented switchable power outputs that allow for the deactivation of modules that are not needed all the time. For example, the laser range finder switches off automatically, if the robot is not moving; the display automatically turns-off in the standby mode. The overall power consumption of the robot for home-assistive applications could, therefore, be reduced to a mean value of less than 80 W. This allows for a theoretical operation time of more than twelve hours. Diverse field experiments confirm this operation time.

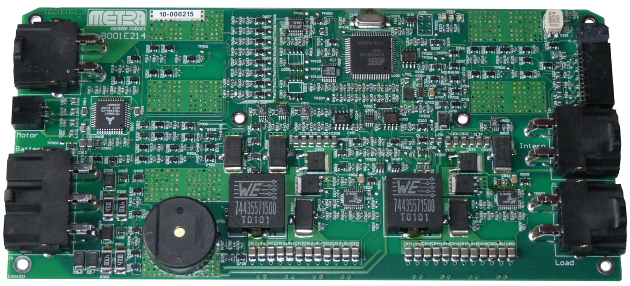

Figure 5: Battery Control Unit of the robot platform developed within the project. It monitors the correct parameters of all battery cells and controls the charging process of the battery.

3.4 Sensor Equipment

Laser Range Finder: The robot is equipped with a laser range finder for localization and obstacle avoidance. We integrated a Sick S300 2D-scanner with a scanning range of 270°. The laser is located at the front side, facing in the driving direction of the robot. Because of the integration inside the robot casing, the field of view is limited to 180°, which is still sufficient for the described applications. The S300 scanner conforms to the SIL2 security level and is integrated into the safety concept of the robot. This simplifies the certification process, required by the German Technical Inspection Agency (TÜV).
Ultrasonic Sensors: We further integrated 14 ultrasonic sensors as a redundant sensor system for the laser range finder. These sensors are located close to the ground and can detect smaller objects on the floor that are invisible for the laser scanner. The measurement principle of these sensors allows for the detection of glass or mirrored surfaces that are invisible for optical sensor systems. The ultrasonic sensors have an angle of beam of 120°. This makes it possible to use crosstalk between different sensors to enhance the detection of obstacles.
Collision sensor: The robot consists of a collision sensor that is placed at the lowest position and outer edge of the robot. For further security reasons this sensor detects collisions with objects, which might be not detected by the laser scanner or the ultrasonic sensors, or objects moving faster than the reaction time of the robot (e.g., a cat moving

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in the way of the robot). The usage of a soft rubber-based collision sensor reduces the impact of a collision.
Cameras: For human-robot interaction, the robot is equipped with the high resolution camera eco274CVGE by SVS-VISTEK in combination with a 180° fish-eye lens. This camera is located in the robot's face and indicates the nose of the robot. It is connected via Gigabit Ethernet to the embedded PC and is able to transmit up to 25 frames per seconds at a resolution of 1600 x 1200 pixels. In addition to person tracking and video conferencing, this camera can also be used for obstacle avoidance. A second camera is located at the rear side of the robot and is used for the detection of the charging station (see above). This camera has an USB interface and a resolution of 1.3 megapixels.
Kinect depth sensor: In addition to the laser scanner and the camera systems, a Kinect depth camera is integrated above the touch display. This sensor delivers 3D information of the environment in front of the robot platform based on an infrared grid projected on the floor. The angular field of view of this camera is 57° horizontal and 43° vertical. The detection range is from 1.2 m to about 3.5 m. The camera is connected to the embedded PC and is used user tracking and for obstacle detection.
Microphones: The robot is equipped with an omnidirectional microphone array using the coincidence microphone technology (CMT) developed by the project partner AKG in Austria. The CMT array is used to localize a sound source or a speaking person based on the beam characteristics of the microphone capsules. The robot changes its orientation to optimize the receiving angle to the sound location, which is important for video-telephony and speech-based person tracking. For an optimal acoustic performance, this microphone array is placed at the top of the robot's head.

3.5 User Interface

Touch Display: The touch display is the main unit for graphical communication between a user and the robot. We decided to use a vertically mounted 15.4 inch wide touch screen display for the presentation of information to the user and the input of user data. To ensure the best usability and to allow for an optimal interaction in standing and sitting positions, the display unit can be tilted, which is controlled by the Head Control Unit.
Eye Displays: To give the robot a friendly and dynamical appearance, we integrated two displays as robot eyes. The displays have a size of seven inch and a resolution of 800 x 480 pixels. These displays can be used to show the robot's internal states (e.g., sleeping, listening, bored) or basic emotions (e.g., friendly or surprised). The eye-displays can either be controlled by the Head Control Unit, which can generate pre-defined pictures or animations as well as the embedded PC, which can show full-color videos. The generation of pictures or animations based on the Head Control Unit is useful in cases, where the embedded PC is turned-off (e.g., a system restart).

RFID Storage Tray: As a suggestion of the user questionnaires, the robot contains a storage tray, were a user can deposit items important for daily usage, like glasses, wallets, keys, or a mobile phone. The tray is located at the same height as the touch display for a good accessibility. The integration of RFID antennas allows for the detection of tagged objects to remind the person, e.g., of taking an item before leaving the house.
Loudspeaker: The robot head also contains two loudspeakers that can be used for speech output or the playing of music. The choice of the best system was based on the sound quality. The loudspeakers can further be used by the Head Control Unit to signalize special system events, e.g., an empty battery or a failure during the system start that cannot be communicated by the embedded PC.

3.6 System Realization and Costs

The integration of all system components (shown in (Figure 6) was carried out under the consideration of a later production of the platform. All components were combined to functional groups that can be pre-assembled independently from each other. Examples are the Embedded PC Unit and the Main Control Unit that are located inside an electronic case; the display unit including the Kinect sensor; or the head with the eye displays, loudspeakers, the fish-eye camera, and the omni-microphone. Furthermore, the integrated system architecture based on standard PC interfaces and the CAN bus simplifies the complexity of the cabling of all system components. Finally, the casing was optimized for low-cost production processes.
Considering all costs and production aspects, described in this paper, we aspire a later sales prize of this robot system of less than 10,000 Euro, which will be unique for a fully autonomous robot platform with such characteristics.

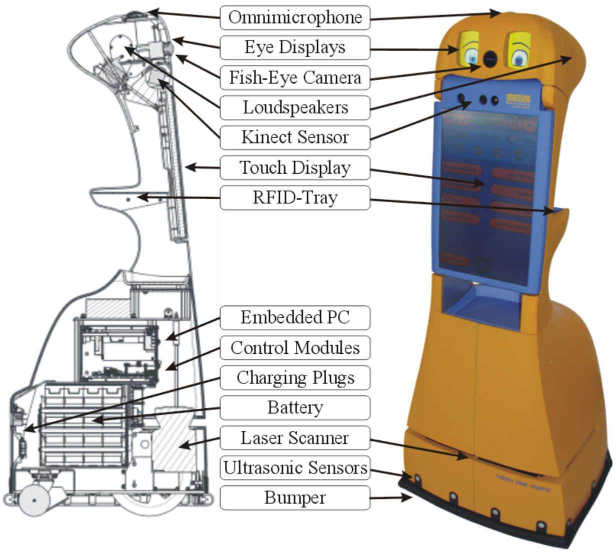

Figure 6: System components of the robot companion. The left picture shows a schematic of placement of internal modules, the right picture shows the final design.

4 Functional Tests and User Trials

The verification process of the described assistive robot is carried out in two steps: functional tests and user trials. Functional tests were accomplished to prove all technical parameters in relation to the robot platform specification. They were executed in laboratory environments. The functional tests basically verified the correctness of all technical systems, i.e., the mechanical design of the drive system and the realization of the mechanical framework of the robot; the system architecture including all control units and communication networks; and implemented software functionalities of the firmware and the embedded PC software. Functional tests further included the review of the safety concept of the robot platform in cooperation with an independent testing laboratory (German TÜV). The usability of the system considering interactive components like the touch display were validated regarding ergonomic standards, e.g., applied to workplaces.

Figure 7: Map of the test environment at the project partner SmartHomes in Eindhoven (Netherlands) [9].

User trials are arranged to verify the usability and acceptance of the robot platform and the applicability of developed software algorithms in real environments. Within the CompanionAble project, user trials in a fully equipped smart home of a project partner are scheduled for the period April to June, 2012. The test environment (Figure 7) has a living space of about 150 m^2, where the robots will operate in two-third of this area, because it is not planned to operate in sleeping rooms and bathrooms. In addition to usability test, a special focus will be given to the interaction with the integrated smart home components. Afterwards, further user trials in ordinary apartments of elderly persons are scheduled to validate the applicability of a stand-alone robot system without supporting smart home technologies. Results of both user trials are not available so far.

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