Engineering 2015, 1(1): 27–35
DOI 10.15302/J-ENG-2015007

Research
Robotics—Article

Architecture and Software Design for a Service Robot in an Elderly-Care Scenario

Norman Hendrich*, Hannes Bistry, Jianwei Zhang

ABSTRACT Systems for ambient assisted living (AAL) that integrate service robots with sensor networks and user monitoring can help elderly people with their daily activities, allowing them to stay in their homes and live active lives for as long as possible. In this paper, we outline the AAL system currently developed in the European project Robot-Era, and describe the engineering aspects and the service-oriented software architecture of the domestic robot, a service robot with advanced manipulation capabilities. Based on the robot operating system (ROS) middleware, our software integrates a large set of advanced algorithms for navigation, perception, and manipulation. In tests with real end users, the performance and acceptability of the platform are evaluated.

KEYWORDS service robots, ambient assisted living, manipulation and grasping, user study

1 Introduction

An aging society is widely considered to be one of the main socio-political challenges of the 21st century. Demographics, improved health care, increasing urbanization, and the trend towards smaller families imply that more and more elderly people are living alone. Recent data for Europe indicates that currently about 17.5% of the total population (88.5 million out of 505.7 million people in 2012) are aged 65+, but this percentage is expected to increase to 30% (164 million people) in 2050 [1]. The number of elderly people living alone varies between countries, and is as high as 67% for people aged 80+ in Scandinavia. Although similar numbers apply for the USA, these numbers are dwarfed by estimations for Asia, due to the large populations and the expected rise in family income over the next decades. In Japan, the percentage of persons aged 65+ is expected to grow from 17.2% (21.6 million people) in 2000 to 36.5% (45.8 million people) in 2050, and the corresponding estimates for China are 6.9% (88 million people) and 23.9% (400 million people), respectively.

Mobile personal service robots, capable of helping people in their daily housekeeping tasks, are one approach to tackling the problem (Figure 1). The Robot-Era project, funded as part of the European Seventh Framework Programme (FP7), proposes a fully integrated system for ambient assisted living (AAL) [2]. The project targets persons aged 65+ who are either living alone or with their families, but who do not have dedicated caregivers. These should be people who still maintain a high level of autonomy according to the usual medical classifications, although they may show the first signs of physical and cognitive disabilities. The system services are designed to help the users with their daily-life activities (communication, dressing, cleaning, cooking, etc.) and to stimulate and encourage mental and physical exercise.

The requirements for the system were derived from focus-group studies using interviews, questionnaires, and the observation of elderly users in Germany, Italy, and Sweden [3]. Unlike typical laboratory robots that are used by experts, the Robot-Era system must be usable by elderly people with no prior knowledge of robots, who may have slight mental or physical disabilities. Therefore, the user interface of the

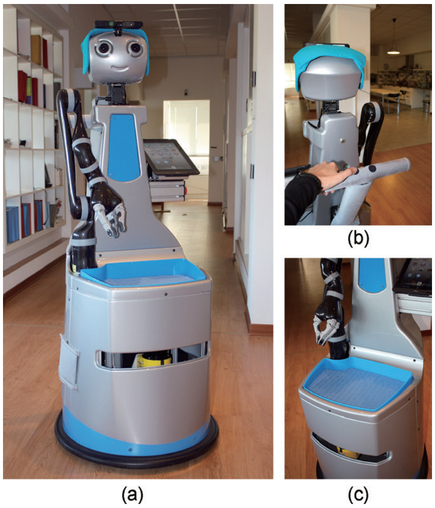

(a) (b) (c)

Figure 1. The Robot-Era domestic robot. (a) The robot combines the ScitosG5 differential-drive platform, the Kinova Jaco 6-DOF arm with integrated three-finger hand, and a pan-tilt sensor head; (b) close-ups of the tilting handle for walking support; (c) the object transportation tray.

Computer Science Department, University of Hamburg, Hamburg D-22527, Germany
* Correspondence author. E-mail: hendrich@informatik.uni-hamburg.de
Received 11 March 2015; received in revised form 20 March 2015; accepted 25 March 2015

robot is intentionally kept simple, and only exposes a set of robot services that are easy to understand and select.

Figure 2 outlines the overall concept. A set of multiple robots with dedicated roles is coordinated by a planner that has access to a variety of ambient sensors. The basic idea is not only to provide services within the apartment of a single user, but also to span the functionality across buildings and a residential area to outdoor zones and perhaps even a whole town. Data is exchanged and integrated using a common middleware, and contextual information is extracted from the stationary and robot sensors and the user commands and stored in the context-awareness module (CAM) database.

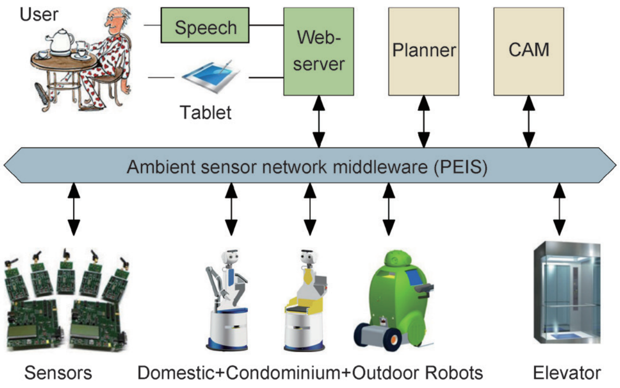


Figure 2. Overall concept and architecture of the Robot-Era platform for ambient assisted living and elderly care. The end users and caregivers interact with the system using a speech interface or an intentionally simple tablet-based graphical user interface. Different robots are used for outdoor, condominium (transport), and domestic (cleaning) uses. Data from ambient sensors, user monitoring sensors, the robots, and smart appliances is integrated in the PEIS middleware layer. The configuration planner coordinates the system and the robots.

Thus far, three different robots are being considered in our demonstration facilities in Peccioli (Italy) and Orebro (Sweden):

- The outdoor robot is designed for autonomous outdoor transportation tasks (e.g., shopping, garbage), but also provides guidance and walking support to the elderly.
- The condominium robot handles object transportation tasks within a building or building complex.
- The domestic robot takes on the role of a dedicated indoor service robot and is designed for manipulation and cleaning tasks as well as object transportation. The robot system is operated by the elderly users via the tablet and speech interfaces.

In addition, elevators and doors have been instrumented to be used by the robots and the planner.

Due to its close interaction with the user and the need for it to be able to perform autonomous manipulation tasks, the domestic robot is by far the most complex component of the overall system. To keep down the cost of this robot, its hardware was assembled from proven standard components (Figure 1).

The rest of this paper describes the design of the domestic robot, and motivates the major design decisions. Section 2 summarizes the state of the art, and Section 3 describes the overall design of the domestic robot and the selection of its key hardware components. In Section 4, we introduce the software architecture of the robot and outline the main building blocks and the interfaces between them. Finally, Section 5 presents results from the first large-scale test of the system with elderly users, and highlights key design changes made according to our experiences. The paper concludes with a summary and outlook to future work.

2 Related work

The design of control architectures for autonomous robots remains at the heart of robotics research, with the plan-based approach first implemented on Shakey [4] and on Brooks' subsumption concept [5], on both ends of the spectrum. The designers of many recent robots take a pragmatic approach, and integrate a multilayer architecture with some variant of symbolic planning and scripted skills on top of a robot middleware framework; examples include Player [6], YARP [7], ROS [8], and MIRA [9]. These frameworks provide a communication infrastructure and proven software for common robot tasks.

Developed since 1998, the Fraunhofer Care-O-bot robots are among the best-known examples of service robots targeting elderly assistance [10–12]. The mobile platform uses four individually steerable wheels for omni-directional mobility. With one robot arm and a foldable tray, these robots can carry objects and perform simple pick-and-place tasks. Originally based on custom hybrid software [13], these robots are now running the robot operating system (ROS).

Research on elderly-care robots began in Japan around the same time as the first Care-O-bot, with work on WENDY [14] at Waseda University dating back to 1999. The PR2 robot [15] also uses a steered-wheel mobile platform. Two compliant 7-DOF robot arms with grippers are mounted on a telescoping spine that enables the robot to lift or lower its arms to increase the workspace. The software is fully based on ROS [16]. This robot has been sold to several universities and research institutes around the world, and provides a reference and benchmark platform from which several groups can share, exchange, and compare their algorithms. A recent design, the HoLLiE assistance robot [17], integrates a wheeled platform with two robot arms for advanced manipulation. Like the PR2, an active torso increases the reach of the robot.

3 Domestic robot hardware

Any robot designed for household manipulation tasks must be able to reach objects and furniture, and its workspace must therefore be similar to the reach of humans. However, the size of the robot is limited by the width of typical doors, while its weight remains a difficult compromise between battery capacity, stability, and the payload of the manipulators. In most scenarios, these robots are expected to move and operate autonomously in direct proximity and even contact with humans, and safety is therefore of the utmost importance.

While it is difficult to estimate realistic prices for research prototypes, the reference robots listed above are all based on rather complex designs. In contrast, the stakeholder interviews and financial analysis carried out by project Robot-Era clearly indicated that only a lower cost robot would be affordable, even for large retirement homes. Given these budget limitations, a differential-drive platform with one robot arm was selected as the basic design. Figure 3 shows the evolution of this robot from the basic design to the prototypes used in the first and second experimental phases of the project.

3.1 Mobile platform

We selected the proven Scitos-G5 differential-drive mobile robot [18] as the base platform for the domestic robot. The form factor allows the robot to pass through narrow doors and corridors, and the weight of the integrated lead batteries results in a low center of gravity that makes the platform safe for the walking-assistance and stand-up-helper scenarios. The runtime with fully charged batteries is several hours, and the robot will return to its charging station autonomously. Sensors for localization and obstacle detection include front and rear laser-scanners (Sick S300 and Hokuyo URG-05), a ring of sonar sensors, the wheel odometry, and a gyroscope.

3.2 Manipulator

Our user studies clearly showed that the robot should be able to grasp a variety of objects including soft objects and clothes. In addition to cleaning tasks, the users also expected help with heavy objects and with reaching objects on the floor and on high shelves. At the same time, the acceptability studies indicated the importance of a good design with an aesthetically pleasing appearance and outer form.

Therefore, we considered several lightweight robot arms for the robot and checked them against our functional requirements, which included the robot weight, payload, kinematics and reach, gripper options, force/torque and tactile sensors, mechanical and electrical interface, vendor-provided software, and, last but not least, costs. Figure 4 shows the shortlist of candidates, namely the Schunk Powerball arm [20], the Kinova Jaco arm [21], the Schunk modular system [22], the compliant BioRob arm with memory-wire actuation [23], and the Universal Robots UR5 arm [24]. At that time, no vendor had a ROS interface to their arm ready, but all indicated that it was planned.

We finally decided on the Kinova Jaco arm because teleoperation tests demonstrated the versatility of its three-finger hand and indicated acceptable performance despite its low payload of 1.5 kg. Originally designed for helping disabled people in wheelchairs, the Jaco arm also has the advantage of existing medical certification and a pleasing appearance [25]. System integration is especially simple for the Jaco arm, since it has just one USB-connection and relies on a 24 V DC supply. The arm lacks torque sensors or tactile sensors, but motor currents are measured and provide a rough estimate of forces and torques.

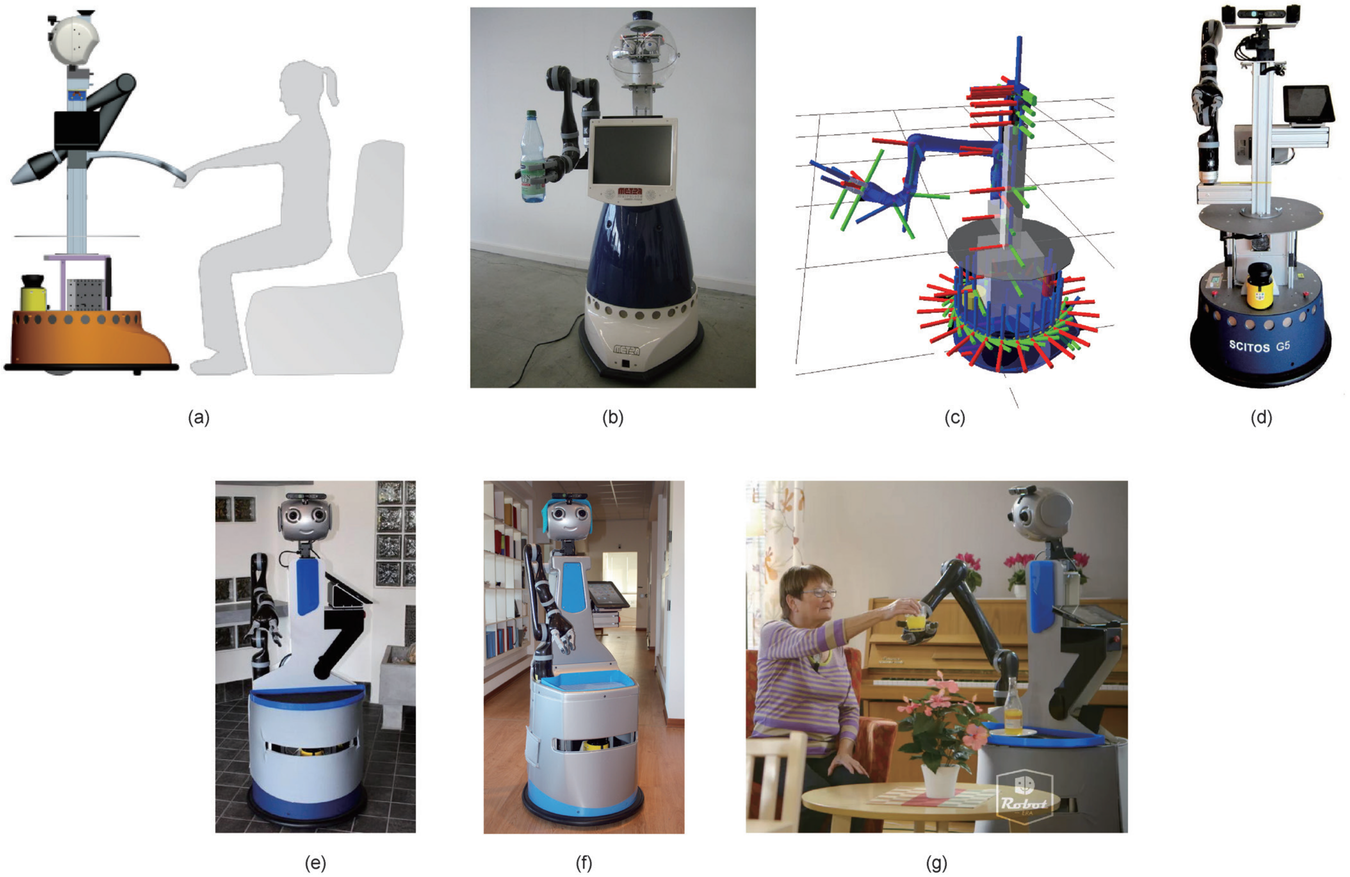


Figure 3. Evolution of the domestic robot. (a) Initial design sketch and concept of the tilting handle for walking support; (b) experimental Jaco arm integration on the astromobile robot [19]; (c) ROS URDF robot model with sensor and actuator coordinate systems; (d) first-year prototype without cover; (e) second-year prototype with soft cover; (f) third-year prototype with hardware updates and new cover; (g) experimental test.

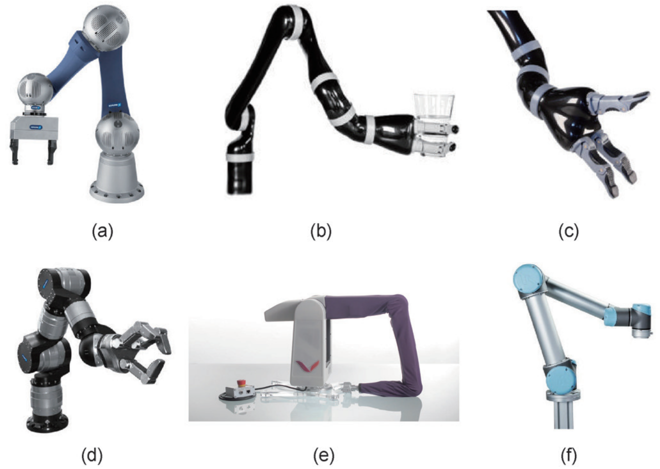


Figure 4. Robot arms evaluated for the domestic robot due to their combination of weight, payload, reach, mobile use, and costs. (a) Schunk Powerball arm; (b) Kinova Jaco; (c) close-up of the Jaco three-finger hand; (d) Schunk modular arm; (e) BionicRobots BioRob arm (memory-wire actuation); (f) Universal Robots UR5. (Images courtesy of the vendors)

Given its reach of about 90 cm and its slightly unusual kinematics, no possible mount point allowed the Jaco arm to reach both the floor and high shelves. We decided to mount the arm at a height that allowed for good workspace dexterity on tabletops and for reaching the floor. The initial and final mount positions of the arm can be seen in Figure 3. Figure 5 shows two examples of our workspace analysis, one for cleaning tasks and one for a hospital scenario. We are considering mounting the arm on a moving spine (similar to the PR2 [15] or HoLLiE [17]) as a later upgrade, to increase the reach of the robot.

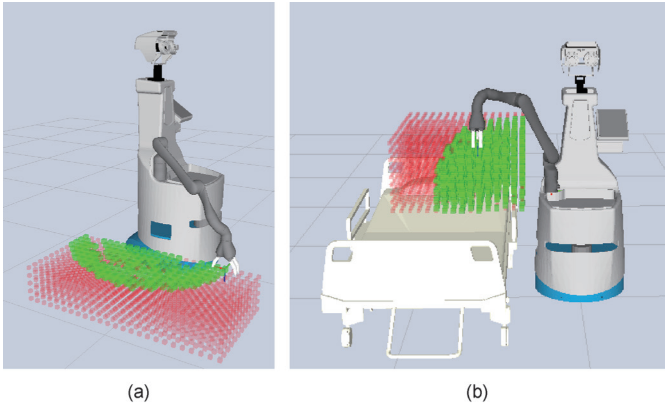


Figure 5. Example workspace analysis of the robot with the Jaco arm in top-grasp hand orientation. The arm-mount position was chosen so that the robot can reach the floor and access its object transportation tray, and so that it has a large workspace on its right side. (a) Reaching the floor; (b) example from a hospital-care scenario.

3.3 Sensors and calibration

The sensor suite of the robot is fairly standard and includes the sensors of the mobile platform (front and rear laser-scanners, sonar, wheel odometry, gyroscope, bumpers, and emergency-stop button). Two FireWire cameras and the XtionPro RGB-D sensor are mounted on the moveable (pan-tilt) head of the robot. Another USB camera on the side of the robot is used to detect objects on the floor to the right of the robot. Standard techniques are used to calibrate the intrinsic parameters of the cameras, and global calibration is done by the tools available in ROS.

4 Software architecture

This section describes the software architecture of the robot. An abstraction layer encapsulates the robot skills into services for use by the ambient sensor network. Most of the computation is performed by a large number of ROS nodes, with state-of-the-art algorithms for environment perception and motion planning.

4.1 Overview and main abstraction layers

The robot software is organized into four main abstraction layers (Figure 6). The topmost layer consists of the user interface (speech, tablet) and the PEIS middleware [26, 27]. The PEIS system maintains the state of all sensors in the ambient assisted living environment, manages the high-level semantic information about objects and tasks, and provides the symbolic multi-robot planner that controls the different robots, sensors, and smart appliances [28].

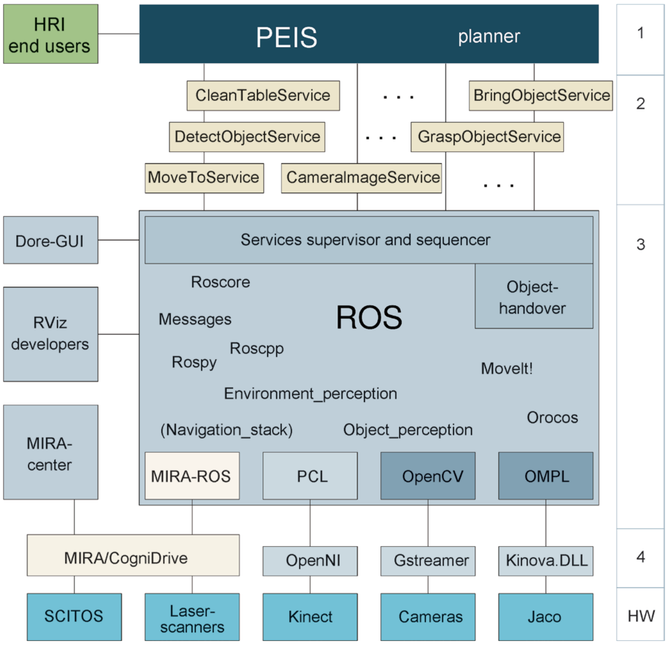


Figure 6. Software architecture for the domestic robot. Users request robot services from the PEIS middleware using speech or their tablet computers (HRI). PEIS manages the ambient sensor network and provides the symbolic planner. The PEIS-ROS *exekutor* modules encapsulate the robot services; this layer is subdivided into high-, medium-, and low-level robot skills (layer 2). The main robot software (layer 3) is fully based on ROS, except for platform localization and navigation handled by MIRA/CogniDrive. Layer 4 includes the device drivers that control the sensors and actuators.

The second level is composed of a set of carefully chosen services that encapsulate the available robot skills. Inside this PEIS-ROS interface layer, the robot skills are further organized into a three-level hierarchy of basic skills (single sensor or actuator), intermediate skills (multiple sensors and actuators involved), and high-level services that require a combination of basic and intermediate skills [29]. Table 1 lists some examples of robot skills, while Figure 7 illustrates the sequencing and interaction for the bring-object service.

Table 1. Example skills defined for the domestic robot.

Skill	Level	Description
Emergency Stop	L	Safe stop of all robot motion
GetCameraImage	L	Send image from camera to PEIS
GetKinectImage	L	Gets image and 3D pointcloud
GetLaserScan	L	Reads laser scan for navigation/docking
MoveTo	L	Drives the robot to the given pose (x, y, q)
MovePtu	L	Moves the robot head to given (pan, tilt)
RetractJacoArm	L	Moves the arm to the save park position
…		
DetectKnownObject	I	Find the requested object, return 6-DOF position (x, y, z) and orientation (j, y, q)
GraspKnownObject	I	Move the hand to the object and grasp it
PlaceObjectOnTray	I	Puts a grasped object onto the robot's tray
MoveHingedDoor	I	Arm motion to grasp and open a door
DockToCoro	I	Drive to position of the condominium robot, align robots for object exchange
HandoverObject	I	Move the arm toward the user, wait for voice command (confirmation) then release the object
…		
DetectPerson	H	Identify a person from camera images
WalkingSupport	H	Move toward the user, rotate until user can grasp the handle, then drive the robot according to the user movements
BringObject	H	DetectKnownObject, GraspKnownObject, PutObjectOnTray, DriveToUser
CleanTable	H	HandoverObject detect all objects on a table, put onto tray, carry to kitchen, then put into kitchen sink
CleanWindow	H	Put sponge/brush onto tray, drive toward window, perform cleaning motions

Notes: L means low-level; I means intermediate; H means high-level.

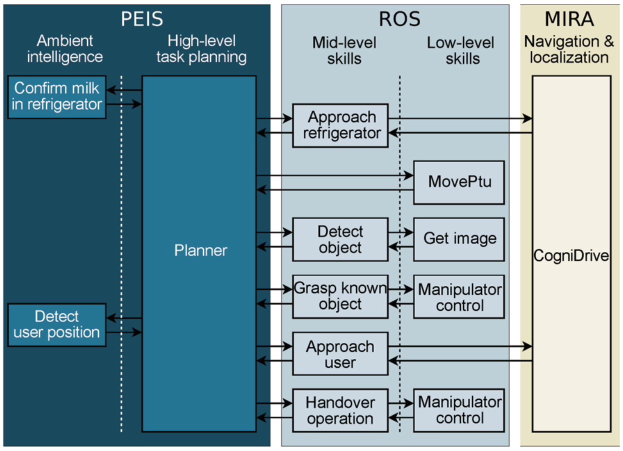


Figure 7. Example sequence diagram for the bring-object service. Following the user request ("bring me milk"), the planner first checks the CAM module to find the position of the selected object, and then plans and calls the corresponding services on the domestic robot. In this case, the two drive commands (first to the refrigerator, and then back to the user) are handled by the MIRA/CogniDrive module, while perception and arm motions are handled by ROS.

These skills are implemented in turn on the third layer by combinations of interacting ROS nodes. Object grasping and manipulation is managed by the MoveIt! framework, which interfaces to the perception modules for collision-aware and self-filtered arm motion planning. Custom ROS nodes are used to control the Jaco hand for grasping. A dedicated supervisor ROS node manages the scheduling of ongoing services, and provides feedback about task and subtask progress to the PEIS layer and the user interface.

The fourth level is made up of the different sensor and actuator drivers, which in turn interface to the actual hardware devices. Robot localization and navigation is performed by the MIRA/CogniDrive software from Metralabs, which is tuned for the Scitos G5 platform and was found to perform much better than the common ROS navigation_stack.

4.2 ROS

Modeling a new robot for ROS begins with the URDF robot model [30], which describes the geometry and kinematics structure of the robot, including all joints and wheels as well as the sensors and actuators. Suitable ROS device drivers were also available for most components, including the laser scanners, FireWire cameras, and the Xtion RGB-D sensor.

4.3 PEIS-ROS interface

The main purpose of the PEIS-ROS interface is a clear encapsulation and mapping of the implemented robot skills to the PEIS tuple space, where information is stored in pairs of keys and payload data. The PEIS middleware receives service requests from the users, keeps the semantic information about tasks and objects, and plans coordinated action sequences for the different robots.

Because most of the robot actions take several seconds or even minutes to complete, the PEIS-ROS layer must support asynchronous service requests with regular feedback during skill execution. Our interface is based on a hierarchy of C++ classes called *exekutors*, one for every robot skill, which provide a ROS actionlib [31] interface to the PEIS network. Each *exekutor* subscribes to the PEIS network and is configured to monitor a set of specific target tuples. When the target tuple changes, the goal function is called with the tuple payload as the parameters, and service execution is started. While active, the *exekutor* class provides periodic status and feedback messages to PEIS, until the service is completed.

4.4 Perception

The design of the multi-modal perception system for the domestic robot has been driven by the different manipulation scenarios. To grasp and manipulate an object, the existence of the object must be detected, along with its position and orientation with respect to the base coordinate system of the robot. In our scenarios, three kinds of objects are relevant:

- Box-shaped household objects (e.g., cereal box, milk carton, instant-coffee package).
- Cylindrical household objects (e.g., bottle, cup, soda pop can).
- Special-purpose buckets and other objects.

We have evaluated and implemented different algorithms for these objects, managed by our Visionhub ROS node. Figure 8 shows the detailed structure and integration of the perception system, and Figure 9 shows a typical recognition result.

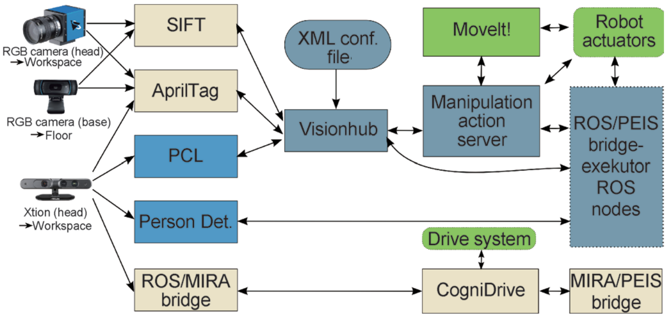
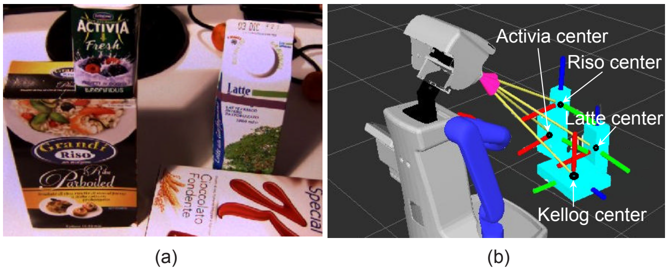


Figure 8. Overview of the multi-modal perception pipeline. The data from the cameras and the Xtion RGB-D sensor is forwarded to the SIFT-based recognition of known objects and a marker-based pose-recognition algorithm. Depth images and point-cloud data from the Xtion sensor are processed using the tabletop_object_recognition stack to find clusters that correspond to (graspable) objects. The recognition results of the different pipelines are then fed into the central Visionhub node, which performs data fusion and outputs a list of detected objects, together with the object pose information and covariance estimates. Point-cloud data is also forwarded to the person-detection modules and CogniDrive for 3D-obstacle avoidance while driving.

The SIFT-algorithm can reliably detect box-shaped objects [32], as long as at least one box surface provides a sufficient amount of optical features. It is necessary to provide a reference image of each relevant surface as well as the exact dimensions of the object. The full 6D pose of the object can then be reconstructed based on the camera calibration data and the dimensions of the reference images.

Cylindrical objects are best detected using the 3D point-cloud from the XtionPro camera. Since such an object is rotationally symmetric, only two of the three degrees of freedom of the orientation can be detected; however, due to the symmetry, side-grasps can be applied from an arbitrary angle.



(a) (b)

Figure 9. Object perception in a cluttered environment. (a) Original robot camera image showing several boxes on a kitchen table. Note that the objects overlap and are only partially visible. (b) Visualization of the robot together with the recognized graspable objects in the ROS RViz tool. For every detected object, the object name, shape, and the full 6-DOF pose (position and orientation) of the object center are calculated and published on ROS messages. In the example scene, all four boxes have been detected correctly by the Visionhub node, and the object shapes (cyan boxes) and object poses (red, green, and blue axes) are visualized.

In addition to common household objects, special-purpose boxes and buckets are defined for the shopping, laundry, and garbage scenarios. These objects have been designed with handles suited for the gripper of the Jaco arm (Figure 10), while AprilTags [33] fiducial markers are used for robust detection and accurate pose estimation. This choice has the advantage that only a small marker and not the whole object must be in the field of view of the camera. Object grasp positions are specified in relation to the marker location, and can also be learned using the joystick.

The Visionhub node acts as the common interface between the different nodes for image processing (AprilTags, SIFT, point-cloud) and the manipulation and grasp-planning nodes. It provides a clean abstraction of the high-level task (grasping an object) and hides the low-level details of the underlying object-detection process. The Visionhub XML configuration file includes the following data:

- Dimensions of the bounding box.
- Surfaces (image files) and their exact position.
- AprilTag markers and their size and position.
- Information on grasps (grasp-points maximum force).

The node can also interface to an ontology or to the PEIS context-awareness module with semantic information about objects, their usage, and how to grasp them.

5 Experiments and results

During 2013 and 2014, the Robot-Era system and services were tested in a large experimental test with elderly users (35 persons in Peccioli, and 35 in Orebro; see Figure 11). Every test user was asked to test and evaluate each of the 11 services implemented at that time, using the tablet and speech interface to interact with the robots. The users evaluated each service for usability, acceptability, and perceived performance. The learning curve for the user interface had a significant impact, and the first services tested suffered from this.

Figure 12 shows example usability and acceptability results based on the SUS (system usability scale) [34] analysis of the user questionnaires. The SUS method combines positively and negatively worded questions, and maps the replies into numbers ranged from 0–100. To summarize the results, we also applied the following classification [35]:

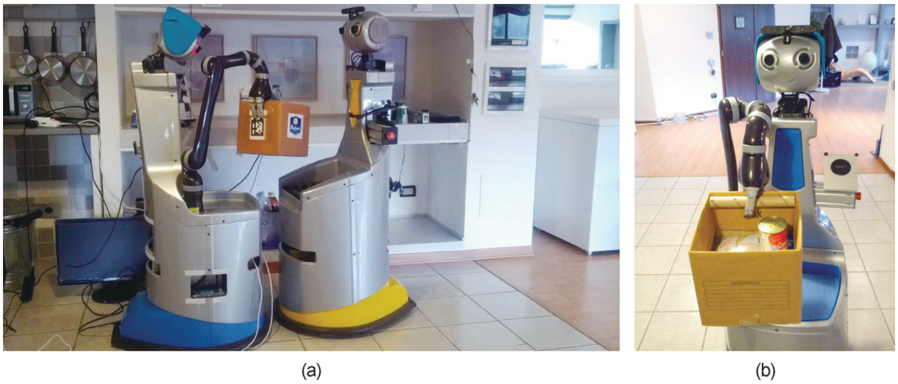

(a) (b)

Figure 10. Object exchange between the domestic and the condominium robots. (a) AprilTag markers are used on the box; (b) the round handle inside the box improves grasp stability for the Jaco hand.

- 0–64 points: not usable;
- 65–84 points: usable;
- 85–100 points: excellent.

The detailed analysis of the experiments has been published as a project report [36]. For most of the services, no significant correlations were found regarding sex, education level, or wealth of the test persons. While the same hardware and software was used in Italy and Sweden, there were slight differences in overall scores and evaluation.

All feedback from the users as well as video recordings and experiences (e.g., crashes) from the experiment runs were analyzed carefully [37]. This analysis resulted in a list of changes to the services and important robot and system updates:

- In general, users preferred the speech interface over the tablet, despite the need to carry a microphone. One interesting observation is that the text-to-speech system on the domestic robot was actually too good, so that users expected that they could simply talk to the robot. As a result, the speech-command interface was completely redesigned, switching grammar and commands depending on context.
- Several test persons criticized the size and appearance of the domestic robot. The cover was redesigned accordingly, using better materials and giving the robot a more slender look (Figure 3 shows both earlier and later models).
- Hardware changes for the robot included an updated arm-mount position, a larger object-transportation tray, and improved on-board computer performance.
- Several tests suffered from performance issues on the network and the PEIS middleware. These problems were identified and the software was improved.
- Perception of unknown objects was found to be too unreliable. Visual markers and known objects will be used in future experiments to improve robustness.

All change items were addressed and implemented, so that the system is now ready for the upcoming second experimental loop. Two test series will again be performed in our prototype apartments, but this time the users will be alone with the robots, and researchers will not help or re-start the robots if problems occur. The final test will take place in a third ambient assisted living apartment in Ancona (Italy), where recently recovered hospital patients will be expected to use the system without any help from developers at all.

6 Summary

In this paper, we outlined an AAL architecture that targets integrated robotic services for elderly users spanning indoor, residential, and outdoor spaces. We motivated the hardware design and the software architecture of the domestic robot, an affordable indoor-service robot. Our software encapsulates the robot functionality in a layered hierarchy of robot services. Advanced perception and manipulation functions of the robot are built from a large number of existing ROS software stacks. The system was tested during 2013 and 2014 in a large field test with 70 elderly users in Italy and Sweden, and the usability and acceptability scores for the robot and the overall system are encouraging. Several improvements were made to the robot as a result of the tests, and additional manipulation and cleaning

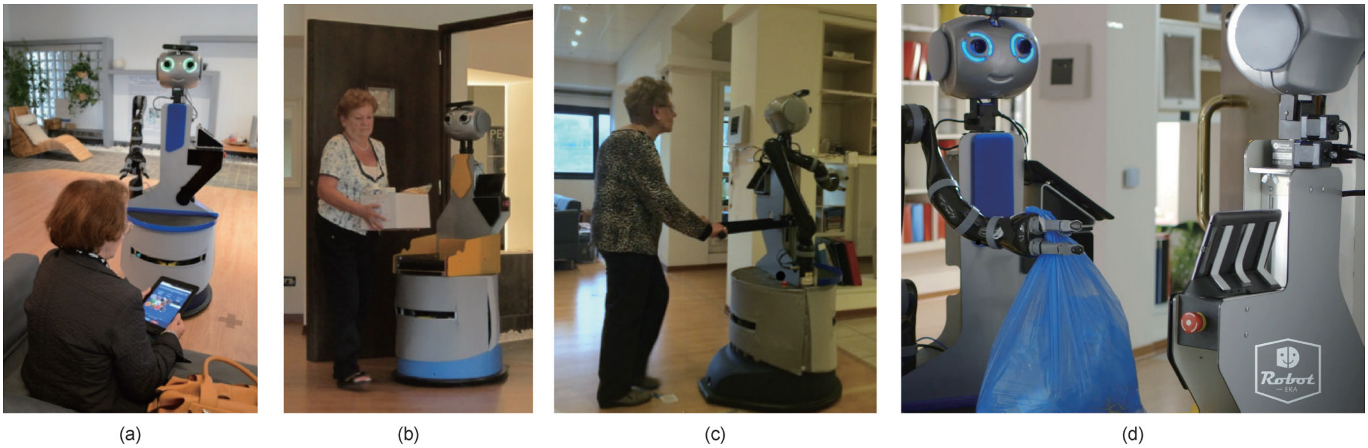

(a) (b) (c) (d)

Figure 11. Photos from the first experimental loop. (a) Tablet-based user interface; (b) condominium robot; (c) indoor walking support; (d) garbage exchange between domestic and condominium robots.

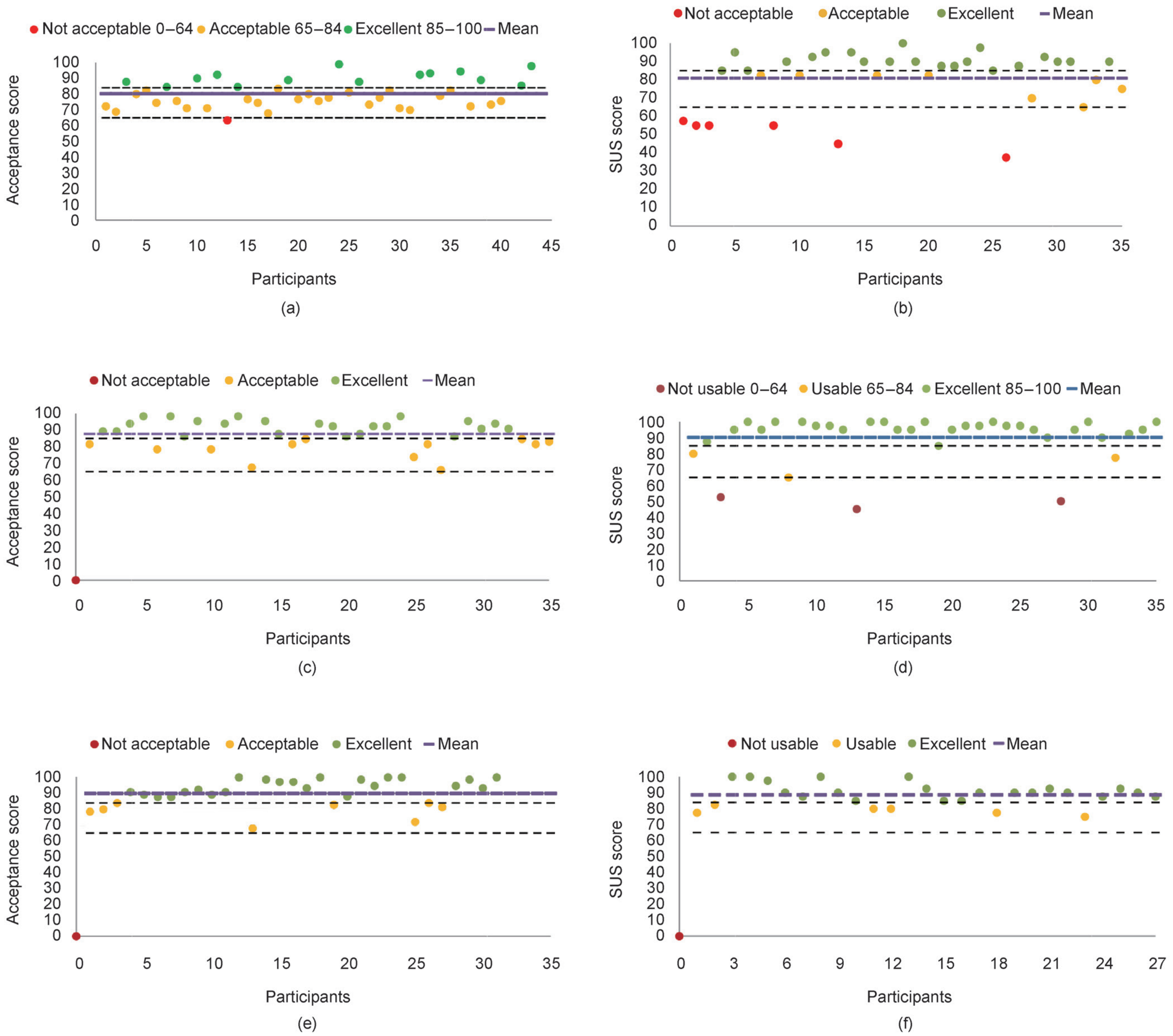


Figure 12. Typical results from the first large-scale experimental test of the Robot-Era system. The usability and acceptability of the three robots and the services were analyzed based on questionnaires (using the SUS score) and video analysis of the experiments. Overall scores are promising, despite bugs and problems during certain runs of the experiments. Scores of 65 and 85 points were used to split the classes. (a) Acceptance of DORO appearance; (b) usability of "shop and drug delivery service"; (c) acceptance of "shop and drug delivery service"; (d) usability of garbage collection; (e) acceptance of garbage collection; (f) usability of indoor walking support.

tasks will be tested in the upcoming second large field test.

Acknowledgements

This work was partially supported by the European Commission in project Robot-Era under contract FP7-288899. Visit the project website at: http://www.robot-era.eu/

Compliance with ethics guidelines

Norman Hendrich, Hannes Bistry, and Jianwei Zhang declare that they have no conflict of interest or financial conflicts to disclose.

References

1. I. Conrad, S. Glende, L. Krezdorn, L. Trieste, G. Turchetti. D9.4, Second report on services, business and marketing models for Robot-Era services, project report, 2015, www.robot-era.eu
2. F. Cavallo, M. Aquilano, M. C. Carrozza, P. Dario. Robot-era project: The vision of 3D service robotics. *Gerontechnology*, 2012, 11(2): 364
3. F. Marcellini, et al. Report on the robotic services analysis with respect to elderly users, project report, 2012, www.robot-era.eu
4. N. J. Nilsson. *Shakey the Robot* (Technical Note 323). Menlo Park, California: SRI International, Artificial Intelligence Center, 1984
5. R. Brooks. A robust layered control system for a mobile robot. *IEEE J. Robot. Autom.*, 1986, 2(1): 14–23
6. T. H. J. Collett, B. A. MacDonald, B. P. Gerkey. Player 2.0: Toward a practical robot programming framework. In: *Proceedings of Australasian Conference on Robotics and Automation (ACRA 05)*. IEEE, 2005: 1–9
7. G. Metta, P. Fitzpatrick, L. Natale. YARP: Yet another robot platform. *Int. J. Adv. Robot. Syst.*, 2006, 3(1): 43–48
8. M. Quigley, et al. ROS: An open-source Robot Operating System. In: *International Conference on Robotics and Automation (ICRA) Workshop on Open-*

Source Software, 2009

9. E. Einhorn, T. Langner, R. Stricker, C. Martin, H. M. Gross. MIRA-middleware for robotic applications. In: *Proceedings of 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2012)*, 2012: 2591–2598
10. R. D. Schraft, J. Neugebauer, C. Schaeffer, T. May. Care-O-bot®: Ein technisches Hilfssystem für unterstützungs- und pflegebedürftige Personen im häuslichen Bereich. In: H. Wörn, R. Dillmann, D. Henrich, eds. *Autonome Mobile Systeme 14*. Berlin, Heidelberg: Springer, 1998: 234–244
11. M. Hans, B. Graf. Robotic home assistant Care-O-bot II. In: E. Prassler, et al., eds. *Advances in Human-Robot Interaction*. Berlin, Heidelberg: Springer, 2004: 371–384
12. C. Parlitz, M. Hägele, P. Klein, J. Seifert, K. Dautenhahn. Caro-O-bot 3—Rationale for human-robot interaction design. In: *Proceedings of 39th International Symposium on Robotics (ISR)*, 2008: 275–280
13. M. Hans, W. Baum. Concept of a hybrid architecture for Care-O-bot. In: *Proceedings of 10th IEEE International Workshop on Robot and Human Interactive Communication*. IEEE, 2001: 407–411
14. T. Morita, H. Iwata, S. Sugano. Development of human symbiotic robot: WENDY. In: *Proceedings of 1999 IEEE International Conference on Robotics and Automation*, vol. 4. IEEE, 1999: 3183–3188
15. Willow Garage Inc. Robot for research and innovation. https://www.willowgarage.com/pages/pr2/overview
16. S. Cousins. ROS on the PR2 [ROS Topics]. *Robot. Autom. Mag., IEEE*, 2010, 17(3): 23–25
17. A. Hermann, et al. Hardware and software architecture of the bimanual mobile manipulation robot HoLLiE and its actuated upper body. In: *Proceedings of 2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*. IEEE, 2013: 286–292
18. MetraLabs GmbH. Scitos G5 mobile platform. metralabs.com/index.php?option=com_content&view=article&id=70&Itemid=64
19. F. Cavallo. Improving domiciliary robotic services by integrating the ASTRO robot in an AmI infrastructure In: F. Röhrbein, G. Veiga, C. Natale, eds. *Gearing Up and Accelerating Cross—Fertilization between Academic and Industrial Robotics Research in Europe*. Springer, 2014: 267–282
20. Schunk Gmbh & Co. KG. Powerball lightweight arm LWA 4P. http://mobile.schunk-microsite.com/en/produkte/produkte/powerball-lightweight-arm-lwa-4p.html
21. Kinova Robotics, Kinova Jaco Research Edition. kinovarobotics.com/products/jaco-researchedition/
22. Schunk Gmbh & Co. KG. Dextrous lightweight arm LWA 4D. http://mobile.schunk-microsite.com/en/produkte/produkte/dextrous-lightweight-arm-lwa-4d.html
23. BionicRobotics GmbH. Bionic robotics: Biorob arm. http://www.bionic-robotics.de/en/products/biorob-arm.html
24. Universal Robots. UR5 arm. www.universal-robots.com/GB/Products/
25. V. Maheu, J. Frappier, P. S. Archambault, F. Routhier. Evaluation of the JACO robotic arm: Clinico-economic study for powered wheelchair users with upper-extremity disabilities. In: *Proceedings of 2011 IEEE International Conference on Rehabilitation Robotics (ICORR)*. IEEE, 2011: 1–5
26. A. Saffiotti, M. Broxvall. PEIS ecologies: Ambient intelligence meets autonomous robotics. In: *Proceedings of the International Conference on Smart Objects and Ambient Intelligence*, 2005: 277–281
27. M. Broxvall, M. Gritti, A. Saffiotti, B. S. Beo, Y. J. Cho. PEIS ecology: Integrating robots into smart environments. In: *Proceedings of 2006 IEEE International Conference on Robotics and Automation* (*ICRA*), 2006: 212–218
28. M. Di Rocco, et al. A planner for ambient assisted living: From high-level reasoning to low-level robot execution and back. In: *AAAI Spring Symposium "Qualitative Representations for Robots"*, 2014: 10–17
29. N. Hendrich, H. Bistry, B. Adler, J. Zhang. User-driven software design for an elderly care service robot. In: *Proceedings of the 8th International Conference on Pervasive Computing Technologies for Healthcare*, 2014: 142–149
30. I. Sucan. Universal robot description format. http://wiki.ros.org/urdf
31. E. Marder-Eppstein, V. Pradeep. ROS actionlib. http://wiki.ros.org/actionlib
32. D. G. Lowe. Object recognition from local scale-invariant features. In: *The Proceedings of the Seventh IEEE International Conference on Computer Vision*, vol. 2. IEEE, 1999: 1150–1157
33. E. Olson. AprilTag: A robust and flexible visual fiducial system. In: *Proceedings of 2011 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2011: 3400–3407
34. J. R. Lewis, J. Sauro. The factor structure of the system usability scale. In: M. Kurosu, ed. *Human Centered Design*. Berlin, Heidelberg: Springer, 2009: 94–103
35. S. McLellan, A. Muddimer, S. C. Peres. The effect of experience on System Usability Scale ratings. *J. Usability Stud.*, 2012, 7(2): 56–67
36. F. Cavallo, et al. D8.2 Report on results obtained in the first cycle of the Robot-Era experimentation, project report, 2014. www.robot-era.eu
37. F. Pecora, et al. D2.8 Second report on the S/T requirements of the Robot-Era components, project report, 2015. www.robot-era.eu