Robot Companion for Domestic Health Assistance: Implementation, Test and Case Study under Everyday Conditions in Private Apartments*

Horst-Michael Gross[1], Steffen Mueller[1], Christof Schroeter[1], Michael Volkhardt[1],
Andrea Scheidig[1], Klaus Debes[1], Katja Richter[2] and Nicola Doering[2]

Abstract— This paper presents the implementation and evaluation results of the German research project SERROGA (2012 till mid 2015), which aimed at developing a robot companion for domestic health assistance for older people that helps keeping them physically and mentally fit to remain living independently in their own homes for as long as possible. The paper gives an overview of the developed companion robot, its system architecture, and essential skills, behaviors, and services required for a robotic health assistant. Moreover, it presents a new approach allowing a quantitative description and assessment of the navigation complexity of apartments to make them objectively comparable for function tests under real-life conditions. Based on this approach, the results of function tests executed in 12 apartments of project staff and seniors are described. Furthermore, the paper presents findings of a case study conducted with nine seniors (aged 68-92) in their own homes, investigating both instrumental and social-emotional functions of a robotic health assistant. The robot accompanied the seniors in their homes for up to three days assisting with tasks of their daily schedule and health care, without any supervising person being present on-site. Results revealed that the seniors appreciated the robot's health-related instrumental functions and even built emotional bonds with it.

I. INTRODUCTION

Assistive robot companions promise high potential for improving the life of older people, in particular supporting a self-determined life-style even at higher age. In numerous user studies carried out in recent years worldwide, thousands of potential end-users (older people, their families, and caregivers) have been interviewed about their individual needs and priorities in assistive services that could be provided by home robot companions. Considerable acceptance was found for a "healthcare robot" in the broader sense that supports physical and mental health and wellbeing, for example by providing health monitoring, giving reminders for medication or appointments, motivating for health provisions, helping to keep in touch with friends and relatives, and serving the role of a fitness coach (for an overview, see [1]). These study results were the motivation for the German research project SERROGA (SERvice RObotics for Gesundheits (Health) Assistance) that was running from 2012 till mid 2015 and aimed at developing robot-based health assistance services for older

Fig. 1: One of our volunteers in her apartment in the AWO residential complex in Erfurt (Germany) during measuring vital parameters with the robot "Max".

people that help keeping them physically and mentally fit to remain living in their own homes for as long as possible. Already in the preceding project CompanionAble [2], [3], user studies revealed that the capability of a companion robot to actively move to its user and give reminders or suggestions was exactly what many of the older people wanted, and what they could not see in comparable quality realized by any other non-robotic smart solution, like tablets or PCs. The initiative of a robot and its proactive behavior were the most valued aspects of robotic assistance. Against this backdrop, in SERROGA an improved companion robot for assisting the user's mental and physical health should be developed playing two roles - as a "Communication, reminder, and emergency assistant" (a kind of secretary) and a "Physical activity motivator" (a kind of fitness coach). To this end, a spectrum of robotic functionalities and services required for a robot-based health assistant suitable for everyday use had to be developed and thoroughly tested under real-life conditions in the users' private apartments. Moreover, the usability, usefulness, and added value of this robot assistant for older people living alone in their home should be evaluated answering the question whether an assistive robot developed with a commercial perspective in mind could already act autonomously in private apartments to provide useful and enjoyable services.

In the following, Sec. II presents related work in the field of socially assistive robotics for domestic health assistance, while Sec. III introduces the robot platform "Max" developed in the SERROGA project. Sec. IV gives an overview of the robot's functional system architecture and essential robotic skills, behaviors, and services required for a robotic health assistant. Sec. V presents a novel quantitative approach

to make domestic environments objectively comparable for robot function tests under everyday conditions and describes the results of comprehensive function tests executed in private apartments of project staff members and older test users. Sec. VI presents the findings of a case study conducted with nine seniors in their own homes, and Sec. VII discusses implications for future robot development and research.

II. RELATED WORK IN SOCIALLY ASSISTIVE ROBOTICS FOR DOMESTIC HEALTH ASSISTANCE

A comprehensive systematization considering numerous facets of healthcare robotics is given in [1]. There, a health-care robot is defined as "*a robot with the aim of promoting or monitoring health, assisting with tasks that are difficult to perform due to health problems or preventing further health decline. Health in this sense encompasses not just physical but mental, emotional and psychosocial problems. Healthcare robots can have many different functions and can be categorised as either rehabilitation robots or social robots*" [1]. As the SERROGA project was clearly focussed on socially assistive aspect of healthcare robotics, the following definition describes it best: "*Social robots can be categorized into service type robots or companionship robots. Service type robots are assistive devices and are designed to support people living independently by assisting with mobility, completing household tasks, and monitoring health and safety. ... Companion robots do not assist the user in performing any task but aim to improve quality of life by acting as a companion. Some robots provide both companionship and assistance*" [1]. The SERROGA assistant presented here can also be assigned to both directions. A good overview of the relevant robotic healthcare solutions developed till mid 2014 is given in [1] as well.

From the robotics perspective to this field two directions can be identified: some research projects rely on developing and using the best possible hardware and range of features, to a large extent disregarding any serious financial constraints. While this is a valid approach, in particular when focusing on developing new and sophisticated demonstrable assistive functions, it leads to mere prototype applications with no real perspective to an end-user market, because too high prime and operational costs are the essential market entry barriers. Typical examples here are the well-known service robot Care-O-Bot [4] or the very advanced PR2 [5] used in diverse research projects dealing with healthcare assistance. On the other hand, a number of assistive robots for domestic use are already available on the market, however, many of them include only very limited autonomy and assistive functions. A typical example are the numerous "light-weight" robot platforms on the market providing mainly telepresence functionality, as for example Giraff [6] or the like. In between those two approaches, there exists a whole bouquet of mainly research-oriented projects trying to develop socially assistive robot companions for domestic use and healthcare. Some of these robots were already used in exploratory pilot tests in nursing homes to see how the older people engage with the robot, but only very rarely in the users' private homes.
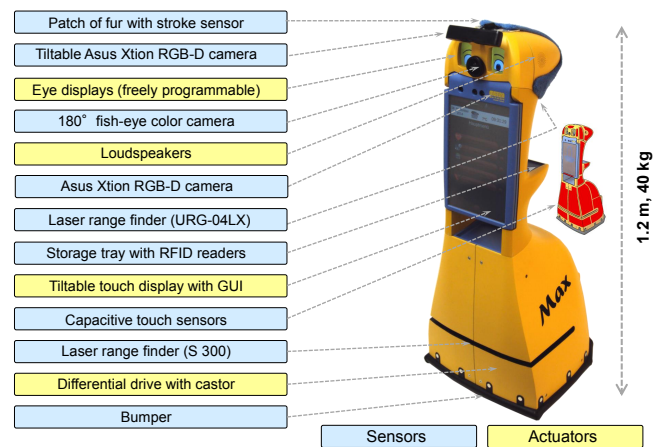

Fig. 2: Companion robot "Max" with its main equipment for environment perception, navigation, and HRI.

Therefore, [1] states: "*Currently robots have not extensively been trialled in the homes of older people, so it is not known how realistically the technology will fit into daily life and whether it will have benefits*". This is consistent with our observation, that user studies with companion-type assistive robots that completely autonomously operate in private homes of their users and assist them in their daily routines over several days without the presence of experts are still a very rare exception, and studies focusing on the long-term use of such robot companions are completely lacking.

III. COMPANION ROBOT "MAX"

The companion robot "Max" that was developed in SER-ROGA is based on the mobile robot platform SCITOS G3 (Fig. 2). A detailed description of this platform is given in [2], [3], [10]. Remarkable hardware features include:

- a small footprint of approx. 50 cm radius and relatively low height of 120 cm,
- a differential drive using two driven wheels and one castor, enabling to traverse thresholds up to 1.5 cm,
- a battery providing capacity for 10 h of operation,
- an autonomous charging system which provides a direct 220 Volt connection via a secure plug,
- a tiltable touch screen that can be adjusted to the suitable interaction angle of a sitting or standing user.

"Max" is a continued development specifically taking into account the requirements of a companion robot for domestic use. For more robust collision avoidance, user perception, and environment monitoring, the robot was equipped with additional sensors: a 45° tilted laser scanner in backward direction from beneath the head, an Asus RGB-D camera installed in the touch screen, a tiltable Asus depth camera on the head, and a 180° field-of-view RGB camera (see Fig. 2).

For the specific requirements of the SERROGA project to a companion robot that is living together with its user in a long-term interaction situation and allowing for an adaptation to the user's needs and preferences by learning, we integrated two new input modalities. Firstly, for socializing and getting

feedback on the user's satisfaction with the robot's interaction or navigation behavior, we developed a new haptic user interface, a "stroke sensor" in form of a patch of fur on the robot's head, like hair. This sensor is able to perceive and distinguish diverse stroke activities of the user (e.g. to stroke, tickle, or slap the robot's head) which cause appropriate reactions of the robot (e.g. purring, crying, etc.) [7] and can be used to change its behavior by learning. Secondly, for fine positioning the robot by its user during interaction, a new low-cost whole-body touch interaction using capacitive touch sensors was developed and integrated on the robot (Fig. 2, right) [8]. This allows a touch-based motion control of the robot by "laying hands on" the robot's casing.

Moreover, an improved eye display concept was developed in SERROGA. Now the eye displays can be used for expressing the robot's internal states or emotions (e.g. sleeping, listening, being surprised or bored) or following the user's movements with the eyes. This feature is very helpful for intuitive HRI and for getting and staying in contact with the user. To enable the user to initiate selected robot activities, as e.g. user search or drive to predefined places in the home, a handheld remote control device was added. That way the user can call the robot to his resting place or send it to a number of other places in the home. The navigation there then occurs completely autonomously.

A robot-based health assistant needs the capability to measure diverse health parameters of its user, like the pulse rate or blood oxygen saturation to make a suggestion if a physical exercise with the user should be initiated or not according to his/her current circulation state. Therefore, additional sensors and measurement methods have been integrated on the robot: a video-based pulse rate monitor [9] and a blood oxygen saturation meter with tethered finger clip device. The RFID-tagged finger clip is carried in the storage tray on the robot's backside, and its use is described by the robot.

IV. FUNCTIONAL SYSTEM ARCHITECTURE

The system architecture is characterized by a clear separation of the robot-specific methods and skills from the application itself resulting in a layered system architecture (Fig. 3). In this architecture, the low-level sensor information is processed in the lowest level, the *Robot Skills* layer, which covers the whole spectrum of robotic-specific navigation and HRI skills which are working independently in parallel. In the layer above the skills, there are modules representing exclusively working *Navigation Behaviors* that make use of the skills in individual control loops for accomplishing the different user-centered navigation behaviors of the robot. Here, for example, the "User searching" or "User following" are realized, necessary for direct interaction as well as passive user observation. At the layer above, all *Health-related Services* necessary for implementing both *Roles* in the topmost layer, the "Secretary" and the "Fitness Coach", are located. The services' exclusive access to the *Navigation behaviors* and the user-frontend is coordinated by the *Dialog manager and Behavior controller* in the middle, which also ensure self-sustainment and user-safety.
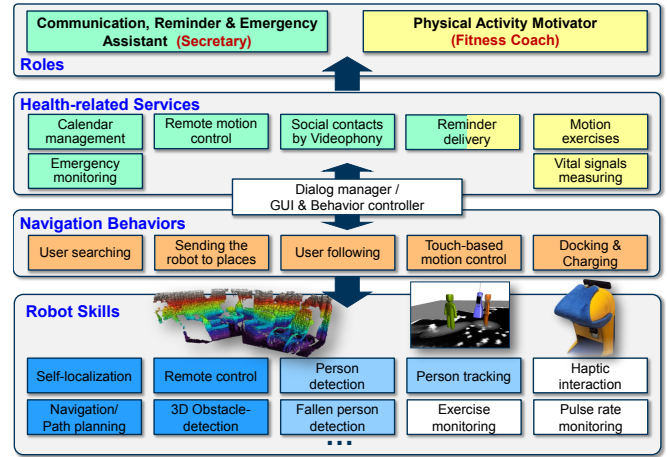

Fig. 3: System architecture with the two intended *Roles* in the topmost layer which are realized by a set of *Health-related Services* in the layer below. The services (for "Secretary" - green; for "Fitness coach" - yellow) are activating *Navigation Behaviors* (orange) and accessing *Robot skills* coordinated by the *Dialog manager and Behavior controller*. In the bottommost layer, advanced *Robot Skills* (navigation - blue, user perception - light blue; HRI - white) are implemented, that use specific hardware components.

The complete architecture is implemented using MIRA [11], a middleware developed for robotic applications, providing a framework suited to the requirements of distributed real-time software. Since a complete description of all services, behaviors, and skills of the robot companion required for a user-centered navigation and multi-modal HRI would go beyond the scope of this paper, only a tabular overview of the whole functionality with references to previous own publications is given in Table I.

V. FUNCTION TESTS AND BENCHMARKING IN STAFF MEMBER AND SENIOR APARTMENTS

The most important requirements for an active and joyful use of a robot companion at home are a robust and stable running system that can ensure uninterrupted interaction over hours and days without the need for supervising persons being present on-site, and an acceptable spectrum of really helpful and valuable services and assistive technologies. Therefore, in preparation of the upcoming user trials a series of function tests and benchmarkings was conducted from January to March 2015 in order to ensure a robust autonomous operation over a whole day and longer. To get a variety of environmental conditions, all function test were first performed in our living lab (LivLab) which was furnished like a real senior apartment, followed by tests in the private apartments of the project staff (Ap.PS1 - Ap.PS3), and then by tests in the private apartments of the elderly study participants described in Sec. VI (Ap.S1 - Ap.S9). Due to the physical conditions of the seniors (see Table VII), the function tests there were limited to 2-3 hours, while extensive tests in the staff apartments took 8 hours each.

TABLE I: Developed skills, navigation behaviors, and selected services with references to previous own publications.

Robot skills	Brief description	Ref.
Person detection	Set of asynchronous detection modules (improved 2D laser-based leg detector, face detector, motion detector, upper-body shape detector) for people standing, sitting or walking around	[12], [13]
Person tracking	Real-time people tracking system that filters asynchronous, multi-modal detections using a 7D-Kalman filter for each person	[14]
Fallen person detection	Depth image-based approach to detect fallen people on the ground even under occlusions (not yet available for user trails)	[15]
Self-localization	Usage of aMCL with 2D occupancy grid maps and 3D NDT maps	-
Navigation / Path planning	Hierarchical approach combining metric path planning (E*) at tactical level with local path planning (DWA with tailored objectives) at reactive level	[16]
3D obstacle detection	Usage of advanced NDT maps for 3D modeling of the robot's local surroundings to enable a usage in dynamic environments with moving obstacles	[17]
Haptic user interface	Low-cost whole-body touch interaction for manual robot motion control using capacitive touch sensors; new haptic stroke sensor in form of a patch of fur on the robot's head to perceive haptic rewards	[8] [7]
Pulse rate monitoring	Non-contact estimation of human pulse rate from video sequences of the face	[9]
Exercise monitoring	Kinect-based monitoring of motion exercises (not yet available for user trails)	-

Behaviors & Services	Brief description	Ref.
User searching	Searching a person by driving through the apartment and verifying hypotheses of the person detector	[18]
User following	Dynamic re-planning (E*) to follow a moving hypothesis of the person tracker	[16]
Docking & charging	Docking and charging concept allowing a direct connection to the line voltage of the home through a secure plug as used for water boilers	[2], [3]
Touch-based motion control	Manual robot motion control considering constraints of differential drive and obstacle avoidance	[7]
Dialog manager, GUI	Frame-based dialog modeling approach for user-adaptive interaction behavior	[19], [20]
Motion exercises	Spectrum of age-appropriate exercises for standing or sitting users demonstrated on the touch screen	-

A. Quantitative Approach to Make Apartments Comparable

In most function and user tests conducted in living labs and real apartments published in recent years, the environmental conditions and the spatial complexity of the test apartments regarding their size, furnishing, free space, constrictions, illumination conditions, etc. are mostly described at a qualitative level. Often only subjective statements and qualitative assessments, as for example "the apartment was relatively cramped", "areas with a lot of furniture and narrow corridors", or "poor lighting conditions", are used to describe the experimental situation. This makes a benchmarking of the different robot platforms and their algorithms and a comparison of the results achieved in different operation areas almost impossible. Therefore, as one of the contributions of this paper we developed a simple but very effective approach to quantify and objectively compare the conditions of the various environments using i) measures describing the geometry of the apartments and thus their spatial complexity and ii) a visualization of the illumination conditions in the apartments. Both aspects are critical constraints that have strong influence on the navigation and interaction performance of a mobile robot companion. Based on the 2D occupancy gridmaps of all apartments learned beforehand and used for navigation, the layouts of these apartments have been reconstructed (see

TABLE II: Measures for describing the navigation complexity of apartments and making them comparable.

Name	Total area A [m^2]	Free space F [m^2]	Nav. area N [m^2]	Clearance $\frac{N}{A}$	Shape factor S	Path length L [m]	Passage width [m]
LivLab	50.3	32.8	17.5	0.35	14.4	44.3	0.98
Ap.PS1	47.3	27.8	12.8	0.27	17.2	46.3	0.91
Ap.PS2	70.7	34.2	16.7	0.24	16.3	48.2	0.80
Ap.PS3	73.8	43.7	23.0	0.31	17.1	58.3	0.97
Ap.S1	35.5	18.5	9.5	0.27	11.3	27.1	0.86
Ap.S2	32.2	15.9	7.6	0.24	11.4	20.5	0.78
Ap.S3	30.0	16.2	6.9	0.23	13.6	27.0	0.75
Ap.S4	31.4	14.5	7.7	0.25	9.9	18.0	0.94
Ap.S5	24.6	13.8	6.1	0.25	10.0	15.6	0.80
Ap.S6	21.6	11.4	4.7	0.22	12.1	15.9	0.81
Ap.S7	46.2	21.6	11.3	0.24	11.6	24.8	0.89
Ap.S8	29.6	12.2	6.3	0.21	9.1	14.1	0.95
Ap.S9	29.7	15.2	7.7	0.26	10.3	18.1	0.95

Fig. 4). Then, for each apartment the following parameters were determined:

- Total floor area A: total area of all accessible rooms
- Free space F: area A minus area for furniture
- Navigable area N: free space F minus an obstacle margin of the robot's radius
- *Clearance N/A*: ratio of navigable area N and total area A as indicator of how "roomy" or "crammed" an apartment is
- *Shape factor S*: ratio of the length of the outer contour and square root of the navigable area N as measure of convexity or jaggedness of an apartment
- *Path length L* along the skeleton of the navigable area: indicates the overall path length of possible ways to drive in the apartment, this value is relevant for the time required for exploration and user search
- *Mean passage width W* along the skeleton: indicates the average distance to the next obstacle along the skeleton

Table II shows a comparison of the spatial characteristics and the extracted complexity measures for our living lab and all staff and senior apartments used during the function tests. The *shape factor S* as measure of jaggedness confirms, that the complexity of our living lab is nearly comparable to that of a spacious apartment. Also the *mean passage width* is in the range of a large apartment, even if the greater *clearance* shows that the obstacle density in real senior apartments seems to be higher (lower clearance). Nevertheless, these differences are small enough that the benchmarking results under lab and staff apartment conditions should be transferable to the apartments of the elderly trial participants. The table also reveals that senior apartments typically are smaller which is why the robot has shorter distances to drive (lower *path length L*). Additionally, the apartments of the seniors are usually optimized for use of walking aids (visible by a mean passage width W of 0.86 m) offering sufficient space for navigating a robot with a diameter of 0.5 m.

Illumination Conditions: Besides the geometrical characteristics, the illumination of the environment is a critical constraint, since the user-centered navigation behaviors *User searching* and *User following* rely on the proper detection and tracking of the interaction partner in the surroundings of the robot. The person tracker on the one hand is based on a contour-based detection in the 180°-fish eye image. High contrast due to backlighting in front of windows can easily reach the limits of the camera's dynamic range and, therefore,

Fig. 4: Layout of our test apartments: the robot operated in the colored regions only; obstacles are restricting the operational area for the robot additionally; red color is indicating areas with incidence of daylight, blue of artificial light.

reduce the accuracy of the person tracker. On the other hand, the second cue for tracking people is the laser range scan, which is detecting leg-shaped objects. In our tests, this second cue usually could support tracking sufficiently when camera images got worse. The same holds in the dark, where exposure had to be increased up to $1/20$ sec, which causes motion blur if the robot turns. Fig. 4 shows a subset of the apartments used for the function tests - our living lab, one project staff apartment and three senior apartments. It is shown that in every apartment there are regions only lighted by artificial light sources (marked blue) and also critical regions where daylight can blind the robot.

B. Results of Selected Function Tests and Benchmarks

1) Benchmarking Autonomous Navigation to Places: Autonomous navigation to a given place in the apartment is one of the most essential capabilities of a companion robot, regardless, if the goal is given by the user or internally defined for proper self-sustainment (e.g. docking to the charger). This benchmark has been conducted in two modi. First, the goals were randomly selected from a *list* of predefined places which resemble typical interaction places close to the couch or chairs, and secondly the goals were selected *randomly* within the whole navigable area N. Aspects of interest were the occurrence of collisions with obstacles which the robot could not recognize with its sensors, the average velocity, and the accuracy of reaching the desired position. Table III shows the results of this test, which has been conducted in the apartments of the project staff only. Five places had been defined in each apartment, and the robot randomly moved between them, while at the goal points the reached position of the robot was marked manually. Limiting factor during these trials was the tolerance parameter for the robot to recognize a goal position as reached. This was set to 5 cm in our case. Therefore, results are not expected to be better than this value. The remaining differences in the goal positions reflect the accuracy of the localization capabilities as a base for all other navigation algorithms. The results show that goals were successfully approached with a mean deviation of 3-7 cm and a standard deviation of 5 cm in

the worst case, which proved to be sufficient for interaction purposes. If required, the user additionally can fine position the robot by means of the touch-based manual motion control shown in Fig. 2. Besides the accuracy tests, the robot could demonstrate its robustness but also remaining weaknesses during about 7.5 km of distance traveled in the several apartments. Table IV summarizes the data of the trials. The column "Goals reached" shows the number of successful runs, while the column "Goals not reached" counts situations in which the robot could not find a path to desired places, but could resume the autonomous trials by means of selecting another goal. Reasons for that were people standing in the way or goals that were randomly selected too close to obstacles that may have been moved or were perceived closer than they were actually situated in the static map for goal selection. Altogether, these situations were not critical and did not circumvent the planned autonomous long-term trials with the seniors. In contrast, the events in the most right column did. In these trials, the robot collided with obstacles it could not perceive with its sensors (horizontal laser range finder at 22 cm above ground, ASUS RGB-D camera at the forehead looking downwards, and 45° tilted laser scanner in backward direction) (see Fig. 2), or it pushed away a carpet not fixated to the floor. In these cases, manual support by the user was necessary to continue the trials. In consequence, for the user trials with the seniors very low obstacles (below 10 cm) had to be removed from the pathway of the robot, and the problematic carpets had to be removed or fixated. Additionally, the test users had to be instructed how to help the robot, if a collision takes place. The average velocity reached in the various environments does not differ significantly (see Table IV). This indicates, that there is sufficiently large free space in all apartments that the robot is not limited in its mobility.

2) Benchmarking "User Following": A second useful navigation behavior of the robot is *Following a person*. For benchmarking this behavior, three to five points were

TABLE III: Accuracy of approaching goals [in m]

Test env.	Distance to goal			Standard deviation	
	Average all trials	Average worst goals	max at all	average all trials	average worst goals
Ap.PS1	0.07	0.11	0.12	0.03	0.04
Ap.PS2	0.03	0.06	0.08	0.02	0.04
Ap.PS3	0.07	0.13	0.16	0.03	0.06

TABLE IV: Results of the autonomous navigation tests

Test env.	Goal select.	Dura-tion [min]	Driven dist.[m]	Mean veloc. [m/s]	Goals reached	Goals not reached	Crit. err.
LivLab	list	255	2600	0.25	595	0	0
LivLab	rand.	240	2500	0.26	419	17	7
Ap.PS1	list	80	589	0.23	85	4	0
Ap.PS1	rand.	72	482	0.23	126	4	0
Ap.PS2	list	47	539	0.25	59	1	0
Ap.PS3	list	52	640	0.27	49	11	5
Ap.PS3	rand	29	355	0.27	50	5	4

TABLE V: Subset of test results of "User following" behavior in staff (Ap.PSx) and senior (Ap.Sx) apartments.

Environment	Guiding User	Type of Illumination	# of Trials	Success rate	v mean (m/s)	Variance v
Ap.PS1	PS0	Daylight	21	0.95	0.24	0.08
Ap.PS1	PS0	Artificial L.	22	0.77	0.15	0.04
Ap.PS1	PS1	Daylight	5	1.00	0.19	0.07
Ap.PS2	PS2	Daylight	11	0.91	0.23	0.05
Ap.PS2	PS2	Artificial L.	6	1.00	0.18	0.03
Ap.PS3	PS0	Daylight	25	0.92	0.21	0.06
Ap.PS3	PS3	Artificial L.	22	0.82	0.21	0.06
Ap.S1	PS0	Corridor l. ON	6	1.00	0.27	0.04
Ap.S1	PS0	Corridor l. OFF	6	1.00	0.27	0.05
Ap.S1	S1	Corridor l. ON	6	1.00	0.21	0.07
Ap.S2	PS0	Table legs vis.	3	0.33	0.19	-
Ap.S2	PS0	Table legs cov.	6	1.00	0.21	0.07
Ap.S2	S2	Table legs cov.	3	0.33	0.13	-
Ap.S3	PS0	Daylight	13	0.92	0.23	0.06
Ap.S3	S3	Daylight	14	0.79	0.13	0.05
Ap.S4	PS0	Corridor l. OFF	12	0.92	0.24	0.07
Ap.S4	S4	Corridor l. ON	12	1.00	0.18	0.04
Ap.S5	PS0	Daylight	13	0.92	0.19	0.10
Ap.S5	S5	Daylight	14	0.86	0.15	0.07
Ap.S6	PS0	Daylight	12	1.00	0.20	0.07
Ap.S6	S6	Daylight	14	0.93	0.17	0.07
Ap.S7	PS0	Daylight	13	0.92	0.20	0.05
Ap.S7	S7	Daylight	12	1.00	0.17	0.03
Ap.S8	PS0	Daylight	14	0.86	0.20	0.05
Ap.S8	S8	Daylight	13	0.92	0.17	0.04
Ap.S9	PS0	Daylight	12	1.00	0.20	0.06

TABLE VI: Overview of all test runs of "User searching"

Apartm.	# of trials	success rate	Driven distance d (m)		Searching time (min)		$\overline{v}$ (m/s)	Detour factor	
			mean	max	mean	max		mean	max
Ap.PS1	15	0.73	7.5	32.6	0:54	3:53	0.10	1.6	3.6
Ap.PS2	18	0.89	13.7	34.3	1:30	3:30	0.12	2.4	9.3
Ap.PS3	21	0.76	11.2	28.2	1:10	2:43	0.13	1.6	2.9
Ap.S1	6	1.00	1.6	3.8	0:13	0:25	0.13	1.1	1.3
Ap.S2	13	1.00	1.1	5.1	0:21	1:10	0.04	1.1	1.2
Ap.S3	11	0.91	2.8	7.6	0:24	1:02	0.06	1.0	1.1
Ap.S4	14	0.93	4.9	8.1	0:39	0:59	0.10	1.1	1.2

defined in each apartment, where the tests were started and finished by the guiding person. By means of this, a reference path length could be determined, yielding to an average velocity, that was used as a base line for benchmarking the robot's following behavior. Furthermore, trials could fail, if the robot obviously lost track of the guiding person and went away searching for the user. In these trials, we also investigated the influence of daylight or artificial illumination on the velocity of the following behavior, which revealed no significant difference. Altogether, there were 397 runs of the "Following" behavior conducted by different users (project staff (PS0-PS4) or seniors (S1-S9)) shown as subset in Table V. The tests could, however, confirm a dependency on the user's guiding behavior. An experienced reference person (PS0) could guide the robot with an average velocity of 0.22 m/s in all environments. In comparison, the seniors (S1 - S9) had difficulties due to the expectations they had regarding the person perception of the robot. So, during the guiding tour they tried to come closer to the robot to avoid moving too far, if the robot did not move continuously (e.g. in narrow places). Caused by this, often free and fluid movements of the robot were prevented as the user was regarded as an obstacle that had to be avoided, causing very slow and jerky robot motions. The average guiding velocity of two of the seniors therefore only reached 0.13 m/s. A dependency of the performance from the complexity of the environment (see Sec. V-A) could not be found except for one apartment (Ap.S2), where the appearance of a table's legs distracted the person tracker yielding a significant drop in the success rate to 33%. When the table legs were covered, the success rate increased to 100% for PS0. In the other apartments, on average 90% of the test runs succeeded.

3) Benchmarking "User Searching": Finding its user standing or sitting in the apartment is another essential capability of a companion robot, which is needed to initiate an interaction. Therefore, systematic benchmarks for this behavior have also been conducted in all staff member and senior apartments. In these tests, the subjects had to go somewhere in the operational area (sitting down or standing), and

the robot started a user search from random start positions. The results are shown in Table VI. All in all, 75% of 54 runs in the project staff apartments (Ap.PS) and 95 % of the 44 runs in senior apartments (Ap.S) were successful, and the robot found the user in 1 to 1.5 minutes. Longest run was 3:53 min. Comparing the actual movement path of the robot to the shortest possible path to the user (determined from the skeleton of the navigable area N) showed that in the comparably spacious apartments of the staff members the path driven by the robot while searching the user (called detour factor) was in average 60% longer than the optimal path length. In runs that failed, the robot could not find the person, or it did not start moving at all, because it believed that the user was already directly in front of it. The apartments Ap.S1 - Ap.S4 of the seniors were significantly smaller, thus the robot very often was already close to the user and could see the person after a short drive, or the person could be seen immediately from the robot's resting position. Therefore, the success rate reached 95%, and the searching time and the detour factor were significantly lower in the senior apartments. As function tests proved that the robot can navigate autonomously and robustly in private apartments under everyday conditions, user trials could be tackled in February and March 2015.

VI. CASE STUDY IN PRIVATE SENIOR APARTMENTS

A. Case Study Design

For the user trials, an explorative case study was conducted to gain detailed, in-depth, and holistic knowledge regarding single, similar but highly individual cases. We compared those cases in order to draw a set of cross-case conclusions and at least identify similar and contrasting patterns, not to gain statistically confirmed, generalizable information. Why did we decide to conduct such a research design? It is obvious that real-life interventions with a mobile robot are quite complex. As the settings do not remain stable, there is only little control over the contemporary set of events. Therefore, an explorative case study was conducted which is best to investigate such complex everyday scenarios. A case study approach can cope with technically distinctive, complex, and highly individual situations appreciating the

TABLE VII: Case characteristics of the user trials

| Sen.	Residence	Sex	Age	Health constr.	Technol. affinity	Familiarity with robot	Presence in apartment
1	AWO	m	68	none	high	mid	1 day (06:04 h)
2	AWO	f	79	severe	mid	high	1 day (05:09 h)
3	AWO	f	86	severe	high	high	1 day (04:08 h)
4	AWO	f	72	none	mid	mid	1 day (05:44 h)
5	ARTIS	f	92	minor	high	none	2 days (09:28 h)
6	ARTIS	f	90	severe	low	none	1 day (07:16 h)
7	ARTIS	m	75	none	high	none	3 days (17:41 h)
8	ARTIS	f	80	minor	low	none	3 days (35:36 h)
9	ARTIS	m	86	minor	mid	none	3 days (28:17 h)
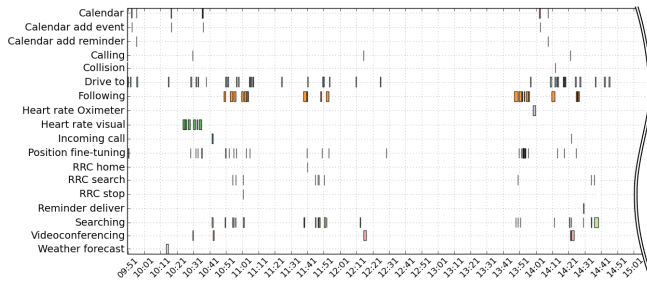
Fig. 5: Usage & event-logs showing user-specific usage patterns of the available services during a user trial (S2).

uniqueness of each case. In our study, nine cases were chosen to capture typical circumstances and conditions of an everyday and commonplace situation. Each case was characterized by varying features of the test environments (see Section V-A) as well as individual user characteristics (see Table VII). All users were living in their own, private apartments managing their daily life independently. Except senior 3 who lives with her spouse, all other seniors are living alone. The seniors were recruited from two different service residential complexes for older people, AWO and ARTIS - both situated in Erfurt (Germany). The four seniors of cases 1 to 4 (AWO) were familiar with the robot and had participated in previous studies over the course of several years. The five seniors of cases 5 to 9 (ARTIS) met the robot for the first time what should make them more objective and unbiased. All nine apartments were mapped and tested regarding technical requirements before the case study was conducted.

1) Procedure of the User Trials: On the day before the testing, the seniors got a demonstration and training of the robot's functions and abilities. They were instructed to freely use the robot as they wish. In addition, individual appointments and daily routines were adjusted in order to incorporate the robot and the test procedure as seamlessly as possible into the usual everyday routine. That way a natural everyday life situation should be provided in order to reduce the novelty effect. Then the robot "Max" accompanied the nine seniors for up to three days each (see Tab. VII). During the trial days, the seniors should live with the robot in their home and stick to their usual daily routines as much as possible. They could use the whole repertoire of the robot's services and functionalities except for remote controlling the robot by a third person (e.g. relatives) from outside the apartment. The trial conductors waiting outside the apartment were available to be contacted by telephone in critical situations, and at least one call was pre-arranged each day, for some intermediate feedback.

2) Data Collection and Data Analysis: Throughout the whole tests, the users' activities were logged in so-called "usage & event logs" used in SERROGA for automatic recording of robotic service usage and unexpected events (see Fig. 5). The event logs were analyzed regarding intensity of use and typical usage patterns. Besides, the seniors were asked to fill in short standardized questionnaires after the first use of each service. On that basis, the users rated

basic functionalities right after using a certain service. On the day after each trial, the participants' experiences were captured through a final qualitative semi-structured interview. To measure how the seniors experienced *instrumental use* of the robot assistant, the data (usage & event log files, questionnaires, and interviews) was analyzed regarding usefulness (the degree to which the seniors believe that particular services could be assistive) and intention to use the robot in the future [21]. To assess information about how the seniors experienced the *social-emotional functions* of the robot companion, the interview data was content-analyzed regarding co-experience (the social abilities that contribute to the sense of social presence and emotional bonding when interacting with a robotic companion), safety (the feeling of security when interacting with the robot), and joy of use (the perceived enjoyment when interacting with the robot) [22].

B. Findings of the User Case Study

1) Acceptance of the Robot as Health Assistant: In general, the robot companion for healthcare assistance functioned technically robust in the private apartments, and the robot's services were usable. The positive ratings of usability were the result of the technical robustness of the robot, but also of the consistently implemented user-centered design process which had integrated seniors in each stage of application development. Nevertheless, handling the robot's services obviously needed some practice - so familiar users (cases 1-4) outperformed unfamiliar users (cases 5-9). Fig. 5 illustrates that usage intensity and usage patterns cannot be interpreted as representative for everyday life. Though seniors had been asked to stick to their usual daily routines, all nine seniors stated that being accompanied by the robot provided a welcome variation in their daily routines. Log files revealed that only the users that were accompanied for three days (cases 7, 8, 9) used the robot less intense over time, with longer breaks between the usage sessions. Moreover, the log files reveal individual preferences regarding the used services as well as regarding usage patterns. For example, in case S2 (Fig. 5) it is noticeable that applications to navigate the robot through the apartment and interacting with it (drive to, follow, search) were preferred. In all nine cases, seniors rated the usefulness of the robot in its current state as limited due to the restricted number of health-related services and the still rudimentary motion exercising. Nevertheless, eight out of nine users reported strong intentions to use a health robot in the future, if more health-related applications were provided (e.g. medication management), its adaptivity was increased, and an immediate feedback could be given by the "Fitness coach" during the motion exercises.

2) Acceptance of the Robot as Social Companion: Each senior confirmed that they felt safe around the robot, but stated that they still kept an eye on it preventing unwanted activities. Users hesitated to leave the robot alone in the apartment over a longer period of time. Seniors that were familiar with the robot (cases 1-4) were not less concerned than those who interacted with the robot for the first time. However, users that were accompanied for three days (cases

7, 8, 9) were a little less concerned. Nevertheless, none of the users was afraid to damage the robot. They were sure to be in control of the robot at all times. Joy of use was rated high, though it could be recognized that users enjoyed the first day they were accompanied by the robot the most. The seniors who had used the robot more than one day, stated, that they ran out of ideas what to do with it.

The findings regarding the perceived *co-presence* of the robot were remarkable for several reasons. Except for case 6, the seniors treated the robot like a social being, whenever interacting with it or talking about it, though they were well aware that the robot was just a machine. Eight out of nine users had named the robot individually, heartily welcomed it, and were sad when they had to say farewell. Although the robot cannot recognize and react to speech, interviews confirmed that all users asked back and commented while interacting with the robot. Seniors responded emotionally to the robot's actions: they praised it, felt sorry for failures, ranted, cared about its condition or even asked for its opinion. Frequent touching and stroking the robot was part of the emotional bonding. Users confirmed that the robotic companion helped them to cope with boredom and feelings of loneliness (e.g. case 1: "*The most important fact is, that I am not alone.*"). Finally, all users described the trials as an enjoyable experience, and many of them confirmed "*The more initiative the robot takes, the more enjoyable it is.*"

VII. CONCLUSIONS AND OUTLOOK

All in all, SERROGA can refer to about 7 days of function tests in private apartments of the project staff and seniors and 16 days (120 hours net) of user trials in seniors apartments where the companion robot interacted completely alone with the seniors without any supervising persons being present on-site. This illustrates the significantly improved maturity level of the implemented methods for navigation, HRI, and health assistance, which is the essential prerequisite and a *must* if one wants to objectively study the usability, user experience, and social acceptance of companion robots in everyday experiments with uncompromising users. Although a multiple-case study has limited generalizability, the results of the user trials indicate that a personal robot assistant has high potential to be accepted by older people as both a useful health assistant and a meaningful social companion. Particularly, the social-emotional aspects of the robot showed strong effects in all nine cases: the robot was accepted as a real social companion. Stroking the robot and its reactions on this, verbal communication as well as the robot's personality (friendly, caring) and its mobility-based "devotion" fostered emotional bonding. This supports our hypothesis, that compared to computers, tablets, or TVs, robots provide psychosocial and instrumental advantages due to their embodiment, mobility, and social presence. Only robots can provide enough social-emotional cues to be perceived as companions that help to overcome loneliness and increase people's well-being. Further research needs to clarify exactly i) which health-related services are most promising to meet the users' expectations, ii) if and how the robot use evolves over longer

periods of time with a focus on adaptation effects, and iii) how instrumental and social-emotional functions best work together. Thus, the next step will be to integrate further health-related services, particularly for the "Fitness coach" which is still rudimentary so far, and to conduct a long-term study over a period of several weeks.

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