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Towards Long-Term Deployment of a Mobile Robot for at-Home Ambient Assisted Living of the Elderly

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***Abstract*— In a social and economic context characterized by a constantly aging population, the research for new technologies able to assist elderly people is becoming a hot topic. In this paper we illustrate the main components of the European project MoveCare, a multi-actor framework designed to assist pre-frail elders living alone. The main component of the system is an assistance mobile robot that provides the user with a set of functionalities to support cognitive and social stimulation, assistance, and transparent monitoring. In view of the long-term deployment of the autonomous robotic system to be carried out for three months inside the houses of end-users, we present in this paper a preliminary experimental evaluation of the system within an apartment, focusing on the evaluation of the platform under the perspective of long-term autonomy (LTA).**

I. Introduction

In this paper we present the general framework of the H2020 MoveCare project [1], [2], whose main objective is to develop an innovative, multi-actor platform that supports the independence of elderly people living alone at home. This is achieved through monitoring, assistance, and stimulation of the elder user provided through activities developed to counteract physical and cognitive decline, as well as isolation.

Lifestyle changes and increase of activity have been proposed as an effective way to contrast or limit cognitive decline when dealing with pharmaceutical treatment of Mild Cognitive Impairment (MCI) [3], [4], but a definite solution for this problem tackling early stage cognitive decline is largely missing. In this sense, assistance robots for elders with MCI or with cognitive impairment have been introduced in multiple projects as [5], [6], with promising results. Following on these leads, the MoveCare project considers a mobile robot (Giraff [7]) as a central component of the system to embody a caregiver that will look after its user on a daily basis.

Whilst a general assisting living framework able to cope with different user requirements could be of great impact and interest, the MoveCare project focuses on a narrower set of needs that are demanded by relatively healthy elders, aging between 65 and 75, who live alone, and who aim to continue living independently at home as long as possible. Several potential risk factors are evaluated and tackled by focusing on two main topics: (i) the development of direct *interventions* in order to encourage the elder to keep an active lifestyle and to socialize, and (ii) a continuous and transparent *monitoring* operating at home. In both of them, the role of the assistance mobile robot is fundamental, enabling a direct interaction between the elder and the robot in a socially acceptable way and promoting the acceptance of the system.

More precisely, interventions are targeted at suggesting and leading physical, cognitive, or social activities and games and at supporting and strengthening the social network of the elder. At the same time, monitoring is performed by collecting data with a pervasive but unobtrusive system composed of physical components (sensors) and virtual components (data collection from digital activities).

The project schedules a *pilot* phase of three months duration at the end of 2019 where all the system's components will be deployed inside the houses of twenty selected participants. Components developed for the project are already undergoing preliminary testing and evaluation sessions (either in the laboratory, in actual houses, or at elders' homes). Yet, due to the long-term duration of the pilot and to the fact that testing will be performed inside the houses of users, the evaluation of long-term autonomy of the proposed system, with special emphasis on the mobile robot, is of paramount importance. In this work we present the results of a preliminary experimental session carried out in a real apartment for a 9-days period, focusing on the evaluation of the system robustness towards the final *pilot* stage. For this reason, we evaluated extensively the core functionalities of the robot, in order to estimate the potential causes of failures and to envisage recovery behaviours.

II. State of the Art

An exhaustive review of previous work exploring the benefits of assistive robots in elderly care can be found in [8], where a functional distinction is outlined between *service* robots, aiming at helping users in daily activities, and *companion* robots, targeting the psychological well-being of their owners.

The review highlights a trend that leverages both service and companion robots for health care interventions [9] within the residential living environment. The first category includes works like [10], which proposed the use of a half-bust robot to assist the cognitively-impaired elder during mealtime, or [11], in which an info-terminal robot was used to provide useful information and reminders to the residents of a care home. On the other hand, a well-known example of a companion robot is the seal PARO [12], which was primarily used to ease distress in elders suffering from mild

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or severe cognitive impairments. In this framework, most of the proposed solutions have proved effective in enhancing the well-being of the elder users interacting with robots.

In its turn, long-term autonomy (LTA) of assistive mobile robots is a complex and still unexplored research topic, due to the unpredictability of potential failure causes of the robot and of the potential situations in which it may find itself. A recent survey on AI-based LTA approaches can be found in [13], which categorizes them according to application features such as Navigation & Mapping or Perception. In this survey, our proposal would fall within the *Service* domain, providing either full or partial integration of all the considered features. Recent works like [14] or [6] have done a remarkable effort in LTA, by deploying an autonomous social robot for several weeks in settings like an assisted living facility. Other relevant long-term applications of autonomous social robots are those of [15] and [16]. Differently from our settings, in both studies the robot was deployed in large-scale environments. In our context we aim to provide an assistance robot to attend the elder inside his/her house during its daily activities.

Despite the established benefits of using assistive robots in the context of residential living, the ultimate goal should be the deployment of robotic assistants to the user's home for remote health monitoring functionalities. To answer this need, the integration of robots in ambient assisted living (AAL) environments has been proposed in works such as [17], [18] or [19], where a tele-operated mobile robot was deployed to the elder's home, together with a network of sensors, to achieve monitoring of daily-life activities.

A system similar to our proposal can be found in the series of works about the CompanionAble and SERROGA projects [20], [21], which presented performance results of long-term tests in private apartments, similar to those planned for our pilot phase. Another recent service robot which is focused on fall detection and that offers other services as reminders and entertainment suggestions is described in [22], [23]. The main differences of our approach lies in the integration of the robot with IoT-based user monitoring, in providing new functionalities such as RFID and vision *object search*, and in the extent and number of robots used for tests with end-users.

III. Project Outline

MoveCare is a multi-actor framework composed of virtual and physical actors embedded in the user's home. A simplified representation of the main components and their interactions can be found in Fig. 1. The physical actors are connected together through an Internet of Things (IoT) infrastructure based on MQTT (a widespread lightweight publish/subscribe messaging transport protocol), and also connected to a centralized cloud-based server which receives, stores, and analyses all data coming from each user. The IoT infrastructure is composed by:

- a set of sensors deployed in the environment (no sensors are worn by the user) such as door sensors, PIRs, smart plugs, etc., used for monitoring.

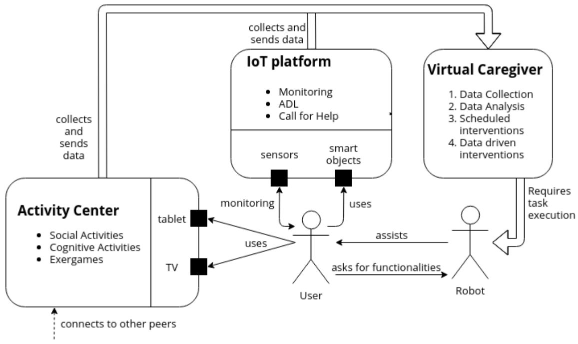

Fig. 1: The components of the system and their interactions.

- A set of smart objects that the user interact with, as a smart pen for monitoring writing, or a smart ball for measuring grip strength.
- An autonomous mobile robot, based on the Giraff robot platform (see Section IV), to provide assistance and as an embodiment of a caregiver to perform interventions.

Besides interacting with the above components, the user can access a virtual community of users through an application that we call Community-Based Activity Center (CBAC). Inside such virtual community, the user can participate in social activities with peers and access to other digital activities like exergames, cognitive games, and serious games, all designed to counteract the cognitive decline of the elders and to strengthen his/her social network.

The data collected by all physical agents and from the participation and execution of the virtual activities are stored and processed by a cloud-based AI, a digital actor denoted as *Virtual Caregiver* (VC), which oversees and coordinates all the components of the system. The entire interaction between all components can be seen, from an abstract point of view, as an instance of the classic Sense-Plan-Act paradigm (see Fig. 2) where the VC collects all the data coming from each *sensor*, including the robot. Under these premises, the role of the assistive robot is crucial as it is the only tool in the system able to autonomously navigate the environment, find and reach the user, and perform the desired interaction (e.g., asking a question, providing a remainder, suggesting some game, etc.).

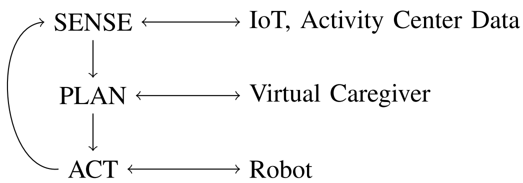

Fig. 2: The system cast into a sense-plan-act perspective.

Consequently, the robot is the connection and the interaction method of the VC with the user. This is done by identifying the elder's position (using the IoT sensors), interacting with them, providing indications on performing an activity, and assisting them during its execution.

MoveCare users can freely use the activities proposed by

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Fig. 3: The Giraff mobile Robot.

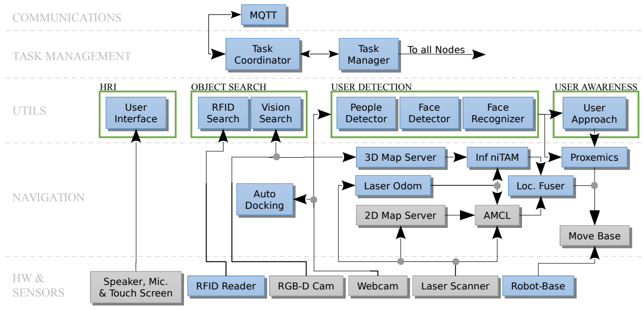

Fig. 4: Robot software architecture with standardized (grey) and specifically-implemented (blue) ROS nodes.

the project. However, if required, the system can detect which user would benefit from participating to one of the activities and can directly intervene with an invitation provided by the robot, aiming to promote their attendance. In this sense, activities can be promoted or initiated directly by the MoveCare framework [24]. The VC is responsible for tuning the frequency and timing of these interventions, in order to find a good balance between their effectiveness and their acceptability (see Section IV).

The VC is also in charge of collecting all the information obtained trough monitoring, which is performed at different granularities. As an example, low frequency data are collected at a daily to a monthly basis, while data indicating an emergency situation (for example, a fall) trigger an immediate response.

The adoption of a modular approach composed by a sensing platform embedded in the environment and of an cloud-based reasoning system allows to handling failures and simplifies the robot, which becomes an executor of commands provided by an external component.

IV. Robotic Platform

The Giraff robot is a platform progressively developed with the support of projects framed in European Union calls for Ambient Assisted Living, namely AAL (ExCITE [25], [26]), FP7 (GiraffPlus [19]), and now MoveCare. This robot is especially designed for HRI with elders.In MoveCare, its configuration has been enhanced with additional sensors for a better awareness of the robot's surroundings (see Figure 3).

A. *Specification*

In its factory configuration, the robot's hardware consists of a motorized wheeled platform (two wheels with independent drive motors plus two caster wheels) with an onboard computer connected to the Internet, and an height/tilt adjustable *head* consisting of a videoconference setup with a touch-screen, a microphone, a speaker, and a fish-eye webcam. Two physical buttons are placed at the front part for interaction with the user (accept/reject buttons). Apart from these, in MoveCare, a set of new sensors has been added to the platform to enhance its localization, navigation and interaction capabilities:

- 2x Orbbec RGB-D frontal cameras (one facing forward, the other facing downwards) for user and object detection, obstacle avoidance, and 3D localization and mapping.
- A NVIDIA Jetson TX2 module to increase computational capabilities for user localization and 3D geometric and semantic mapping.
- A Hokuyo URG-04LX-UG01 2D laser rangefinder for robust localization and navigation.
- A RF-ID module and 2x antennas to perform RF-ID-based object detection.

B. *Software Architecture*

The on-board PC runs the Robotic Operating System (ROS) as the main environment to execute the software architecture that controls the behavior of the robot. Standardized ROS nodes (e.g., MoveBase, AMCL, etc.), as well as specifically-implemented (e.g., *TaskManager*, *Human-Robot Interaction* –HRI–, etc.) and third-party ones (e.g., OpenNI, PCL or OpenPose) have been integrated into this framework.Figure 4 shows a simplified schema of the nodes in the proposed robotic architecture and their interactions. These nodes are structured into five layers according to their scope and purpose.

HW & Sensors. They implement the drivers for the on-board sensors and actuators and are traversal to the architecture.

Navigation. These nodes are in charge of autonomously moving the robotic platform, including the generation and management of 2D and 3D maps of the environment, self localization and path planning at both global and local levels. Furthermore, autonomous docking [27] and proxemic navigation are implemented. The latter is handled by means of the so-called *costs maps* defining how and from where the robot should approach the user once this has been detected.

Utilities. This layer provides four main utilities: (i) HRI performed through a multi-modal interaction system composed of voice and visual interfaces, as well as two action buttons to get the user feedback. (ii) *Object Search* by detecting and recognizing objects from either image and depth data from the RGB-D cameras, or by RF-ID technology. (iii) *User Detection*, in charge of detecting and locating users in the house. The use of multiple camera and of computer vision techniques allows the detection of the user's body even if this lies on the floor. (iv) *User Awareness*, to safely approach the user attending to obstacles and proxemic rules.

Task Management. This includes a *task coordinator* in charge of scheduling all the intervention requests sent to the robot (e.g., by their priority, time of arrival, etc.), and a *task manager*, which, for every intervention request, builds a decision-tree-based plan with multiple sub-tasks, executes it and provides feedback.

Communication. The robot interacts with the other system components by means of JSON messages for both commands and feedback, sent through a MQTT channel to a shared cloud platform.

C. Functionalities

In MoveCare, the Giraff robot provides a set of functionalities or services as the main actuator of the system, embedding the caregiver at the elder's house. These functionalities can be categorized in four classes.

Services requested by the VC involving the user. These functionalities are triggered automatically by the VC according to a schedule or information inferred from the environment. They involve the robot to look for the user within the house and interact with him/her. This service is triggered in scenarios such as: *spot questions* (the user is asked to answer a set of questions to assess indications of cognitive decline), *reminders* (the user is informed about some scheduled task that should perform, e.g., measure their weight), or *invitations* (the user is informed about an activity suggested by the VC, e.g., going out for a walk). Moreover, the robot can oversee the execution of standardized tablet-based *cognitive tests*. Such tests are administered by the VC, following an approach improved from that of [28] and [29].

Services requested by the user involving the VC. These functionalities play their role in help and emergency scenarios. In this case, the user triggers the intervention by asking the VC for help. The robot is then commanded to look for the user, confirm the emergency and establish a communication with the caregiver (e.g. providing video-conference capabilities with remote control of the robot).

Services requested by the user not involving the VC. In this category we include the *search for lost objects* service, which is directly triggered by the user by asking the Giraff to find a particular object. The robot searches in the entire environment while trying to locate it either through RF-ID (for having a rough estimation of the object's location) and/or computer vision (for identifying the exact position), and informs the user via speech interaction.

Self-management. This functionality is triggered by the robot itself in order to maintain a proper autonomy level, including performing auto-docking if the robot has been idle for a long time or the battery level is critical.

In order to offer such functionalities, the robot is able to autonomously navigate in the environment. Robot navigation is performed by using a topological map that has been manually built on top of the metric map used for localization, following an approach similar to that of [14]. A topological location is placed in each room. When needed, an expected position of the user is also provided to the robot by the VC using data collected from the IoT sensors embedded in the environment. To search the user, the robot reaches at first the topological location indicated by the VC as the most probable user location. If the user is detected, the robot completes its intervention. Otherwise, the robot performs an exhaustive search of all other topological locations. A similar behaviour is used in order to find lost objects by using RF-ID tags.

V. Pilot Validation and Current Status

The characteristics of the pilot (duration, number of robots, environment complexity), involve several challenges [14], [15], [16]. To address them, the MoveCare project foresees the deployment of a total of 12 Giraff robots: 10 will be used in two testing stages (in Spain and Italy), while the other 2 will remain for development refinement and testing. In this line, the evaluation of the system will be performed with a pilot study involving 20 elders who match the description provided in Section I. The entire system will be deployed for three months inside the house of each participant, and will be evaluated according to different factors: (i) social (e.g., impact on the elders' life, usability or user's acceptance), (ii) clinical (e.g., cognitive decline) and technical (e.g., robustness or fail tolerance). Preliminary tests of the entire system have been performed in both lab environments and some elders' houses.

A. Testing Scenarios

Besides the independent components of the system, which are already undergoing preliminary testing, the assistive robot has been tested in different scenarios to evaluate the fulfillment of the expected functionalities described in Section IV-C. For most of these scenarios the robot follows this sequence of actions:

1) receives the intervention via MQTT message,
2) undocks (if necessary),
3) safely navigates to the expected user location (updated by the system in real time),
4) locates the user and, if not found, performs a search in the whole house,
5) approaches the user, taking into consideration the proxemic distances [30],
6) interacts with the user to carry out the specified action,
7) provides feedback to the VC, again through MQTT, and
8) returns to the dock station if there is not any other intervention planned in a short time interval.

The main purpose of the robot is to perform this procedure autonomously (i.e., without any help from the system or the elder). In this sense, robustness is a crucial parameter, since a failure of the robot requiring physical or remote intervention by a technician will be undesirable and costly. From the elder point of view, such an intervention may undermine the perceived utility of the robot undermining its acceptability.

B. Testing Places

In order to evaluate the robustness of the robot, we performed extensive in-lab testing. However, the controlled

Fig. 5: Map (approx. $65\,\mathrm{m}^2$) of the tests with topological locations and robot trajectories for all experimental runs.

conditions that the robot may face in a lab are usually less challenging than those of an actual deployment, where long-term runs can reveal different anomalies and unexpected behaviours that cannot be predicted otherwise.

Thus, we conducted a 9-days long trial of the entire framework inside a small apartment in Milano (Italy), in which the MoveCare system was installed. Multiple tests were performed having in mind the evaluation of the system robustness and the potential failure causes of the core components of the robotic platform. The selected apartment has approximately $65\,\mathrm{m}^2$ of free area and is composed of three small, fully furnished, rooms with cluttered spaces: a living room with an open kitchen, a bedroom, and a bathroom. Similarly to the pilot requirements, a single user lived in the apartment for the duration of the test, where no arrangements were made in order to adapt it to the robot before or during the experimental runs.

C. Evaluation

Different interventions were triggered automatically by the VC while the user performed his daily activities. The IoT sensors deployed in the environment provided the VC with the ability to detect the presence and location of the user inside the house. During the 9 days of the experimental trail, the robot was successfully used for a cumulative time of more than $32\,\mathrm{h}$. Overall, the robot was asked to perform repeated interventions every $15\,\mathrm{min}$ in order to test its basic functionalities by going through the entire sequence of actions (1)-(8). During the pilot, we envisage at most five robot interventions per day. During this experimental evaluation, we relaxed such a limit to acquire as much data as possible and to perform a stress test on the robot. Overall, the number of generated interventions corresponds to that we would observe during a month of system's usage.

One critical point to evaluate is the robot ability to autonomously return to the docking station, even under the event of a failed intervention (e.g., navigation problem, user not detected, sensor issues, etc.). The Giraff robot has a working autonomy of approximately $2\,\mathrm{h}$, but in case of a failure during auto-docking, a full discharge would require manual intervention. To properly evaluate this functionality, we intentionally force a high number of this type of interventions, tracking the events that prevented the robot to fulfill

TABLE I: Results of the experiments. *err*: task was unsuccessful, *crit. err*: manual intervention was required.

Intervention type	#	err	err %	crit. err	crit. err %
identify, approach, and interact	116	3	2.6%	3	2.6%
docking	133	22	16.5%	0	0%
TOTAL	249	25	10.0%	3	1.2%

the action, paying special attention to those where manual intervention was needed. The entire set of experiments was logged using a MongoDB database for further analysis and evaluation. Data are available upon request.

Overall, we performed 249 interventions requiring the robot action. In 116 of those, the robot was requested to find, identify and approach the user to provide a voice message. The other 133 correspond to the autonomous recharge functionality, where the robot had to move back to the predefined location where the docking station was located, and perform the docking action till recharge was detected. The total moving time of the robot during these experiments was approximately $5\,\mathrm{h}$. The average duration of an intervention was of $71\,\mathrm{s}$, while the longest and shortest runs were of $453\,\mathrm{s}$ and $11\,\mathrm{s}$ respectively. Figure 5 shows the 2D geometric map of the house where the experiments have been performed and the trajectories followed by the robot in all of the experimental runs. In Table I the results about the completion rate of the robot's interventions are provided. As can be seen from these results, a total of 25 errors were detected, being only 3 of them critical failures requiring manual recover. Those cases relate to a software exception not properly caught in some of the robot modules, not restored with the implemented recovery behaviours, and eventually causing a restart of the system. Apart from that, the robot was robustly able to search for the user in the entire house and to identify, approach, and talk to him (even when he was lying in bed, sitting at the sofa, or in the kitchen). An interesting aspect that was detected is that during the approach of the user phase, the robot often placed itself in a position useful for HRI but eventually challenging for further movements. That caused the failure of 22 (docking) interventions, suggesting that the proxemic module should be appropriately revised to avoid setting navigation goals which may be challenging to get out from. However, the robot was always autonomously able to recover, to successfully compute and execute a new path, and to charge itself.

VI. Discussion and Conclusion

In this paper, we have presented the MoveCare framework for Ambient Assisted Living, targeted to elders and centered around an autonomous mobile robot. We have provided an overview of the entire system, and focused the attention on the need of robustness in the view of the scheduled long-time pilot stage to be executed at the end of the project.

A crucial component for this robustness analysis is the Giraff mobile robot, which represents the main actuator of the system and the primary way to interact with the user. Due to the modularity of the system, the robot is able to perform robust complex behaviours obtained composing simple core functionalities. We evaluated autonomous navigation, people detection, user approach (proxemics), HRI, and autonomous docking. Intensive testing cases in a real apartment for a 9-days showed that the robot functionalities present an acceptable degree of reliability. These conclusions will be extended with those from the pilot experiment, with more robots involved, for a longer period, and in more diverse scenarios.

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