Robots in assisted living environments as an unobtrusive, efficient, reliable and modular solution for independent ageing: *The RADIO perspective*

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Abstract. Demographic and epidemiologic transitions in Europe have brought a new health care paradigm where life expectancy is increasing as well as the need for long-term care. To meet the resulting challenge, European healthcare systems need to take full advantage of new opportunities offered by technical advancements in ICT. The RADIO project explores a novel approach to user acceptance and unobtrusiveness: an integrated smart home/assistant robot system where health monitoring equipment is an obvious and accepted part of the user's daily life. By using the smart home/assistant robot as sensing equipment for health monitoring, we mask the *functionality* of the sensors rather than the sensors themselves. In this manner, sensors do not need to be discrete and distant or masked and cumbersome to install; they do however need to be perceived as a natural component of the smart home/assistant robot functionalities.

1 Introduction

Demographic and epidemiologic transitions have brought a new health care paradigm with the presence of both growing elderly population and chronic diseases [1]. Life expectancy is increasing as well as the need for long-term care. Institutional care for the aged population faces economical struggles with low staffing ratios and consequent quality problems [2], [3].

Although the aforementioned implications of ageing impose societal challenges, at the same time technical advancements in ICT, including robotics, bring new opportunities for the ageing population of Europe, the healthcare systems, as well as the European companies providing relevant technology and services at the global scale. The full realization of this technological potential depends on:

- Concrete evidence for the *benefits for all stakeholders*, including the elderly end-users and their formal and informal care givers (secondary end-users), as well as the health care system
- *Safety of and acceptability by* the end-users
- *Cost-effectiveness* in acquisition and maintenance, *reliability*, and *flexibility* in being able to meet a range of needs and societal expectations
- The provision of functionalities that can *reduce admissions and days spent in care institutions*, and prolong the *time spent living in own home.*

RADIO project will develop an ***integrated smart home/assistant robot system***, pursuing ***a novel approach to acceptance and unobtrusiveness***: a system where sensing equipment is not discrete but an ***obvious and accepted part of the user's daily life***. By using the integrated smart home/assistant robot system as the sensing equipment for health monitoring, we mask the *functionality* of the sensors rather than the sensors themselves. In this manner, sensors do not need to be discrete and distant or masked and cumbersome to install; they do however need to be perceived as a natural component of the smart home/assistant robot functionalities. In pursuing these goals, the main objectives of RADIO are:

- To develop methods for detecting the *activities of daily life (ADL)* and *mood* conditions that are pertinent for *detecting early symptoms of cognitive impairment* and *social exclusion*, and to compare their accuracy against that of more obtrusive setups.
- To place the robot as the *central focus of interaction* for a whole range of automations offered by the smart home, besides the assistance offered by the robot itself. This enhances acceptance of the robot's *sensing equipment* as a necessary part of the robot's functionality.
- To base the design on existing *reliable*, *safe*, and *low-cost robotic and home automation solutions*, without requiring specialized hardware.
- To embed recognition methods in *hardware sensing and processing components*, which form a *modular system* that can be deployed in *different configurations and mixes of components* without requiring extensive effort or specialized knowledge for reconfiguration.
- To evaluate how well the RADIO-provided information can *drastically reduce precautionary admissions and days spent in care institutions* by *detecting early symptoms of cognitive impairment*.
- To integrate individual home deployments into a wide area network of RADIO home deployments, medical institutions, and mobile devices of informal care givers; into an *information transmission and management system* that is by design *scalable* and *secure and privacy-preserving*.

In order to achieve its ambitious objectives, the RADIO project will carry out research in several ICT fields. In the remainder of this paper we first frame this research in the context of the RADIO architecture (Section 2) and then proceed to present the envisaged smart home/robotics environment (Section 3), data analysis (Section 4), embedded system design (Section 5) and communications infrastructure (Section 6), and conclude (Section 7).

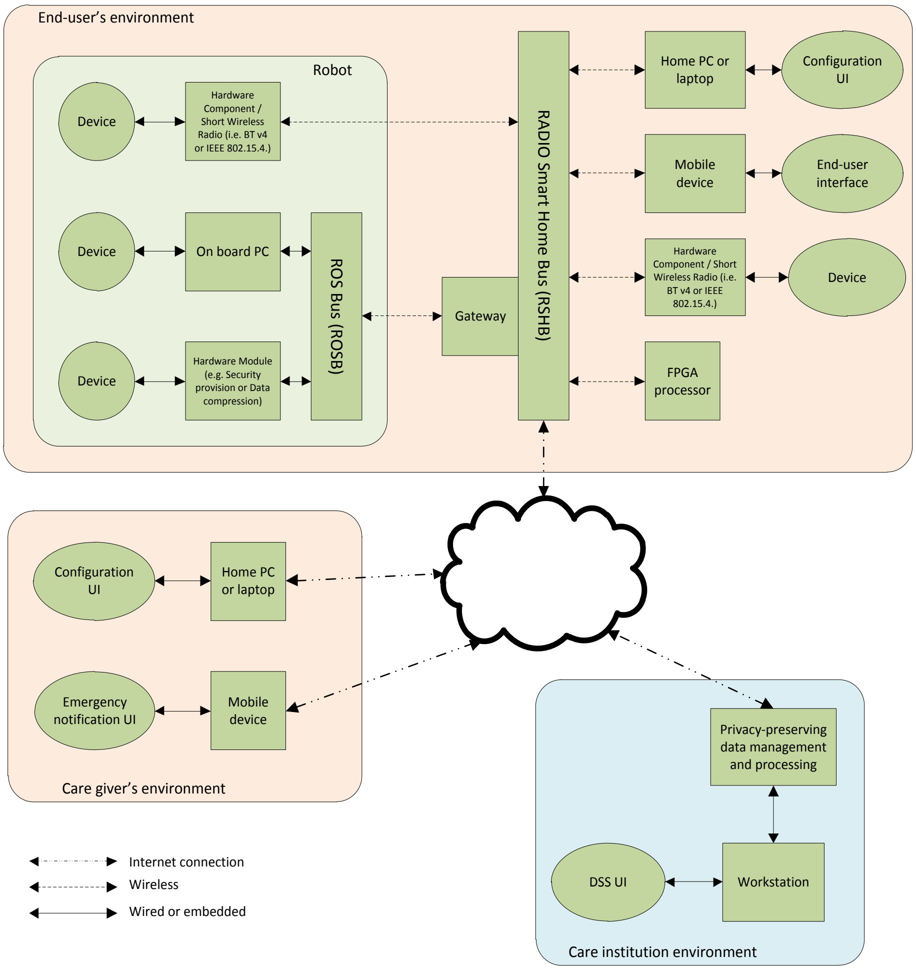

Figure 1: Conceptual architecture of the RADIO system

2 Use Cases and System Architecture

One of the core premises that RADIO will test is that *user acceptance* can be achieved by minimizing the levels of awareness being monitored: system actions and behaviours are apparently serving the end user's convenience and no action is explicitly motivated by health monitoring. RADIO also assumes a pragmatic stance towards the technology readiness level of robotic autonomy and cognitive systems, and actually turns into its advantage the relatively low level of autonomy that robots enjoy: it lowers user expectations on its cognitive abilities and gains acceptance and familiarity by not presenting itself as an omnipotent helper but rather as a pet that depends on the user more than the user depends on it.

The primary end users are elderly people who need assistance in order to maintain their independence and quality of life. *RADIO* aims to offer a number of smart home automation conveniences including a thoroughly integrated *domestic assistant* robot. Besides running errands such as looking through the house for eyewear or keys or bringing medication, the robot also acts as the contact point for home automation conveniences, such as lights that can be switched on and off, heating that can be turned up or down, etc. It collects and analyses behavioural data in order to attract a doctor's attention when necessary, helping diagnose symptoms early and take timely remedial action. Through its direct involvement in the end-users daily activities, RADIO observes *Activities of Daily Life (ADL)* and aims to exploit these observations to establish ADL patterns and to identify deviations.

The RADIO system will be accessed via *user interfaces (UI)* specifically designed for the elderly *primary end-users*, their *care givers*, and the *clinicians*. The main design goals for the *primary end-users* and the *care givers* UI are ease of use by people with minimal familiarization with ICT systems and, especially the former, by people suffering from cognitive impairments that affect memory. The *clinicians UI*, by contrast, is a more complex front-end for *decision support systems* that allow monitoring by clinicians as well as research and experimentation using aggregate and anonymous data collected from multiple deployments of the system (Figure 1).

3 Integrating Smart Home Systems and Robotics Technology

Home automation is not a passing trend but is expected to become as prominent feature of our daily lives as television sets, phones and tablets are today. It is natural that integrating robotics technologies into home automation infrastructure is going to afford us the most seamless integration of the robot in its smart home environment.

This integration, however, is a major undertaking due to the large number of competing protocols and standards related to home automation. Smart home systems integrate mature, off-the-self sensing and actuation components around a *home gateway* that provides telecommunications, central control, and intelligence. However, fast development by many companies who wanted to position their products on the market led vendors to develop incompatible communication protocols for their products. Although some standardization has been achieved, there are still several standards for physically wiring devices in actual use in homes that need to be considered in the context of RADIO:

- The *Digital Addressable Lighting Interface (DALI)* is used to control light systems, means transformers, dimmers, LED lights, and other endpoints.
- The *European Installation Bus (EIB)* standard describes how sensors and actuators in a house automation system have to be connected. It also describes the communication protocol. EIB is used for alarm systems, light control, and shutter for windows.

- *Konnex-Bus (KNX)* describes the connection of sensors and actuators in house automation and integrates three bus systems: EIB, BatiBus, and EHS.
- *Local Operating Network* (LON) is a Fieldbus and US standard with was adopted also in Europe. The standard allows that devices of different vendors can communicate.
- Last but not least, the *Standard Motor Interface (SMI)* allows to control drives e.g., in shutters for windows.

The wireless communication systems are also manifold. Currently the following standards are used for wireless home automation: *EnOcean*, *ZigBee*, *Z-Wave*, *WLAN*, and *Bluetooth*. In robotics, integration is typically centred on an on-board PC that uses the *Robot Operating System (ROS)*[1] middleware to integrate sensing and actuation over the Ethernet, WiFi, and USB communication channels typically available to PCs.

The RADIO project focuses to handle the communication between the most relevant wired and wireless home automation standards and the robots. For this purpose, based on a standard the gateway functionality will be deployed. The *OSGi Framework*[2] is an open, modular and scalable *service delivery platform*. It enables as software basis platform the networking of devices from different vendors. However, the platform has to be extended and evaluated to handle also the domain of robotic. Since the standard was developed for connecting end points e.g., from Telemetry, Assisted Living, mobile phones, and PDAs, it is not dedicated for the usage in the robot domain. However, since this is an open standard which is established, the consortium decided to use this platform as the start for the integration of robots into house automation.

4 Data Collection and Processing

RADIO aims to detect ADL related to *basic self-care tasks*, such as dressing, eating, feeding and functional mobility, as well as *instrumental ADL* related to housework and device usage (e.g., telephone). ADL detection will be based on visual, depth, and audio signal analysis as well as their fusion. For instance, detecting eating-related events will be based on audio-visual analysis, while functional mobility will be based on recognizing motion patterns in depth and range data.

Apart from the ADL mentioned above, the project will also experiment with detecting more complex events, such as meal preparation, cleaning up, using technology and taking medications. RADIO will also face significant communication and technology integration challenges, ranging from efficient and secure data transfer, cooperative communication, data processing, sensors-actuators efficient cooperation, low power operation, and communication technologies heterogeneity. Besides ADL, the project will also integrate methods for recognizing *mood* from speech and facial char-

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[1] ROS is maintained by the *Open Source Robotics Foundation (OSRF)*. More information about ROS and OSRF can be found at http://www.ros.org and http://www.osrfoundation.org

[2] More information about OSGi can be found on the homepage of the OSGi alliance (http://www.osgi.org)

acteristics. Since the robotic platform will only be able to react to simple spoken commands and not engage in any type of conversation, audio analysis will be mostly based on acoustic features rather than the content of the user's utterances. In addition, *speaker diarization* will be used to isolate utterances by the person of interest, but also to provide information about social life and other signs of social exclusion.

The relevant literature is rich, but extension and adaptation will be needed in order to meet RADIO requirements. In instance, [4] try to monitor certain dressing activity failures, using both radio frequency Identification (RFID) tracking and computer vision processing. The failures they monitored were: putting on clothes a) in the wrong order, b) backwards or other way around, c) only partially d) at an inappropriate number of layers for the current temperature and e) at a wrong part of the body. They used a Bayesian model in order to infer the dressing step using the RFID tags, which had been embedded in clothes and a clustering scheme to infer simple dressing events using rules and finally fused the results. [5] tackled also the problem of clothes change, however in that case only the result is tracked (i.e., the change of a particular clothing) based on depth and RGB information that stems from a Kinect sensor.

Various already existing efforts will be considered for the purposes of RADIO. [6] used RFIDs to detect nine ADL activities. Wireless gloves with embedded RFIDs have been successfully used, among which oral hygiene, toileting, washing and personal appearance. Fusion of RFID and visual properties have also been addressed: [7] tackles the problem of automatically learning of object models from video by using sparse and noisy RFID readings, common-sense knowledge and visual features, in a kitchen, in order to recognize activities by identifying the objects which are being used in the scene. [8] focuses on five basic ADL activities: telephone use, hand washing, meal preparation, eating and medication use, and cleaning. They used various sensors (e.g., motion, temperature, sensors that monitor water and stove burner use etc.) They applied naive Bayes classifiers and Markov models so as to recognize the aforementioned activities. [9] presents a system that uses visual features and custom logic rules in order to recognize steps in hand washing by tracking a) of hand location and b) of step-specific object locations, specifically the soap and towel. [10] successfully fused several sensors with an SVM classification scheme to recognize several ADLs (e.g., dressing, hygiene). [11] uses kinematic sensors (specifically, wearable wireless accelerometers) to detect several ADLs. [12] uses an RGB-D camera to recognize potentially dangerous activities for elderly people, along with several ADLs. They track joints on the human body, which have been provided by Microsoft Kinect API1 and extract kinematic features. For the recognition of simple activities, they use several one-vs-all SVM classifiers, while for finer activities (i.e., ADLs) they adopt a bag-of-motion-features approach and then apply SVM classifiers. [13] also used the Kinect sensor in order to monitor intake gestures in the context of spotting specific ADL's of eating and drinking in a home setting.

A critical and quite challenging area will be sound and speech processing algorithms. Sound analysis has been mainly used to detect bathroom activity, e.g., [13], in the context of recognizing bathing, toilet use, and personal hygiene ADLs. Also, acoustic information has been used (e.g., in the USEFIL project) in order to detect sounds relevant to general events: doorbell, phone ring and speech, while [14] adopts baseline audio analysis approaches to detect ADL-specific audio events (dish washing, step sounds etc.). In addition, audio information can be rather useful when recognizing emotions from speech [15]. In most cases, due to the importance of face in emotion expression and perception, most of the affect recognition studies focus on combining information from visual-based facial expression analysis [16]. It has to be noted here, that speaker diarization [17] will be used in order to discover speaker-specific information before applying the speech-based emotion recognizer. In addition, the application of a speaker diarization step will help us to extract useful information regarding the social activity of the users (dialogue detection, types of dialogues etc.).

5 Embedded systems design and hardware accelerators

In the RADIO project, a significant effort will be given to the design and implementation of the underlying hardware platform. Our vision is to equip the robotic system with dedicated FPGA-based processors, memory systems, and accelerators. Apart from the low power requirements, prime design objectives of the hardware substrate will be safety, availability, reliability, and fault-tolerance. We plan to strike the best balance between those partially contradictory design goals through two main directions.

First, sophisticated offloading techniques will be devised. Our target towards this direction is to formulate a synergistic environment in which specific parts of the computational workload will be forwarded to the backbone for (further) processing. Those parts of the workloads can be either computational intensive pieces of code or critical parts of the executing applications. A combination of local and remote execution taking into account the well known communication vs. computation ratio will be also examined. However, in our case, this classic "communication vs. computation" trade-off will be extended to include the concerts of reliability and fault-tolerance [35]. For example, given a set of processing (local or remote) units, which is the most reliable unit for a given algorithm or a program phase of an algorithm? In principal, bit-level processors can execute more reliable bit-level algorithms (e.g., security algorithms), but bit level processors are too slow, that in turn means, power inefficient. In addition, the data transactions between the local (robotic) system and the remote system (back office) are also a significant source of errors.

Second, at the lower level, we plan to attack the challenges posed at the hardware level thought extensive reconfiguration [36]. While reconfiguration is widely considered as a technique to improve the performance or the power of a system [37], our aim is to use the concept of reconfiguration in order to increase the reliability, the safety, and the responsiveness of the robotic system. This requires to build power vs. performance vs. reliability (as well as safety) Pareto curves and use the notion of a reconfiguration in order to traverse those curves (statically or dynamically) in order to identify the ideal point(s) that meet specific (user or system) objectives. More importantly, in order to maximize the resulting benefits, we plan to include in the design space, application-level reconfigurations [36]. The application domain of the RADIO project is amenable to reconfiguration either at the algorithmic level (e.g., more relaxed data transformations) or at the data representation level (e.g., floating point vs. fixed points variables). In other words, the innovation in our case is that core and memory reconfigurations are going to happen in concert with application reconfiguration so as to be synergistic towards meeting specific objectives.

Memory reconfiguration entails a vast array of techniques: resizing on-chip memory to fit program needs [37], optimizing cache architectures for dynamic and static power consumption [38], optimizing shared-memory communication via custom cache coherence protocols [39], modifying the replacement policies for minimizing miss rates in caches [40], compressing data and removing data redundancies, managing caches shared by multiple applications, partitioning the on-chip memory for different functionalities (caches, scratchpads, loop buffers, etc.) and any combination of the above. While the reconfiguration space is vast in this project we will combine the mechanisms that work synergistically and provide global, application-driven policies for applying these mechanisms. Our goal is to provide a malleable core and memory system that can be efficiently adapted to the needs of an application using both static (application information) and run-time information (hardware monitoring & feedback).

6 Communication Infrastructure using WSN

Concerning *Wireless Sensor Network (WSN)* technologies, the embedded sensor that will be used in the context of distributed sensor data analysis will include experimental development boards as well as off-the-shelf commercial products. In the context of the RADIO platform, communication and interfacing capabilities of WSN sensors will be enhanced through low power advanced operation as well as advanced communication approaches including cooperative communication, data fusion and multi-hop communication.

In that respect, significant progress beyond the state-of-art is anticipated in ICT areas including efficient wireless sensor networks. Targeting on one hand a system able to handle a wide range of different and diverse sensors and one the other a highly extendible and evolving platform an adequate codification approach must be followed enabling communication in a structured and open way. Such schemes will significant ease the management of enormous and diverse amount of information. Significant input to this approach will be provided by open standards such as VITAL [18] and DICOM [19] and relevant research efforts [20]. During the last few years interesting research efforts have been presented concerning home monitoring of people with a specific condition. However most of them are based on a passive approach [21], [22] whereas RADIO aims towards a more active approach which will engage the user himself in order to make him feel more active, creative, self-reliant and useful.

Additionally, most efforts assume a single, specific communication technology and/or limited types of sensor which significantly limits flexibility and extendibility. In both aspects RADIO aims to offer wide support of available options so as to maximize usefulness and practicality [22], [23], [24]. Supporting state-of-the-art communication technologies such as Bluetooth v4 and IEEE 802.15.4 and extending low power communication capabilities will comprise a critical goal of the project. At the same time enhancements will be pursued in data management areas concerning context aware data process, data fusions etc. aiming to offer a more intelligent and efficient wireless sensor network. When multiple and mobile sensors are deployed in a home environment a critical challenge that must be addressed is potential disconnections of specific nodes (e.g., a person wearing sensors transferring data using IEEE 802.15.4 and the respective receiver are more than two rooms away from each other will probably lose direct connectivity to the receiver). In such scenarios the nodes can still be connected over multi-hop communication paths. Of course multi-hop communication is not new to WSN but RADIO aims to study the possibility to furthered enhance the usefulness and practicality of such features compared to existing state-of-the-art efforts. A common characteristic of relative efforts is the goal to address a very specific case usually characterized by quite limiting assumption including the use of specific communication technology or the transferring of specific sensor data [25], [26], [27], [28]. In that respect RADIO aims to offer to enhance usefulness in terms of flexible support of various communication technologies and data types using a common and extendible codification scheme. A very interesting approach is presented in [29] where multi-hop communication is used as a way to actually enhance security. Such approaches can also be extended in RADIO through the use of efficient encryption components while identifying and taking into consideration adequate data management processes able to address soft security issues such as data mishandle, authorized access, EC security regulations compliance etc.

Another area able to offer significant performance and efficient benefits yet not receiving adequate interesting in WSNs is cooperative communication [30]. In general the term cooperative communication in RADIO is used for approaches where nodes receiving (or overhearing) data don't just convey them to the final receiver but instead they use data in order to enhance communication efficiency. Such approaches have attracted significant interest in more resource rich network technologies such as WiMAX [31], [32] but can also benefit RADIO network setups as well. In [33] and [34] a very interesting use of cooperative communication aiming to enhance communication security is offered, which can also be exploited in the context RADIO and extended through the use of state-of-the-art encryption components.

7 Conclusion

The RADIO project provides an integration of robotic equipment in the environment of house automation. The high number of solutions in terms of protocols requires the development of a platform, which unifies all these different standards to enable a common interface for the robot's data access. This platform can be seen as gateway between the robot's data access and the connection to the house automation busses. Such a platform needs to support different real-time requirements, specific bus operations (e.g., cyclic messages, spontaneous messages etc.). A setup like this has the complexity like a gateway in the automotive domain. Due to this fact, a platform with sufficient computational capacity has to be selected. We envision here an FPGA-based design which is high performant and also flexible to future bus systems, which may be developed after the projects end.

An FPGA-based platform is also envisioned to host the algorithms used on the robotics platform. Here the best trade-off between communication and computation (at the local node) has to be found. Definitely, the processing of data near the sensor node might be the preferred solution in terms of power efficiency, but the highly dynamic scenario within the context of RADIO might lead to new approaches and solutions.

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