Computation and Communication Challenges to Deploy Robots in Assisted Living Environments

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***Abstract*—Demographic and epidemiologic transitions have brought forward a new health care paradigm with the presence of both growing elderly population and chronic diseases. Recent technological advances can support elderly people in their domestic environment assuming that several ethical and clinical requirements can be met. This paper presents an architecture that is able to meet these requirements and investigates the technical challenges introduced by our approach.**

Keywords*— *RADIO; healthcare; daily-life activity; IoT platform; image and sound processing; wireless sensor networks.

I. Introduction

As robotics and automation assume an increasingly prominent position in everyday life and consumer goods, issues associated with robustness and user-friendliness, integration of heterogeneous specifications, and power consumption are accordingly assuming an increasingly prominent position in the field's research agenda.

Naturally, robotics and automation have such a broad spectrum of application in everyday life and consumer goods that the open research questions in addressing these issues also vary broadly. In this paper, we investigate *elderly care* as a challenging but feasible application. Elderly care automation has great societal impact as the aging of global population usually relies on a smaller younger population for its support. In addition, it is also suffering from an increased probability of chronic diseases, further decreasing its mobility and capability of self-support. From the technical perspective, elderly care automation, tests robustness and user-friendliness to the extreme due to the low flexibility of the end users. The requirements for clinical data collection also test the integration of heterogeneous specifications by necessitating the integration of specialized devices in existing home automation solutions. Finally, low power consumption becomes a core requirement by the introduction of a mobile Robot as a sensing and actuation device.

Our investigation is in the context of the EU Horizon 2020 project *Robots in Assisted Living Environments: Unobtrusive, efficient, reliable and modular solutions for independent ageing* (RADIO). RADIO aims to provide a real-life solution to support elderly people in their domestic environment [1]. The core concept and approach of the project has been presented in more details previously [2]. For the purposes of the work described here, it suffices to re-iterate that RADIO emphasizes on being *unobtrusive and well accepted* while remaining *fit for its clinical purpose*. Technically, these requirements pertain to user interfacing specifically adapted to the elderly; ethically and clinically adequate data collection, transmission and processing; integrated and power aware data collection, transmission and processing; and an efficient and flexible architecture that can integrate heterogeneous health and comfort-related devices.

In this paper we investigate the particular use case of integrating into a smart home environment a mobile robotic platform that collects medically relevant information and everyday life activity information (**Section II**). We then proceed to present our computation and communication architecture (**Section III**) and discuss the communication (**Section IV**) and computation challenges (**Section V**). **Section VI** concludes this work.

II. Background

Assistive environments and telemedicine systems are typically implemented as smart homes or similar sensor networks that collect and analyze data related to *mood* and to *activities of daily life (ADL)*, as well as automatically providing notifications to care-givers in falls and similar emergencies. This is a well-studied subject with a rich literature and developed systems. One major line of research takes advantage of wearable sensors or sensors embedded in household items and appliances in order detect a wide range of ADLs [3][5][6][7]. Such approaches are not well aligned with the objective of developing a system that is unobtrusive by,

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among other features, also avoiding requirements on what the end-users should wear or use.

RADIO concept follows the line of research that uses computer vision and audio analysis to recognize interesting events. In fact, one of the main outcomes of the project is our analysis of the extent to which unobtrusive monitoring is sufficient to satisfy the clinical requirements. To the best of our knowledge, the presented methodology is unique in assisted living environments; we do not assume as a goal the maximal detail and accuracy that state-of-the-art sensing hardware can achieve. Instead we assume as a goal the collection of the minimum amount of sensitive content and personal information, at the minimum obtrusion, that will allow medical personnel to make an informed decision.

Naturally, such a broadly defined goal needs to be refined to reflect the societal impact that RADIO aims to achieve: allowing elderly people with mild cognitive impairment to maintain an independent life, at their own home, for longer than what is safely possible today. In order to have a guideline about what information (and at what level of detail) is used by medical doctors to assess such conditions, we have analysed the *interRAI Long-Term Care Facilities Assessment System (interRAI LTCF).* interRAI LTCF enables comprehensive, standardized evaluation of the needs, strengths, and preferences of persons receiving short-term post-acute care in skilled nursing facilities as well as persons living in chronic care and nursing home institutional settings. As a result of this analysis [8], we have determined the mood and ADL recognition items that can be immediately and automatically extracted and those that appear to be outside the reach of the current state-of-the art.

Some characteristic examples include clothes change detection, where recognizing the end-result of having changed clothes [4] is sufficient while the detailed capture of all the motions performed in order to change clothes offers no medically relevant information. Similarly, depth camera data can be used to detect potentially dangerous activities [9] and food intake [10]. Moreover, acoustic processing can provide information about several ADLs, such as such as hygiene, washing and walking [11]. Finally, mood can be inferred from both visual and audio analysis [11][12][13].

These observations have led us to a design where the main data collection device is a *mobile Robot* equipped with audio, visual, and depth camera. The mobility of the robotic platform is important for placing the sensors at positions that offer the maximum level of details (e.g., full-face images for recognizing mood from facial expressions) without placing requirements of the end-user such as having to move in front of a sensor or having to use specific equipment. This choice, however, also introduces challenges due to the heterogeneity of the home automation and robotics infrastructures, as well as due to the low power consumption requirements necessary for having a mobile platform with sufficient battery autonomy.

III. RADIO IN A NUTSHELL

The operating environments targeted by RADIO are domestic homes of elderly people. These homes generally do not have sufficient technological infrastructure to provide ad-hoc ambient assisted living services. Since unobtrusiveness is

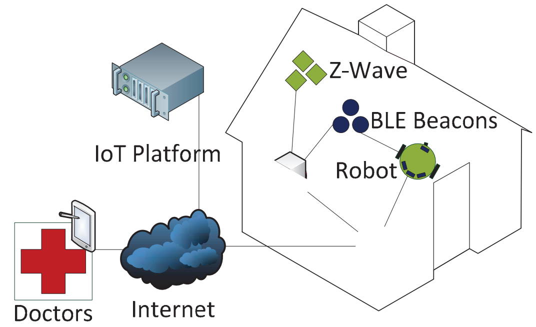

Fig. 1: RADIO architecture with IoT platform, Robot platform, and wireless sensor infrastructure.

a first-class requirement of the project, building an unobtrusive infrastructure connecting all hardware and software components is one of the main RADIO objectives. At a high level, the RADIO architecture is divided into the s*mart home services* and the *Internet-of-Things (IoT) platform* located in the cloud, as seen in Fig. 1. The smart home environment itself is comprised by the *Robot platform* and the *home controller gateway*. A brief description of those three basic components is given below.

Home Controller Gateway. The RADIO home controller gateway serves as the single point of communication between all the different network technologies that coexist in the RADIO environment (see Fig. 1) and the remote elements of the RADIO ecosystem, such as the IoT platform. This is because the gateway is connected to all available devices in the smart home environment such as the mobile Robot platform. No actual data processing (e.g., ADL recognition) is expected to happen in the gateway.

Robot Platform. Our mobile Robot platform is based on TurtleBot2 [15]. Out of the box, the TurtleBot2 features sensors for odometric measurements as well as bump, cliff, and wheel drop sensors. Since the Robot should act autonomously and not be remotely controlled, the Robot has to perform several computationally intensive tasks perpetually like cognition, motion control, perception, and localization. The main processing unit of the Robot will be a Xilinx PicoZed with a Zynq-7000 all programmable System on Chip (APSoC) [16]. Additionally, the Robot is outfitted with an audio-visual sensor for mood recognition purposes and navigation. The Robot's main objective is to monitor and perform tasks for the patient without disturbing him. The patient should never be bothered by the Robot but should perceive it as a "pet" which has to be taken care of.

IoT Platform. The main task of the IoT platform is to provide caretakers and doctors with relevant data regarding the patient's activities, health, and mood. In other words, the IoT Platform is used as the central repository of abstract, high-level historical information and it provides an easy-to-use API for patient monitoring and smart home control.

IV. CHALLENGES IN COMMUNICATION INFRASTRUCTURE

The smart home environment contains several protocol domains which fulfill different tasks while different entities are present in each domain. Transferring data between those protocol domains in a power-conservative manner is a challenging problem. The three protocol domains employed in RADIO are:

Bluetooth - WIFI/LAN domain. The Bluetooth domain consists of two different entities: *the smart home gateways* and the *Robot platform*. The Robot platform has a direct connection to Bluetooth beacons and to the smart home LAN. Therefore, the Robot can potentially function as cross-domain interface for Bluetooth-to-LAN. The smart home gateways are also able to communicate with the Bluetooth domain. In the Bluetooth context, the gateways, on one hand, are responsible for aggregating data from Bluetooth devices and conveying them to the IoT platform and vice-versa. On the other hand, the gateway can serve as connection entity between specific Bluetooth devices that cannot communicate directly. In order to offer the above features and functionalities the following challenges will be addressed in the context of the RADIO project.

Challenge: Bluetooth Data Exchange Infrastructure. The gateways need to extract the payload of each Bluetooth message and send it via LAN to the router and then to the IoT platform exploiting RESTfull API services and development designs [25][26]. Provision should be offered regarding communication in the reverse direction, i.e. from the IoT to the gateway (using LAN/WiFi communication) and from the gateway (using Bluetooth communication). In this way, cases of issuing commands, reconfiguration options and even reprogramming can be supported. Additional challenges such as multi-hop communication will also pose critical objectives in the RADIO communication environment.

Challenge: Gateway Data Management. A main aspect of the Gateway infrastructure concerns the management of information from the moment useful information is extracted from Bluetooth packets until the moment of the web-service invocation and vice-versa. An effective solution to this problem needs to take into consideration various parameters like data buffering capabilities, application specific traffic balancing policies, security policy application etc. Additionally, a mechanism to cope with temporal connectivity loss in either side will be offered. In that respect, different approaches will be evaluated ranging from straightforward parsers to sophisticated data management infrastructures such as producer-broker-consumer message passing protocol infrastructures.

Challenge: Indoor Localization and Monitoring. Bluetooth Low Energy (BLE) Beacons are small devices that continuously transmit data, allowing the identification of the respective sender. By using Bluetooth 4.0, it is possible to determine the signal strength at the receiver side. The data transmitted by the Beacons are unique as every device has its own id. The presence of at least three Beacons is sufficient to roughly estimate a position using trilateration. Consequently, this approach can enable an indoor positioning as well as monitoring system that is not dependent on GPS signals. Beacons can also be used to provide additional input data for simultaneous localization and mapping (SLAM), resulting in a more accurate positioning system. The respective services will be critical for the efficient navigation of the Robot.

Z-Wave - WIFI/LAN domain. The Z-Wave domain only interfaces with the smart home gateways (Fig. 1). Z-Wave is a wireless protocol designed for close range sensor and actuator networks. It does not require a coordinator node as it automatically initializes a full mesh network [14]. Thus, it is possible to modularize the architecture and expand it with additional sensors if necessary.

Challenge: Z-Wave Data Exchange Infrastructure. In order to analyse data from Z-Wave devices, an interface between the Z-Wave domain and the WIFI/LAN domain has to be developed. On one hand, respective communication infrastructure will be able to control the type of data that is transferred outside of the RADIO Home. On the other hand, adequate attention will be paid to enriching raw data with metadata needed for analysis, such as metadata regarding the functionality and position of the collecting device.

The challenge of putting everything together. In order to evaluate and optimize the data exchange between the various sensors and platforms residing in the home environment, an IoT simulation framework is being developed. The framework is based on OMNeT++ network simulator. The original OMNET++ simulator is extended, following a Hardware-in-the-Loop (HiL) approach, in order to build a virtual environment with physically available devices (e.g., sensors, actuators, but also processor models) to achieve maximum flexibility. The simulator allows the evaluation of components and devices that are not physically available and provides gateway functionality for the translation between different device-specific protocols.

In the current development phase, the IoT simulator allows the integration of Z-Wave and EnOcean periphery. The next step is to take into consideration Bluetooth transmitters (e.g., BLE Beacons).

V. Challenges in Data Processing

The RADIO approach relies heavily on the collection and processing of audio and video streams for analysing and recognising activities of daily life (ADL). Recognizing the emotional status of patients and the identification of emergency situations, such as the detection of falls, are also of high importance. There are two types of data which are going to be processed in the RADIO system:

- Streaming data: These are high throughput data which come from the continually receiving output of a microphone (audio stream) or a camera (video stream).
- Event/measurement data: These are event/control-like data with relatively small size, collected by the sensors or the detection mechanisms. Event data can also be the outcome of an algorithm which analyses streaming data, e.g. processing of video can lead to the generation of an “exit” event if the camera looks towards the door.

Fig. 2 illustrates the Robot processing elements and their interfaces. As the figure indicates, the bulk of processing is performed on the FPGA platform as this is the point where

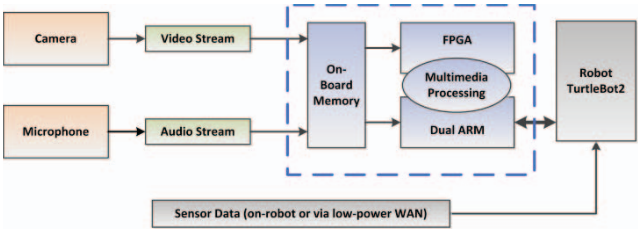

Fig. 2: A high level diagram of the on Robot processing nodes.

sources of audio (microphone) and visual (camera) streams are located. These two sources of high-content streaming data are directly connected via wired links to the on-board FPGA memory (so as the memory transfers are minimized). The FPGA platform will be a Xilinx PicoZed with a Zynq-7000 all programmable System on Chip (APSoC) [16]. It includes an ARM Cortex A9 dual core processor (equipped with a Neon co-processor) interfaced with the FPGA programmable logic.

The camera and audio data streams will be continuously monitored by the processing elements of the FPGA platform and when activity is detected the corresponding algorithms (which can analyze and recognize the activity) will be triggered. Depending on the specific combination of algorithms that get triggered, some or all computational tasks may be executed in the processor (ARM cores) or accelerated with fixed logic or reconfigurable hardware components inserted in the FPGA reprogrammable logic.

A. Robot Control

For the Robot to act autonomously (as opposed to being remotely controlled), several computationally intensive tasks must be perpetually performed. These tasks are shown in Fig. 3. The cognition phase is responsible for planning a path or a sequence of movements towards the Robot's current goals. The motion control task is responsible for the physical interaction with the environment. The perception task is required in order to process all available sensor information and let the Robot gain a sense of its environment. Lastly, the localization task tries to determine the Robot's location inside the current environment.

Localization and mapping (SLAM) represents a fundamental problem in robotics [17]. It arises when neither a map of the surrounding, nor the actual position of the Robot is known. For RADIO, SLAM allows to deploy the system without requiring that the map of each deployment's environment be predefined. There are two main lines of research on SLAM, one using *Extended Kalman Filters* and one using *Particle Filters*. Both create simultaneously a map of the environment and localize the Robot relatively to this map. This allows the Robot to autonomously plan and realize its movement. In RADIO, we will use SLAM based on particle filters. The main advantages of this approach is that (a) it allows sensor data fusion by taking into account heterogeneous information from a motion update model, odometry, and multiple range finders and localization aids (such as RFID tags) and (b) it is an *elastic* algorithm [18], meaning that the number of particles can be adjusted to find an appropriate trade-off between accuracy and processing requirements.

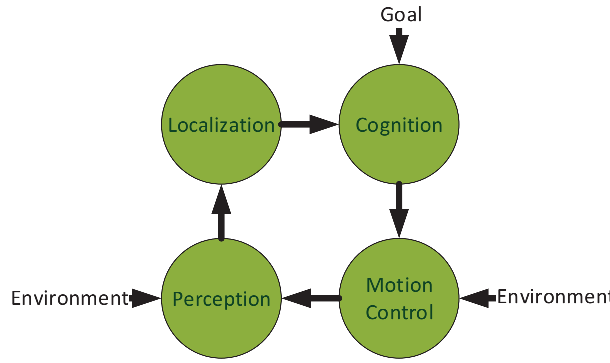

Fig. 3. The four task phases of an autonomous Robot.

As shown in Fig. 3, localization is important for the cognition task since it provides the relevant data regarding current distances to obstacles for navigating in a way that is safe for the Robot as well as the people in its environment. The main challenge as well as an active area in man-machine interaction research is to push beyond by simply avoiding obstacles. The goal is to move in a manner that takes into account the movement of humans in the environment in order to plan a Robot movement that is not only safe, but also never becomes an obstacle for the human.

B. Sensor Data Analysis

Another important task of the Robot is to unobtrusively scan the patient for his current mood or signs of fatigue. The first step to achieve this task is to detect the patients face and then perform mood or fatigue analysis on the region of interest. Most relevant audio-visual analysis is based on *feature extraction* followed by using the extracted features in *Support Vector Machine (SVM)* or *AdaBoost* classifiers. Since the Robot platform uses a PicoZed as the main processing unit, all algorithms should be optimized for runtime performance. By speeding-up the processing time of the algorithms on PicoZed, more processing time is left for other tasks, making the Robot more responsive.

Histogram of Oriented Gradients (HOG). In order to reliably detect humans, features which are also mostly independent from external influences such as lighting conditions or changing background have to be extracted. One feature detection algorithm is the histogram of oriented gradients (HOG) algorithm [19]. It is often employed in computer vision scenarios for human detection since it provides a high success rate in real-time. The basic idea of HOG is that an accurate feature set for a human body is based on its silhouette.

The flow of the algorithm to extract this feature set can be divided into six parts: luminance calculation, gradient computation, magnitude and theta computation, cell histogram formation and block normalization. If a colored image serves as input to the algorithm, the luminosity of each pixel has to be calculated. Luminosity calculation is of course excluded when a grayscale image serves as input, as the grayscale values represent the luminosity. The resulting luminosity image is then used for vertical and horizontal gradient computation. The output of the gradient computation is an horizontal and a vertical gradient image. Out of these two images the gradient magnitude and the direction for each pixel can be calculated. With these two parameters, the cell histogram can be computed. The last step normalizes these histograms to improve invariance to illumination and shadowing. The feature descriptors resulting from the HOG algorithm have been proved to be robust and reliable descriptors for human detection [19]. An implementation of the HOG algorithm for real-time human detection running on a Xilinx Zynq SoC can be found in [21]. In the context of RADIO it will be used for the unobtrusive integration of the mobile Robot platform to the smart home.

Face Detection. For face detection, the Viola-Jones algorithm [20] has proven to be effective. With the help of cascaded rectangular Haar-like features, robust face detection can be performed. Since larger images require more processing time for facial feature detection, the input image's size for the face detection should be reduced as far as possible beforehand. Therefore, a detected face in the last image is stored and the region of interest should be analyzed first before resorting to the analysis of the full image. If a face is already detected in the image, the position and size of the rectangle surrounding the face is stored for future face detections. A simple face tracking method is to increase the size of the region of interest around the detected face. Then a slightly larger region of interest than optimal is analyzed, but with a great increase in the detection rate between several images with moving people. With the help of depth images, the image size can be permanently reduced through foreground isolation resulting in accelerated face detection. Foreground isolation is achieved through binarization and contour detection on the depth image, so that the whole image never needs to be processed.

Acoustic modelling. The audio channel offers itself to extracting features pertaining to both mood [23] and events that can lead to infer ADLs [24]. In order to minimize the required computations, RADIO will extend the audio extraction pyAudioAnalysis Toolkit.[1] The toolkit records and segments audio and then processes it to extract features in two stages:

- Short-term feature extraction splits the input signal into short-term windows (frames) and computes a sequence of short-term feature vectors for the whole signal.
- Mid-term feature extraction computes statistics on the short-term feature sequences described above, such as mean and standard deviation over each short-term feature sequence.

The exact features computed are determined by the event and mood classifiers that will be used. Experimentation within RADIO will determine if the computational benefits outweigh the architectural complexity of centralizing audio feature extraction, especially when fusing input from multiple microphones.

C. *Additional Challenges in RADIO*

Challenge: Managing RADIO Platform using Profiling Tools. As noted, a PicoZed FPGA platform will act as the computational heart of RADIO. The FPGA will be responsible for managing the multimedia workloads (image, camera, sound, and speech workloads) targeting to extract specific ADLs from the elderly people. In addition, information captured by the various communication nodes will be also conveyed to FPGA for further processing and consolidation. The various multimedia and communication workloads must be executed simultaneously in order to shape a global and centralized view of all AAL components.

To deal with the above requirements, we must take advantage of all processing capabilities of the PicoZed platform. Our view is not to "see" the PicoZed as a typical FPGA acceleration mean, but as *an effective heterogeneous multicore platform*. Under this direction, three different types of processing nodes are co-allocated in a PicoZed platform. Those are: the dual core ARM processors, the Neon co-processor, and the FPGA programmable logic itself. Operating this apparently heterogeneous system in tandem formulates, inter alia, a mapping-allocation problem.

Obviously, the problem is more complex since the FPGA logic is a "morphable" computation resource without predefined capabilities. In any case, the first step in managing efficiently the underlying heterogeneous system is to formulate a toolchain of profiling, visualization and software analysis tools. The target is to extract specific characteristics from the executing applications (or from kernels/program phases of the applications) that will allow us to i) make safe mapping-resource allocation decisions and ii) guide the upcoming FPGA implementation phase.

Interestingly, there are a plethora of available profiling tools both open-source and proprietary. After reviewing the characteristics of the majority of those tools, we have ended up to a set of open-source tools that exhibit all the required aspects. Each tool is used to extract specific application characteristics e.g., ILP vs. memory bound phases. Based on our analysis, the combination of valgrind[2], oprofile[3], and vampir[4] offer all the necessary characteristics to assist us through the envisioned direction (the latter tool will be used for visualization purposes). Exercising and operating those tools in an integrated manner is one of our current activities.

Challenge: Identification of High Priority Data Processing Tasks and Hardware Task Scheduling. The goal of the software profiling tools is to orchestrate the execution of a specific Ambient Assisted Living (AAL) algorithm. However, several AAL algorithms will run simultaneously in the system, therefore an identification and categorization of the existing

1 https://github.com/tyiannak/pyAudioAnalysis

2 Valgrind Developers. http://valgrind.org, 2015.

3 OpenSource project. http://oprofile.sourceforge.net, 2015.

4 GWT-TUD GmbH. https://www.vampir.eu, 2015.

algorithms must be performed. High priority algorithms must be immediately executed or not be pre-empted by other tasks.

Since the main processing unit of the Robot platform is a PicoZed with a Zynq-7000 APSoC, two different types of scheduling have to be considered. The first handles the traditional scheduling of processes on the available hardware resources. The second deals with scheduling of the hardware tasks on the programmable logic. These hardware tasks can be interpreted as dedicated hardware resources which are specialized in executing one specific task efficiently and fast. However, the services of these specialized tasks are not required continuously during the lifetime of the system. This results in inefficient area usage of the FPGA when the whole hardware configuration is considered to be static. Therefore, a dynamic scheduler (operating in real-time) is required and this scheduler should take as input a "signature" or a profile of all available tasks and their designated priority. The goal is to fully utilize the available hardware resources for the acceleration of the currently executed tasks. If another task needs to be executed, the processing platform of the Robot should then automatically reconfigure its hardware to suit its current needs.

The scheduling method has to handle several conflicting design goals such as real time constraints, resource efficiency, and energy efficiency. Based on these constraints, the best task graph and the resulting sequence have to be determined by the task scheduler.

VI. Summary and Future Work

This paper presents the vision and the technical challenges of RADIO project, which intends to offer an efficient, reliable and adaptable system that employs Robots and heterogeneous IoT infrastructures for unobtrusive elder monitoring in assisted living environments. A major goal of RADIO is to drive the research one step further by exploring novel, highly efficient device architectures and associated services that can be applied in different domains and IoT infrastructures. Handling heterogeneity and efficiency -technically and methodologically- in a world that is expected to numerate more than a trillion interconnected devices in the near future, is a real challenge that can be the holy grail in the Internet of Everything world!

In this direction, RADIO project intends to make the first step by targeting a highly demanding domain such as real-time home monitoring and decision making for elderly people with mild cognitive impairment. This area, due to the restrictions and the design challenges it poses, is expected to act as a first domain evaluation of a new innovative concept that can be both commercially successful and academically challenging in other domains and research areas as well.

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