Distributed ICT Architecture for Developing, Configuring and Monitoring Mobile Embedded Healthcare Systems

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Keywords: Distributed Systems, eHealth, Mobile Health - mHealth, System Architecture, Smartphone Gateway, Embedded System, Mobile Wearable System.

Abstract: This paper presents a system architecture to support remote access to mobile embedded healthcare systems during development and use. It describes the system architecture developed to allow remote debugging, configuration and monitoring of mobile healthcare systems as well as the prototypes that have been developed to explore the architecture. The architecture has been applied in a concrete wearable embedded healthcare system for treatment of leg venous insufficiency through compression therapy.

1 INTRODUCTION

Distributed, mobile and wearable embedded healthcare systems give rise to many challenges both during the development and maintenance phases. In many situations the testing phase has to be carried out in another physical location than where the development is done, this can be caused by different reasons e.g. that the actual systems are coupled to a given physical environment or as in our case that the testing should be carried out on a certain location due to the placement of testing equipment and testing experts.

The wearable embedded healthcare systems which are target for the architecture described in this article are safety-critical, thus requiring special attention to fault tolerance, and have a limited user interface consisting of e.g. a push button and one or more LEDs, for which reason they can be difficult to monitor and debug during both test and maintenance phases.

The distributed architectures described in this paper are developed for the e-Stocking EU Ambient Assisted Living (AAL) Project. The aim of the project is to develop an intelligent, mobile and embedded healthcare system, an ICT-enabled medical Graded Compression Stocking (GCS) solution (described in section 5.1). Key features of the novel intelligent stockings are easy application and operation, compliance with individual patient's clinical needs, and enhanced mobility and self-sufficiency.

This paper is structured as follows: Section 2 presents the state of the art on the topic. Section 3 yields a list of requirement for the proposed architecture. Section 4 describes the architecture and scenarios proposed to meet the requirements . Section 5 describes design and implementation details. Section 6 presents and discuss the results obtained. Section 7 describes future work and conclusions.

2 STATE OF THE ART

The AAL program aims to find efficient solutions to help elderly persons maintain self-sufficiency. The promises and challenges of AAL have been described in (Sun et al., 2009) and (Estudillo-Valderrama et al., 2010).

To enhance self-sufficiency of patients who wear the ICT-enabled medical GCS, the GCSs must to be mobile and preferably be monitorable regardless of location. An obvious solution to this is to use a smartphone as a communications gateway between the embedded system and external systems as described in (Germano et al., 2009) and (Bialy et al., 2011), in which the local wireless communication with the embedded system is based on the Bluetooth standard commonly supported by smartphones. Trends and importance of using wireless technologies in E-Health are described in (El Khaddar et al., 2012).

Architectures for smart homes and home healthcare systems have been researched in many projects,

Hansen F., Jensen T. and Esparza Isasa J..
Distributed ICT Architecture for Developing, Configuring and Monitoring Mobile Embedded Healthcare Systems.
DOI: 10.5220/0004911904840489
In *Proceedings of the International Conference on Health Informatics* (HEALTHINF-2014), pages 484-489
ISBN: 978-989-758-010-9

four of which are evaluated in (Fabbricatore et al., 2011). This has not been the focus of our current research, which describes a stand-alone healthcare system for the single medical purpose of delivering an intelligent compression solution. Our approach could readily be integrated with a common ICT platform in the home for extending the possibilities of the current solution or for integrating other patient-related healthcare measurements such as vital signs.

Extensive research has been conducted in Wireless Body Area Networks (WBAN), e.g. (Latré et al., 2011), (Chin et al., 2012) and (Hansen and Toftegaard, 2011), where the WBAN integrates several sensors or actuators located on a patient which communicate with a wearable gateway node, such as a smartphone. In (Yang and Gerla, 2011) they presents a personal gateway, where a specially designed device, called a PHM-Gate, preprocesses sensor data, as in the WBAN case, before the data is forwarded to a smartphone acting as a gateway for external communication.

To our knowledge, no research has been published on the design and use of a distributed ICT architecture to support the combined development, configuration and monitoring of mobile embedded healthcare systems.

3 REQUIREMENTS FOR THE SYSTEM ARCHITECTURE

This section lists the key requirements for the system architecture:

R1 The system shall use a portable gateway for connection to external systems

R2 The gateway shall enable mobility by supporting mobile internet communication to centralized systems

R3 Communication to centralized systems shall be over the internet

R4 The system shall have a simple user interfaces, preferably consisting only of buttons and LEDs

R5 The system shall support remote software debug and download

These requirements, along with others, have formed the basis for the development of the system architecture and scenarios presented in Section 4.

4 SYSTEM ARCHITECTURE AND SCENARIOS

The system has four envisioned main application scenarios: Calibration and configuration, remote software debugging, remote software updating, and health status monitoring. To support the implementation of these scenarios the system architecture depicted in the UML deployment diagram in Figure 1 has been defined.

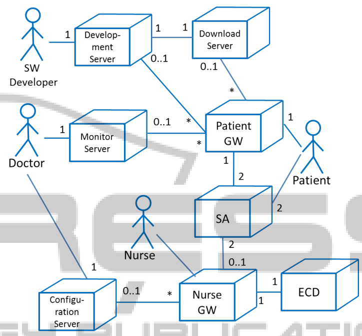

Figure 1: System architecture.

The actors in Figure 1 are briefly described below.

Patient: The wearer of the Stocking Assembly (SA) and recipient of compression therapy. The Patient may interact with the Patient Gateway on a regular basis to follow treatment progress.

Nurse: A nurse (or similarly skilled person) who is responsible for the calibration of the configuration of the SA to the patient through the use of a Nurse Gateway

Doctor: A Doctor who is responsible for the compression therapy. The Doctor issues the SA to the Patient, defines configuration parameters for the SA and remotely monitors treatment progress.

SW Developer: A skilled person responsible for the development and continued support of software for the SA. The SW Developer remotely debugs the deployed SA software and makes new software updates available through the Download Server.

These actors interact with the system through a number of nodes described below.

SA: Stocking Assembly (SA): The actual stocking worn by the Patient which administers compression to the Patient's leg in accordance with calibration parameters.

ECD: e-Stocking Calibration Device. A device used to provide the SA with actual on-skin pressure readings in the calibration scenarios.

Nurse GW: Nurse Gateway. A smartphone used by the Nurse for calibration and configuration of the SA for the individual patients.

Patient GW: Patient Gateway. A smartphone used by the Patient to monitor treatment progress. Also the gateway used for remote debugging of the SA and the remote installation of software updates

Development server: A computer system used to develop and debug software for the SA.

Download server: A server which publishes SA software versions.

Monitor server: A server which makes health status indications for specific SAs available to the Doctor.

4.1 Calibration and Configuration

This subsection describes two closely related sub-scenarios, namely calibration of the SA and configuration of same. The calibration scenario covers the initial calibration session of the SA. Calibration ensures that the SA will deliver the correct compression to the patient's leg regardless, within the dynamic range of the SA, of the patient's leg shape and size. Periodic follow-up calibration sessions, e.g. once every month, can be carried out to ensure that the compression therapy administered to the patient's leg is optimal even as the patient's leg changes size and volume, and as the elastic properties of the SA changes over time.

To support optimal results of the compression therapy, the compression levels applied to the patient's leg are configured initially and can be reconfigured periodically as the treatment progresses.

The actors and nodes involved in configuration of the SA are the Doctor (primary actor) and the Configuration Server (see Figure 1) who specifies the compression levels of the SA's individual compression sections as he sees most prudent to the compression therapy. To support his decision-making, the Doctor may leverage results retrieved from the SAs (further details provided in subsection 4.4). Having defined a new configuration, the Doctor uploads this to the Configuration Server. Configurations are stored on the Configuration Server and retrieved during calibration (see below).

Calibration involves the Nurse (primary actor) and Patient (secondary actor), see Figure 1, and the SA, Nurse Gateway, ECD and Configuration Server as nodes. Calibration is to be performed in the patient's home or a nursing home. When calibration shall take place, the Patient applies the SA and the Nurse connects the SA and the e-Stocking Calibration Device (ECD) through an application running on the Nurse Gateway. The Nurse then uses the Nurse Gateway to retrieve configuration parameters, defined for the Patient by the Doctor, from the Configuration Server and downloads them to the SA. Subsequently, the Nurse commands initiation of the calibration, during which the SA compresses the Patient's leg to the configured level, all the time evaluating the actual on-skin pressure through communication with the ECD. When the correct level is reached, the SA is calibrated. At this time, the connections to and from the Nurse Gateway can be dismantled and the SA again be left to operate in its regular stand-alone mode.

4.2 Remote Software Debugging

In this scenario the system developers remotely retrieve information regarding the system's execution, errors occurred etc.

The actor involved in this scenario is the SW Developer (primary actor) while the nodes involved are the Patient Gateway, the SA, and the Development Server. In this scenario, the SW Developer will initiate a debugging session with a specific remote device. The Patient Gateway is commanded to execute a remote debugging application which will connect to the SA and the Development Server. When connected, the SA can pass debug information through the Patient Gateway to the Development Server and thus to the SW Developer who may then evaluate the information. During this session, the Patient may be required to participate, e.g. by pushing a button etc. If this is the case, the Patient Gateway may be used to communicate instructions directly to the Patient by simple text messages or telephone conversation.

4.3 Remote Software Update

This scenario facilitates remote updating of the SA software, e.g. to distribute a software update or bug fix, both in the development, test, and deployment phases. The actors and nodes are the same as in the aforementioned remote debugging scenario with the addition of the Download Server node.

When an update to the existing SA software has been produced and properly evaluated, the SW Developer may push this update to the Download Server, thereby making it available to all SA's deployed. At regular intervals, e.g. once per day, the Patient Gateways will establish contact to the Download Server to check for software updates for the Patient's SA. If such an update is found, the Patient Gateway will download it, request connection to the SA and initiate the download of the updated software to the SA.

As the SA is considered a safety-critical system, care must be taken to ensure that the software update which is installed in the SA is indeed functional, and a fall-back mechanism which resorts to the last known functional software must be in place. Several alternatives exist for this purpose, of which the simplest one is to let the Patient Gateway upload the existing software from the SA, download the new version to the SA and have the SA verify the software. Should verification of the new software fail, the Patient Gateway may resort to re-downloading the previous version of the software. Alternatively, the SA shall be equipped with sufficient persistent memory to hold two software versions at the same time so that the functional software version can be present while a new software version is downloaded and evaluated.

4.4 Health Status Monitoring

Health status monitoring refers to the monitoring - remote or local - of key health status indicators emanating from the SA. This scenario can be divided into two sub-scenarios: Local and remote health status monitoring.

In the local health status monitoring scenario, we find the Patient, the Patient Gateway and the SA involved. The Patient uses the Patient Gateway to establish communication with the SA. When the connection is established, the Patient uses a health status monitoring application to review health status indications, both current and historical, provided by the SA (e.g. usage statistics) and derived treatment progress indications. It is envisioned that the possibility to continuously monitor health status indicators will motivate the patient to engage in continued treatment and thus improve therapeutic results.

Remote monitoring covers the scenario in which the health status indications, again both current and historical, are monitored remotely. The participants in this scenario are the Doctor, the Monitor Gateway, the Patient Gateway and the SA.

The Doctor, who is responsible for the patient's treatment, periodically requests health status indications from the SA (e.g. leg volume) and reviews them. This scenario will not replace the regular visits of the Patient to the Doctor, but the data harnessed and knowledge derived from objective health status monitoring including usage statistics are believed to be a valuable supplement, which will qualify the Doctor's discussion of treatment progress with the Patient. Furthermore, this scenario will allow the doctor to proactively adjust treatment parameters, e.g. changes in compression configuration, thus increasing the efficiency of the compression therapy. Finally, as evaluation of health status indications is considered to be much faster than as-many face-to-face visits, this scenario would also allow the doctor to evaluate the treatment of more Patients more often.

Figure 2: The Stocking Assembly, constituting the mobile embedded healthcare system in this study.

5 DESIGN AND IMPLEMENTATIONS

This section presents design and implementation issues for the different subsystems that compose the different architectures presented in the section above.

5.1 Mobile Embedded Healthcare System

The Stocking Assembly (SA), which constitutes the mobile embedded healthcare system in this study, is shown in Figure 2. The SA consists of the stocking itself (items 1 and 2), an actuator box for supplying air (item 3) to the compression sections and an Electronic Control Unit (ECU) for controlling the compression of the patient's leg (item 4). The three individual compression sections of the SA are mounted laterally to cover the entire length of the stocking. Each compression section consists of two air chambers mounted at same height on both sides of the leg.

By compressing the sections to different levels the compression applied to the patient's leg can be graded from ankle level to just below the knee. The compression delivered to the leg is continuously regulated through measurement of the air pressure in the air chambers or the on-skin pressure. The compression applied is calibrated to each individual patient by means of the e-Stocking Calibration Device (ECD).

The compression is managed by an object-oriented embedded software application executing atop an operating system on the ECU which controls sensors, actuators, user input and other external interfaces. The ECU hardware consists of an ARM Cortex-M3-based processor implemented on a Cypress PSoC5 hardware platform and various peripherals and custom-made hardware interfaces.

5.2 e-Stocking Calibration Device

The ECD interfaces pressure sensors mounted to measure on-skin pressure and provides these measurements as data to the ECU against which the SA can calibrate the air pressure level in the compression sections. The ECD features a Bluetooth interface to communicate with the SA during calibration. The ECD has been implemented using the same hardware and software technologies as the ECU.

5.3 Smartphone as a Gateway

Both the Patient and the Nurse Gateways consist of an Android-based smartphone device which runs a Gateway application. The Nurse Gateway will execute a Gateway application which facilitates the Calibration and Configuration scenarios described in 4. This provides bridging services when the SA and ECD should be connected as well as the graphical user interface for use in the calibration process. The Gateway connects wirelessly to the SA and ECD, respectively, and forwards sensor data requests and responses to the counterpart.

The Patient Gateway application will support the other scenarios described in Section 4 by supporting remote debugging and downloading of software updates, and by supporting system and medical diagnostics data retrieval from the SA.

5.4 Wireless Communication

The ECU, ECD and Gateway make use of a Bluetooth-based wireless communication interface. This technology will be replaced by Bluetooth Low-Energy (BLE or Bluetooth 4.0) in the next version of the prototype. This technology has not been incorporated yet into the prototypes since the number of smartphones supporting BLE is reduced. The incorporation of BLE will bring a number of advantages to the system, of which a more simple link establishment compared with Bluetooth 3.0, energy efficiency and low latency are the most relevant ones.

5.5 Communication from Gateway to Centralized Systems

The Gateways communicate with a number of centralized systems through the Internet. This is achieved through the mobile internet access or a Wifi connection, both incorporated in the smartphones used for Gateways. A design alternative is to integrate the Internet access interface in the ECU. This would make it possible to eliminate the Patient and Nurse Gateways from the architecture and thus simplify the architecture. However, this would make the SA heavier and more power demanding, and eliminate the possibility of having a graphical user interface for the SA on the Gateways.

5.6 Centralized Systems

The embedded healthcare system interfaces a number of services which can be deployed on the same or different servers. The services are:

Configuration Service: Allows retrieving and changing the treatment parameters without needing physical access to the SA.

Development Service: Allows remote debug and inspection of the state of the SA.

Monitoring Service: Allows remote monitoring of health status and usage statistics.

Download Service: Allows remote deployment of software updates to the ECU.

6 DISCUSSION AND RESULTS

At the current time, a prototype of the architecture supporting the calibration scenario described in 4 has been implemented and is used as an integral part of the e-Stocking project. Furthermore, a prototype of the remote debugging scenario is under development. Presently, the SA-Patient Gateway interface is established and rudimentary debugging information can be requested remotely by transmitting raw messages to the Patient Gateway.

Being able to remotely gauge the performance of a safety-critical such as the e-Stocking discussed here by evaluating a number of pre-defined parameters remotely while the system operates is foreseen to be of substantial value in the development, test, and early deployment phases in which system information may be harnessed from the field in the event of system failure or to gauge the efficiency of e.g. recent system updates. Such information, gathered in the field and made available to developers, is crucial to remove errors, enhance the user experience and increase system effectiveness.

As is the case with remote debugging, remote software updating is believed to be of substantial benefit to both healthcare bodies and patients, as the system can be updated without requiring the system (and thus the patient) to return to the doctor or nursing home.

In a longer perspective it may be beneficial to feed the health status indications into an Electronic Patient Record (EPR) system to fuse information harnessed from the SA with patient information harnessed from other sources to supplement the big picture of the treatment of a patient. If this is the case, the architecture depicted in Figure 1 will have to be expanded as necessary to provide access to the EPR system.

7 FUTURE WORK AND CONCLUSIONS

On the SA, future work remains for the integration of the remote debugging and remote software update scenarios to enable the SA to handle debug and download requests, respectively. The latter will require the SA to be extended so that it may also receive and verify the new software prior to its use.

Work also remains to be done on the individual Gateways, most notably in the implementation of the common connection handling and secure protocols to the Development, Download, Monitoring and Configuration Servers.

Further work is also required to provide the human actors with proper user interfaces, e.g. to allow the Doctor to retrieve health status indications for a specific Patient's SAs, and to specify configuration parameters for same.

This paper has listed the requirements of an distributed ICT architecture supporting development, configuring and monitoring mobile healthcare systems, using the e-Stocking project as a case study. It then described the architecture, design and implementation issues and the current status of the development of this architecture and the e-Stocking prototype. Furthermore, it has described the technical challenges posed and how they were overcome, and what work remains to be done.

ACKNOWLEDGEMENTS

This research is funded by the EU Ambient Assisted Living Joint Programme, eStockings Project under grant agreement no. AAL-2011-4-020.

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