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Mobile and wearable devices in an open and universal system for remote patient monitoring

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ABSTRACT

This paper describes the results of research in the area of remote patient monitoring. We present an innovative data acquisition module, detailing its architecture as well as design decision undertaken during our work. The module is implemented as a mobile application executed on top of the Android OS. The modular and open architecture of the application and the unified measurement processing it exemplifies facilitate easy integration with new medical devices. The proposed installation and pairing process simplifies the configuration of the mobile application, which is important in this type of system. Our solution is already undergoing pilot evaluations and has been successfully applied by medical practitioners in the treatment of patients with cardiovascular diseases.

1. Introduction

The structure of our society is changing. As discussed in [1], the number of people aged 60 or more will triple in the next 40 years. In addition, the number of persons who suffer from chronic health conditions or disabilities is increasing. Non-communicable diseases (NCD – such as cardiovascular diseases, diabetes, cancer and chronic respiratory diseases) were responsible for 63% of all deaths in 2008 [2]. The treatment of NCDs is usually long, costly and requires frequent medical consultations. As a result of societal aging and increased number of patients with chronic conditions, more and more people will require long-term personalized medical care.

Medical Cyber-Physical Systems (MCPS) are a class of systems which integrate physical processes with computations and communication for treatment of patients. One of the interesting applications of MCPS is remote patient monitoring. The development of new types of medical sensors, as well as the increasing availability of mobile and wearable devices, make MCPS feasible. To be effective, such a system should be easy to install and to use even for disabled persons, and should be open to integration with new types of medical devices.

Ongoing developments in the area of mobile health technologies and pervasive Internet access can make healthcare services more affordable, accessible and available. The availability of mobile phones in developed countries is on the order of 100%. Moreover, the latest generation of smartphones have powerful computing capabilities, enabling open application development. Such an environment allows data to be rapidly gathered from external and internal sensors built into mobile phones.

While there are many applications in the mobile healthcare domain, most of the offered solutions are of the closed variety. They typically provide a solution for a single treatment unit and are delivered by a specific care provider [3]. In contrast, our TeleCARE system for remote patient monitoring is open. The architecture of our solution allows patients to easily integrate with different service providers as well as different sources of medical data. In this paper we discuss the concepts applied in the design of the mobile part of the system (deployed on mobile phones).

This paper is an extended version of [4] presented in the Medical Cyber-physical Systems track at the IFAC/IEEE International Conference on Programmable Devices and Embedded Systems held in Krakow, Poland. We have added results of research aimed at extending our concepts to wearable devices. The results were verified in practice, based on a proof-of-concept deployment.

The contribution of the paper is (i) open modular architecture of mobile telemonitoring systems, (ii) simplified pairing process of the mobile application with the server, (iii) concept of *MedicalIntents* enabling easy integration of hardware and software medical devices for the Android OS on handheld as well as wearable devices, (iv) examples of new medical devices implemented for the TeleCARE system.

The paper is organized as follows. Section 3 discusses the TeleCARE system while Section 4 describes the mobile part of the sys-

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tem. Section 5 introduced the *MedicalIntents* mechanism useful in extending our data acquisition capabilities. Section 6 presents preliminary results of ongoing pilot studies. Section 2 compares results of our research with the current state of the art. The paper ends with conclusions presented in Sections 7.

2. Related work

Mobile healthcare applications are the focus of various research initiatives and clinical trials. They are also often used in the treatment of chronic diseases. From the functional point of view, mHealth applications can be divided into the following categories [3]: assisted healthcare, supervised healthcare, continuous monitoring and self-healthcare management. Our solution is an example of the continuous monitoring group – the most sophisticated among the first three categories. This type of system offers fully automatic analysis of patient vital signs, enabling automated responses from the supervising system as well as non-automatic responses from physicians. Analysis is performed by the reasoning engine which can correlate data from different sources and provide feedback to patients. Several examples of such systems are described in literature. *The WANDA.B* system [5] is an integrated architecture where each subsystem measures a different vital parameter. *The WANDA.B* provides mobile applications for monitoring patients in real time. If any measured value exceeds its corresponding acceptable range, the system alerts caregivers. Unfortunately, the WANDA.B system [5] does not support medication dosage and individual health plans. *The MyHeart Project* [6], in addition to built-in sensors and Bluetooth-enabled devices, offers support for body-area sensor networks (for measuring and analyzing ECG signals). The system, however, does not support medicine intake management and sophisticated treatments plans – although from the data acquisition perspective the mobile application has a modular design which allows it to integrate with various medical data sources. *The MediNet* [7] system allows patients to measure glucose level and blood pressure. It can also monitor medication intake, physical activity and dietary habits. It should be noted that the presented systems are focused on specific diseases and it might be difficult to adjust processing rules to take into account additional vital signs. In contrast, the TeleCARE system supports more personalized health plans and is open to any type of disease.

In the presented systems, medical data can be gathered from many sources, utilizing both external devices as well as built-in smartphone sensors (as shown in Section 5.3). External sensors comprise not only medical devices, but also all devices that can form a *Body Sensor Network*. In the latter case, the sensors can gather a wide variety of vital parameters as well as contextual information (e.g. regarding patients' spatial orientation or activity patterns). By using built-in sensors we can measure, for example, ECG, EEG, SpO2, heart and respiration rates, as well as glucose levels. Recent developments in biosensing technology allow researchers to apply devices that determine stress levels or assist with mood disorders, perform continuous blood screening or detect toxic substances in the patient's body. Patients can use wearable systems and devices in remote (and also direct) monitoring scenarios over extended periods of time. As a result, this technology can have a direct impact on citizens quality of life. First of all, it provides clinicians and researchers with data that is often inaccessible outside of a clinical environment, except via expensive and obtrusive ambulatory devices. Second, it provides an opportunity to study complex patterns and signals, helping prevent and predict events for the benefit of non-clinical populations. As an example of this kind of wearable system we can point to medically-certified wearable ECG products, such as the *VitalJacket* [8]. The device can process data on the fly, or can store it for later analysis (depending on available resources, such as smartphone connectivity or battery life). Researchers are currently using these devices in studying stress among bus drivers [9]. There are also efforts to enable ECG processing services in the cloud [10]. Wearable devices can be placed directly on the patient's body: for example, temporary electronic tattoos can perform useful measurements while being as close as possible to the source of the data. A smartphone application can then read all available measurements (such as body temperature, heart rate, blood pressure and stress levels) using, for example, *NFC* [11].

Data acquired from an external sensor can be transmitted in many different ways. Currently, one of the most interesting standardization initiatives is pursued by the Continua Alliance [12]. The main goal of this organization is to improve interoperability between remote patient monitoring devices. The TeleCARE framework currently supports devices compatible with the *Bluetooth Health Device Profile (HDP)* [12] as well as non-standard data access protocols based on Bluetooth (e.g. pillbox or protocols used by A&D devices). In addition, the open architecture of our framework facilitates integration with other communication and data access protocols (such as *ANT+, NFC* or Bluetooth Low Energy), owing to our uniform high-level abstraction of medical measurements.

Cardiovascular treatment is not the only area which can benefit from wearable devices – indeed, such devices are also widely used in general pervasive health scenarios [13]. In this approach several vital signs are continuously monitored in the patients' home environment, using various sensors (embedded in some device, such as a smartphone, or worn by the user). In the elderly, wearable devices are often used for fall detection and prevention. These systems may be based on inbuilt smartphone accelerometers or wrist-worn devices. Wearable devices help in detection and treatment of Parkinson's Disease (PD), and can assist PD sufferers. The finger-tapping method uses touch sensors (worn on the index finger and the thumb of the patient) to calculate a score. Evaluation of this index helps determine the severity of PD. Pervasive healthcare for children can help in the management of autism. In this scope, wearable devices can provide information related to child movement, while a smartphone can be used to analyze other contextual information. In asthma treatment, GPS sensors, accelerometers and gyroscopes can monitor the activity of the patient, delivering important data regarding location and exposure to air pollution. Wearable devices can monitor patients' sleep patterns and help detect sleep disorders such as snoring. This information may be valuable in treating apnea. Gesture or activity recognition systems using wearable sensors, e.g. accelerometers or gyroscopes, can be used in automatic diet monitoring.

In addition to the abovementioned solutions, there is ongoing research on applying activity tracking applications in medical practice [14]. As a result, the user receives a tool that can collect and monitor a range of fitness-related data in one place. Google Fit is a simple activity tracker released by Google that runs on top of the Android platform [15]. It can automatically recognize and track physical activities such as walking, running or cycling. Users can define their own goals regarding such activities, and track their progress (e.g., how far they are from a given daily goal). The application provides customized reporting based on e.g. location or duration of individual activities, as well as estimated number of calories burnt. It can also provide real-time statistics as well as recognize and track progress in strength training (if the patient owns an Android Wear watch, it will detect and count sit-ups, push-ups and squats). Moreover, the application can be integrated with external service providers. Using these mechanisms the user can track nutrition data and weight loss, as well as sleep patterns. *Apple's HealthKit* [16], originally released for iOS 8, works in a similar way to *GoogleFit*, alongside the company's standalone *Health* application. Much like Google, *Apple* mainly focuses on providing a generic framework, allowing application developers and device