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A smart mobile, self-configuring, context-aware architecture for personal health monitoring

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ABSTRACT

The last decade has witnessed an exponential increase in older adult population suffering from chronic life-long diseases and needing healthcare. This situation has highlighted a need to revolutionize healthcare and provide innovative, efficient, and affordable solutions to patients at any time and from anywhere in an economic and friendly manner. The recent developments in sensing, mobile, and embedded devices have attracted considerable attention toward mobile health monitoring applications. However, existing architectures aimed at facilitating the realization of these mobile applications have shown to be not suitable to address all these challenging issues: (i) the seamless integration of heterogeneous devices; (ii) the estimation of vital parameters not measurable directly or measurable with a low accuracy; (iii) the extraction of context information pertaining to the patient's activity to be used for the interpretation of vital parameters; (iv) the correlation of physiological and contextual information to detect suspicious anomalies and supply alerts; (v) the notification of anomalies to doctors and caregivers only when their detection is accurate and appropriate. In light of the above, this paper presents a smart mobile, self-configuring, context-aware architecture devised to enable the rapid prototyping of personal health monitoring applications for different scenarios, by exploiting commercial wearable sensors and mobile devices as well as knowledge-based technologies. This architecture is organized as a composition of four tiers that operate on a layered fashion and it exploits an ontology-based data model to ensure intercommunication among these tiers and the monitoring applications built on the top of them. The proposed architecture has been implemented for mobile devices equipped with the Android platform and evaluated with respect to its modifiability by employing the ALMA (Architecture Level Modifiability Analysis) method, highlighting its capability of being rapidly customized, personalized or eventually modified by software developers in order to prototype, with a reduced effort, novel health monitoring applications on the top of its components. Finally, it has been employed to build, as case study, a mobile application aimed at monitoring and managing cardiac arrhythmias, such as bradycardia and tachycardia, confirming its effectiveness with respect to a real scenario.

1. Introduction

The last decade has witnessed an exponential increase in older adult population suffering from chronic life-long diseases and needing healthcare. Indeed, the number of patients requiring health care services has raised proportionally with the growth in population, reaching approximately 2 billion by 2050, with 80% in developing countries (WHO, 2002). Therefore, it is predicted that the cost of hospitalization and patient care will rise worldwide and patients will find increasing difficulties to receive necessary treatments and assistance even in emergency situations. In light of the above, it is clear that there exists a need to revolutionize healthcare and provide innovative, efficient, and affordable solutions to patients at any time and from anywhere in an economic and friendly manner.

In such a direction, recently, a patient-oriented model is being considered, where patients are being equipped with knowledge and technologies to play a more active role in his/her health monitoring. This health monitoring can be rigorously defined as "repeated or

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continuous observations or measurements of the patient, his or her physiological function, and the function of life support equipment, for the purpose of guiding management decisions, including when to make therapeutic interventions, and assessment of those interventions'' (Hudson, 1985). This model embraces the principles of proactivity, independence, accessibility, and cost-effectiveness by using a wide range of mobile technologies such as smartphones, tablets, and wearable sensors for the continuous monitoring of patients' behavior and vital signs (Banos et al., 2014).

This allows for the possibility of an increased focus on individual health promotion and health maintenance rather than the traditional focus on dealing with the consequences of illness and injury after they occur. Such a transformation could have a profound impact on the cost of providing healthcare and on the level of health enjoyed by individuals during their lifetimes (Giffen et al., 2015).

This new trend of mobile health monitoring applications has been made possible due to a fabulous development in mobile devices and wearable sensors alongside wireless and cellular communication networks (Serhani et al., 2016). Existing applications of this typology essentially utilize wearable sensors to continuously monitor different physiological parameters of the patient. The observed information is sent to a hub, which collects the measurements and sends them, through communication networks, to the final destinations, i.e. the healthcare professionals or doctors. These latter observe the current medical condition and activities of the patient and provide a diagnosis or assistance based on the information provided by the applications. They can also get in touch with the patient through either the reversed channel or traditional communication media, such as the telephone or the SMS system (Serhani et al., 2016). The hub can be represented by the cloud, where sensed information is sent for being analyzed and accessed by the healthcare professionals or doctors (Forkan et al., 2014). Alternatively, it can be an intermediate personal computer or a mobile device, which in turn relays the received information to the healthcare professionals or doctors. Both these solutions are often adopted due to one of the main limitations of up-to-date wearable sensors, i.e. their processing and storage capabilities (Banos et al., 2014). Indeed, they are able to measure physiological magnitudes and convert them into machine-readable information, but they are equipped with very limited resources to process this information.

However, currently, a set of issues hampers both innovation and development of new mobile health monitoring applications.

Firstly, the heterogeneity of communication protocols and the mixture of addressing schemes used by wearable sensors of different vendors and models is challenging to be handled when developing integrated mobile health monitoring applications (Evensen and Meling, 2009). Most of the applications offered today is based on proprietary all-in-one solutions, where sensors might use either a proprietary RF protocol over the 868MHz band or ZigBee, Bluetooth, WiFi or another IEEE 802.x-based protocol over the 2.4 GHz band. Furthermore, many sensors have their own application-level protocol for communicating control commands and retrieving data. This implies that applications need to know anything about the physical or logical communication protocols used by each specific sensor, and that they can become unusable when a different sensor model is used even if they share the same basic functionalities.

Secondly, due to the miniaturization of electronic devices and the development of new ways of mobile computing in recent years, wearable technology has seen substantial advances, mainly triggered by the need for non-invasive, non-obtrusive ways to monitor physiological signals over long periods of time (Marques et al., 2011).

However, some vital parameters cannot be measured precisely, easily and noninvasively. For instance, today, systolic and diastolic blood pressures can be measured by means of digital monitors able to communicate their readings to smartphones via a wireless Bluetooth connectivity. The most accurate monitors feature an upper arm cuff, which is extremely invasive to be used to perform a continuous health monitoring. On the other hand, other monitors make use of non-invasive devices placed on the wrist or on the finger, and thus are characterized by a higher degree of freedom and easiness of use, but they generate less accurate blood pressure readings.

Thirdly, physiological parameters alone are not enough to characterize the patients' health status. For instance, an increase in the heart rate is considered abnormal when evaluated singularly, whereas it is classified as normal when it is registered while the patient is running. As a result, context information, and, in particular, information pertaining to the patient's activity, should be used as an additional factor in the interpretation of the vital signs. However, context information coming from sensors is often characterized by a lack of precision and accuracy as well as a fine granularity that make it difficult to use at the application level (Clear et al., 2007). Monitoring applications respond to events that should be generally richer than a single sensor reading and sensitive to user activities also affected by uncertainty. For example, the activity ''running'' is richer, and of more use than, the accelerometer motion values over the x, y and z axes, but it cannot be defined precisely, for instance, in terms of number of steps.

Fourthly, the capability of correlating physiological and contextual information, detecting suspicious anomalies and supplying warnings or suggestions to enable personalized monitoring and health management is undoubtedly a real-added value for monitoring applications. Embedding intelligent components able to reason over mobile devices and locally perform an accurate and continuous analysis of the patient's health status allows minimizing network transmission with remote stations, avoiding communication delays or interruptions and maintaining appropriate levels of security and privacy (Minutolo et al., 2015). However, the capability to reason over different forms of information and knowledge, often graded and affected by uncertainty, directly on the mobile devices represents a critical point, still pending to date.

Fifthly, notifying anomaly conditions to the healthcare professionals or doctors plays an effective role in enabling personalized monitoring and health management only in case when it is accurate and appropriate. However, notifications or alerts can be generated inappropriately, especially in cases when anomaly conditions are detected without taking into account that physiological data may vary for each patient. In these situations, they become ineffective and bothersome, leading to alert fatigue, a state in which the healthcare professionals or doctors become less responsive to them in general.

In literature, various solutions, architectures, and frameworks have been proposed for personal health monitoring, but they are not completely adequate to address all the above-mentioned issues. Starting from this consideration, in this paper, a smart mobile, self-configuring, context-aware architecture for personal health monitoring is proposed. This architecture enables the rapid prototyping of personal health monitoring applications for different scenarios, by exploiting commercial wearable sensors and mobile devices as well as knowledge-based technologies, in accordance with the following functional model. Sensor data are collected by wearable sensors and transmitted through a wireless communication network, stored and analyzed on mobile phones by exploiting knowledge-based formalisms and technologies, and finally sent from mobile devices to the healthcare professionals or doctors for subsequent storage and processing. A proper action depending on the patient's condition is determined and communicated to the healthcare professionals or doctors through mobile communication channels.

The word ''*smart*'' refers to its capacity to be adaptive, configurable, dynamic, and reactive, which accordingly makes it able not only to provide information about physiological condition but also personalized assistance for each patient in terms of notifications when he/she may be at risk. As the term ''*self-configuring*'' advocates, it is not based on a specific kind of sensor, but different and heterogeneous sensors can be used, offering uniform communication interfaces to external applications. The word ''*mobile*'' refers to its capability of using portable and wireless sensors as well as embedding data storage and data processing completely inside a mobile device, without requiring the usage