LONG-TERM MONITORING OF VITAL SIGNS FOR MOBILE PATIENTS

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Abstract: Hospitalization is a very expensive and resource consuming alternative for those patients that have to be continuously monitored. The design and realization of health monitoring applications has attracted the interest of large communities both from industry and academia. Currently many cardiac diseases are unpredictable; remote and continuous monitoring for reliable detection of these problems becomes essentially useful especially for elderly patients.

In the paper it is described a novel long-term wearable vital signs monitoring system which can real-time measure physiological signs such as ecg and spo2 (saturation of arterial oxygen) equipped with bluetooth connection. We propose a system architecture for pervasive healthcare that will open up new opportunities for continuous and reliable monitoring of assisted and independent-living residents by means of a set of services already included in Uranus (a service oriented middleware architecture for smart environments which provides basic functions for the rapid and easy integration of different kinds of biomedical sensors) and new added services to achieve a higher dependability level. A final analysis is shown to comprise the advantages of this monitoring system.

1 INTRODUCTION

The medical field is one of the areas, where pervasive healthcare computing appears as a tool of growing importance and the commercial applications developed for medical and healthcare systems are rising both in number and in users (Sarashon-Kahn, 2010). Although a rising elderly population worldwide has led to the establishment of an increasing number of long-term care institutions, the rate of healthcare nursing personnel is growing far slower than that of growth in the elderly population.

Wearable sensor technologies have made many improvements during the last decade and have attracted the interest of stakeholders from different domains like, as an example, healthcare.

A new concept in healthcare, aimed to providing continuous remote monitoring of user vital signs, is emerging. Currently many cardiac diseases are unpredictable; thus, remote and continuous monitoring for reliable detection of these problems, such as ventricular arrhythmia, becomes essentially useful especially for elderly patients with end-stage heart disease. The advances in sensor technology, as well as in communication technology and treatment of data, are the basis on which the new healthcare systems can be realized. Also, systems that are designed to be minimally invasive for health monitoring and are based on smart technologies conformable to the human body will help to improve considerably the autonomy and the quality of life of patients.

In-home and nursing-home pervasive networks mayassist residents and their caregivers by providing continuous medical monitoring, memory enhancement,control of home appliances, medical data access, and emergency communication.

Such kinds of environment are very critical forhuman safety and so the related applications must beconsidered safety critical and such a criticality shouldbe analyzed during the design phase. Some criticalityfor a long-term monitoring system of vital signs isthe *battery low power*, the *WiFi disconnection*, *the sensed data not delivered*, the *sensed data corrupted, etc.*

This paper presents a system design oriented

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around remote, continuous medical monitoring using medical devices. Its advantages for indoor and outdoor monitoring are described in the next sections. The proposed system allows health personnel to monitor patient's vital signs from a remote location without requiring the physician to be physically present to take the measurements.

Moreover, we concern on dependability (Avizienis et al., 2004) as the ability to avoid service failures that are more frequent and severe than acceptable. In pervasive computing, fault tolerance techniques help us to enhance dependability and some recent projects have employed related techniques, as described in (Chetan et al., 2005). Faults in a system are unavoidable and so the systems are never totally reliable, safe, available or secure (Avizienis et al., 2004). Pervasive healthcare systems need to take into account how to recover from such faults.

So, it is described a novel long-term wearable vital signs monitoring system which can real-time measure physiological signs such as ECG, SpO2 (saturation of arterial oxygen) and is fault tolerant.

The system presented uses an underlying middleware infrastructure, namely Uranus, which provides a set of basic services for the development of vital signs monitoring applications and also uses new services and facilities to make the system more reliable.

The rest of the paper is structured in the following paragraphs. The related work is presented in Section 2; Section 3 presents Uranus, which is a middleware infrastructure that we have specifically developed for dependable pervasive healthcare applications.

Section 4 describes the architecture of the long-term vital signs monitoring system. In Section 5 we discuss about the results on the dependability of the proposed system. Finally, Section 6 reports our concluding remarks.

2 RELATED WORK

Monitoring of physiological signals is not a new domain for research. A large number of monitoring systems, whose effectiveness and convenient economic impact have been widely demonstrated (e.g. (Darkins et al., 2008)), have been realized for many diseases. Concerning, for example, cardiovascular diseases, which represent the leading cause of death worldwide, many wearable and portable eHealth systems have been developed (e.g. (Cleland et al., 2005) (Lee et al., 2007)) (Mortara et al., 2009). The non-invasive monitoring capability of these systems concerns not only the prevention of cardiovascular diseases (e.g. myocardial infarction and stroke), but also their management, as in the case of chronically ill patients.

The number of recent research projects and commercially available systems proves the great useful of biomedical devices in the pervasive healthcare field. In the research presented in (Rodriguez et al., 2005), there are two main architectures for ambulatory vital signs monitoring systems, which use the mobile device with a direct link (wireless, usually Bluetooth) to the wearable sensors.

In (Khanja and Wattanasirichaigoo, 2007) a ZigBee sensor data collection network is the basis of the acquiring system, being responsible for routing all data to a server. The received data are then available to be visualized either through a web browser or through a PDA based application. Chen et al. (Chen et al., 2005) described monitoring of a set of vital signs based on mobile telephony and internet.

Although there are many papers that have proposed systems for monitoring vital signs, currently there is still no system to ensure reliable and continuous monitoring even when a patient is in motion (inside and outside the home). Also, our goal is to combine wireless communication, PDA phones and the new advances in sensor technology to enable the elderly to have their vital signs long-term monitored and recorded anywhere and at any time.

3 UNDERLYING MIDDLEWARE ARCHITECTURE

This section provides a description of both the architectural model of *Uranus* (Coronato and De Pietro, 2011) and its main services, which are depicted in figure 1.

We briefly describe the Uranus' components that are important for proposed system architecture of long-term monitoring.

Human Computer Interaction section includes mechanisms for the handling of natural and advanced interactions in a smart environment. Currently, it provides services like *TextToSpeech Service* to synthesize vocal messages, *SpeechRecognition Service* to recognize vocal commands and *Messaging Service* to send textual messages to the user's mobile device. This section is structured in different layers. The lowest layer integrates hardware devices; the heterogeneity of the

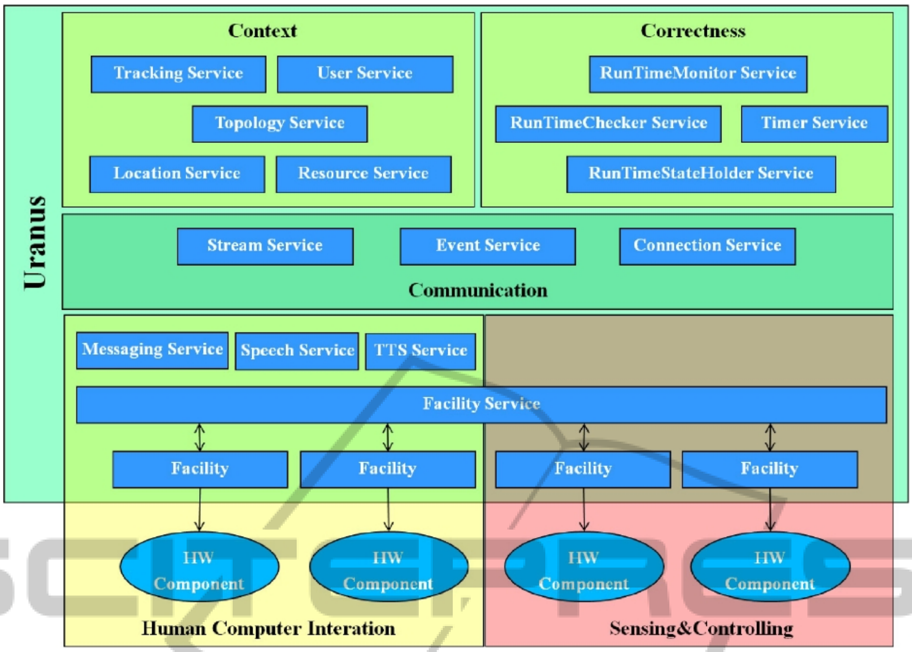

Figure 1: The underlying middleware architecture.

components at this layer is handled by means of software elements called facilities, which hide hardware devices to upper layers.

Upon this layer, a *Facility Service* provides the set of homogeneous facilities that stand below. As an example, for the case of RFID sensors (not shown in the figure), *RFID Facilities* handle all the RFID antennas deployed in the environment; thus, each RFID antenna has its own facility that will manage interactions between the hardware component and the rest of the software system. Upon this layer, information coming from all *RFID Facilities* (even for different kind of antennas) are collected by the *RFID Facility Service* which provides it to the rest of the services after a preliminary elaboration.

Hardware sensors and actuator are included in the Sensing and Controlling section (bottom-right side). Also, it is present a Communication section that offers communication functionalities. The *Event Service* exposes an asynchronous communication mechanism. This service supports the publish-subscribe mechanism (Felber et al., 2003) and is in charge of dispatching events between software components.

There are other services to provide the network connections (*Connection Service*) and to handle the data streams (*Stream Service*). The context is provided by the services that are in the top-left section of the middleware. The *Topology Service* is useful to represent the topology of the environment in a unique and uniform manner. In particular, locations are classified as semantic locations (buildings, floors, rooms, specific pieces of a room) and physical locations (the area sensed by an RFID antenna, the area covered by a WiFi access point, etc.) (Coronato et al., 2009). All movements of a mobile resource or user among the locations are tracked by means of a mechanism offered by the *Tracking Service*. The *Location Service* provides physical location information for mobile resources and users: it locates mobile users and resources that are tagged with RFID tags or WiFi enabled (Coronato et al., 2009). The User Service provides basic authentication mechanisms for users and by means of a list it controls the people that are active in an environment. Finally, the *Resource Service* extends standard mechanisms for registering and monitoring resources, like laptops, PDAs and sensors.

Last section is related to the correctness. We just report the services that compose it: the *RunTimeStateHolder Service* (this service holds and exposes the state of an ambient as intended in *Ambient Calculus* (Cardelli and Gordon, 2000)); the *RunTimeChecker Service* (this service checks, on behalf of an ambient, the correctness properties); the *Timer Service* (this service holds and verifies temporal constraints), and the *Monitoring Service* (this service monitors the entire system).

One of the key points of Uranus is the possibility of conferring stringent dependability requirements, which is an emerging issue in eHealth monitoring applications (Bohn et al., 2003).

4 SYSTEM ARCHITECTURE

This section presents the system architecture (see figure 2) developed on top of Uranus which performs a long-term monitoring of vital signs.

This system has been realized to monitor long-term (e.g. for 48 hours) the value of the oxygen in the blood of a chronically ill patient. A residential gateway is deployed at the home of the patient, although the monitoring must continue even when the patient is at work or elsewhere outside the home. This rises the need of handling implicit requirements like the power consumption of battery driven devices, network switching, and reliability assurance.

The system includes an oximeter, equipped with Bluetooth connection, permanently attached to the patient, which senses the value of the oxygen and transmits it to a PDA. The PDA, in turn, forwards data to the residential gateway. Data are transmitted either over the WiFi domestic network while the patient is at home, or over the GPRS network otherwise. The system must be able to detect connection failures when the patient leaves the house; i.e. it must switch from the WiFi connection to the GPRS connection. On the contrary, when the patient comes back home, the system must reuse the WiFi domestic connection. Current implementation integrates the resources described in table 1. Another important issue concerns the power consumption of battery driven devices, which is a limiting factor for long-term monitoring. Although the emerging of new technologies (Kansal et al., 2007) and new standards like the bluetooth low energy profile, this issue can not be considered definitively solved (Zhang and Xiao, 2009). For this reason, the system must be able to detect low battery levels and to migrate onto spare devices.

To realize this system we have implemented new services and facilities in addition to those offered by Uranus; they are useful to add new functionalities: the management of the different kinds of communication (Bluetooth, WiFi and GPRS), the inquiry (by means of the Bluetooth communication) of medical devices to use for the monitoring, the level of the PDA's battery and finally the switch of the connection type (WiFi -> GPRS and vice versa). By means of these added modules, we are able to tackle dependability issues for these systems.

The new Services and Facilities are:

BatteryMonitor **(service)** checks the level of the battery of the PDA;

ConnectionMonitor **(service)** handles connection handover and switches if necessary;

Discovery **(service)** provides the BluetoothDiscovery;

BluetoothDiscovery **(facility)** looks for the devices with Bluetooth enabled;

IPConnection **(facility)** to realize a communication between the residential gateway and the PDA through a WiFi or GPRS connection;

WiFiConnection **(facility)** to realize a WiFi connection when patient is at home;

BluetoothConnection **(facility)** to realize a communication between the PDA and the medical device (ECG or SpO2) equipped with Bluetooth connection;

GPRSConnection **(facility)** to realize a GPRS connection when patient is not at home.

We can assume that the patient is equipped with one (or even more) spare PDA. When the level of the battery of the primary PDA reaches a certain threshold, the *Battery Monitor Service* alerts the *Coordinating Midlet*, which sends a message - through the Messaging Service- requiring the turning on of the spare PDA. Next, the two coordinating midlets start a coordination protocol. In particular, they discover each other by means of the *Discovery Service*. Then, the primary PDA releases its bluetooth and WiFi connections, while the spare PDA starts to handle the data stream.

The PDA receives data -sensed by the oximeterthrough a *Bluetooth Connection* facility. Next, the PDA's *Stream Service* transmits the data to the Residential Gateway's *Stream Service* either through a *WiFi Connection*, while the patient is at home, or a *GPRS Connection* if the patient is elsewhere. Finally, the data stream is received and analyzed by a *Monitoring Application* built on top of the residential gateway. The *Connection Monitor* surveys the availability of the domestic WiFi. In particular, in the case of the patient leaving home, the *Connection Monitor* detects the WiFi disconnection fault and requires the *Connection Service* to start a GPRS connection. In contrast, when the patient comes back home, the *Connection Monitor* reveals the availability of the domestic network and imparts the *Connection Service* to which from the *GPRS Connection* to a *WiFi Connection.*

Table 1: HW resources.

	Producer	Model
PDA	Nokia	N8
ECG Sensor	Alive Tech. Pty.	Alive ECG
Oximeter	Alive Tech. Pty.	Alive Pulse Oxim.

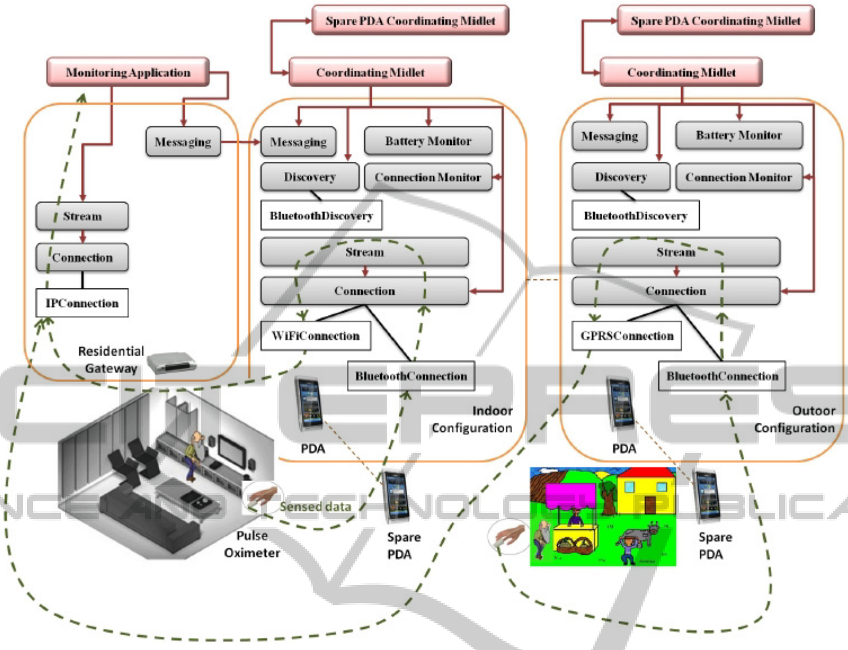

Figure 2: System architecture.

5 DISCUSSION

This section presents some considerations concerning the usefulness and effectiveness of *Uranus*. Some results on the dependability of the presented system can be deduced. We focus on the fault coverage.

We consider four types of faults:

- *Battery low power*
- *WiFi disconnection*
- *Sensed data not delivered (on the time)*
- *Sensed data corrupted*

Concerning the first two types of faults, the system, being equipped with battery and connection monitors along with additional logic for coordinating the spare PDA, is able both to detect and recover the fault. In addition, if the system is equipped with a timer (also available in Uranus) for monitoring the delay and jitter of transmitted data, it will also be able to detect excessive delay in the transmission of vital signs.

However, with the current architecture there is no mechanism for recovering from this fault. Finally, in the case of sensed data corrupted, the system is not able to detect the fault and then recover it.

In the table 2 we report the types of faults considered; in particular we indicate the detected faults and if there is a recovery procedure. For example when a *Battery low power* fault occurs, by means of BatteryMonitor Service, the system detects it and activates a recovery procedure alerting the patient to turn on another spare PDA.

Table 2: Example of fault coverage.

	Detection	Recovery
Battery low power	✓	✓
WiFi disconnection	✓	✓
Sensed data not delivered	✓	
Sensed data corrupted		

6 CONCLUSIONS AND FUTURE WORK

Vital signs monitoring is a field of application that is receiving great attention from several kinds of stakeholder interested in the realization of systems and applications which are effective, reliable, economically convenient, and capable of improving the quality of life for patients.

The proposed long-term vital signs monitoring system can measure various physiological signs, such as ECG, SpO2. The system allows health personnel to monitor a patient from a remote location without requiring the physician to be physically present to take the measurements and also is able to detect and recover some fault that may occur such as battery low power, WiFi disconnection, sensed data not delivered and sensed data corrupted.

We believe this system design will greatly enhance quality of life, health, and security for those in assisted-living communities.

The current implementation, as discussed above, is the first version of our system. Future enhancements to the system include: i) a graphical display of the incoming data; ii) an alarm generation capability to alert the care provider of a reading outside the given limits. This alert will be automatically sent to a PDA or similar device; iii) interfacing of additional medical instruments, including a blood pressure; iv) the ability for the care provider to view stored readings remotely from a PDA or computer.

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