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Ubiquitous health monitoring and real-time cardiac arrhythmias detection: a case study

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Abstract. As the symptoms and signs of heart diseases that cause sudden cardiac death, cardiac arrhythmia has attracted great attention. Due to limitations in time and space, traditional approaches to cardiac arrhythmias detection fail to provide a real-time continuous monitoring and testing service applicable in different environmental conditions. Integrated with the latest technologies in ECG (electrocardiograph) analysis and medical care, the pervasive computing technology makes possible the ubiquitous cardiac care services, and thus brings about new technical challenges, especially in the formation of cardiac care architecture and realization of the real-time automatic ECG detection algorithm dedicated to care devices. In this paper, a ubiquitous cardiac care prototype system is presented with its architecture framework well elaborated. This prototype system has been tested and evaluated in all the clinical-/home-/outdoor-care modes with a satisfactory performance in providing real-time continuous cardiac arrhythmias monitoring service unlimitedly adaptable in time and space.

Keywords: Ubiquitous health monitoring,smart healthcare,cardiac arrhythmias,ambulatory ECG detection

1. Introduction

In the 21st century, healthcare is facing a serious shortage of financial and human resources due to the global population aging issue [1]. To cope with the rapid increase in medical cost and the growing shortage in care capabilities, a personalized out-of-hospital healthcare model which supports independent lifestyle is highly desirable [2]. As a beneficial complement to the existing healthcare systems, a novel care model is thus developed to provide smart care services for patients with more than one chronic disease. This care model can be characterized with: (1) excellent chronic disease management in 7*24 hours, by assisting medical experts with technologies of pervasive biomedical sensing, computing and communication; (2) excellent abnormality detection ability, which effectively helps avoid emergencies (sudden death); and (3) timely and accurate healthcare services and emergency handling capability, available anytime anywhere [3] [4].Yet, the emergence of the ubiquitous care model also brings about new technical challenges, such as how to setup a service model with the integration of

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existing computing resources, how to develop the abnormality detection algorithm, and how to implement environment adaptive technologies.

In a previous study, the authors implemented a remote cardiac monitoring system named STAR (SystèmeTélé-Assistance Réparti) [5]. STAR is the first-generation cardiac monitoring system with the classical framework of telemedicine, which provides off-line care and remote care. However, this system cannot offer ubiquitous cardiac care (UCC) service at different scenarios due to its outdated system architecture and limited system capability in information collection/transmission/processing. This paper proposes a new generation UCC system which adopts pervasive service and IT technology, and infuses pervasive computing concept into healthcare services. UCC is a new attempt of IoT (Internet of Things) technology in the field of health care, i.e. smart care. In section 2, this paper introduces UCC architecture and its service modes. Section 3 lists the applications of UCC and makes a final analysis.

2. Framework of UCC system

With the development of pervasive computing and IoT technology, its applications have extended to all fields of remote monitoring, such as smart home and intelligent medical care, especially in the application of pervasive health care, which can provide light load, non-contact, long-term real-time remote intelligent monitoring services.

Cardiovascular diseases, usually being paroxysmal and unpredictable, rank as the top threat to human health and the number one cause for sudden death. More than half of the acute myocardial infarction events occur without any symptom or aura, and more than half of the death cases occur out of the hospital. Clinical experiences indicate that the most effective approach to preventing sudden cardiac death is to detect cardiac arrhythmias in time by making long-term regular cardiac monitoring.

Traditional healthcare systems are incapable of pervasive cardiac monitoring due to time-and-space constraints in healthcare applications. Ubiquitous cardiac care is able to offer the service of real-time cardiac monitoring without affecting the normal life of subjects under surveillance. UCC can also alarm the high-risk events of sudden cardiac diseases in time and earn valuable rescue time. In addition, it can capture the paroxysmal symptoms which are hard to be detected in clinical testing. Therefore, as an effective auxiliary diagnosis approach, UCC will play an important role in modern medicine and healthcare.

A UCC system for monitoring cardiac arrhythmias has thus been developed to do both long-term heart surveillances for people who have a history of heart diseases, and regular heart examinations for healthy people. UCC adopts the service-oriented IoT architecture, which contains three basic layers: data collection layer, information transmission layer and service provision layer, as shown in Fig.1. On the data collection layer, a wearable ECG sensors (WES) device is equipped for the subjects under surveillance to collect ECG signals and other auxiliary information. On the information transmission layer, UCC utilizes the existing IT infrastructures to establish interactions between subjects under surveillance and service providers, which can provide cardiac surveillance services under different application environments, e.g., indoor, outdoor or in clinic. On the service provision layer, the real-time ambulatory ECG detection algorithm is designed to enable the auxiliary diagnosis for cardiac arrhythmia events.

2.1. Wearable Information Collection Device

As a data collection and storage device, WES consists of three main functional modules: signal collection module (ECG electrodes), signal preprocessing module (AED algorithm in microcontroller) and signal transmission module (wireless mediums), meets the requirements of mobile computing and also corresponds to the latest AHA recommendations for ECG signals [6]. WES has the following characteristics: light-weight, low-cost, low power-consumption, and with mobile computing capability and high resolution signal quality, as shown in Fig.2.

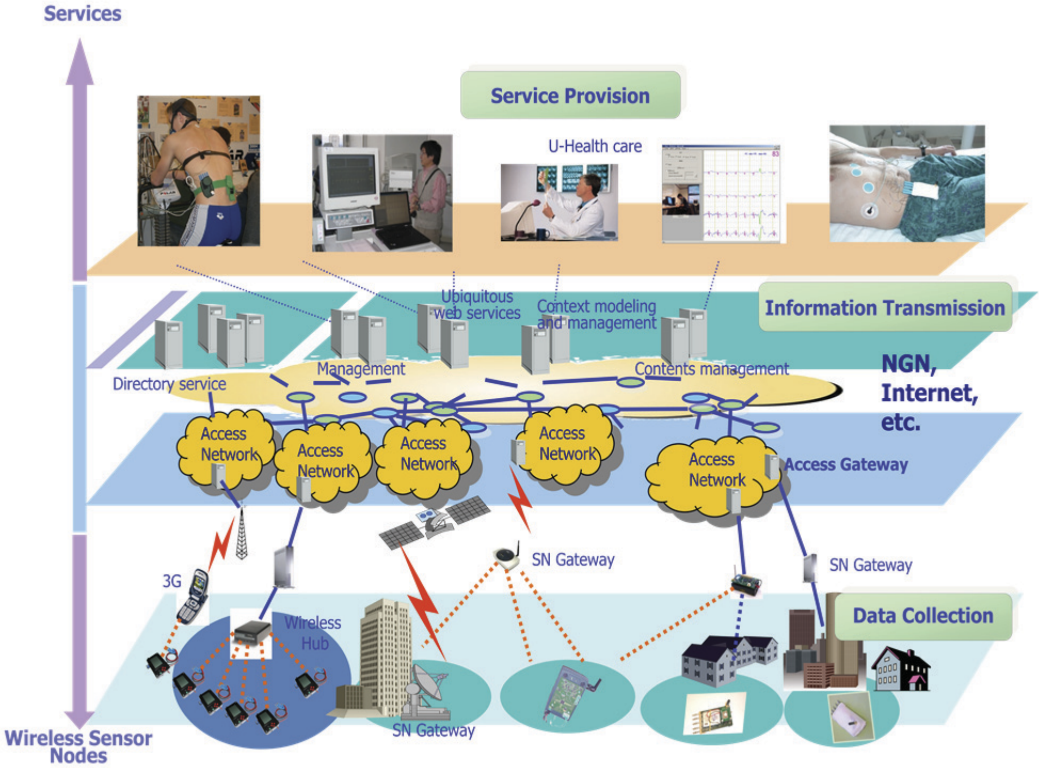

Fig.1.Framework of UCC system.

WES enables the real-time data capture of 4-lead ECG signals sampled at 500Hz.In WES, the signal filtering circuit is integrated into WES hardware motherboard and the corresponding signal preprocessing algorithm is loaded into the in-chip flash of microcontroller. The preprocessing signals are transmitted up to the transmission layer or even the service provision layer via wireless mediums (e.g., Wi-Fi, Bluetooth or 3G). Furthermore, the sample ECG signals will be displayed on a LCD screen. The 3G module is optional, which enables the direct connection between WES and the service providers through the 3rd-generation mobile telecommunication networks, such as WCDMA, CDMA2000 or TDS-CDMA in China. The GPS module provides the location function for subjects under surveillance, especially the high-risk population of sudden cardiac death.

Given that a case study supporting the service provider is unavailable, WES is then adaptively self-configured to operate in the off-line mode, and the sample ECG signals will be stored into the external flash memory (e.g., SD card) for later signal analysis. The maximal time duration of data storage can be calculated in Eq.(1):

$$T = Fc / (Rs * Nc * Fs) \tag{1}$$

where T is also the maximal operation time in the off-line mode, Fc the capacity of flash memory (byte), Rs the byte number needed to record one sample point related to the signal resolution, Nc the number of signal channel, and Fs the sampling frequency (Hz). For example, a 256MBSD memory card can continuously store 4–lead ECG signals sampled at 500Hz with 12bit (1.5Byte) resolution for more than one day (T=256MB/1.5B*4*500 ≈24H).Hence, a 4GB SD card can store data for more than 16 days, which serves well for long-term continuous cardiac surveillance. Furthermore, ECG signal compression algorithm based on WFDB 'WaveFormDataBase' standard [7]is adopted in UCC to reduce the amount of data storage.

Fig.2. Evolutionof WES device.

2.2. Transmission Middleware

To realize ubiquitous care services, UCC allows service access at any scenario, whether the subjects under surveillance are indoor, outdoor or in clinic. By utilizing the existing infrastructures, WES is configured to connect directly with the service providers through 3G or broadband network *via* wireless or wired local infrastructures. Taking into account the differences between network bandwidths for different infrastructures, a reliable data transmission mechanism, which is adaptable to the changes of network transmission rates, is highly desirable on the information transmission layer.

UCC adopts UDP/IP protocol stack for data transmission between subjects under surveillance and service providers. Given the incapability of UDP to offer a guaranteed datagram delivery service, a transmission middleware is therefore developed to guarantee a reliable data transmission. Moreover, this middleware covers the differences among service classes and among basic network infrastructures, which enables service providers to focus on the provision of UCC services. This middleware contains two basic mechanisms: *retransmission* and *competition*.

The *retransmission* mechanism guarantees a reliable data transmission between clients (subjects under surveillance) and servers (service providers) by adopting the circular buffers to cover the differences in network transmission rates. In UCC, the signal frame encapsulates the ECG signals within the data length of 5-second sampling duration. Two circular queues are allocated to the client peer (*Hold_Queue*) and the server peer(*Wait_Queue*), respectively. *Hold_Queue*stores signal frames generated in WES and *Wait_Queue* stores signal frames from the client peer. When the consecutive 5-frame signals are received in *Wait_Queue*, a confirming frame will be sent to the client peer to release the corresponding frames in *Hold_Queue*. If the network transmission rate is changed, *Hold_Queue* can buffer those unsent frames for the next transmission later. If a signal frame is lost in transmission, an error will be detected in the server peer and a retransmission requirement frame will be sent to the client peer to resend that frame.

The *competition* mechanism guarantees a reliable service provision between clients and servers according to the services' priority. The transmission frames in UCC are classified into two categories: *contro*l frame and *data* frame. The former is responsible for the interactions by exchanging control signals, *i.e.*, connection, configuration and management contents. The latter is classified into three categories: textual frame, signal frame and image frame. Generally the control frame has the highest priority, and after that the textual frame that encapsulates the information of QRS detection and arrhythmia diagnosis is applied to the service modes of *textual emergency message* and *diagnosis report* (see section 2.3). The lowest-priority frame, the image frame, provides the auxiliary diagnostic information, i.e. the images of subjects under surveillance, for cardiologists.

Indeed, these mechanisms operate collaboratively to offer UCC services on different infrastructures. For example, assume that UCC operates in the *remote surveillance* mode with the service of *real-time continuous ECG signal*, and the video signals are transmitted as the additional information. Therefore, there are two classes of data frames (signal frame and image frame) in this instance. When the queue length of *Wait_Queue* is equal to or greater than 5, it means that there are at least 25-seconds ECG signals stored in the server peer. Then it is acceptable to allow the client peer to transmit images. In contrast, when the queue length of *Wait_Queue* is smaller than 5, it means that the network transmission rate is fluctuating and the network quality is deteriorating. Then the image transmission must be terminated to reduce network traffics. Moreover, if the queue length of *Hold_Queue* is greater than 10, it means that the network connection to the server peer is unavailable, and in such cases the ECG signals will be stored in the external flash memory card automatically.

2.3. Service Provider

On the service provision layer, UCC provides the service of real-time cardiac arrhythmias detection by adopting a dedicated AED (Ambulatory Electrocardiograph Detection) algorithm [8]. The service providers (*i.e.*, cardiologists) check signals, analyze arrhythmias and report results on an interactive visualization GUI (Graphical User Interface), as shown in Fig.3.

UCC supports multi-subject on-line surveillance and one–subject real-time diagnosis simultaneously. The 4-lead ECG signals and related diagnostic results from the AED algorithm are displayed on the LCD screen and stored into medical record database in the 'WFDB' format. The diagnostic report is generated automatically and is printed as ECG signals sequence and the related statistical results. UCC is adaptable to meet diversities in application environments and subjects under surveillance, which makes it possible for UCC to be operated in multiple service modes.

– *Automaton Surveillance*: As a Holter machine, WES is configured to work as an independent ECG surveillance automaton for long-term cardiac monitoring. In this mode, ECG signals are displayed on the LCD screen in real-time and stored into the external flash memory card. No real-time connection to the server peer is available in this mode, and subjects under surveillance therefore should go to hospitals/clinics or submit off-line ECG signals over the Internet.
– *Clinical Surveillance*: As a Agilent telemetry system, UCC works as a telemetry cardiac arrhythmia detection system. In this mode, the subjects under surveillance and service providers are in the same physical area and share the high-speed local infrastructures. UCC supports multi-user multi-lead continuous real-time ECG signals monitoring.
– *Remote Surveillance*: As a remote telemedicine platform, UCC contains all the functional components. There is no limitation in its application environments, and subjects under surveillance can

be anywhere, whether near or far from the service providers, e.g., at home, office or en route. Through the existent infrastructures, UCC enables connection between subjects under surveillance and service providers, and provides different service modes according to the application environments and requirements.

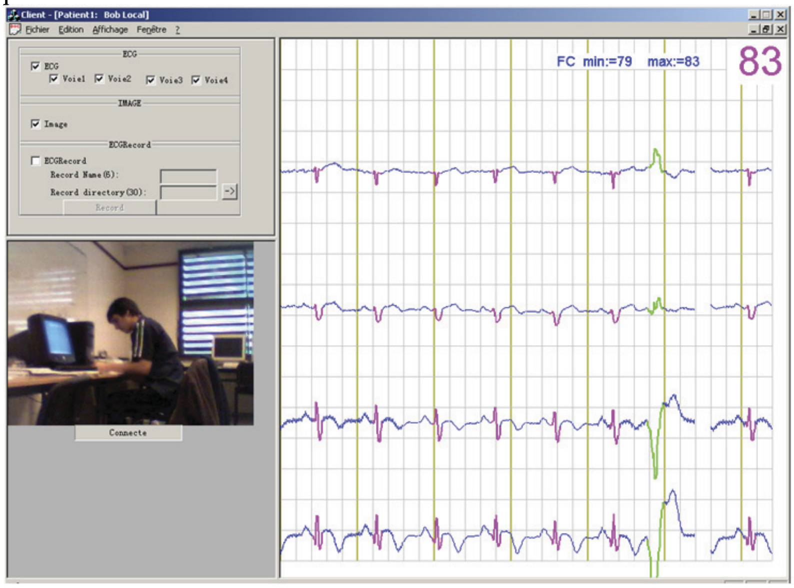

Fig.3. Graphical interface of remote surveillance platform in service provision peer.

3. Conclusion

UCC that aims to implement a ubiquitous healthcare system dedicated to real-time continuous cardiac arrhythmia detection and monitoring, has been developed and evaluated on the basis of the joint research among SMIR team at LIMOS laboratory of Blaise Pascal University (France), FTCL team at Harbin Institute of Technology(China) and the cardiology department at C.H.R.U de Gabriel Montpied hospital (France). UCC provides multiple cardiac care services, including anomalies detection, arrhythmia diagnosis, real-time surveillance, and crisis intervention.

UCC adopts the service-oriented architecture that consists of three main layers: data collection layer, information transmission layer and service provision layer. On the data collection layer, subjects under surveillance are equipped with a dedicated wearable ECG sensor, which provides the capability of real-time data collection and transmission for 4-lead ECG signals. On the information transmission layer, a reliable data transmission mechanism (competition and retransmission) is proposed to enable the provision of UCC services in different application environments, e.g., indoor, outdoor or in clinic. On the service provision layer, the real-time ambulatory ECG detection algorithm has $O(n)$ algorithm complexity and more than 99% algorithm sensitivity and specificity [8], which enables the auxiliary diagnosis for cardiac arrhythmia events.

Currently, UCC has been applied to different subjects under surveillance in different environments. Fig.4.(L) shows the application of the periodic heart examination for the healthy population, e.g., the athletes of French national youth cycling team, and Fig.4. (R) shows the application of the long-term heart surveillance for the population who has a history of heart diseases, e.g., patients in the cardiology department of C.H.R.U. of Gabriel Montpied's hospital. In the former case, UCC is configured as *Au-*

tomaton Surveillance service mode to provide more than two hours' off-line cardiac monitoring service. The *real-time continuous ECG signal*s and *related AED results* are stored into the external flash memory card in WES. In the latter one, since patients and cardiologists are both located at the hospital, UCC is configured as *Clinical Surveillance* service mode to provide more than half an hour's on-line cardiac monitoring and diagnosing service, which supports multi-user multi-lead continuous real-time ECG signals monitoring. Moreover, UCC has been evaluated by being compared with HP telemetry system, each running a group of 30-minute clinical tests on more than 30 patients. The results prove that UCC meets the requirements of real-time cardiac arrhythmias monitoring application.

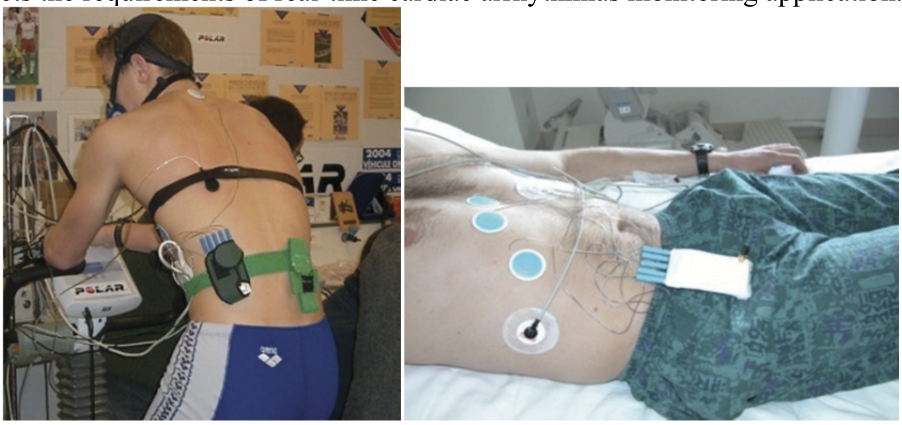

Fig.4.UCC application examples: athlete (L) and patient(R)

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