A Mobile Phone-based Wearable Vital Signs Monitoring System

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Abstract

Design and implementation of a multiple vital signs monitoring system based upon mobile telephony and internet infrastructure for e-health are described. The system hierarchy comprises three layers for sensing, communication, and management. The core of the sensing layer is a wearable sensor unit, including a cordless sensor device and a sensor-wear garment, suitable for vital signs real-time monitoring without discomfort and constraint during daily activities. The communication layer performs bi-directional data/command exchange via either wired or wireless means to bridge between the sensor layer and management layer. The management layer conducts comprehensive data analysis and evidence-based health management. This article describes the architecture design considerations and systemic implementation to meet various practical needs and provide scalable solutions not only for home healthcare but also other applications driven by vital signs. Three applications platformed on this architecture are explained.

1. Introduction

Cancer, cerebrovascular, and cardiovascular diseases have been the 3C top killers for many years [1] . The dramatic changes from acute illnesses to chronic conditions demand creative action at both institutional and professional levels. To meet the increasing needs for ubiquitous vital signs monitoring and healthcare management, many R&D projects and public administrative reforms are being conducted worldwide. In Japan, a ten-year campaign, “Healthy Japan 21”, is conducted from 2000 to 2010 nationwide to promote good life-style practices and to manage the growing problem of chronic diseases like the 3C, diabetes, and increasing incidence of mental illnesses [2] . A lot of big enterprises and research institutes, universities are applying mobile phone-based infrastructure and matured IT technologies to provide new services for ambulatory vital signs monitoring and daily healthcare management. Mitsubishi released a health management assistant system called “Wellness Navigator” for home use. Multiple vital signs, such as body temperature, blood pressure, pulse rate and weight, can be monitored via a series of relevant peripherals. Collected data are transmitted via either internet or mobile phone network to a management server in data center. Based upon the long-term accumulated vital signs, risk factors, such as arteriosclerosis and adiposity, are assessed individually by “Multimarker”, a health comprehensive assessment tool [3] . NTT Data Corporation introduced “Health Data Bank” for a life-long health management [4] . It provides an integrated ASP service for hospitals, companies and individuals to utilize and communicate through this common database. Kyocera Co. Ltd and Fukuda-Denshi Co. Ltd established a joint venture

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corporation, Medical Data Co. Ltd., to provide an open platform "D@TA Center" for health and medical data storage and secure distribution [5] . The partnership is oriented to medical equipment manufacturers, hospitals and ASP providers. Omron Healthcare Co. Ltd. developed a package of life-style betterment program "Healthy Master" to provide "One to One advice", an individual recipe for more than 13 million patients who are suffering from diabetes, hypertension and hyperlipidemia [6] . In this article, an overall concept of a mobile phone-based wearable multiple vital signs monitoring system is described. The design and implementation in both hardware and software, as well as perspectives in real world applications are explained.

2. Methods

2.1. Overall architecture

For a mobile phone-based project intended to enable effective long-term vital signs monitoring and health management in various application domains [8] , system ubiquity, scalability, and interoperability in the system design are the highest prior considerations. The ubiquity feature is applicable not only in medical and clinical use, but also in many industries, government agencies, and academic organizations through a variety of partnership options. The scalability will enable customization of a cordless sensor or the system from any terminal connected to internet. The interoperability is achieved through compliance with the HL7 international standard [7] to provide a seamless connection with other existing medical information systems. The overall system implementation is structured into three functional layers: sensing, communication, and management. Figure 1 shows the overall layered system architecture and relevant application domains. This platform is supported by four pillars deployed in a three-layer architecture.

The four pillars consist of:

- Ambulatory monitoring techniques for multiple vital signs,
- Short-range wireless data transmission by Bluetooth,
- Globally wireless data transmission using mobile phone network, and
- Globally wired data transmission using the internet infrastructure.

The three layers are:

- Sensing– multiple vital signs detection,

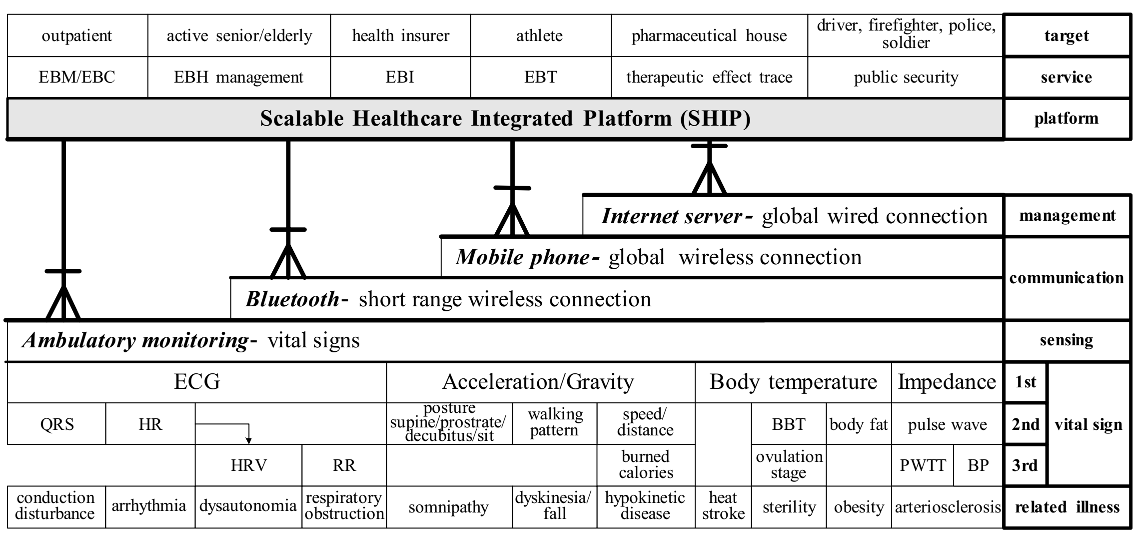

Figure 1. Layered system architecture and application domains. Three layers include management, communication and sensing layers respectively. Sensing layer performs an ambulatory monitoring for multiple vital signs. Communication layer includes a Bluetooth for short-range wireless connection and a mobile phone for global wireless connection. Management layer consists of an internet server array for all data processing and management tasks. Application domains cover from hospitals to government agencies upon this platform.

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signal processing, and data analysis,

- Communication– Bluetooth for short range, mobile phone for worldwide, and
- Management– an internet server array for data mining, risk factors assessment, and health management.

The most important features in this three-layer model of the system architecture include real-time processing capability, hotline monitoring, scalability and interoperability.

Four kinds of physiological parameters can be obtained in the sensing layer. The 1st set of parameters comprises vital signs measured by the cordless sensor directly, including continuously acquired ECG, acceleration/gravity vector, body temperature, and impedance.

By analyzing the 1st set of physiological parameters, more than 10 parameters can be derived as 2nd and 3rd sets of parameters. Combination of these parameters can be related to more than ten correlated illnesses.

2.2. Prototype implementation

The prototype implementation of the entire system is diagrammed in Figure 2. Callouts denote the number of each component. Arrows represent data/command flow over the system.

The innermost layer is a wearable sensing layer, comprising a sensor-wear garment (1) and a cordless sensor (2). A sensor-wear consists of underclothing and a sensor belt. The underclothing vest is washable and comfortable to wear next to the skin. A body temperature sensor and electrodes for detecting ECG and body impedance are arranged together on the sensor belt, attached via Velcro beneath the underclothes. Both underclothes and sensor belt are stretchable to keep tension and guarantee the best fit on irregular body surfaces. The cordless sensor is connected to the sensor-wear through a one-touch connector. By simply attaching the cordless sensor to the sensor-wear, the wearable unit starts working automatically.

The cordless sensor integrates analog bio-amplifiers, digital circuitry, and RF circuitry within one box of dimensions of 117(w) $\times$ 36(h) $\times$ 16(d) mm. The cordless sensor, including rechargeable battery, weighs totally 55 grams, about half that of a mobile phone. Bio-amplifiers can detect ECG, body temperature, and impedance. Body movement in three orthogonal directions is detected by two on-board accelerometer ICs. Other 2nd and 3rd set physiological parameters—

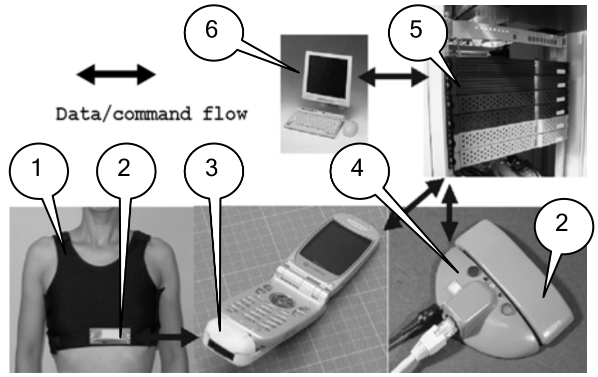

Figure 2. Implementation of the prototype and data/command flow diagram. ① is a wearable garment embedded temperature sensor, ECG electrodes and electrodes for body impedance detection. ② indicates the cordless sensor. ③ is a Bluetooth adapter for a mobile phone. ④ is a data docking station for bulk data transmission and cordless sensor charging. ⑤ is a server array. ⑥ indicates an internet-ready client PC. Arrows show the bidirectional data/command flow over the system.

such as heart rate, heart rate variability, systolic blood pressure change, body fat ratio, walking cadence, and body gesture— can be derived from these directly measured vital signs. The digital circuit includes an ultra low power consumption 16-bit RISC type CPU (NEC V850 series, 24 MIPS at 20 MHz clock rate), 256 KB FEEROM and 4 MB RAM. It performs continuous real-time processing of the acquired vital signs. The RF circuit is actually a short-range digital transceiver implemented by a class III Bluetooth core chip. Simultaneously, several ring buffers for raw data (1st set of parameters), de-noised data, and the 2nd and 3rd sets of parameters are cyclically processed in real-time mode. Figure 3 shows the illustration of the real-time processing flow.

The second layer is the communication layer conducting data and command transmissions. This layer is implemented by a Bluetooth adapter (3), a mobile phone, and a data docking station (4).

The Bluetooth adapter is an attachment to the PDC serial port of a mobile phone. This adapter performs short-range wireless communication between the cordless sensor and a mobile phone. The mobile phone itself acts as a long-range wireless communication tool between the nomadic user and a remote database server.

The data docking station combines two functions: battery recharge and high-speed data transmission. When a cordless sensor is connected to the docking station, its rechargeable battery is charged. At the same time, data saved within the cordless sensor is read-out sequentially and uploaded automatically to a database server through ADSL or any wired Internet connection.

The third layer is a management layer, in charge of data fusion from multiple sensors, decision-making, and functional assessment. A server array (5) contains database servers, web servers, application servers, and load balancing servers. Database servers are data warehouses for Terabyte-order storage. Web servers provide an interactive interface with operators and users. Application servers perform all calculation tasks, including vital signs signal processing, denoising, feature extraction, potential risk assessment, and so on. All processing procedures are either event- or timer-driven. Event-driven procedures are triggered by received data from the communication layer. It responds to emergency situations to provide real-time feedback. Timer-driven procedures perform automatic regular batch processing to handle a great amount of data accumulated through long-term monitoring. Load balancing servers distribute required tasks to appropriate servers, to ease computational complexity and guarantee prompt reply capability.

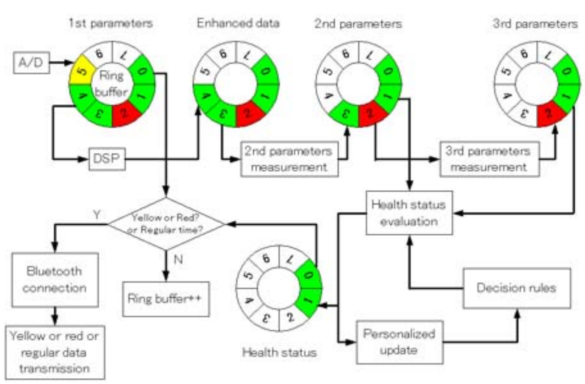

Figure 3. Real-time signal processing diagram within a cordless sensor. Four ring buffers update the detected parameters sequentially and compare these parameters with personalized decision rules to evaluate health status. The evaluation will give three signs, i.e. red, yellow and green, to indicate emergency, warning and normal cases respectively.

3. Results

In experiments using the prototype implementation, several key technologies, such as bidirectional data/command communication and real-time ECG signal processing performance, have been investigated.

Two channels of ECG signal and three channels of accelerometry signal were picked-up by the cordless sensor and transmitted to a mobile phone via Bluetooth wireless connection. ECG signals were digitally processed to suppress noise and enhance the QRS complex, finally perform heart rate and PVC detection.

Data received by a mobile phone can be both performed real-time data processing on a mobile phone and transmitted to an internet server via HTTP protocol for an online comprehensive analysis. Data can be archived in a database server.

An authorized doctor can use an internet-ready PC to search for archived data sent from mobile phones. Figure 4 shows a 20-sec data frame of two ECG waveforms and three accelerometry waveforms retrieved from the database server. These data were

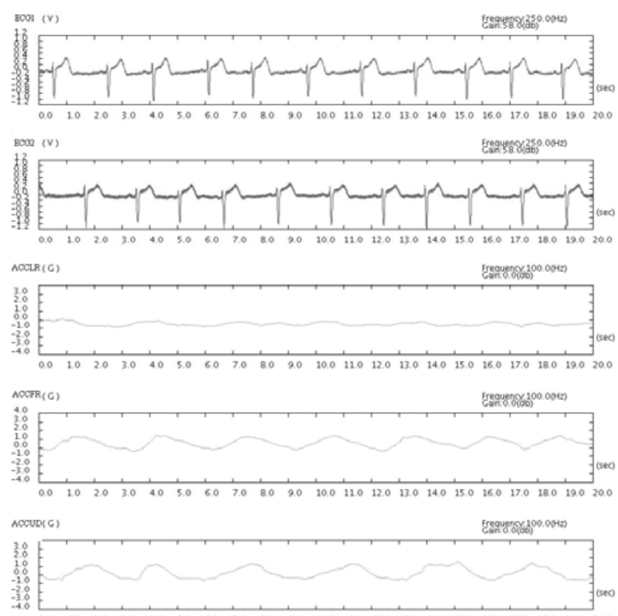

Figure 4. Retrieved ECG and accelerometry waveforms that were obtained during normal working by a cordless sensor and transmitted via Bluetooth and mobile phone. ACC LR indicates the accelerometry signal in left (-)-right (+) direction. FR and UD are front (+)-rear (-) and up (+)-down (-) directions, respectively.

measured and transmitted to an internet database server during normal walking. The upper two show ECGs and the lower three show accelerometry signals in three orthogonal directions.

Comprehensive data analysis, such as PVC detection is performed in the server side. Figure 5 shows the PVC and QRS peak detection result of a 32-sec ECG data segment. To evaluate the detection performance, a de-facto standard database for arrhythmias ECG algorithm development from MIT/BIH is investigated as a comparative reference. The results showed totally satisfactory and promising with 93.29% sensitivity and 94.41% specificity.

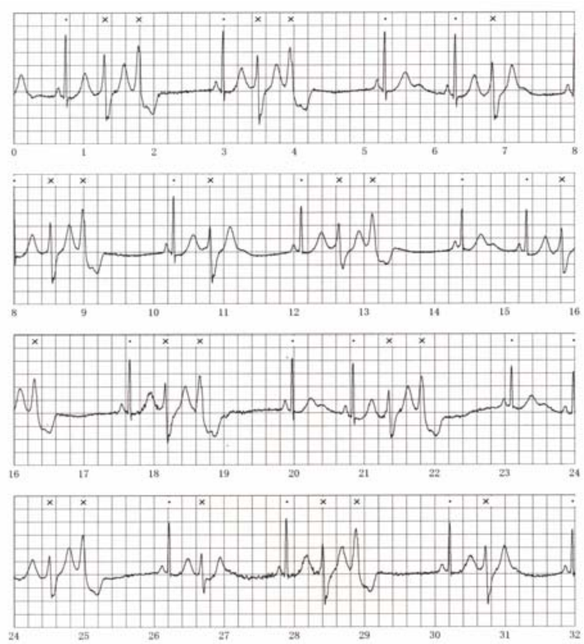

Figure 5. PVC detection results applying to MIT/BIH arrhythmias database. A "circular dot" indicates a normal QRS detected. A "cross marker" indicates PVC event.

By combining these elementary technologies, potential applications are available to span most health-related fields where vital signs are important. Different kinds of solutions can be provided for many industries, government agencies, and academic organizations through a variety of partnership options. Two of these options are described below.

3.1. Hotline monitor

A hotline feature can keep live data/voice communication with control/management center via a mobile phone.

One of the hotline monitor applications is providing an ambulatory ECG monitoring service. Conventional Holter is a long-term ECG monitoring device. Recently many commercialized products combine additional sensors, such as gyro or accelerometers to monitor daily activities. Occasionally, frequent arrhythmia may cause fatalities, but such products feature only offline batch processing.

A hotline ECG monitor, or hotline Holter, can monitor the above-mentioned vital signs continuously for a long period and also provide real-time detection of arrhythmia, bradycardia, and tachycardia to provide prompt service and summon first-aid support when a situation is urgent. Fig. 6 shows the concept of a hotline Holter.

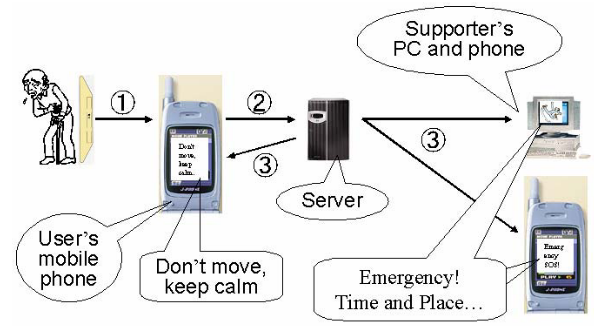

Figure 6. When an accident heart attack was detected by the cordless sensor ① an event would be transmitted to a management server array②, which then notifies supporters③ and gives advice instantly back to the user③.

Osteoporosis is one of the mortal fears among the elderly population, since falls may fracture bones. Emergency rescue is indispensable to avoid lethal accidents. Another application of the hotline feature is to monitor an emergency situation, for example, an unintended fall. When a user is prone to falling, the embedded three-axis acceleration sensor can detect not only the walking cadence but also the body gesture. It can promptly tell the direction (forward, backward, leftward, and rightward) to which the user falls through real-time processing of the three-axis accelerative signal. In addition, location information regarding where the user has fallen is also transmitted to a support center within about thirty seconds.

3.2. Training mentor

Athletes or sports gym exercisers want to be trained more effectively based on their own personal situation. A training mentor provides an evidence-based training (EBT) tool. As being showed in Fig. 7, a trainee's heart rate and respiratory rate can be monitored continuously and in real-time during exercise. Through monitoring heart rate and respiration rhythm profiles, characterizing running and walking, it can estimate exercise strength in real-time to facilitate an optimal training course individually according to trainee's age, gender, and condition.

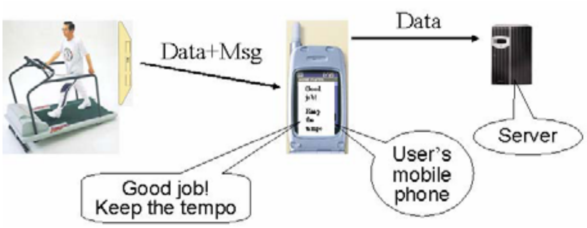

Figure 7. A trainee's heart rate was detected by the cordless sensor and the advice message was showed on the window of user's phone in real-time. Trainee's data was also transmitted to an internet server for long-term comprehensive analysis.

4. Discussions

A number of elementary technologies have been developed under the "Univenture 20" project [8] . Scalability promises that this platform is customizable depending on specific applicable needs. An operator can selectively activate required functions of the system to obtain a combination optimal for a particular application. Each vital sign measurement channel of a cordless sensor can be enabled or disabled via a PC through the network, or via a mobile phone through Bluetooth connection. Based upon these key technologies, applied systems can be configured to meet different needs from e-health to emergency rescue service in order to satisfy different target clients.

The system can be customized to coordinate with doctors in hospitals as an ambulatory monitoring system for outpatients, providing evidence-based medicine and evidence-based care. When cooperating with community facilities, it can provide a means to assist caregivers attending elderly patients at home or elsewhere.

Active seniors, who are health-conscious but might be susceptible to chronic or lifestyle-related diseases, can use our system to monitor physiological parameters during daily activities. It can provide risk factor assessment and evidence-based healthcare recommendations individually.

For professionals that might especially require urgent rescue, such as public transportation drivers, adventurers, public safety personnel (fire fighters, police, soldiers, etc.), this system can act as a real-time monitor and remote interactive secure device.

The wearable sensor is one of the most critical factors concerning applicability of our system. Various types of sensors and measuring sites were taken into consideration. We tried to make the sensor assembly more like a piece of clothing and less like a medical device. We expect that the wearable sensor will evolve into a form of increased comfort, wearability, and washability.

Acknowledgement

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