A 24-hour health monitoring system in a smart house

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H. Lee, Y.T. Kim, J.W. Jung, K.H. Park, D.J. Kim, B. Bang, Z.Z. Bien. A 24-hour health monitoring system in a smart house. Gerontechnology 2008; 7(1):22-35. This paper presents a 24-hour continuous health monitoring system installed in an Intelligent Sweet Home, which is an advanced smart house developed at Human-friendly Welfare Robot System Engineering Research Center in Korea. Aiming to aid independent living of the elderly and/or people with disabilities, this system is composed of three parts: (i) a measurement device of biosignals, (ii) a monitoring system for caregivers, and (iii) client/server personal computers (PCs) for processing and archiving of history data. The measurement device measures electromyogram (EMG), electrocardiogram (ECG), body temperature, and blood pressure, and delivers the data to the client PC via Bluetooth channels. For the process, some surface-type active electrodes have been developed to measure, amplify, and filter the biosignals more clearly and conveniently. The monitoring system sends the information on health condition and security status to the caregiver's cellular phone via a short message service (SMS) server. The caregiver only can access the system using a password and observe the situation in the Intelligent Sweet Home.

Keywords: biosignals, health monitoring, wearable measurement device

It is well known nowadays that the number of the elderly is drastically increasing while at the same time the number of people with disabilities is not decreasing, possibly caused by a variety of accidents in the complicated and diversified society[1,2]. To cope with the challenge, there has been a strong suggestion to utilize the ever-progressing scientific technology to meet various forms of demand of the people in need, giving support and benefits to them by means of care-giving aids and let them lead safer and more independent lives along with ordinary people with the feeling of equality. As an approach to realize such a state of well-being and achieve independence, a smart house has been proposed with emphasis on continuous monitoring of health status of the residents. Such a solution also has strong positive emotional impacts on the inhabitants, improving their quality of life, giving them privacy and letting them feel that they live in an ordinary house, not in a hospital, and reducing significantly the medical care costs per person.

The importance of a smart house for the elderly and people with disabilities can be well understood from many existing studies conducted by numerous institutions[3]. In Tönsberg, Norway, eight care flats have been designed to support home living for persons with dementia. Across Japan, fifteen Welfare Techno Houses have been built for demonstration as well as for doing R&D to promote the idea of independence for the elderly and people with disabilities by creating accessible environments and maximizing the use of assistive technologies. Also, a 'Robotic Room' project has been under way at the Research Center for Advanced Science and Technology in the University of Tokyo[4]. The environment of the Robotic Room consists of a ceiling-mounted robotic arm and an intelligent bed with pressure sensors for posture monitoring. All the functional modules are network-connected and the room can monitor the person's respiration or posture of rolling-over without a special attachment. As another example, we may mention the wireless wearable body area network (WWBAN) that has been used in measuring ECG signal for estimating ST-segment and RR interval, and acceleration signals (x and y axes) for estimating gait phase and walking activities[2,5]. The WWBAN consists of a communication platform based on ZigBee and a custom intelligent signal processing module, which is responsible for acquiring biosignals and preprocessing. Three kinds of signals, such as ECG signal and two acceleration signals (x and y axes), are collected and analyzed during normal walking for metabolic energy expenditure and step recognition. The goals of WWBAN include personal ambulatory health monitoring, supervised rehabilitation, early detection of abnormal condition for preventing complications, and knowledge discovery based on the whole data set gathered by the network.

For a smart house to be capable of helping the elderly and people with disabilities to live independently with a minimal number of external helpers[6], it becomes mandatory to implement a network-based environment that would provide the functions of collecting various data regarding the current health state of the dweller and setting various parameters for obtaining a proper environment. In network-based environments with pervasive intelligence, various vital signals such as ECG, EMG, EEG, blood pressure, voice signals, body temperature, facial expressions, gait patterns, gestures, and postures can be measured via various sensors such as vision sensors, electrodes with electrical amplifier, pressure sensors, etc., and can be processed to extract emotion information, physical information, and behavioral information. Then, the processed data and information can be used to estimate the health status of the residents by medical doctors and caregivers. Here, the caregiver is an important component to increase the reliability of operation when some devices of the pervasive intelligent circumstances malfunction. The network-based environment may also provide the caregiver with a decision support mechanism as in a human-in-the-loop system.

In this paper, we introduce and discuss a health monitoring system based on a sensor network environment, which has been developed as a part of the Intelligent Sweet Home project. The monitoring system measures and records 14 signals, including an ECG signal, signals for blood pressure and pulse, 10 EMG signals, and body temperature. Two EMG signals, which are measured from the temples, are used in an EMG mouse for user-friendly interface and control. When the right teeth are held together tightly, the right temple generates a quite significant EMG signal with large amplitude, which is used for control signal of the EMG mouse. The EMG mouse has three control functions, which are a left direction moving function, a right direction moving function and a selection function. The cursor of the EMG mouse moves from a button to its nearest button in a graphic user interface (GUI). A possible heart disorder is estimated by an average period of ECG signal. Eight EMG signals are used for estimating body motion states and for multimodal processing with ECG signal.

Network-based health monitoring

As mentioned earlier, a 24-hour continuous health monitoring system is an important component of the smart house. Table 1 shows the key aspects of the 24-hour continuous health monitoring system under consideration. For older persons or people with disabilities having multiple impairments, the health condition can worsen suddenly and rapidly, and timely detection of symptoms can prevent serious complications[7].

For the residents in a smart house, certain abnormal situations may be put under control if the health monitoring system does function properly in gathering and processing data regarding the current health state of the residents in real-time and, if necessary, in providing some critical information about emergency status to the medical doctor and/or caregiver in charge. Thus, the health monitoring system is designed to measure some basic biosignals by telemetrics based on the sensor network, to extract and record relevant data about the emergency conditions of the impairments, and tell the doctors or the caregivers the situation of the current health status continuously via a network[8,9]. The 24-hour continuous health monitoring system thus serves for prediction and timely diagnosis of abnormal health states

Table 1. Key aspects of the 24-hour continuous health monitoring systems

Characteristic	Description
Goal	Enhancement of quality of life based on early detection and prevention of complications
Decision objects	Abnormal states, variation of living pattern, emotion state, intention, etc.
Mode of operation	continuous operation of monitoring 24-hours a day
Extracted information:	**Sensors used:**
Emotional: facial expression, voice tones, gestures	Data glove, vision sensor, motion capture device, sound sensor
Physical: EEG/EMG/ECG, blood pressure, temperature, respiration	Electrode, pressure sensor, chemical sensor, sound sensor
Behavioral: posture, gait patterns, gestures	Vision sensor, motion capture device, pressure sensor, data glove

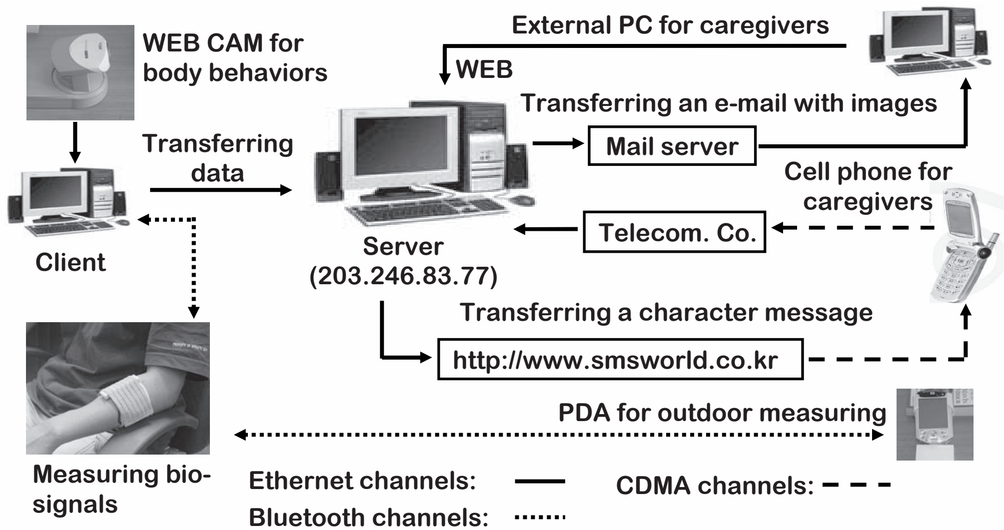


Figure 1. The overall configuration of the developed health monitoring system

of the residents in daily life. For instance, when someone has a stroke, his or her body is unable to move possibly very suddenly. At the initial stage of the stroke, it is reported that usually the person experiences no feeling in his or her body, and becomes unable to move due to the weak strength in muscle systems. One of the most common symptoms is lack or loss of abilities to move legs and variation of gait patterns. In this case, the measurement of EMG signals is very useful for prediction and on-time detection of stroke because the symptoms are reflected in the EMG signals.

The statistical parameters of bio-signals can reveal variation of patterns representing abnormal states of a person. If this system decides on current health status based on the history of the user's health state and specifics of the body parameters as well as the standard values, then the reliability of the system will be increased. Older persons and people with disabilities are the residents in these categories, who can strongly benefit from such a personal health monitoring system.

One of the main problems in a health monitoring system is to design and develop a method of sensing signals continuously. This should often be done in daily living conditions without hindrance to the user. For convenience and minimization of interference by body motion or hindrance, the signals are measured by wearable sensing devices with long-lasting wearability and comfort[5,10,11].

Realization of the system

With not noticeable sensing and portability in mind, we have developed a 24-hour continuous health monitoring system, taking into account various aspects for the units of the system to possess such as wearable/wireless device, low power, small size, and minimization of interference (*Figure 1*). The system is composed of three parts:(i) a measurement system for biosignals, (ii) a monitoring system for caregivers through e-mail and phone call, and (iii) client/server PCs for processing and keeping history data. The collected data and information are transferred through an Ethernet channel, a code division multiple access (CDMA) channel and a Bluetooth channel. The Bluetooth channel is used for transferring the basic biosignals.

The caregiver can see and check the situation in a room with the observed person via the CDMA channel. The server has a

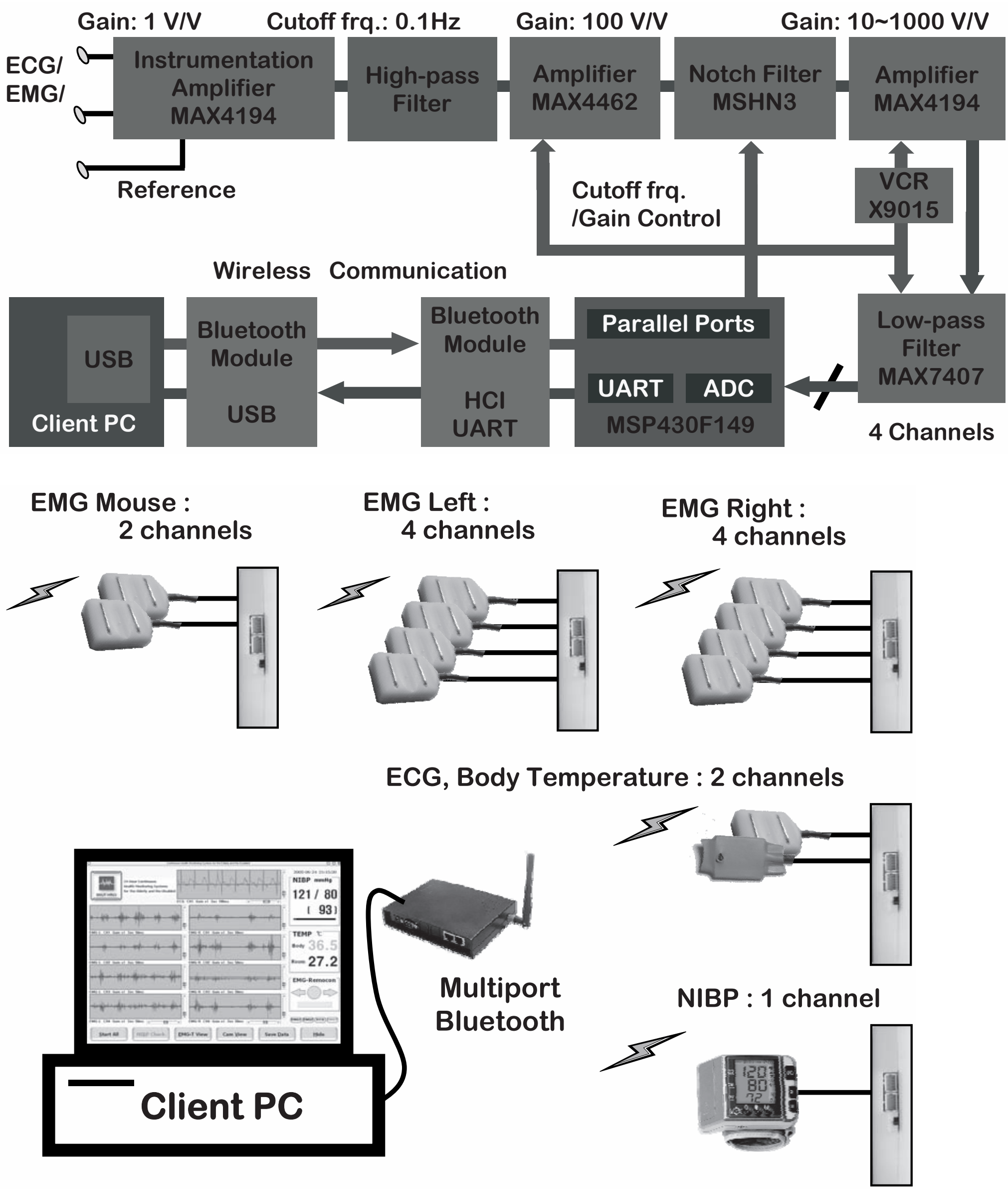
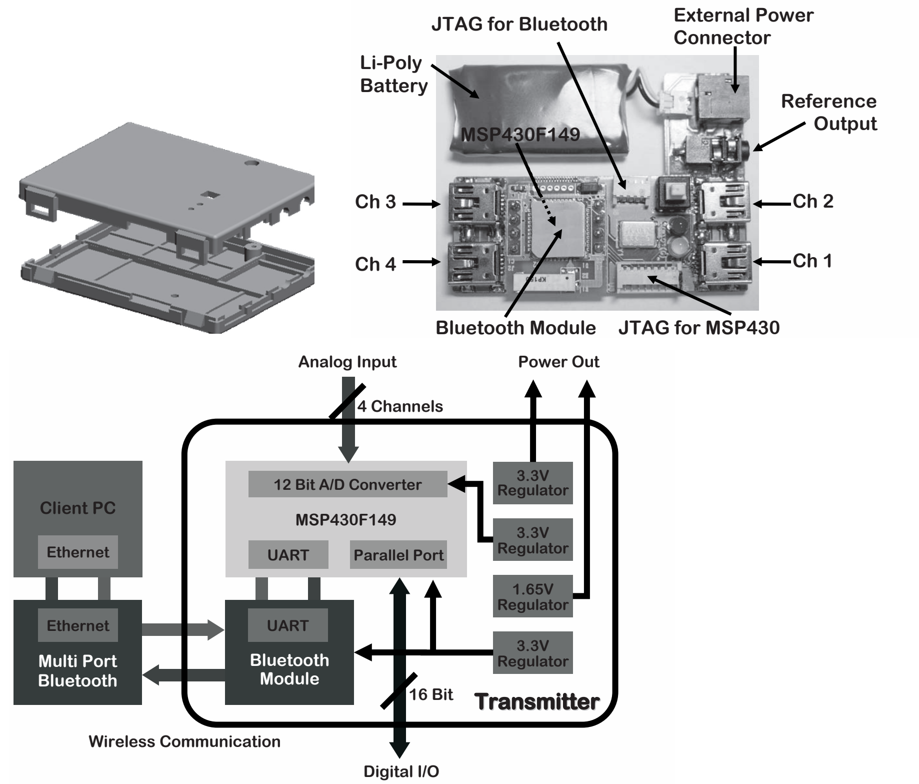


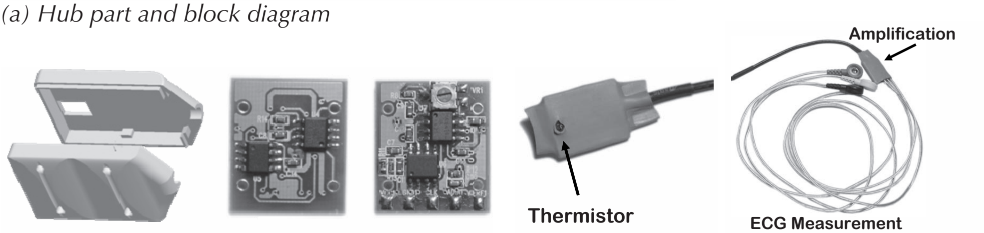
Figure 2. Block diagram of the measurement system and connection diagram

log in procedure with a password to prevent access of an unauthorized person through CDMA channel.

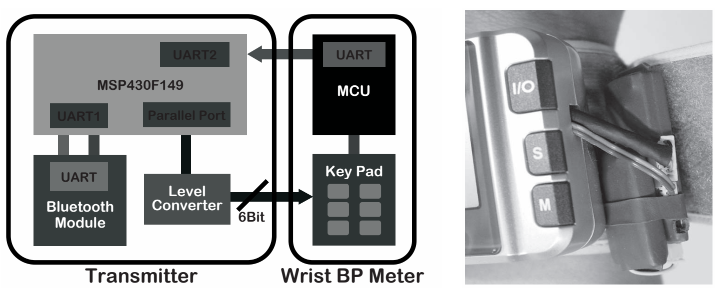
Figure 2 shows the block diagram of the developed biosignal measurement device. We used the MAX4194 instrumentation amplifier as differential amplifier to reduce measurement noise. A high pass filter with cut-off frequency 0.1 Hz prevents introducing drift noise in the measured signal. The 60 Hz power line noise is removed by the notch filter between MAX 4462 and MAX 4194. The amplified analog signal is converted by a 12 bits ADC in a MSP430F149 converter to a digital signal. The client PC is interfaced with the biosignal measurement device through the host computer interface (HCI) layer of the Bluetooth protocol.



(a) Hub part and block diagram



(b) Active dry electrode, thermistor and ECG amplification parts



(c) UART connection of blood pressure meter and transmitter

Figure 3. Wearable biosignal measurement devices

Figure 3 shows wearable biosignal measurement devices. The hub part has 4 ports and 12 bits analog-to-digital converters (ADCs). The quantized data is transferred to the client PC through a Bluetooth channel. Blood pressure and heart beat information are measured by a modified commercial blood pressure meter. The blood pres-

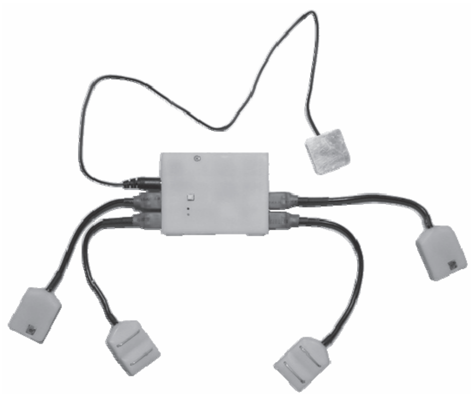


Figure 4. Integration of hub part and active dry electrodes for EMG measurement

	7	6	5	4	3	2	1	0
Byte 1	1	1	0	0	Channel 1 High			
Byte 2	Channel 1 Low							
Byte 3	1	1	0	1	Channel 2 High			
Byte 4	Channel 2 Low							
Byte 5	1	1	1	0	Channel 3 High			
Byte 6	Channel 3 Low							
Byte 7	1	1	1	1	Channel 4 High			
Byte 8	Channel 4 Low							

Figure 5. Data transmission protocol for EMG signals

sure meter is connected to MSP430F149 through a universal asynchronous receiver/transmitter (UART) channel.

Figure 4 shows the integrated active dry electrodes for EMG measurement. The rails and common ground are made of 99.9% silver. Figure 5 shows the data transmission protocol for EMG data. The data quantized by 12 bits ADC is transferred with a 4 bits channel code for synchronization. Table 2 shows sampling and data rate of biosignals. EMG, ECG and body temperature are measured regularly. However, blood pressure and heart beat are measured irregularly.

The control signal for the modified blood pressure meter is generated by the client PC. The duration per measurement is about 30 seconds. To reduce the blood pressure measurement error an attentive sound is generated by the client PC during measuring.

The electrical and mechanical specifications of the bio-signal measurement

Table 2. Sampling and data rate of biosignals

Biosignal	**Sampling**	**No. of channels**	**Data rate (kbps)**
EMG	1 kHz sampling 12 bits data 4 bits channel code	10	160
ECG + temperature	500 Hz sampling 12 bits data 4 bits channel code	2	16
Blood pressure and heart beats	600 bytes / measurement	1	.
Total data rate			176

Table 3. Specifications of the biosignal measurement system; dimensions include one battery cell

Function		**Specification**
Dimensions	Main part	50.5 (L) x 40.5 (W) x 10.0mm (H)
	Active electrode	29.2 (L) x 20.2 (W) x 4.7mm (H)
Measurement life time		5 hours / battery cell of 180mAh
Wireless communication		110kbps 10 m covering range Bluetooth BC TM 02 HCI interface through UART
Electrical characteristics		3.3V operating voltage 1 kHz sampling per channel 12 bits quantization 4 channels variable cutoff frequency and gain

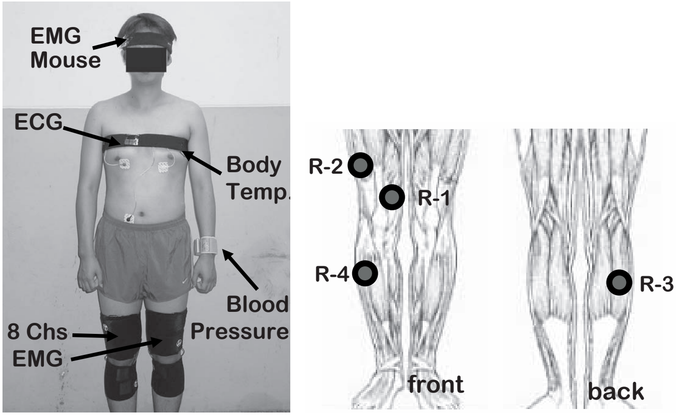


Figure 6. Experimental setup and contact points[12]

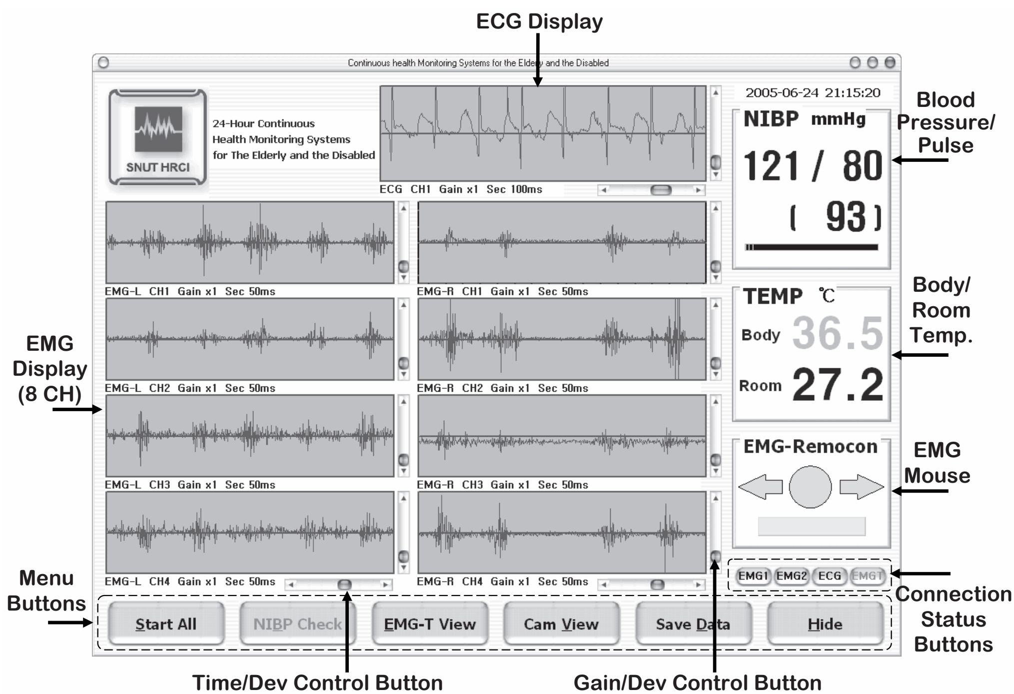


Figure 7. GUI of biosignal measurement system

system are shown in Table 3. The power supplied by the rechargeable battery is mainly consumed by the Bluetooth device. The power consumption of the active electrode is less than 1 mAh. Figures 6 and 7 show the experimental set-up and graphic user interface. The EMG-remote controller with 2 degrees of freedom and 1 selection option is used for having a user friendly interface. The cursor of the EMG mouse moves one button to the right when the right temple EMG signal is sufficiently measured and one button to the left when the left temple EMG signal is sufficiently assessed. The buttons shown in the graphic user interface are selected when the EMG signals from both the left and right temple are sufficient. The EMG mouse can be helpful for a disabled person with severe impairments such as c-4 spinal cord injury when s/he wants to

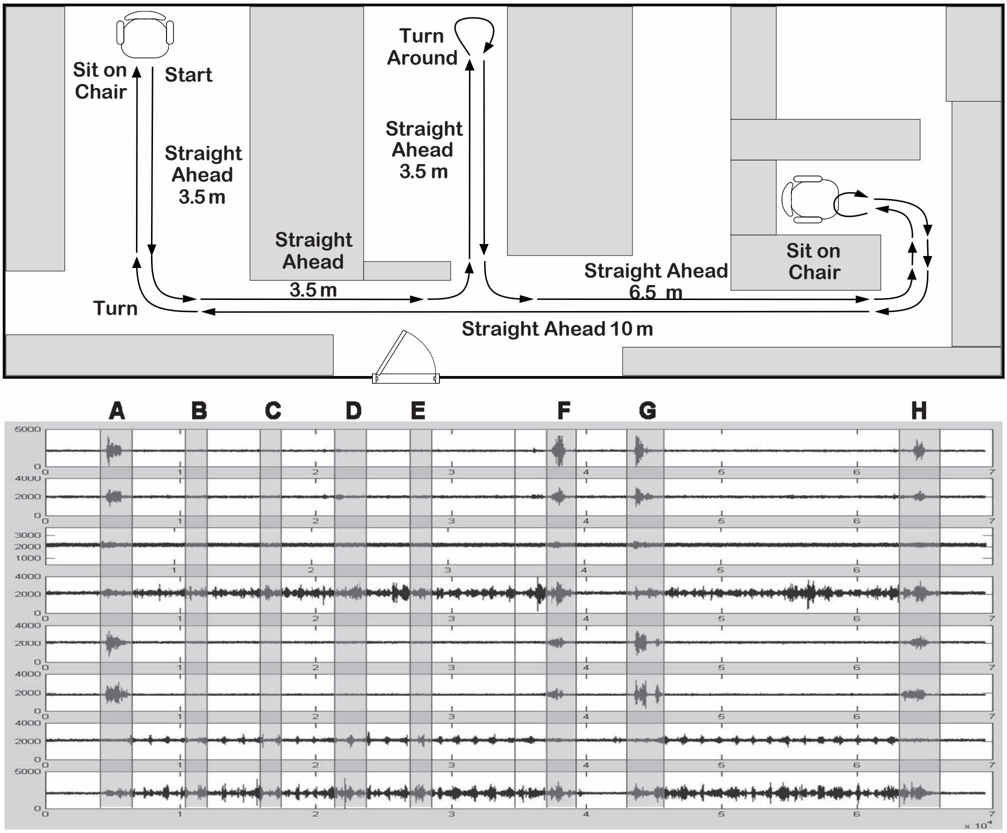


Figure 8. EMG signals measured during body motions

control the health monitoring system and the home environment.

Figure 8 shows the experimental set-up in which EMG signals through eight channels are measured during various body motions such as sitting on a chair, walking straight ahead and turning around. The EMG signals are used for a more stable estimation of the status of the heart system.

Deciding on emergencies

When an emergency situation takes place, a character message is transferred to the caregiver's cellular phone. Simultaneously, ECG signal and blood pressure are recorded in a server PC for diagnosis by medical doctors. Also, six images with information about the emergency state are stored in the server PC and an e-mail with the images is sent to a predefined e-mail server. For image capture we adopted the AXIS PTZ 2130 web camera with pan, tilt and zoom control functions. The web camera has been interfaced with a graphic user interface (GUI) in the server PC through activeX control.

Figure 9 shows the image capture procedure and six captured images. The captured images are stored in the server PC. The caregiver can see the situation of the inside of the home via the cellular phone and make a final decision whether the state is truly an emergency state or not. We used a cellular phone with the function of the mobile browser KTF KUN version 1. A security program with some predefined cellular phone numbers and corresponding security codes, which was coded by the hypertext preprocessor scripting language (PHP), was installed in the server. The security program prevents

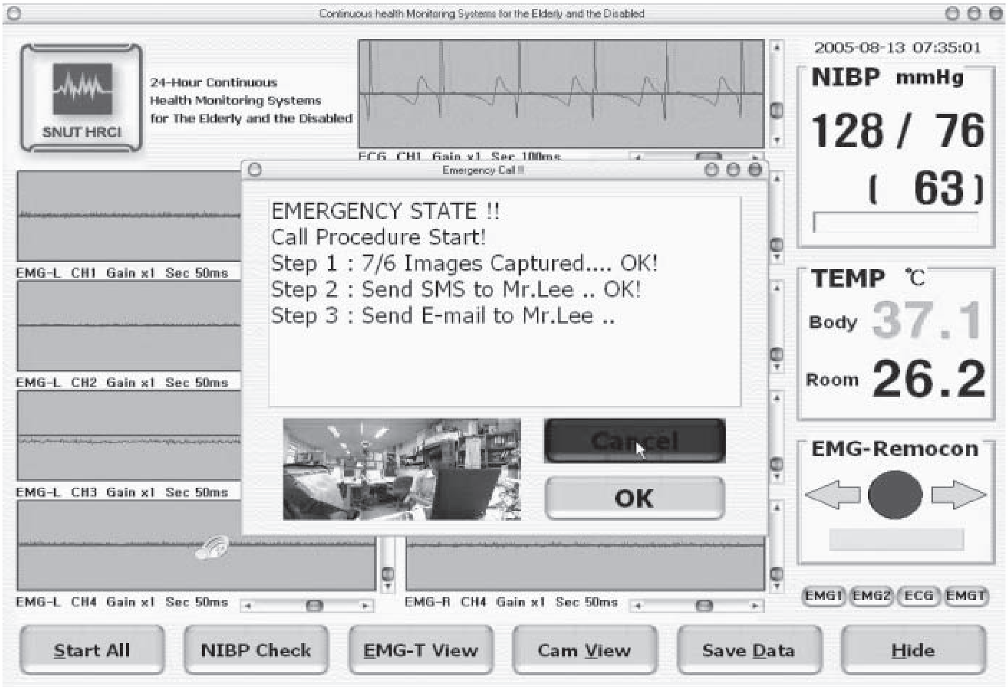


Figure 9. Sending an alert to a predefined caregiver

unauthorized cellular phones from accessing the monitoring system.

Emergency states are estimated by a set of prespecified parameters such as the degree of disorder in the ECG signal, blood pressure and body temperature. In the steady state, the ECG is a quasi-periodic signal due to rhythmic phenomena known as respiration sinus arrhythmia[13]. When the body is moving, the ECG becomes more quasi-periodic. That is, the heart rate fluctuates with the phase of respiration and waveform changes. Figure 10 shows the clean ECG signal and noisy ECG signal measured during rest and moderate walking with arm movements. In general, the ECG signal measured during exercise is corrupted by various noises due to muscle activities, agitation and incomplete contact of electrodes etc. A hard exercise introduces severe motion artefacts in the measured ECG signal.

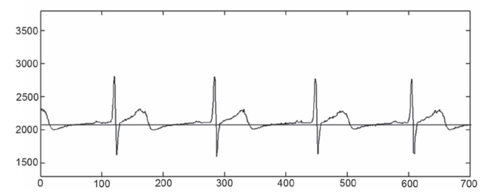
In general, motion artefacts disturb an accurate estimation of the status of the heart system. When this status is problematic, various forms symptoms appear such as distortion of P, Q, R, S, T and U waveforms, phase shift and inversion, and irregular heart rate, etc. In this paper the short term average period of the ECG signal is used for detection of irregular heart rate and decisions to alert the predefined caregiver to emergency situations. The degree of disorder of the ECG signal is estimated based on the short-term average period of the ECG signal. For an ECG signal $x(t)$, the cross-correlation function $R_t(\tau)$ at a time instant t is defined by

$$R_t(\tau) = \int_{-\infty}^{\infty} x(\eta) y(\eta - \tau) d\eta$$

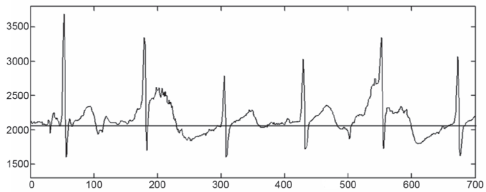
Where

$$y(t) = \begin{cases} x(t), & \text{if } -W/2 \le t \le W/2 \\ 0, & \text{otherwise} \end{cases}$$

The signal $y(t)$ is the template of the ECG signal at a time instant t. The constant W, which is 2 seconds, is the width of the template. For the ECG signal being considered here, the short-term average period $P_a(\tau)$ at a time instant t is obtained



(a) Clean ECG signal



(b) Noisy ECG signal corrupted by motion artifacts

Figure 10. Normal ECG signals measured by the health monitoring system

from the cross-correlation function $R_t(\tau)$. That is,

$$P_a(\tau) = \frac{1}{2M+1}\sum_{k=-M}^{M} T_k$$

where $T_k = T_{k+1} - T_k$ is the k^{th} peak-to-peak interval, and $R_t(\tau)$ has the peak values at τ_k. $2M+1$ is the number of the considered peak-to-peak intervals. $2M+1$ peaks near time instant τ are used for calculation of $P_a(\tau)$.

The template $y(t)$ is updated continuously at every time instant t to cope with the variation of the ECG signal due to physical exercise and emotion changes, etc. If the template is corrupted by severe noise, the consequent processes will generate erroneous results. Therefore, the updating is

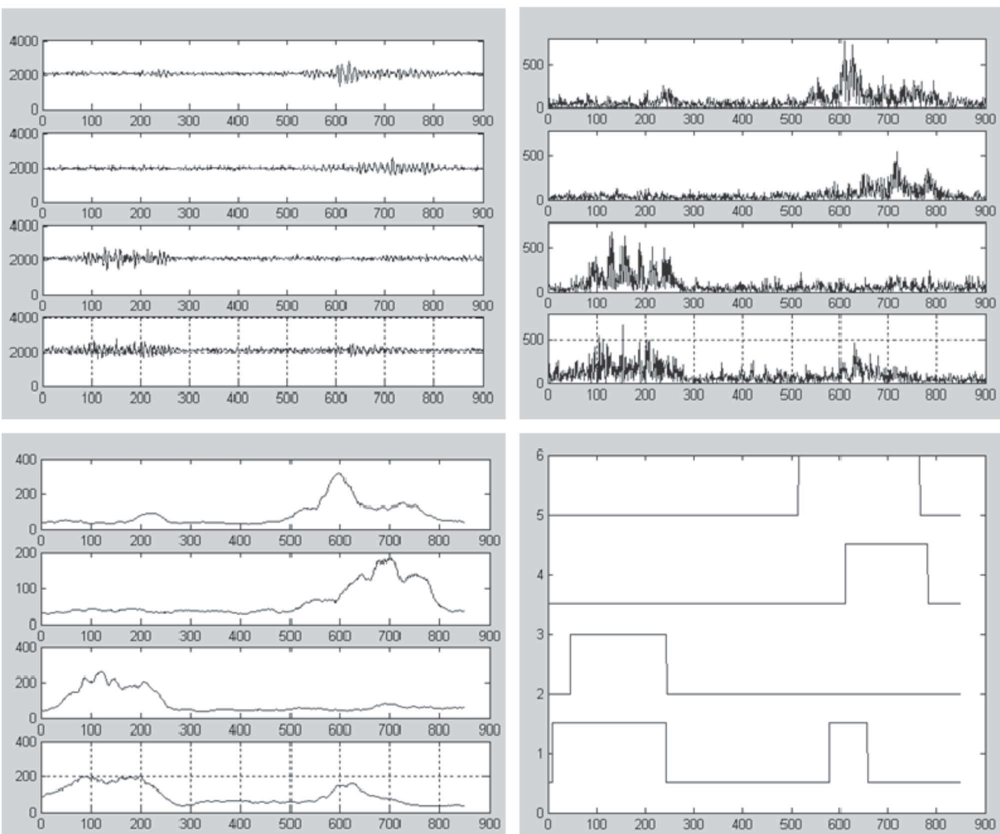


Figure 11. Processing EMG signals for estimation of the body motion state

Table 4. Conditions for biosignals to generate emergency calls

Biosignals	Conditions		Typical value
ECG	C1	S high	> 0.1 s
Blood pressure	C2	P high	> 160 mmHg
	C3	P low	< 80 mmHg
Body temperature	C4	T high	> 39 °C
	C5	T low	< 34 °C
EMG	C6	L long	> 3 hours

paused if the energy density of EMG signals is very large, since high level noise is introduced in the ECG signal when the body movements are intense. The multimodal processing of ECG based on EMG decreases the estimation error of the ECG disorder. Also, the EMG signal can be used as feedback signal for supervised rehabilitation such as post-stroke rehabilitation, and orthopedic rehabilitation in a smart home environment.

In figure 11, the signals at the top-right are the absolute of the signals at the top-left which are raw EMG signals. The signals at the bottom-left show the moving average of the absolute signals with window width of 50 samples. The signals at the bottom-right show the durations of the average signals that exceed a threshold level of 100. The template ECG is updated when all of the threshold crossings are zero.

Table 4 shows several conditions for recoding biosignals that generate emergency calls. The variable S is the short-term standard deviation of intervals with M=10. The value of S is high when the heart system is unstable. The variable L is the time interval when all the threshold crossings of EMG are zero. Although we use the short-term standard deviation to prevent generating false alerts, the possibility that an emergency call is false is very high if the body is strongly moved. Multimodal decision making with ECG and EMG will increase the reliability of decisions for alerting. That is, the degree of reliability for the decision is very high if all of the threshold crossings of EMG are zero. On the other hand, an alert generated by the condition C6 could be false if S is very small. We use six simple conditions for generating alert signals in this paper. For better performance of the developed monitoring system, we found that optimization of the conditions and related parameters, and combination of the conditions and exact rules extraction are desired.

This paper describes also a full integration of individual devices for checking communication burden and data recording performance. Integration of modularized sensors depends on specific applications. In case of continuous health monitoring, the integrated system should be optimized case by case based on medical requirements. According to some medical reports, sinus arrhythmia may cause a sudden death of a healthy person although the probability that this happens is very low. In case of disabled persons, this probability will be increased since they may not be able to do physical exercises regularly. In several cases the symptoms of sinus arrhythmia can be identified based on very long time observations (for instance, for a period of several months or longer) with attentiveness, since the symptoms are very short and irregular. Multimodal processing and recording based on the ECG and EMG mitigates the labor intensive attention of a physician in identifying sinus arrhythmia and, moreover, will increase the possibility of successful identification.

However, a person with severe heart disease should be observed intensively every day. This ambulatory case needs real time monitoring. The health monitoring based on the body area network will decrease medical costs for care-giving service and eventually increase independence and activities of the elderly and disabled during daily life. The proposed system has been tested by three persons including one disabled person with spinal injury of code 5-6 and two healthy persons in their twenties.

Surface electrodes with silver rails have been developed for reducing the inconvenience of gel type electrodes. It was observed that the parallel silver electrodes in surface EMG sensors induce a pain when the sensor is attached to a hard region of the body and pressured by band, although the surface EMG sensors increase convenience for measuring EMG signals from soft points such as the back side of the legs.

Conclusion and future research

In this paper, we have presented a 24-hour continuous health monitoring system that we have developed by using various wearable measurement devices, a cellular phone and communication network. We have shown actual realization of a real-time recording function for biosignals, generating alert signs for a caregiver, and of a checking function based on the notion of human-in-the-loop system which increases performance of the monitoring function. Eventually the final goal of this system is to monitor some basic biosignals continuously with long-lasting wearability and comfort and to transfer the gathered data to medical doctors for timely alert which leads eventually to prevention of complications. Although simple methods for triggering are used in showing the benefits and effectiveness of the developed system, a further improved and optimized version can be achieved if rigorous algorithms for diagnosing an abnormal state are available. For a full-fledged system that is capable of 24-hour continuous health monitoring, intense collaboration among various parties including medical doctors, users and engineers is required.

The health monitoring system includes many sensor modules for filtering and amplifying various biosignals. Although all modules are integrated for experiments of checking communication and recording speed, the optimized integration of modules based on medical prescription reduces the amount of data to be recorded and mitigates the load for communication and the graphic user interface. Also, optimization of the sampling frequency for each sensor reduces power consumption for transferring data through wireless channels.

Using accelerometers instead of EMG sensors can increase wearability and might give more simple methods for estimating abnormal states of the heart system, based on multimodal processing. However, not only health monitoring but also rehabilitation is an important function of a smart home environment. In this paper, we have employed surface EMG sensors, since these EMG signals can be used for supervised physical rehabilitation.

Several methods based on embedded sensors in furniture such as chair, toilet and bathtub were reported. Most difficulties of these non-contact methods are caused by motion artefacts. For instance, ECG signals measured by a sensor embedded in a chair are corrupted by heavy noise. Although high CMRR reduces measurement noise, the ECG still has heavy motion artefacts due to swings of body. Contact and noncontact methods have merits and demerits. Although this paper focuses on the contact methods, complementary use of contact and noncontact methods will increase performance. Future research topics include embedding technologies reducing size and increasing wearability.

The body area network may entail privacy and security problems although the security levels of CDMA and Bluetooth are very high and the server has the log in procedure to prevent accessing by an undefined person. Recording and discarding data after alarming will mitigate improper use of personal medical data. All data and information should be encrypted to protect user's privacy and more effort should be focused on the security system to avoid ethical problems. Also, legal regulations of accessing patient-identifiable data should be established. Establishment of social regulations and improvement of the security function will enable persons of a high age to accept monitoring for their health in a smart home environment.

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