Issues in Wearable Computing for Medical Monitoring Applications: A Case Study of a Wearable ECG Monitoring Device

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Abstract

In this paper we discuss issues surrounding wearable computers used as intelligent health monitors. Unlike existing holter monitors (for example, ECG and EEG holters), that are used mainly for data acquisition, the devices we discuss provide real-time feedback to the patient, either as a warning of impending medical emergency or as a monitoring aid during exercise. These medical applications are to be distinguished from applications of wearable computing for medical personnel, e.g. doctors, nurses, and emergency medical technicians. Medical monitoring applications differ from other wearable applications in their I/O requirements, sensors, reliability, privacy issues, and user interface. The paper describes a prototype wearable ECG monitor based upon a high-performance, low-power digital signal processor and the development environment for its design.

1. Introduction

An increasingly important application of wearable computers is as an intelligent medical monitoring device providing real-time feedback to the patient. A patient can wear the device during normal daily activity, allowing medical staff to obtain a much clearer view of the patient's condition than is available from short periods of monitoring in the hospital or doctor's office. Note that the intelligent medical monitoring device is to be worn and used by a patient, not by medical personnel, e.g. doctors, nurses, and emergency medical technicians [1]. It should also be distinguished from medical data acquisition devices currently available, which have little or no computer processing, limiting their functionality to recording signals that will later be processed off-line [2][3][4][5][6].

Low-power CPU's now have sufficient performance to process the signals in real-time, allowing prediction of impending medical emergencies and feedback about current patient activity. For example, a wearable device could be used to monitor the recovery of heart rate after exercise, which has been shown to be useful as a prognostic tool [7]. A wearable device could also be useful for low intensity monitoring in the case of elderly patients; it has been shown that such monitoring can reduce costs of hospitalization and care for heart failure patients [8]. In order to be most useful to the patient, the device must be designed properly in terms of size, weight, performance, reliability, and privacy. This paper describes how wearable computer medical monitoring applications differ from other wearable applications in each of these respects and then details a prototype ECG monitor and our development environment for medical monitoring applications.

The remainder of the paper is organized as follows. Section 2 describes the differences between medical monitoring applications and other wearable computing applications and some of the difficulties that lie in the way of their wider acceptance. Section 3 describes ECG waveforms and morphological analysis, our prototype wearable computer for monitoring the user's ECG, and the development environment. Finally, Section 4 presents our conclusions and future work.

2. Wearable medical monitoring applications

Medical monitoring applications of wearable computing differ from general purpose wearable computing applications in several respects, in degree if not in kind. First, user interaction tends to be much more limited. Second, the performance/power trade-off can often be made in terms of size of data storage, i.e. the battery must only provide enough life that the data storage is filled, or conversely, the data storage must only be large enough to be filled when the battery is fully discharged. Third, there is an emphasis on signal processing that does not exist to the same degree in general purpose wearable computing applications. In this respect, wearable medical monitoring applications more closely resemble scientific computing applications than

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other wearable applications. Finally, the wearable medical computer faces more stringent requirements in terms of privacy, reliability, government regulation, and the manufacturer's legal responsibility.

It is reasonable to expect that many types of medical monitoring that currently require the patient to visit a hospital or doctor's office and be connected to a tethered machine can eventually be performed using a wearable device. However, in the near term, we see the following applications:

- monitoring of myocardial ischemia [4][9][10][11]
- epileptic seizure detection [12]
- drowsiness detection (alertness monitoring) [13][14]
- physical therapy feedback, such as for stroke victim rehabilitation [15][16]
- Sleep apnea monitoring
- long-term monitoring for circadian rhythm analysis of heart rate variability (HRV)

The major obstacles to wider use of intelligent wearable medical monitors include the following:

- Existing sensors are difficult to wear for long periods of time without irritating the skin after prolonged periods.
- Changing contact resistance between electrode and skin over time (For example, gels that are used to improve contact in the case of EEG electrodes dry out over time.)
- Size and weight of intelligent device. Available data acquisition holters are typically the size of a Walkman, which is larger and heavier than desirable. Device intelligence in addition to data storage can increase size and weight, unfortunately.
- Routing and connection of sensors. Most medical monitoring applications require a large number of analog input channels. For example, three channels are necessary for ECG monitoring, up to 8 or 16 channels for EEG monitoring, and more than 8 different physiological signals for sleep studies, each with their own particular requirements in terms of signal range, amplification, and filtering.
- Regulation by government medical agencies, such as the Food and Drug Administration in the United States.
- Responsibility for outcome of medical conditions, i.e. a manufacturer will want to minimize the chance of being sued if the device does not correctly predict a medical event. It is difficult to determine if there was a malfunction of device, a lack of knowledge of other conditions of the patient, or whether the law suit was justified.

As noted above, privacy and reliability are particularly important for wearable medical monitoring devices.

The main privacy issue with wearable medical monitoring applications is how not to disclose the information collected about the user, rather than an issue of what information about others the user is allowed to record or access [17]. In this respect, the wearable medical monitoring applications are somewhat at an advantage over other wearable applications, which likely have a great number of societal and legal barriers to overcome.

Since the user would like the data collected to remain private, the data should be encrypted and made physically secure. One issue of the encryption is that it must balance strength of encryption with power (both in terms of Watts and MIPS). It would be undesirable to use an encryption mechanism that is only slightly more secure while requiring a great deal more performance and power. The development environment described in the next section allows us to study such tradeoffs of functionality, performance, and power consumption.

The one privacy issue that medical monitoring applications raises that other wearable computing applications do not is that simply wearing the device may be information that the user would like to keep private, as wearing the device may disclose to the user's employer/insurer/acquaintances that the user is suffering from a medical condition. While this particular issue is shared with other medical equipment, so far as we know, no one has raised this as an issue in wearable computing. Such disclosure requires that the wearable monitoring device be as unobtrusive as possible. The larger and bulkier the device, the more likely it is to be observed by those around the user. Thus, a proper balance of power and performance is desirable even from the standpoint of privacy.

As for reliability, medical wearable electronics must be more reliable than their general purpose counterparts. A wearable ECG must function for as long as expected (i.e., for its full estimated battery life) without any failures, otherwise its purpose is defeated. For wearable medical electronics that are intended to give advance warning of the serious conditions, a failure could be life threatening.

Finally, we envision a collection of wearable medical sensors, communicating with a central processing element, also wearable, which processes the data in real-time and provides information to the user about medical status, akin to Gordon Bell's body network and "guardian angel" [18].

This "guardian angel" could be connected via a wireless network, so that 911 or a specialized medical response service could be contacted in the event of a medical emergency, or the doctor if an episode is not life-threatening but still requires intervention. The user or doctor or both could formulate triggers that cause even more data to be collected, additional sensors to be enabled, or medical personnel to be contacted.

3. Wearable ECG application and development environment

While we envision a host of medical monitoring applications, our first application is an ECG monitor. This section provides background information on the need for wearable ECG monitoring and describes the signal processing involved.

3.1 Background on ECG waveforms and cardiological feature extraction

The existence of silent myocardial ischemia creates the need for Holter monitoring of the asymptotic patient [2]. Holters are portable, battery operated, devices for monitoring of physiological signals [2][3][4][5]. Lack of processing power has limited the function of Holter devices primarily to data acquisition. Traditionally, Holters have been used to monitor ECG or EEG (brain electrical activity) and record 24-hour activity on cassette tape. Recorded signals are then analyzed off-line using dedicated diagnostic systems. Recently, new generations of Holter devices use solid state memory instead of magnetic tape [5][6].

With the current state of processor technology, standard processing of biomedical signals (such as filtering, spectral and statistical analysis) does not require significant processing power. This is particularly the case for the new generation of DSP processors with processing power in excess of 100 MIPS, even in a portable environment. The main reasons for this are low sampling frequency (typically less than 1KHz) and a relatively small number of channels (usually three for ECG Holters). On the other side, new sophisticated signal processing algorithms require significantly larger processing power (for example, non-linear dynamics [19], wavelets [20], etc.).

In the first period of computerized electrocardiography, real time processing was used to detect and document arrhythmias. Improved performance of monitoring devices allowed morphological analysis and pattern recognition. The most important application of ECG pattern recognition is detection of transient ischemic event [3][4]. Ischemia is considered a primary cause of cardiac infarction and life threatening cardiac arrhythmia.

Real time processing of heart electrical activity is a relatively simple task for the current generation of digital signal processors. With the sampling rates of 250 Hz (long term monitoring) to 1 KHz (heart rate variability analysis), most signal processing procedures could be performed in a fraction of the sampling period. However, morphological analysis of the signal is much more time-consuming.

Typical electrocardiogram is presented in Figure 1. The most important ECG phases for morphological analysis are:

- ***P-wave*** (representing contraction of the atria)
- ***QRS complex*** (representing contraction of the ventricles)
- ***T-wave*** (representing the recovery of the ventricles)

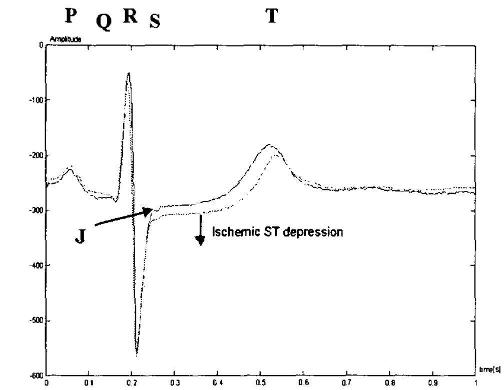

Figure 1. Typical ECG waveform phases P,Q,R,S and T, and characteristic J-point; ST segment depression/elevation indicates an ischemic event.

The atria also have a recovery phase, but the QRS complex masks this event. ST-T segment changes indicate ischemic episodes during Holter monitoring or the exercise test [21]. The J-point characteristic (as presented in Figure 1) is frequently used to assess ST-T segment changes [2].

Typical ECG processing algorithms consist of the following phases [9]:

Initialization - Used to determine initial signal and timing thresholds, positive/negative peak determination, automatic gain control, etc.

Filtering - This is performed first as analog filter on ECG amplifier board, and then as digital filter on DSP board. In addition, 50 or 60 Hz notch filter is sometimes used to reduce power line interference.

QRS complex detection - Reliable detection of R-peak is crucial for morphological analysis.

Baseline correction - Compensates for low-frequency ECG baseline drift.

ST segment processing.- Detects changes in ST segment.

In addition to the above processing, the ECG waveforms may require additional processing if any of several forms of variation are present. These variations must be accounted for in order to properly analyze the waveforms when predicting cardiac events. The most important problems in real time ECG analysis are [2][22]:

- *Base-line wander* A very low frequency change of isoelectric level of ECG (Figure 2a)

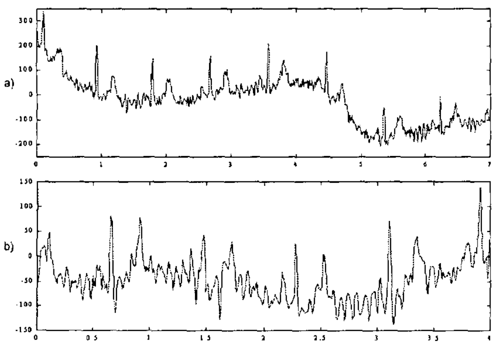

Figure 2. Characteristic problems of ECG processing: a) baseline wander, b) distorted morphology of the signal with hardly recognizable ECG phases (compare with the signal in Figure 1).

- *Physiological variability of QRS complexes.* Large variability in waveshape of the QRS complex, for instance large T waves with a high frequency characteristic similar to QRS complex, requires a reliable recognition algorithm (Figure 2b)
- *Power line interference* (50 or 60Hz noise induced by power lines) [23]
- *Muscle noise*
- *Artifacts due to electrode motion*
- *Patient dependent abnormal ST depression levels*
- *Varying ST-T patterns*

3.2 Description of wearable ECG monitor prototype

We have implemented a wearable, DSP-based, real-time ECG holter prototype, shown in Figure 3. A real time portable ECG development environment is implemented using an off-the-shelf Texas Instruments TMS320C5410-100 processor board [11][24], and a Del Mar PWA ECG Amplifier [5]. The amplifier is a dedicated three-channel ECG Holter amplifier with low power consumption. A set of electrodes and their leads are optimized for Holter applications. We use on board flash memory as program and small-scale data storage.

As Figure 3 shows, the prototype board has several functions that are unnecessary for our ECG application, but are desirable from a prototyping standpoint. For example, the board has LCD output and keyboard input as well as a serial interface. The codec samples at 44.1 KHz, a much higher frequency than required for an ECG, because the prototype board was intended for digital audio applications. This added functionality burdens the prototype in size, weight, and power consumption, although it considerably eases debugging and allows us to develop a wide variety of applications on a single platform. Ongoing experiments with the prototype platform will allow us to tune both the hardware and the software to the ECG application, especially its power consumption and size. Table 1 shows several features of the prototype, including the measured power consumption and the estimated battery life.

Table 1: Characteristics of wearable ECG monitor prototype

Processor	TI C5410-100 DSP
Program Memory	128 KB
Secondary Storage	30 MB (compact Flash)
Codec sampling freq.	44.1 KHz
Power consumption	0.5 W (150 mA @3.3V)
Battery weight	100 g
Estimated battery life	10 hours

3.3 Improving battery life and system weight by energy profiling of applications

Holter applications typically require battery life of 24-48 hours, so power consumption of the ECG monitor is a critical issue. As Table 1 shows, our expected battery life is much less. Removing some of the unnecessary functionality described in Section 3.2 will decrease the power consumption markedly, but not enough to meet the target battery life. Since batteries are large fraction of the system weight, we cannot simply add more batteries to extend battery life because the system would become too heavy.

One possibility to improve battery life is to find optimum trade-off between energy spent on storing raw data versus energy to compress data. Long-term monitoring applications require significant storage space. As an example 24-hour ECG record with 250 Hz sampling frequency requires approx-imately 42 MB of memory. This can be easily accommodated using standard compact flash memory card as secondary storage for long term monitoring. This amount of storage could be significantly reduced by data compression. However, data compression will consume considerable CPU energy. This trade-off involves a number of variables including the relative power consumption of the storage subsystem and CPU, level of compression, possibility to use lossy compression, and the quality of compression that can be achieved for the given type of data. In some applications whether or not data would be decompressed by the same battery operated system is also an issue.

The proper balance of power and performance for optimum system organization requires precise profiling of the power consumption of different hardware subsystems as well as software functions.

Average power consumption is only a crude estimate of power requirements and battery life; a much better estimate can be made using dynamic power consumption [25]. Dynamic power consumption is a function of the execution profile of the given application running on specific hardware platform.

We are developing a new environment for energy profiling of DSP applications, similar to that described by Flinn for profiling general purpose systems [26]. The environment consists of a JTAG emulator, a high-resolution HP 3458A multimeter and a workstation that controls devices and stores the traces. We use a standard Real Time Data Exchange mechanism (RTDX) [27] to generate an execution profile and custom procedures for energy profile data acquisition using GPIB interface. By correlating power consumption with application execution profile, the environment allows us to improve the system power consumption through changes in software organization and measure real battery life for the given hardware, software and battery configuration.

The proposed environment correlates the application execution profile with power consumption profile. Consequently, we will be able to identify the specific hardware and software components whose power consumption has the most critical impact on battery life.

Once these components are identified, we will be able to optimize for the proper balance between performance and power consumption. As mentioned above, data compression may reduce power consumption due to the secondary storage, although at the cost of increased CPU power consumption. In addition to data compression, we have also identified filtering and encryption of data as primary areas for reducing power consumption of the wearable ECG prototype. Both areas appear to have a large number of trade-offs at the algorithmic level that should be explored to finely tune power consumption and performance.

Our environment for energy profiling of DSP systems allows us to explore the system design space and find optimum solutions for the given application. Moreover, we can measure system operation time for a particular battery family. Therefore, we can more accurately predict battery life in the presence of non-ideal battery behavior.

4. Conclusions

Medical monitoring applications for wearable computing offer a powerful new way to keep track of a patient's medical condition and predict impending events. We have described the issues surrounding these wearable medical monitoring applications and have shown how they differ from other wearable computing applications. We have also described our initial medical monitoring application, a wearable ECG device, which gives the

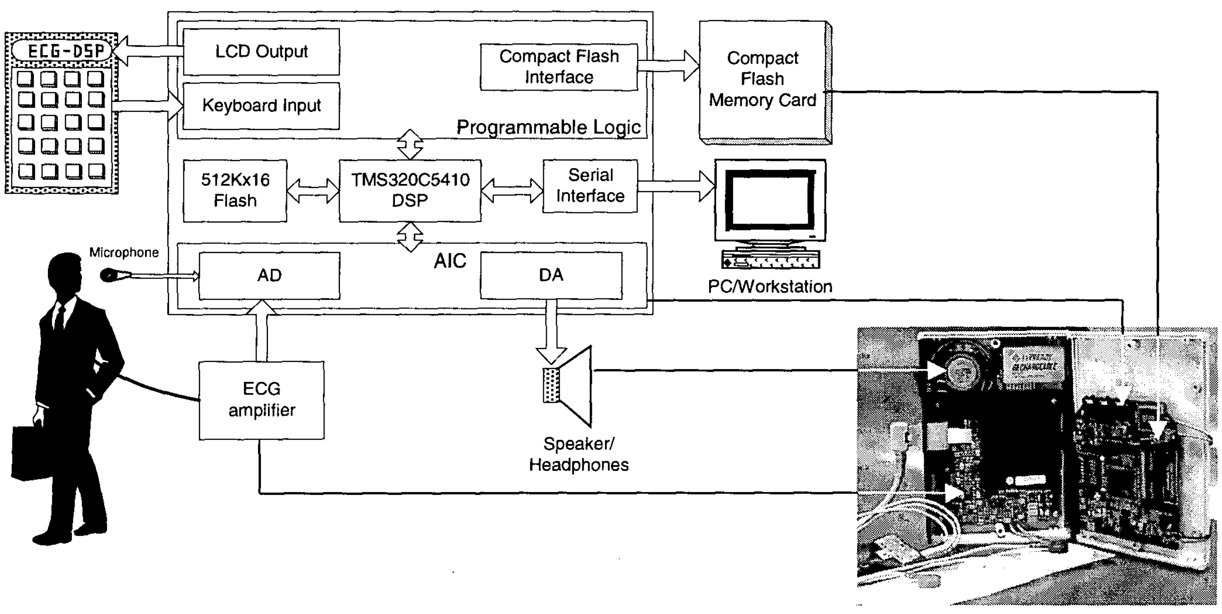

Figure 3. Block diagram of the portable ECG development environment.

patient real-time feedback about the onset of serious condition, as well as our development environment, which when complete will allow us to rapidly create new applications and study the power consumption of their software.

Our future work includes the development of other wearable medical monitoring applications, such as monitoring brain waves (EEG) for alertness detection and seizure prediction [28]. Our ultimate goal is a system of wireless medical sensors communicating with a central processing element, to provide continuous real-time feedback and monitoring of a user's condition. Such a device can easily be integrated into a telemedical environment [29]. Our development platform allows us to fine-tune the processing and power consumption of the devices.

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