

Control, Analysis, and Visualization of Body Sensor Streams

Andrew D. Jurik and Alfred C. Weaver

{jurik, weaver}@virginia.edu

Department of Computer Science, University of Virginia, Charlottesville, VA, USA 22904

Abstract

Personal medical monitoring technology can be used to instrument the body and enable the exportation of a variety of physiological signals, either directly to mobile devices or via web services to a “health portal” accessible by authorized viewers. For example, both warfighters and cardiac patients would benefit from continuous medical monitoring of their electrocardiograms (ECGs). Such a monitoring system would require at least two major subsystems: an ECG sensor with a processor and a radio that can be packaged for use on the body, and a base station that collects or forwards information so that the data is accessible to relevant entities. We developed an end-to-end telemedicine system that enables on-line ECG data analysis and viewing of that data at a distance. We posit that such a system would prove valuable in military and civilian healthcare settings such as cardiology, emergency medicine, neonatal units, and assisted living centers.

Keywords:

Telemetry, Ambulatory Monitoring, Computer Systems

Introduction

The emergence of enabling technologies such as low-power body sensors and the Internet has propelled new classes of applications including self- and remote monitoring. When outside the confines of a doctor’s office cardiac patients may encounter transitory conditions and experience intermittent episodes, but the doctor may have only anecdotal evidence to support a diagnosis. On the battlefield soldiers may be out of contact with the medics that can help them.

There are many physiological parameters that can be obtained and analyzed, but the electrocardiogram is arguably one of the most well studied and clinically significant. The electrical activity of the heart provides a valuable indicator of the health of one of the most important organs in the human body. In fact, other signals may be derived from the ECG such as respiration and blood pressure [1]. In 2005, 17.5 million deaths around the world were due to cardiovascular disease (which represents approximately thirty percent of all deaths) and at least twenty million people survive heart attacks and strokes every year [2]; clearly constant vigilance and prompt response has the potential to save many lives.

Telemedicine is a medical discipline in which healthcare transactions can take place from afar. While the scope of telemedicine can range from medical counsel during a telephone call to remote surgery, we focus on a form of telemedicine that can be provided using an automated service yet requires little user interaction. Numerous innovative systems [3, 4, 5] have endeavored to deliver telemedicine functionality through various communication schemes. With healthcare costs rising and the general population growing older, telemedicine is viewed as a potential solution for freeing up healthcare providers’ time and mitigating costs [6, 7].

The desire for data-driven diagnosis can be met with a robust, secure telemedicine system that conveys information retrieved by a body sensor or network of body sensors. When a patient is feeling ill, we envision a suite of sensors that automatically relays information to a telemedicine center to be analyzed by a healthcare professional.

To this end, we propose a system in which a body sensor detects and processes an individual’s ECG waveform and transmits the processed signal to a base station (in this case, a mobile device). The goal of our system is to respond dynamically to signal changes from the sensor and to incorporate that information into a set of policies that defines how the information is sent to a remote location. A database stores the information for subsequent web portal access either in real-time or later.

Such a system presents several challenges. First, the entire system must have a reasonable lifetime. The sensor is severely resource-constrained and energy use is at a premium. Second, the performance of the mobile device must not be dramatically affected by the presence of the data processing service. A process that dominates the CPU’s cycles or drains the mobile device’s battery is not tolerable. Third, potential faults and transient errors must be well understood and mitigated such that the number of false event triggers is kept at an acceptably low level.

We use the ECG as the primary signal for propagation through the system. We assume that the wearer of the sensor (and user of the mobile device) is initially strongly authenticated by some mechanism (password, smart card, biometric, etc.) inherent to the mobile device. Our main contributions include:

- An algorithm in both the sensor and in the mobile device for detecting heart rate
- A user-level application with several generic interfaces (sensor type, radio frequency (RF) medium, processing algorithm, etc.) for receiving a signal and applying policies to control the state of the mobile device
- A web services interface for the mobile device to communicate with an external or back-end network
- A web portal for authorized users to view either past or current sensor data.

Related Work

Telemedicine systems have been developed in both industry and academia. CardioNet [10] is an example of a commercial cardiac monitoring service that offers automatic arrhythmia detection and wireless transmission of the ECG through the cell phone network. Medtronic [11] and Biotronik [12] have also developed wireless remote monitoring solutions with implantable cardiac devices such as ICDs and pacemakers. Personal Care Connect [13] is a platform for a set of heterogeneous biomedical devices to communicate with a data hub, which then communicates with a server. Due to the proprietary nature of these systems, none provides the option, as we do, of user control of the sensor's operational mode.

One of the notable challenges in health informatics is automated data capture [6] which body sensors are well-positioned to do. While Bluetooth-based sensor systems have been implemented [3, 14], our design provides a more extensive solution with a custom sensor and web services, rather than WAP. Previous work has limitations in the way that data is entered (i.e., manually from a web site) while we use automatic data capture and delivery. Some systems do not have a sophisticated base station, and some do not forward data to a location beyond the base station.

Several system architectures for telemedicine applications have been proposed. The CodeBlue architecture [15], for example, provides multiple services and acts as an information plane that promotes sensor intercommunication. CodeBlue's primary limitation is its application to emergency scenarios whereas our system is focused more on wearability and regular usage. Pollard et al. [7] designed a three-tiered medical monitoring system but consider the three tiers to be the user interface, the web server, and a "real-time server" that contains temporary storage and servlets. Our system emphasizes the distinction between the sensor and the mobile device as separate entities with separate responsibilities.

Other sensor-oriented research projects would not fit well within our system framework. The Human++ research program [16] has investigated placing body sensors on flexible substrates with the goal of improving wearability. The focus of their research is more on low-power options and sensor hardware design rather than a full end-to-end system. AMON [4] is a wrist-worn device for collection and processing of vital signs and leverages the GSM infrastructure for commu-

nication. While AMON collects data for a large suite of sensors, the location of their ECG sensor (on the wrist) makes the collection of clinically useful data extremely difficult. The location of our sensor (on the chest) is much more conducive to receiving high quality ECG signals.

Methods

In this section we develop the approach to our solution. Our hypothesis is that our system conforms to the system specifications below, and in so doing, provides accurate analysis of an ECG waveform with acceptable low-latency transmission through all the component tiers from the sensor to the web portal.

System Specification

The technical capabilities of the system must support the ultimate clinical purpose of the system. The metrics that we quantify are performance and accuracy. Sufficient performance dictates that the sensor data is processed and propagated through the system with reasonable delays (which will be inevitable due to the routing of the sensor data from the sensor to a mobile device to the Internet). Accuracy demands that false positives and false negatives are minimized.

Several factors play a role in specifying the functionality and constraints of our system. Here we list the system specifications.

- **Wearability and usability.** In order for a system to be successful users must be willing and able to use it. Therefore, the sensor must conform to a reasonable form factor and require as little user intervention as possible to use it.
- **Long lifetime.** The sensor and mobile device must conserve energy to extend the life of the battery for as long as possible. Reducing communication costs and active computation serve to meet this objective.
- **Accuracy.** The signal processing on board the sensor must be accurate and resilient to many types of signals. No body sensor will be able to sense the 'perfect' waveform because of changes in the electrode-skin interface, motion artifacts, and quantization errors, for example.
- **Near real-time.** The immediacy of medical information calls for timely data examination when a patient feels ill. Sensed data should be viewable via the web portal interface in seconds, not minutes.
- **Conformity to security best practices.** A design that treats security as an afterthought or ignores it altogether is inappropriate in today's society. Basic encryption, authentication, and authorization protocols should be utilized throughout the system.

Architecture

The approach we take to solving this problem is based upon a unique, tiered, and service-oriented architecture. We differentiate our architecture from others because of (1) our use of web services to make data visible at a distance and (2) our provision for fine-grained control of the sensor's operational mode. The first tier is the sensor in which data is sensed, processed, and transmitted. The second tier is the mobile device in which data is received, further processed, and transmitted via a web service. The third tier is the web portal and database that interact to display the data on the Internet.

The individual being monitored wears three electrodes to obtain a one-lead ECG signal with common-mode rejection to reduce noise such as power-line interference. Addressing noise at the earliest stage reduces complexity further on in the system and provides a cleaner signal for digital filter analysis. The circuitry feeds the signal into an analog-to-digital converter with a sampling rate of 1000 Hz. We programmed the heartbeat (QRS) detection algorithm in C for the Texas Instruments MSP430 microcontroller and in C# for the mobile device. Based on the operational mode, either the raw ECG waveform or the processed heart rate information is delivered. Rather than sending the ECG waveform indefinitely, a portion of the ECG waveform can also be specified, with the default behavior being the transmission of heart rate data. The sensor transmits the data via Bluetooth.

There are PDA and laptop versions of the mobile device client, thus enabling multiple computing modalities. Both versions provide the same underlying functionality. In our design, only the mobile device is permitted to control the operational mode of the sensor. While functionality could be implemented to permit the web portal to exert such control, we choose not to do this because of the potential security vulnerability. Since the sensor produces protected health information, it would be advantageous for the monitored individual to determine what kind of (and how much) information is delivered remotely. That is the approach we implement.

Figure 1 illustrates the interaction between the sensor and the mobile device independent of the communication with the web portal. The first two tiers (shown in Figure 2) are sufficient for self-monitoring and could be applied to situations in which one would desire a more informed perspective on one's health.

There are two primary web services, one that serves as the interface between tiers two and three, and one within tier three

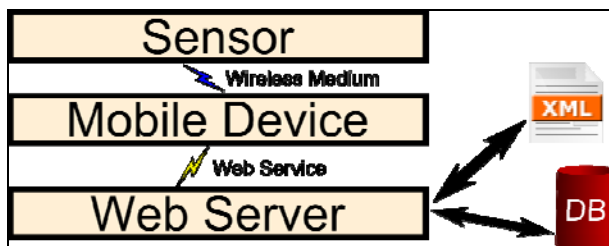


Figure 1 – There are several levels of communication from sensor data production to web server publishing.

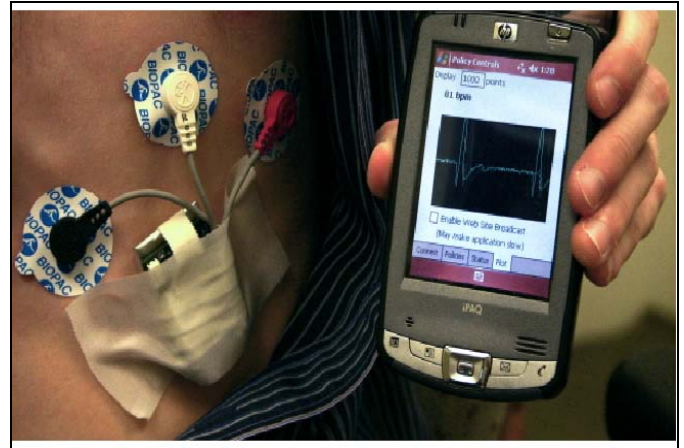


Figure 2 – The communication between the sensor and the mobile device permits a real-time view of one's ECG and heart rate.



Figure 3 – The charts produced by the web portal facilitate a view of either an ECG signal or the heart rate variability over a period of beats.

that provides the link between the database and the web portal. The mobile device invokes a web service to push data through the Internet and into the database. The web portal invokes a web service to pull data from the database and generate an XML file for defining the graph. We use the XML/SWF library to generate the chart, an example of which is shown in Figure 3, and update it automatically. We make heavy use of the AJAX design paradigm to create a rich, interactive user experience.

We must manage concurrency and scalability issues as there may be several people accessing the web portal at one time. Accesses to the database and generation of the chart XML files (which rely on the information from the database) are done in such a way that multiple clients may view the web portal and multiple mobile devices may push data to it.

When an anomaly in either the sensor data or the connection arises, the mobile device can send a message to the web server notifying it of the event. When the heart rate is above or below certain programmable thresholds or when sensor data is not received for an extended time, the mobile device will noti-

fy a web service so that the web portal reflects the current state of the sensor and device.

Experimental Setup

We have designed several experiments in order to evaluate our proof-of-concept system using both accuracy and performance metrics. These metrics provide insight into the overall operation of the system.

We developed the web services and the web portal on a Microsoft ASP.NET platform and a Microsoft IIS server delivers the web services and web portal. We use a MySQL relational database consisting of three tables that log users, connections, and sensor data. Signals are identified by a numerical tag. The two recognized data types that may be stored are the raw ECG signal (in 2-kB chunks) and heart rate.

Results

The purpose of our system is to offer an end-to-end solution using Bluetooth and web services. The novelty of the system is in the results of our accuracy and performance evaluation.

QRS Detection

In order to detect heartbeats (QRS complexes), we analyzed the forty-eight recordings in PhysioBank's MIT-BIH (Massachusetts Institute of Technology – Beth Israel Hospital) Arrhythmia database [8]. Each half-hour recording contains cardiologist annotations denoting the frequency and type of beats (e.g., normal, atrial premature beat, etc.). These annotations provide a gold standard by which to compare automatic detection algorithms.

The framework for our QRS detection algorithm is derived from the Pan-Tompkins algorithm [9]. As displayed in Table 1, at a sampling rate of 1 kHz we achieve 99.54% QRS sensitivity (the proportion of QRS complexes correctly identified as such) and 99.79% positive predictivity (the probability that a QRS detection is correct).

For many ECG applications 1 kHz is more than sufficient for performing signal analysis [1]. In order to quantify the effect of reducing the processing overhead on accuracy, we reduced the sampling rate and carried out the tests again. The benefits of reducing the sampling rate are manifold. First, the processor may idle for a longer period of time, which conserves energy. Second, there are fewer memory requirements because the number of samples that must be stored is tied to time, not sampling rate (and reducing the sampling rate reduces the number of samples in a unit time period). The primary reason for not reducing the sampling rate is clinical accuracy—when reproducing the entire ECG waveform it is important to sample relatively frequently.

Table 1 further shows that our heart rate algorithm is resilient to a decrease in sampling frequency. We chose the lowest sampling frequency, 100 Hz, for two reasons. First, the difference filter operates on 10 ms of data so sampling at 100

Table 1 – Decreasing the sampling rate has only a slight effect upon the average accuracy of the QRS detection on 48 signals.

Sampling Rate (Hz)	Average Sensitivity	Average Positive Predictivity	RR Error (ms)
1000	99.54%	99.79%	60.55
500	99.48%	99.50%	91.33
250	99.40%	99.72%	72.91
100	99.12%	99.09%	80.95

Hz produces one sample during that time. Second, it is a factor of 10 smaller than 1 kHz, but is still sampled frequently enough to prevent significant aliasing.

Performance

We examined the performance of the web site by accessing it via another computer on the same intranet. This minimizes the effect of network latency on the measurements, emphasizing the performance of the web service.

We varied the number of samples viewed on the web site to test the responsiveness of the web service, database, and XML chart data. Each experiment was run for 10 minutes.

When viewing 100 samples, which corresponds to 100 heartbeats or 100 ms of ECG waveform data, the average round trip time of the web service is 298 ms. The median time is 348 ms. This means that the distribution is skewed left—a somewhat surprising result because the response time is lower bounded by zero whereas there is no limit to how long a response could take.

When viewing 1000 samples, the average round trip time increases to 755 ms and the median time is 452 ms. When viewing 5000 samples the average round trip time surges to 3.039 seconds with the median time slightly lower (2.770 seconds). The response time of the site becomes noticeably slower as the amount of data viewed increases. Thus five seconds of data at a time, given the constant update, is a reasonable upper bound. When the user interacts with the graph, which interactively displays the sensor readings, the response time of the web service increases (as expected).

We believe that our system is sufficiently responsive to accommodate multiple users with real-time data updates. Our conclusion is reinforced by the fact that the web server runs on a development, rather than a dedicated, system. Using a dedicated system would allow the number of users to scale up and further decrease the response time.

Discussion

In this section we examine the limitations and future phases of the project.

Limitations

There are three main limitations of this work. First, current sensor technology is often inhibited by the unreliability of wireless connectivity. When the connection between the sensor and mobile device or between the mobile device and Internet fails, the mobile device must respond with a warning.

Second, the availability of the Internet (and wireless Internet in particular) is assumed. With access to the Internet being nearly ubiquitous (and growing more so), and the mobile device being an inherent cost of the system, we submit that these limitations will only become 'less limiting' as time goes on. However, if wireless Internet is involved, the system can only be as available as the wireless connection.

Finally, the small memory available on the sensor and the relatively high-bandwidth ECG signal (1 kB/s uncompressed at a sampling rate of 1 kHz) prohibits many store-and-forward options. Potential solutions such as compression or reducing the sampling rate still don't provide enough savings to contend with the limited size of the sensor's 8-kB flash memory.

While we did not directly evaluate security, it is a system property that must not be overlooked in the context of medical systems. We have adopted available standards in addressing the security problem. For example, we utilize encryption and authentication in the Bluetooth module and require encryption (SSL) for both the web services and the web portal.

System Evolution

We seek to extend the project in multiple directions in both the hardware and the software. For the hardware we seek ultra-low-power operation through sub-threshold logic design techniques and ultimately we will investigate the potential of energy scavenging. For the software we will further explore the fusion of multiple sensor signals and how a network of body sensors may affect data identification and security.

Conclusions

We have presented a service-oriented system that incorporates a custom, wearable body sensor, a mobile computing device, and a web portal to provide an end-to-end telemedicine solution for cardiovascular ailments. The ability to control the sensor via a mobile device is a powerful utility for obtaining information. A web services approach for storing the data at a remote server can provide great flexibility and usability for those concerned with an individual's health. Our design and implementation have demonstrated the feasibility of the architecture and the accuracy of our processing algorithm in a constrained environment.

Acknowledgments

We gratefully acknowledge the work of our collaborators in the Department of Electrical and Computer Engineering at the University of Virginia: Jonathan Bolus, Benton Calhoun, and Travis Blalock. This work is sponsored by the National

Science Foundation through the Wireless Internet Center for Advanced Technology (WICAT).

References

- [1] Clifford GD, Azuaje F, McSharry PE. *Advanced Methods and Tools for ECG Data Analysis*. Boston: Artech House; 2006.
- [2] American Heart Association. *International Cardiovascular Disease Statistics*. Available at: <http://www.americanheart.org/presenter.jhtml?identifier=3001008>. Accessed September 15, 2008.
- [3] Hung K, Yuan-Ting Zhang. Implementation of a WAP-based telemedicine system for patient monitoring. *IEEE Transactions on Information Technology in Biomedicine*. 2003;7(2):101-107.
- [4] Anliker U, Ward J, Lukowicz P, et al. AMON: A wearable medical computer for high risk patients. In: *Sixth Int'l Symposium on Wearable Computers*; 2002:133-134.
- [5] Kong K, Ng C, Ong K. Web-based monitoring of real-time ECG data. In: *Computers in Cardiology*; 2000:189-192.
- [6] Altman RB. Informatics in the care of patients: ten notable challenges. *West J Med*. 1997;166(2):118-122.
- [7] Pollard J, Fry M, Rohman S, et al. Wireless and Web-based medical monitoring in the home. *Medical Informatics and the Internet in Medicine*. 2002;27:219-227.
- [8] Goldberger AL, Amaral LAN, Glass L, et al. PhysioBank, PhysioToolkit, and PhysioNet: Components of a New Research Resource for Complex Physiologic Signals. *Circulation* 101(23):e215-e220; 2000 (June 13).
- [9] Pan J, Tompkins WJ, A real-time QRS detection algorithm. *IEEE Trans. Biomed. Eng.*; 1985: 32 (3):230-236.
- [10] CardioNet. Available at: <http://www.cardionet.com/>. Accessed September 15, 2008.
- [11] Medtronic CareLink Network. Available at: <http://www.medtronic.com/carelink/>. Accessed September 15, 2008.
- [12] Biotronik Home Monitoring. Available at: <http://www.biotronik-healthservices.com/sixcms/detail.php?id=201>. Accessed September 15, 2008.
- [13] Blount M, Batra VM, Capella AN, et al. Remote health-care monitoring using Personal Care Connect. *IBM Systems Journal*; 2007;46(1):95-113.
- [14] Park C, Chou PH, Bai Y, Matthews R, Hibbs A. An ultra-wearable, wireless, low power ECG monitoring system. In: *IEEE Biomedical Circuits and Systems*; 2006:241-244.
- [15] Lorincz K, Malan D, Fulford-Jones T, et al. Sensor networks for emergency response: challenges and opportunities. *IEEE Pervasive Computing*; 2004;3(4):16-23.
- [16] Gyselinckx B, Vullers R, Hoof C, et al. Human++: Emerging technology for body area networks. In: *IFIP Int'l Conference on Very Large Scale Integration*; 2006:175-180.