

WEARABLE BLOOD PRESSURE MONITORING SYSTEM

Case Study of Multiplatform Applications for Medical Use

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Abstract: Blood pressure measurement methods used nowadays have considerable drawbacks, as non-invasive measurements are non-continuous while invasive measurements are confined to in-hospital use. In this paper, we expose our solution of a continuous, non-invasive blood pressure measurement method, using electrocardiogram (ECG) and photoplethysmograph (PPG) as a basis of calculation. We present the two applications we designed in order to collect, process, display and monitor the gathered information accurately. A mobile application, using a smartphone connected to a sensor data logging device, is in charge of controlling data acquisition from wearable sensors, displaying general information and signals for real-time monitoring. A desktop application is designed to perform more detailed processing and complex analysis on the recorded data and is therefore aimed at doctors and/or researchers.

1 INTRODUCTION

In an attempt to prevent frequent lifestyle-related diseases, the authorities in charge of health in various countries are seeking efficient ways to detect this kind of problems at an early stage. One of the possible solutions is to develop new wearable instruments able to measure or monitor physiological data during daily activities. Since blood pressure (BP) is a good indicator for potential cardiovascular disorders and circulatory system diseases, it requires constant attention and an efficient monitoring system.

The methods of measuring blood pressure used nowadays are usually of two types :

- Though Ambulatory Blood Pressure Monitoring (ABPM) devices are non-invasive and designed for home use, they suffer from the non-continuity of their data. Indeed, blood pressure measurement with an ABPM device takes dozens of seconds, and can only be repeated every two minutes at most. In addition, it is rather uncomfortable and as it requires users keeping their arm in a defined position, it tends to be inappropriate for use during effort and most daily activities.

- Arterial blood pressure measurement method allows continuous measures and has reliable results, but is not usable at home and does not allow any movement, making it unsuitable for most applications. Furthermore, it introduces a significant risk of infection and injury.

In this context, previous works lead to other ways of monitoring blood pressure continuously, but with non-invasive methods such as a calculation based on pulse and ECG data and using the Pulse Arrival Time (PAT) value (Espina et al., 2008; Fung et al., 2004; McCombie et al., 2007). So far, we have developed and evaluated a new method to estimate accurately blood pressure from PAT even during physical exercises (Lopez et al., 2010). Based on the encouraging experimental results of our new method, we have been developing a wearable device capable of recording physiological signals, processing them immediately to estimate beat to beat blood pressure, transforming it into context adapted understandable information, and returning feedback to its user (a patient or a doctor, for example), while saving it for further detailed analysis by other potential users (such as doctors or researchers).

The objective of our research is to use this device

in combination with applications targeted at specific users, and be able to monitor blood pressure in a non-invasive, continuous way both for medical and daily life use.

This paper is organized as follows; section 2 introduces our system, explains its target and specifications and how it differs from usual BP measurement devices. Section 3 gives more information about the applications designed to log and analyze the data from the sensors. Section 4 explains how we adapt the user interface of our mobile device so that it gives immediate feedback to its user. Section 5 mentions encountered issues and improvements ideas that will be realized in a near future and will most probably give a second dimension to this project.

2 SYSTEM OVERVIEW

In this section, we will try to give a precise, yet concise explanation of this system's design and the different features it has.

2.1 Design Concept

Our system has been designed as a complete solution to keep track of blood pressure, from the end-user (the monitored person) to the people able to understand and process this data (usually doctors following their patients or researchers trying to gather data for a study). Using this approach, we decided to create two distinct applications:

- a mobile application, gathering data from wearable sensors, processing this data using simple algorithms, giving immediate feedback to its user and saving the data to a memory card;
- a desktop application, using the data recorded earlier for processing using more advanced algorithms and calculation techniques.

2.2 Mobile Device and Sensors Prototype

To fulfil the task of recording physiological data from sensors, we used a device able to transform analog ECG and PPG signals into digital data, then store these data on a memory card while updating the user interface, in our case an iPod touch¹ with a dedicated application.

Conceived so that the iPod touch can be docked on it, the device communicates with the latter through

¹iPod touch is a trademark of Apple Inc., registered in the U.S. and other countries.



Figure 1: Overview of the mobile device.

the serial line of the Dock port. It includes an original ECG and PPG sensor unit, capable of recording data at a 1 kHz sampling rate, necessary condition to ensure accurate estimation of high blood pressure values as during physical exercise for example. This unit has the advantage of being able to synchronize pulse and ECG signals, ensuring that the time difference between characteristic points of these signals is correct with a millisecond accuracy.

The sensors used in our device and shown on figure 1 are the following:

- ECG signal is captured using a 3-electrode set-up, each electrode having a distinctive color (Positive, Negative and Earth electrodes) and connected to the device through 3 wires, guaranteeing better robustness to motion artefacts;
- PPG is captured using an ear lobe sensor, connected to the device using one wire; this sensor measures pulse wave by transmitted-light plethysmography principle and using the ear lobe makes the signal less prone to noise induced by body motion than frequently used finger PPG sensor (McCombie et al., 2008; Muehlsteff et al., 2008).
- acceleration values are captured using a 3-axis accelerometer, again connected to our device using one wire. Combined to motion recognition algorithms it will enable detecting which activity triggers blood pressure augmentation and which do not have any effect.

The device itself has a microSD card module, to which are logged files containing the sensor data during acquisition and can also be used to write other related files directly from the iPod touch.

Finally, the prototype has a three-states power management switch. It is able to charge the connected iPod using the embedded battery on one position. The two other positions are used to select whether the micro-controller in charge of collecting the sensor data and converting them to their digital format

will be powered on either manually or through messages sent on the serial line. This latter option adds measure control flexibility and saves power when the device is not acquiring data.

These features make our device different from other non-invasive BP monitors, as seen when comparing the number 1 selling blood pressure monitor in the U.S., Omron HEM-711AC with our blood pressure monitoring prototype (see table 1).

Table 1: Characteristics comparison between our device prototype and Omron HEM-711AC.

	Our prototype	HEM-711AC
Timing	Continuous	Punctual
Signals	Acceleration, ECG, PPG, HR, BP	Pulse rate BP
Sampling rate	ECG, PPG: 1 kHz HR, BP: 1 beat	1 BP reading per 2-3 min.
Weight	250 grams	355 grams
Battery life	2 consecutive hours	1500 readings w/ 'AA' battery x 4
Memory	4 days	60 readings

Our aim is not only monitoring these physiological data, but also being able to prevent any related disorder. The design of this device reflects this objective, by keeping the size of the unit as small as possible and combining it with an easily adaptable terminal.

3 DATA LOGGING AND ANALYSIS APPLICATIONS

The mobile application is used as a data accumulation application and as a controller for the recording device. When the data is saved, it can be used by other applications. The desktop software we designed is able to process the data and apply various analysis algorithms.

3.1 Mobile Measurement Control Application

The Commands tab is the first screen you see when starting the mobile application, and is the first of three function tabs (figure 2). While the two other tabs are aimed at visualizing the recorded data, this tab is mainly used to issue commands to the data recording device and manage the data files from previous acquisitions.

The Commands tab is separated into two parts: one is called WBMD mode and the other is microSD mode. Both involve interaction with the logging device, but while the former is used to trigger and

stop acquisition of data, the latter is used for file management on the microSD card. The choice between these two modes is done by triggering a mechanical switch on the logging device. Two other modes are available, independently from the previous ones: one is called normal mode, and is used when the logging device's power is controlled by the iPod touch; the second one, manual mode, is used when the device's power is activated manually via a mechanical switch.

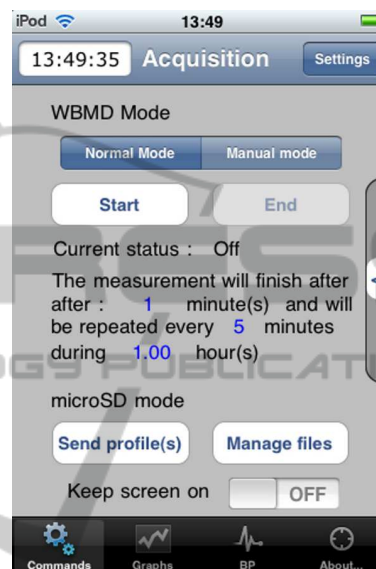


Figure 2: The Commands tab.

In WBMD mode, it is possible to start an acquisition campaign, which can be defined as:

- a single or multiple measurements, each one lasting a certain time span;
- in case several measurements are performed, they are repeated at regular intervals, and stop after the designated overall duration.

The uSD mode operations involve file management on the device's memory card. These operations are mainly:

- writing patient profile information, making each measurement correspond to a patient (see section 3.2 for more information);
- managing files on the memory card, i.e. deleting unnecessary files or performing a backup of these files on the iPod's internal memory.

3.2 Settings Menu and Patient Profile

As the device can be used in several different situations, a settings menu was added to enable the user specifying the measurement parameters easily.

Through this screen, the user can choose a set of sensors to enable or disable, depending on the type of information he needs; measurement duration and repetition options are also available.

Finally, as the data files recorded on the device only contain physiological data, it was necessary to make each measurement correspond to a patient profile, so that each set of data can be identified and classified accordingly to patient characteristics.

In order to achieve this goal, an interface designed to specify crucial patient information was added in the Settings menu (figure 3). Each measurement will trigger the creation of an associated patient profile containing the information filled in in this interface. They are then written on the microSD card, using the process mentioned in section 3.1.



Figure 3: The Settings and Patient data menus.

Thus, when the ID contained inside the patient profile is compared to the database of the doctor, it can be used for diagnostic, whereas the same data used by a researcher can just give an outline of the patient without revealing his identity and can be used for data mining purposes.

3.3 Offline BP Analysis Application

The desktop application is a way for doctors and researchers to process and review the data recorded by the mobile device. As our mobile device lacks some processing power for complex algorithms, and its screen is not really adapted for reviewing large data, we prepared an application executable on a personal computer which is able to import files and apply algorithms on them.

In order to facilitate the programming and make the use of the application easier, we decided to use Qt² framework for interface. Indeed, it is free and cross-platform. Qt also offers the Qt Creator IDE which makes interface design quicker and has good performance components.

3.3.1 PPG and ECG Signal Display and Analysis

Before the calculation of blood pressure, the ECG and PPG signals have to undergo some filtering algorithms. Although the data logging device already includes some band-pass filters, other noises can appear on the signals (for instance, noise due to power lines). We chose to use a simple Fast Fourier Transform (FFT) filter, for its good computing speed and zero-phase filtering properties. Once this filtering step is cleared, the signal is processed by the blood pressure algorithm designed to determine the ECG peaks and the PPG foot points.

Figure 4 shows the screen displaying the filtered ECG and PPG graphs with additional marks pinpointing the results of the blood pressure algorithm calculation. A zooming function can also help a doctor to identify eventual cardiac troubles, such as arrhythmia. It can also help to correct eventual calculation errors manually.

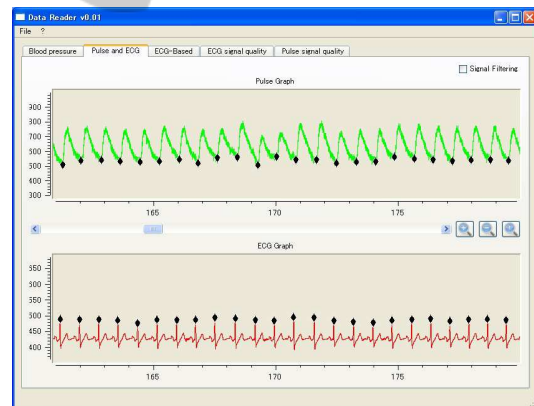


Figure 4: The filtered ECG and pulse graphs with features detection result.

3.3.2 Heart Rate Analysis

By determining the position of ECG peaks, it is possible to calculate heart rate values accurately. Indeed, heart rate is an interesting indicator for both unhealthy patients, for example with cardiac disorders, and healthy people.

²Qt is a trademark of Nokia Corporation in Finland and/or other countries worldwide.

Additionally, former studies showed that psychological state changes are reflected in the heart rate variability (HRV) and can be successfully monitored (Itao et al., 2008). Based on these observations, we added two graphs showing heart rate and its variations over time (figure 5).

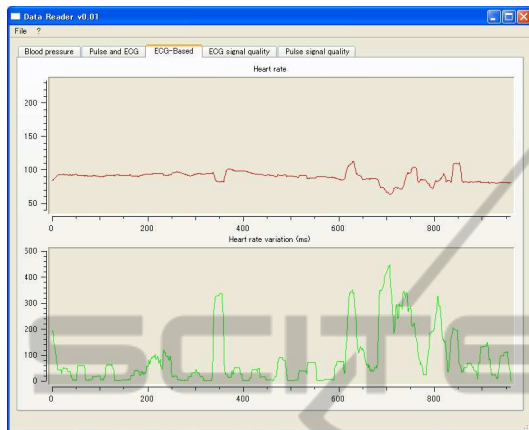


Figure 5: The heart rate and HRV visualization.

3.3.3 Blood Pressure Visualization

As our main objective is to monitor blood pressure efficiently, the top feature of the application is to calculate blood pressure on a chosen set of files, and display to the user a graph of the computed blood pressure, such as shown on figure 6. Before displaying the graph, the application detects obviously incorrect values and removes them. A moving average algorithm is then used in order to smoothen the curve and make the trend variation analysis easier.

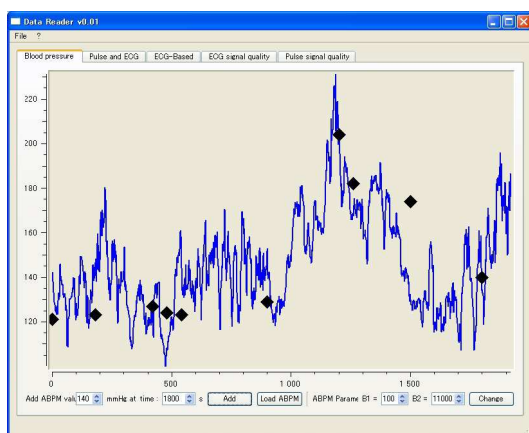


Figure 6: Continuous Blood Pressure variation visualization.

The parameters used to calculate blood pressure

vary according to various conditions such as blood vessel thickness, blood fluidity, etc. (Lopez et al., 2010), it is possible to input reported conventional BP results (such as ABPM) into the interface and change the calculation parameters according to the conventional BP variations.

The aim is mainly to do an initial adjustment to realize a calibration of the device by determining the optimal parameters for blood pressure calculation for each individual.

Once these parameters adjustments are done, the blood pressure algorithm results seem satisfying, as the trend of computational blood pressure follows this of ABPM.

4 REAL-TIME BP MONITORING

In addition to accumulating data for further use, the mobile application is also used for real-time monitoring. It is therefore possible to get feedback from the device immediately, by displaying ECG and PPG signals as well as preliminary results from BP algorithm.

4.1 Quick View of Measured ECG and PPG

When the acquisition of data starts, the logging device sends data to the iPod touch so that it can be processed and displayed to the user. The Graphs tab is a good way to monitor the current input from the sensors and see important information at a glance.

This tab features two graphs displaying the raw values from ECG and pulse signals, so that the user can verify that the signals have satisfying shapes and amplitudes for our algorithms to be effective (if it is not the case, a warning message appears on the graphs area). These graphs can help adjusting the position of the sensor for better performance. In addition to that, users can see their current Heart Rate (HR) and Blood Pressure (BP) values (both being frequently used by doctors) as they are calculated using the ECG and pulse data.

A second-precision clock is also present in order to synchronize blood pressure variations with eventual external events which have no input in our system (contextual data).

4.2 Short and Long-term Variations

As explained in the previous section, the current blood pressure is shown on the Graphs tab with a single numerical value (figure 7). In order to detect short or long-term trends in the blood pressure values, it is

necessary to represent the blood pressure as graphs. The BP tab is designed to address this issue.



Figure 7: The Graphs tab.

Two graphs, as shown on figure 8, are available:

- the short-term graph, displaying only the last 30 seconds of data, can be used to monitor very sudden and punctual variation in blood pressure - this can happen frequently when switching from a laying position to a standing position for example;
- the long-term graph, displaying the last 10 minutes of data, can be used to monitor increasing or decreasing trends of blood pressure due to other phenomena, such as sustained effort or use of antihypertensive medications.

In addition, two modes of graph are available: the "spike" graph shows all raw calculations of blood pressure, whereas "moving average" makes trends more readable by smoothing the curves using a simple moving average algorithm.

5 ISSUES AND FUTURE DEVELOPMENTS

This project was designed as a first "proof-of-concept" to ensure this method of non-invasive blood pressure measurement was fairly reliable and that such system could replace actual monitoring devices. Our first experiments seem to validate this assumption. But to go further, some new developments and features are considered and will unquestionably improve the general response to this system.

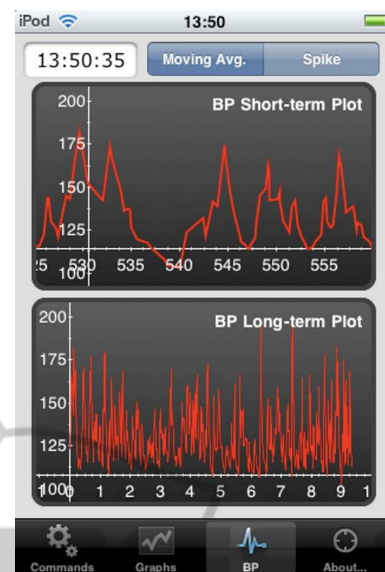


Figure 8: The BP tab.

5.1 Network-related Improvements

More than a simple monitoring device, using a mobile application on a smartphone or equivalent has the advantage of being able to communicate with other computers through wireless connections. Other devices can be used for monitoring blood pressure, such as simple micro-controllers (Isais et al., 2003), but it is possible to make good use of the almost unlimited features and good processing power of the present smartphones in an health-care context.

One considered feature is to send, directly from the mobile system, data files to a health-related database or application server, in charge of storing them and, eventually, apply algorithms on them. The application server would then be able to display information to interested parties (for the patient, reports based on the monitored data; for doctors, to be able to follow up their patient easily without even seeing them; for researchers, to have complete anonymous health profiles to study)(Lopez et al., 2009).

This networking ability will probably change drastically the way the current system works: instead of having the "complete" profile of a patient written on the SD card next to the files, the opposite operation of sending raw data to the database by relying on the ID of the patient would be more appropriate. Thus, each patient would have its own access to the database to upload his files, so that they are available to doctors and researchers who can issue reports of their diagnostic in return. The existence of the SD card itself is also questionable, as the data can be sent in real time to the application server or saved in the

smartphone's memory in case of a network failure.

Such a server would be designed to accept multiple health-related informations and can therefore be used not only as a blood pressure diagnostic tool but as a whole health analysis helper, preventing a large set of lifestyle-related disorders.

5.2 Blood Pressure Calculation Methods

As mentioned in section 3.3.3, the blood pressure calculation method relies on multiple parameters depending on various physiological factors. As some of these physiological factors cannot be determined without thorough examinations, it is necessary to start from so-called "reference" parameters issued by computational or empirical methods.

Our goal is, using various data from initial experiments, to determine these reference parameters and link them to certain patient profiles.

For that intent we are currently conducting experiments at the University of Tokyo Hospital. Through these experiments, we hope to find empirical parameters for determined age and sex groups, in order to make our device usable out-of-the-box.

If the results of these experiments, which will be the subject of a future study, prove this approach to be unsuccessful, an alternative solution will be set. This alternative solution may simply consist in making a unique initial calibration using ABPM values measured during a classical cycle-ergometer load test for each patient (Lopez et al., 2010).

5.3 Use During Daily Activities

Until now, our system's design is mainly being tested in an hospital environment as a blood pressure and heart rate monitoring tool, replacing the system currently used for this purpose. But the small size of the wearable device and its adaptation to a popular and ordinary smartphone makes it potentially usable for home use, and moreover for use during daily activities. Indeed, daily activities have an impact on blood pressure. Continuous blood pressure measurement can reveal sudden blood pressure variations impossible to detect using ABPM.

On top of PPG and ECG sensors, our wearable device also features a 3-axis acceleration sensor. Using a movement recognition algorithm detecting which activity is being done based on the acceleration data, it is possible to detect which activity triggers blood pressure augmentation and which do not have any effect (figure 9).

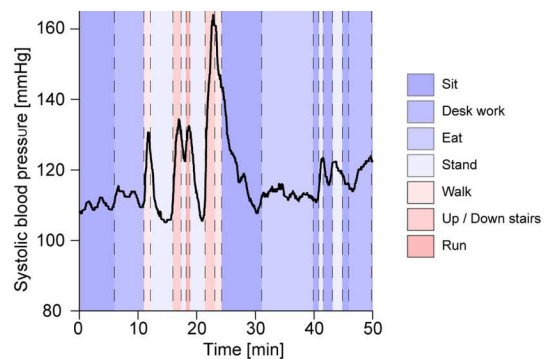


Figure 9: Daily activities blood pressure evolution.

5.4 Sensors and Mobile Device Issues

Our preliminary tests using our current mobile prototype shed light on some difficulties the user can experience while using this device.

One of the main concern is the weight and the way to wear this device. Indeed, our prototype features a battery and consequent electronics, making the lightweight iPod touch very bulky. Wearing it as a necklace proved to be very uncomfortable, and elderly people seem to consider it a very large burden.

Furthermore, all sensors are connected through wires. When the sensors are wore under clothes, the wires can hamper body movements or provoke alterations of the sensors' positions, with a consequent risk of generating various noises.

We are therefore working on some new prototype clearing these issues, by introducing wireless wearable sensors as suggested by former studies (Kang et al., 2006), and a lightweight smartphone module to collect the data.

6 CONCLUSIONS

The system presented in this paper covers all types of users (patient, doctors and/or researchers) and the use of a mobile terminal such as a smartphone does not limit the device to the features found on conventional ABPM devices. Moreover, it is efficient enough to validate the calculation model. The first experiments conducted suggest that our wearable blood pressure monitoring device using PAT method returns reliable results, and the system is relatively lightweight so that it used during daily activities. Therefore, if further experiments realized using this system prove it to have reliable and constant results, and if it is improved so that the results can be easily sent to a network content managing server, this system could be a great step for

continuous blood pressure monitoring, be it at home or for an hospital use.

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