# Monitoring Human Activity through Portable Devices

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***Abstract* — Monitoring human activity may be useful for medical supervision and for prophylactic purposes. Mobile devices like intelligent phones or watches have multiple sensors and wireless communication capabilities which can be used for this purpose. This paper presents some integrated solutions for determining and continuous monitoring of a person's state. Aspects taken into consideration are: activity detection and recognition based on acceleration sensors, wireless communication protocols for data acquisition, web monitoring, alerts generation and statistical processing of multiple sensorial data. As practical implementations two case studies are presented, one using an intelligent phone and another using a mixed signal processor integrated in a watch.**

## I. Introduction

Mobile and portable devices with increased intelligence open new possibilities in the field for medical supervision, assistance and prevention [1]. From medical point of view, continuous supervision of patients' medical state is a qualitative improvement compared with more traditional sporadic tests and analysis procedures. Some rare critical states may be detected and early alerts can be generated in order to prevent more critical pathologic states. Such devices may also be used by persons who want to improve their lifestyle through attentive monitoring of their physical activity. Athletes are another category of persons who want to monitor their physical activity and physiological state during a long period of time.

In order to continuously monitor and evaluate the state of a person someone may use different kind of intelligent mobile devices, from general purpose ones (e.g. mobile phones, PDAs) to those specialised for medical purposes (e.g. holters) [3],[4].

Today's integration and miniaturization technologies allow placing multiple sensors, sufficient computing resources and enough power on a portable device in order to be used for continuous activity and state monitoring purposes. Such devices may be integrated in the patients' clothing making them easier to ware [5].

This paper investigates the issues and proposes some solutions to this problem.

## II. Monitoring with Mobile Devices

The monitoring problem can be divided into a number of issues:

- acquiring data from different kind of sensors
- pre-processing and filtering the acquired data
- sensor data fusion and intelligent recognition and interpretation of incoming data
- data storage and efficient data management
- data communication
- integration of mobile devices into a distributed supervision system

### *A. Sensorial data acquisition*

In the case of sensorial data acquisition the question is what kinds of sensors are available and how to make the acquisition. Today, many intelligent phones are equipped with acceleration and localization sensors. Acceleration measured on 3 directions is a useful information for determining the state or the kind of activity the holder is performing. Through acceleration we can determine the position of the body (standing or sitting) if the phone is kept in the same usual place (e.g. pocket) or the kind of activity the holder is performing (running, walking or staying still). Unfortunately, the acceleration information provided by the 3D sensors is very noisy and sometimes the useful information is hidden by other artefacts (e.g. trembling, vibrations, etc.). Figure 1 shows the acceleration signals measured on 3 directions (x, y and z) during a normal walk. It can be observed that the signals are quit different on the three directions and in some cases the noise level is comparable with the useful information (see the signal on x direction).

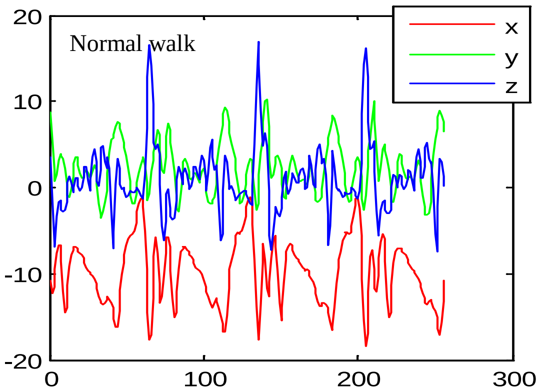



Figure 1. 3D Acceleration signal

An important factor that influences the quality of the acquired acceleration information is the sampling rate. A higher sampling rate increase the quality of the measurement, but overloads the devices with too much activity and consequently the power consumption. This aspect is critical in case of mobile devices because they have a limited energy source. Based on our experiments we established that a sampling rate in the interval 50-

100Hz is a good compromise between quality and energy preservation conditions.

Another solution which may be used for long time monitoring periods is to have windows of higher sampling frequency separated by gaps when no sampling is done. For instance in every minute an acquisition window is started in order to establish the kind of activity the holder is performing. In this way the gaps between the measuring windows increase significantly the lifetime of the battery. The length of the window is established so that a given type of activity can be accurately determined. In case of activities like running or walking the window must cover at least 4-5 steps. This method of periodic measuring windows cannot be used in case we want to count the number of steps made by the user, the distance covered or the number of calories burned. Therefore we suggest to implement two regimes (selectable by the user) one for long term monitoring and one activated for some specific activities.

The position information can be obtained from a GPS receiver (for outdoor activities) or by triangulating the transmission intensity of multiple wireless access points. The last one is less precise but it can give at least an information that the person is around a given access point (e.g. in the house). The acceleration and the localization data may be fused in order to obtain distance and speed information.

Other sensors which may be used for medical state detection are: temperature sensor, ECG sensor(s), blood pressure sensor, hart rate sensor, oxygen concentration, etc. These are more specific for medical applications and therefore these kinds of sensors are not present in general purpose mobile phones. However, there are a number of wearable devices, such as the Chronos intelligent watch made by Texas Instruments [2], or dedicated medical devices that are equipped with such sensors. For instance the TI's Chronos watch contains a temperature sensor, acceleration sensors, pressure sensor and it can get heart rate information from an external, attachable chest belt (BlueRobin) [6]. Other devices such as holters can measure one or multiple channels of ECG signals, blood pressure or oxygen concentration.

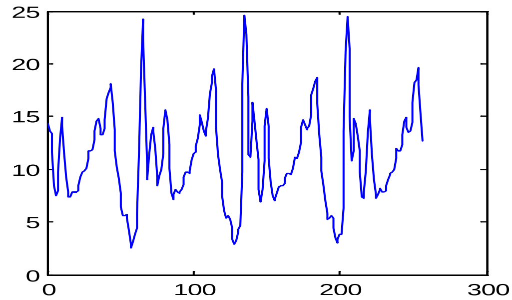
We developed a number of prototypes of wearable devices for measuring ECG signal, blood pressure and temperature. These prototypes have three interchangeable modules: a sensor (data acquisition) module, a processing unit (based on a microcontroller) and a communication module (for wired or wireless transmission). These prototypes allowed us to evaluate the possibilities but also the limitations of such devices. Using an on-the-shelf low-power microcontroller (e.g. PIC16Fxx family from Microchip or MSP430FXXX from Texas Instruments), a wireless communication transceiver (e.g. CC2500, multi-channel RF transceiver) and some analogue circuits (low power and low voltage operational amplifiers and sensors like AD620 [8]) we have build wearable devices at an affordable price.

### *B. Pre-processing and filtering the acquired data*

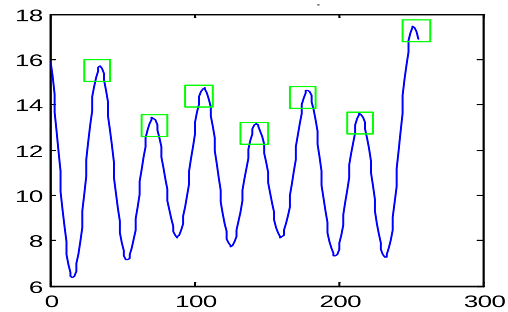
In our case, the main challenges for pre-processing and filtering of sensorial data were twofold: the limited internal memory capacity and the real-time execution. For devices based on microcontrollers (like PIC16Fxx) the internal RAM memory is extremely small and it cannot preserve the amount of samples necessary for a complex and high quality signal filtering and processing. The filtering window and the sampling rate must be adapted to the maximum available RAM memory. For instance in our experiments with an ECG sensor attached to a microcontroller, the buffer had to cover a number of heart beats and the minimum sampling rate should not affect the shape of the QRS complex (the wave with the highest frequency components in the ECG signal).

Another problem related with the use of microcontrollers as the computing element is the fact that they do not implement floating point operations. Implementing filters in integer arithmetic implies a number of artifices (e.g. magnification, virtual decimal point, etc.) in order to eliminate the errors caused by integer rounding.

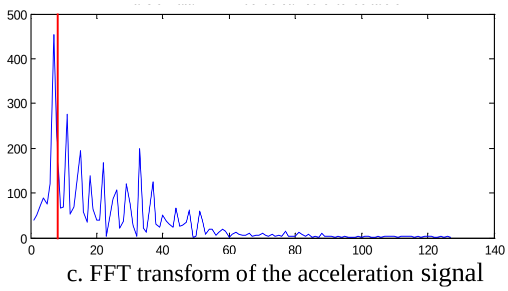
In case of intelligent phones the memory limitation is more relaxed but it is still a problem if the sampled data must be preserved longer time for future analysis (e.g. post processing of ECG signals).



a. Raw acceleration signal



b. Filtered acceleration signal



c. FFT transform of the acceleration signal

Figure 2. Processing of acceleration signals

Filtering of sensorial data is used to eliminate inherent noise and to emphasize those components of the initial signal that are useful for later interpretation. In case of acceleration signals the collateral artefacts are multiple, their frequency is comparable with the useful components and therefore the filtering process is not trivial.

For detecting different kind of activities (running, sitting, walking) we had to use adapted averaging filters (low pass filters). For instance we had to eliminate the vibrations of the device in the users pocket caused by the user's steps, preserving in the same time the envelope of the signal that describes the running or walking steps.

Figure 2 shows the initial acceleration signal (a) the filtered one (b) and the FFT transform of the signal. The FFT transform was used to determine the stepping rate of a person as the most dominating frequency in the acceleration signal's spectrum.

In case of ECG signals, multiple filters eliminate the 50Hz component, reduce the artefacts produced by the muscles and amplify the ECG's complexes (QRS, P and T waves).

The implementation of complex filters is limited by the available program memory and by the real-time restrictions.

### *C. Sensor data fusion and intelligent recognition and interpretation of incoming data*

The goal of this step is to extract quality and aggregated information from the raw sensorial data [7]. The final result of this step is in most cases a human activity type or a medical state. In order to establish such a result we compare the patterns extracted from multiple sensor data with some patterns memorised in the learning process.

For instance, in order to establish the type of activity a person is performing, we extract different characteristics from the acceleration data and compare them with those measured a-priory in the learning process. We are using a neural network trained for recognizing activities like walking, running, standing, sitting or other. The experiments showed that for a higher recognition rate the neural network must be trained for every user, because the acceleration profile differs between them. Taking into account the complexity of the neural network training process we decided to make the training on a PC-type computer and only the generated network parameters are loaded and used on an intelligent phone.

For devices based on microcontrollers a simpler activity recognition method is used. We are using a fuzzy approach in which only some measured parameters are used (e.g. basic frequency, amplitude variation, dominance of one acceleration direction over the others etc.).

In order to establish the medical state of a patient, data from multiple sensors may be used, such as temperature, acceleration, heart rate, blood pressure, etc. For instance a high heart rate is reasonable if a person is performing an activity like running, but it is detected as abnormal if a high heart rate or blood pressure cannot be correlated with an active state. In this area we have to make more research in order to develop tools that can decide between normal and critical states.

### *D. Data storage and efficient data management*

Mobile devices have usually limited storage resources, fact that implies an intelligent storage management. In case of microcontroller-based mobile devices the data and program memory is extremely limited (hundreds of bytes for data memory and tens of Kbytes for program memory). This memory must be shared between program variables, data buffers and logged results. In most cases this is not a trivial task and the success of an implementation depends on the ability of the programmer to manage the limited memory space and optimize the code.

For instance in the case of a device that has to handle ECG signals or a communication protocol the internal memory's dimension is comparable with the minimal processing window for an ECG signal or with the minimum packet dimension of the protocol. The programmer must limit the sampling rate or reduce the time interval which is analysed. This may influence the quality of the results. The data which must be logged for a longer period of time may be written in the non-volatile (EEPROM or flash) memory of the microcontroller. If necessary, this memory can be extended with extra-memory connected to the microcontroller on the serial bus (e.g. I2C bus or SPI interface).

In case of intelligent phones the internal memory limitation is not so significant. The data processing and inherently the quality of the results are similar with the solutions on a usual PC. The data logging process may be influenced by the limited external memory of these devices. For instance, if we want to preserve the data obtained from all the existing sensors at the operating sampling rate than after a few days the capacity of the external memory is exceeded. Therefore the programmer must implement a data logging policy that assures continuous data acquisition without space limitations. We implemented a data logging policy in which data sampled at high frequency is preserved just for a limited time interval close to the present time. The data acquired before this interval is preserved just as aggregated or statistical information. There is also a periodic deleting strategy established in accordance with the dimension of the external memory.

### *E. Data communication*

The transmission of the acquired and processed data is an important issue for mobile devices. Data may be transferred in an off-line or on-line mode. In the first case the mobile device is performing as a data logger and the data is downloaded into a PC-like computer whenever the user decides to do so (usually when the memory is full or the data must be further analysed and stored). This solution does not assure continuous and remote monitoring of the person's activity. Critical states or alerts cannot be transmitted in real-time. The data download may be performed on a wired (e.g. RS232 interface) or wireless connection (e.g. BlueTooth, ZigBee).

The second approach (on-line) assures continuous transmission between the mobile device and a stationary computer or more generally a server. In order to facilitate the person's movement it is recommended to use a wireless connection.

Intelligent mobile phones can use the phone connection or an incorporated personal area network (e.g. BlueTooth) as support for the data transmission. The operation system of these phones offers powerful tools and services for communication on the Internet. The data can be transmitted periodically to a web server, making data available for distributed medical surveillance applications. The data may be downloaded into a stationary computer in order to perform more complex evaluations, to display it with higher resolution or to store it for later evaluations. Another goal is to transmit alerts in case of critical state detection (e.g. the person has abnormal medical parameters, he/she is not moving for a long period of time or a fall is detected).

In case of mobile devices developed with the help of a microcontroller the communication can be made on a serial channel (e.g. RS232, RS485) using a physical cable or a wireless transceiver (radio or infrared). Some microcontrollers have a network interface (e.g. CAN interface), which can be used as well. In order to release the microcontroller from the communication tasks, mainly when a more complex protocol is used, a communication controller may be added. For instance, the CC2500 controller can be used for radio transmission of serial data.

In our experiments with the Chronos watch we used the TI's SimplicIT™ protocol in order to transmit continuously the data acquired with the watch's sensors. This protocol can connect multiple mobile devices to an access point. The same radio interface of the watch was used to acquire the heart rate information measured with the BlueRobin's chest belt device.

### *F. Integration of mobile devices into a distributed medical supervision system*

A distributed medical supervision system is meant to provide remote assistance to a group of users (e.g. patients with chronic diseases or elderly people.) registered for such services.

Mobile devices may be important components in such a system, offering real-time data about the state of the users. In case of critical states the system can alert supervision medical personnel, for a faster intervention. Doctors can follow constantly the evolution of patients and they can adapt the treatment adequately. Rare cases which occur just in some special conditions or moments of time may be detected and recorded for later analysis.

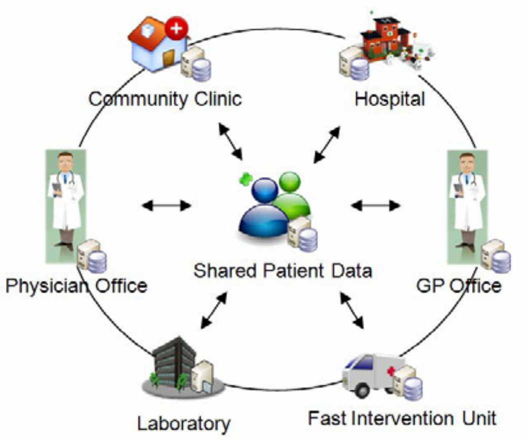



Figure 3. Patient-centric distributed medical supervision system

Figure 3 shows a patient-centric distributed medical supervision system in which different kind of medical applications are interconnected in order to serve the medical needs of patients. Such a system requires a unified medical terms coding system (e.g. LOINC, SNOMED), standard data exchange formats and protocols (e.g. HL7).

We implemented such a distributed medical supervisory system, called CardioNet [9], [10], using the following components:

- mobile medical devices – dedicated mobile devices measuring one or two medical parameters (ECG, temperature, blood pressure)
- mobile phones – as measuring device or as a "rooter" for transmitting the data on the Internet
- stationary computer – as rooter for transmitting the data on the Internet
- a web server application – used to store the acquired data and to supply the information for client applications
- client applications for the medical staff – used by the medical personnel to supervise the patients
- client application for users – used to manage and display their own medical records

We developed a protocol used between a mobile device and its router station (computer or mobile phone) that simplifies the mapping of data packets containing measured data into HTTP messages.

The CardioNet system provides access to medical services through the Internet in a similar way as home banking of e-commerce services. The system provides the means for patient and doctor interaction through web interfaces and services. The interaction may be off-line or on-line: it may or may not require the simultaneous presence of the patient and doctor during an Internet consultation.

The CardioNet system can integrate mobile medical devices in order to monitor the state of the patients and continuously adjust the treatment. Initially the system was developed for patients with cardio-vascular diseases but with the extension of its medical ontology it can be used also for other groups of patients with chronic diseases that require continuous supervision

## III. CASE STUDIES

In order to evaluate the possibilities of using mobile devices for human activity and state monitoring systems we developed two solutions: one based on the capabilities of an intelligent phone and one based on an intelligent watch, a system with much less computing and energy resources.

### *A. Activity supervision with intelligent mobile phones*

Based on the sensorial capabilities of an intelligent phone we developed an application that determines and record the activities performed by its user. We used the information supplied by acceleration sensors to identify the activity types and the communication channel of the phone to transmit the data to a server through the Internet.

Figure 1 shows the shape of the signals generated by the acceleration sensors for different type of activities. It can be seen that besides the signal shapes that suggest walking or running there are many more artefacts that make the identification of stepping moments difficult. A simple threshold technique is not enough for determining the stepping moment. The amplitude of the variations depends on many factors. Therefore, we used low-pass filters to smooth the signal and eliminate artefacts caused by the devices vibration.


Figure 4 Statistical data displayed on the phone

In order to identify different types of activities, from the current filtered signal we extract a number of characteristics (amplitude, energy, entropy, correlation, covariance). These characteristics are input nodes for a neural network a-priory trained for recognising activities like: running, walking, sitting, standing or other activity. In the training process we give examples of signals acquired during different kind of activities. Table 1 shows the experimental results regarding the recognition ratio.

Table 1

| | Conditions | Precision |
|---|---|---|
| Activity detection | activities recognised: running, walking, sitting, standing, other | 99% |
| Step count | for walking | 98% |
| | for running with different speeds | 97% |
| Distance | for walking | 91% |
| | for running | 70% |

For running and walking activities the application determines the frequency and the number of steps made by the user. For the frequency we are computing the FFT of the acceleration signal from the frequency spectrum we select the most dominant one. Using the steps cont and some physical characteristics of the user (e.g. height, weight) the application computes the distance covered by the user and the calories consumed during the process. Through the interface the user can see activities performed during a day or a week, percentage of different activity types and other statistical data.

### B. *User's state supervision with the TI's Chronos intelligent watch*

In this second case study our goal was to minimise the device, which must be worn by the user. Therefore we used a small intelligent watch built by Texas Instruments around a CC430F6137 system-on-chip. This watch contains 3D acceleration sensors, temperature and pressure transducers. It has also a radio transceiver for wireless communication. The watch can communicate with a wearable device (a chest belt [6]) that can measure the heart rate.


Figure 5. TI's Chronos watch and BlueRobin's chest belt

In its initial design the watch can work as a stand-alone device or as a data logger. In the first mode it can display on its LSD the values measured by its sensors, including the altitude (which is aggregated from the pressure and temperature data). In the second mode the device logs the data measured periodically from the sensors and downloads the data when it is connected to a PC through an access point.

Our goal was to transform the device into an on-line acquisition device. For this purpose we had to re-write the firmware of the watch in order to transmit continuously the acquired data. The process was aggravated by the fact that the watch was using the same radio interface for communication with the chest belt and with the access point, but with two different protocols: the SimplisIT and the BlueRobin. We had to implement a communication mode in which the two protocols are multiplexed in time. Through experiments we established the proper delays between moments when the two protocols are switching.

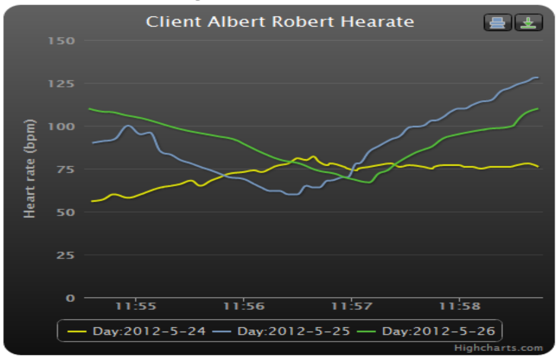



Figure 6. Heart rate recorded on 3 days

In this case study most of the signal processing procedures had to be implemented on the host PC because the program memory of the mixed signal processor is very limited. The advantages of this solution are that the watch has a much smaller weight (compared with an intelligent phone), the battery's lifetime is longer and it costs much less (50$).

## IV. Conclusions

This paper analysed the issues and possible solutions regarding the use of mobile devices as support for user's activity and state supervision. Experiments shoved that intelligent phones with their sensorial and computing capabilities are good candidates for human activity interpretation and monitoring. Phones' communication facilities allow easy transfer of data to a supervisory center. Many types of applications may be built upon the sensorial data, from personal time and diet assistant to remote patient supervision and alert generation.

Smaller mobile devices, based on microcontrollers or mixed signal processors are a much cheaper, smaller and less power consuming solution. Sensorial and communication capabilities may be built upon these components that may be useful in a remote patient monitoring system. The limited processing and storing resources of these devices make the signal processing and recognition more difficult. Therefore the time and resource consuming complex signal interpretation procedures are shifted to stationary computers.

Mobile devices can improve the quality of medical supervision through continuous data transmission and early alert generations. These devices assure mobility and higher safety to their users.

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