Complete Platform for Remote Health Management

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***Abstract*— Practical usability of the majority of the current wearable body sensor systems for multiple parameter physiological signal acquisition is limited by the multiple physical connections between the sensors and the data acquisition modules. In order to improve the user comfort and enable the use of this type of systems on active mobile subjects, we propose a wireless body sensor system that incorporates multiple sensors on a single node. This multi-sensor node includes signal acquisition, processing, and wireless data transmission fitted on multiple layers of a thin flexible substrate with very small footprint. Considerations for design include size, form factor, reliable body attachment, good signal coupling, and user convenience. The prototype device measures 55mm by 15mm and is 3mm thick. The unit is attached to the patient's chest, and is capable of performing simultaneous measurements of parameters such as body motion, activity-intensity, tilt, respiration, cardiac vibration, cardiac potential (ECG), heart-rate, body surface temperature. In this paper, we discuss the architecture of this system, including the multi-sensor hardware, the firmware, a mobile phone receiver unit, and assembly of the first prototype.**

***Index Terms*— Pervasive healthcare, physiology monitoring, sensor platform, wearable electronics, wireless sensors, body area networks.**

I. INTRODUCTION

INFORMATION on multiple physiological parameters such as vitals and physical activity can form valuable complementary datasets for a variety of personal and emergency healthcare applications.

To address the existing challenges in multi-parameter body activity and vitals monitoring, a small, thin, flexible, one-piece, wireless multisensor node and its receiving system are proposed in this paper. Three types of sensors are included: biopotential, vibration, and temperature, allowing derivation to a large set of primary physiology parameters such as ECG, heart-rate, respiration rate, body position, movement intensity, cardiac vibration, and body surface temperature. To achieve such small and thin form factor while incorporating multiple sensors, signal conditioning, processing, radio, and powering electronics, several new concepts in wearable body sensors are introduced. The most important of them are stacking of multiple layers of electronics on a flexible polymer substrate, sharing of signal conditioning circuits among multiple sensor channels, intelligent firmware, and novel powering schemes. The presented multisensor is a part of a monitoring system using a standard mobile phone as a data storage, display, control, and global communication device.

II. SYSTEM OVERVIEW

The presented multi-sensor architecture is based on the idea of having one very small, inexpensive and low power consumption wearable device along with a bigger, universal controller providing data display, storage, processing, and communication capabilities. Therefore, the system is composed of three main elements:

- one or multiple wireless multi-sensor nodes, attached to one or multiple subjects,
- data display, control, and global communication unit – we propose to use a standard mobile phone for this purpose,
- node's radio interface bridge attached to the phone, serving as the interface between different radio standards and as a network coordinator, in case of using multiple nodes.

The data gathered by the wearable node is transmitted using ZigBee protocol to the bridge, which communicates with the phone using the Bluetooth (BT) standard. Control messages are generated by the phone and sent to the node through the bridge.

Figure 1 schematizes the proposed system composition.

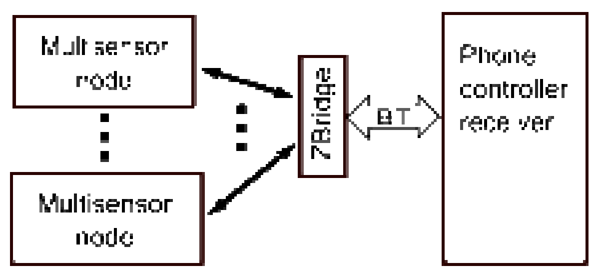

Figure 1: Composition of the proposed multi-parameter wireless monitoring system.

III. HARDWARE ARCHITECTURE OF THE MULTI-SENSOR NODE

The presented multi-sensor node implements the following tasks:

- acquire signals from multiple sensors,
- perform processing of the data, using both analog and digital filters,
- perform heart rate calculation,
- assess level of acceleration on all three axes in order to provide information on position and activity,
- transmit application specific data to the receiver.

The challenge of incorporating electronics that implements all these functions from packaged components is the inherent parts size and board real-estate. Many System-on-Chip (SoC) solutions have been presented for multi-parameter sensor systems [Wang 2002], [Yazdi 2000], [Zang 2007] but these do not offer application engineers freedom of tailoring modules in their system to suit their specific application. Our solution enables use of off-the-shelf electronics and SoCs together, while maintaining small foot-print and small body surface area occupied by the node.

A. Overall Hardware Design

The multisensor node electronics consists of 1) the sensors; 2) the signal acquisition and conditioning module; 3) the microprocessor and radio module; and 4) the device powering module. **Figure 2** shows the major system blocks.

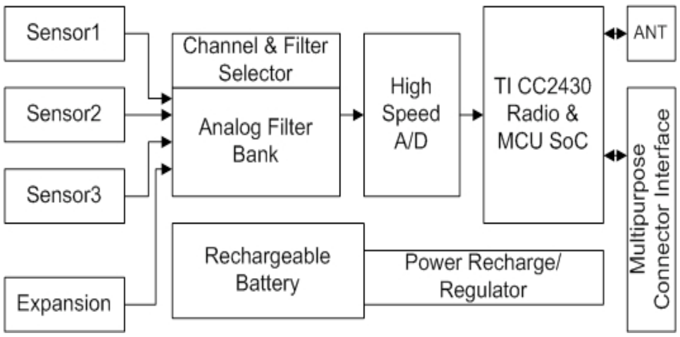

Figure 2: Functional block diagram of the multi-sensor node.

B. Flexible Multilayer Structure

The electronics of the node are distributed across multiple layers of flexible electronics carrier. Up to now, most of wearable devices are either rigid or composed of multiple rigid elements. Possibility of having a small flexible device greatly improves not only the comfort of use but also provides a much better and more reliable attachment to the body.

Figure 3 shows a diagram of the folded configuration (a), the distribution of various modules across layers (b), and the conceptual behavior of the multiple stacked layers when flexed (c).

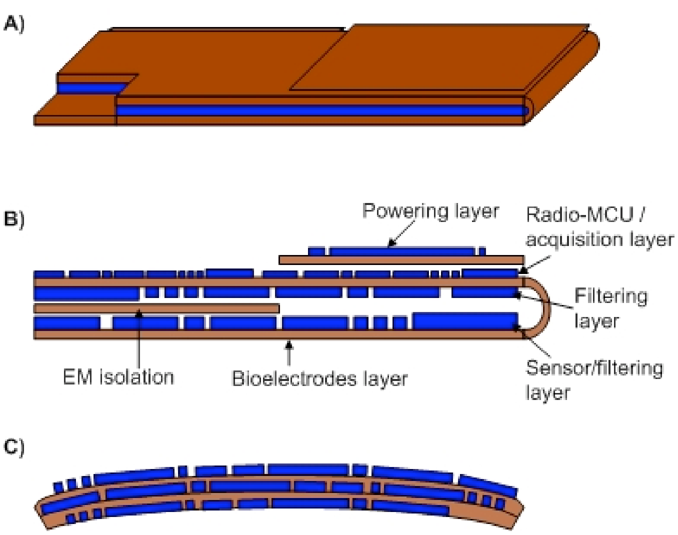

Figure 3: Conceptual assembly of multiple folded-stacked layers for the multisensor node: A) folded assembly; B) cross section of the multilayer assembly expanded in vertical axis showing various modular layers; C) collapsed cross sectional view of the multilayer assembly showing flexure with embedded components.

Figure 4 shows a fabricated device attached to the chest of a patient.

Figure 4: A complete device attached to a patient's chest.

C. Sensors

The presented node contains three sensors. A 3-axis MEMS accelerometer , thermistor and a printed electrode pattern used to measure biopotential at two distinct locations in order to measure subject's ECG.

The main purpose of the bioelectrodes is to measure the cardiac biopotential, or ECG. Based on test results obtained with the first prototype of our device, we evaluated a minimum spacing between the two separated electrode patterns. This spacing is a tradeoff between the device size (the more apart the electrodes are, the bigger the device has to be) and amplitude of the signal acquired. We decided that it is necessary to have at least 30mm spacing (Figure 4) in order to obtain a recognizable ECG when the sensor is placed along the length of the heart. Although the electrode pair does not form a standard ECG lead, our tests indicate that it provides a sufficient resolution of the R-peak for calculation of heart rhythm, identification of heart-rate variations, and segmentation of consecutive beats.

The thermistor, along with the accelerometer, are both placed on the top surface of the sensor layer, closest to the body surface, such that the best sensor-to-actuation coupling can be achieved. The biopotential electrode pattern is printed on the bottom surface of the sensor layer for direct contact with the body. The multiple sensor nodes can be attached to a subject for a full ECG signal.

D. Signal Conditioning and Acquisition

In most sensor systems, integrated analog signal conditioning is one of the modules that require the most discrete components. Alternatively, signal conditioning can be handled in software but the performance may be inferior and power consumption is usually higher. The proposed approach aims at keeping the component count low by using efficient analog filtering, with subsequent digital signal processing handled by the microcontroller.

In order to further reduce the number of components, while allowing multiple analog filtering configurations, filter chains are shared between multiple sensors rather than having redundant sets of similar filters for each sensor. This approach disables parallel sampling, and requires fast switching and digitization, but greatly reduces the number of analog filtering components resulting in saved board space.

Figure 5 schematizes the proposed system architecture.

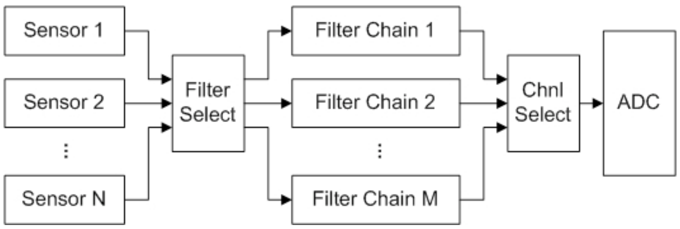

Figure 5: Shared selectable signal acquisition and conditioning.

E. *Central Processing and Radio*

The heart of the system is the TI CC2430 SoC device containing a microcontroller (8051 core) and a ZigBee compatible radio operating in the unregulated ISM 2.4GHz range. The use of SoC device saves space, reduces component count and overall cost of the system. It is one of the few low power SoC solutions available in the market today that offers flexibility to power saving design through firmware control, convenient standard input/outputs, and modifiable radio control stack for application customization.

One of the biggest challenges in the design of wearable wireless devices is the tradeoff between device size and its lifetime. Usually, devices rely on finite energy reservoirs like batteries or supercapacitors. In case of systems that are meant to be unobtrusive and worn unnoticeably, the trend is to decrease the size and weight. In order not to compromise their lifetime, clever energy management has to be implemented in this type of devices.

F. *The Bridge Device*

The purpose of using a bridge device lies in the unsuitability of the Bluetooth standard for our application. In fact, most mobile phones are equipped with Bluetooth radio interface, therefore using this standard to communicate with phones makes our implementation universal. On the other hand, Bluetooth has some major disadvantages, mainly high power consumption, low customizability and closed feature set. That is why we opted on using ZigBee standard to communicate with the sensor nodes. In order to be able to use a standard mobile phone, not equipped with ZigBee radio interface, we implemented a wireless converter device called ZBridge (
Figure 6), translating ZigBee (TI CC2430) packets into Bluetooth (BlueGiga WT11) ones. This device is data transparent, does not modify contents of the packets. It is currently also used as a ZigBee network coordinator in case of multiple sensor nodes. The bridge can be easily eliminated if a data receiver equipped with ZigBee interface is used. This device is designed to be used permanently attached to the mobile phone and powered from its battery, Figure 6.

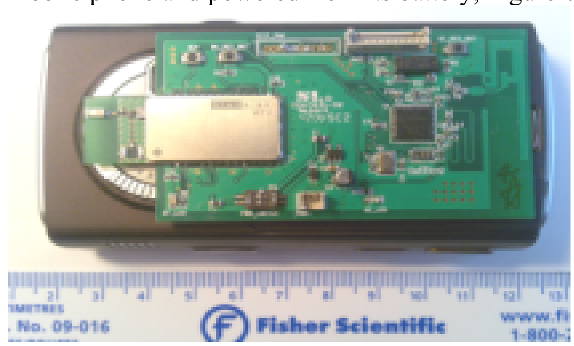

Figure 6: Zigbee to Bluetooth bridge shown attached to a standard mobile phone.

G. *Mobile Phone Data Receiver*

We use a standard Symbian-based mobile phone as the data receiver and system control device. The biggest advantage of using a mobile phone as a part of our system lies in its common availability and polyvalence. Most prospective users of health monitoring systems already use a mobile phone, therefore extension of its capabilities into health monitoring seems very attractive. Current mobile phones posses very high computation power, are portable, have big data storage capabilities and convenient big screens. All these features make them perfect candidates for our application. Furthermore, the collected data can be communicated in real time over wireless networks (GSM, Wi-Fi, EDGE etc. depending on availability) for further analysis. Real time warnings can be generated as well, alerting recipients such as for example relatives or medical care providers. This feature is very important in cases where a subject (patient) cannot be supervised and can lead to significant reduction of costs of medical care.

The main tasks of the mobile phone data receiver are detecting available nodes and their capabilities, receiving, storing and displaying the data, and optionally generating alarms upon detection of anomalies. The extended data processing potential of current mobile phones enables implementation of various data analysis algorithms for detection of different anomalies in the received data or for other purposes such as training or rehabilitation

IV. Firmware Architecture of The Multi-sensor Node

In wearable sensor devices, power consumption is one of the critical design factors. The TI CC2430 is a very convenient low-power true System-on-Chip incorporating a microcontroller and ZigBee radio. It is why the TI CC2430 SoC was chosen as the main processor and radio link for both the multi-sensor node and bridge device. The TI CC2430 operates at the 2.4 GHz radio frequency (RF) band using the IEEE 802.15.4 ZigBee protocol standard. The TI CC2430 uses a pipelined architecture 8051 microprocessor core that offers an average of one clock cycle per instruction at an active clock speed of 26 MHz. Its integrated RF module allows direct access from a set of special RF registers to provide faster radio communication operations compared to accessing external RF modules through an SPI interface.

A. Overall Firmware Flow

The TI-ZStack version 1.4.3, based on ZigBee's 2006 standard, is used as the application program interface (API) for the firmware implementation of the multisensor node and the ZBridge device. The multisensor node is configured as an End Device, while the ZBridge is configured as the Coordinator Device in the ZigBee network topology. A set of clusters defined in the private application profile is used for OTA message communication between these devices. The endpoint applications for the multi-sensor node and the ZBridge are built on top of the existing ZigBee API. Each endpoint application occupies a single task event loop on the operation system level for concurrent operation with the existing ZigBee API tasks.

B. The Multisensor Node Firmware

The functionality of the multi-sensor node includes sampling, signal processing and streaming of multiple types of physiology signals to the ZBridge. During operation, the multi-sensor node also continuously listens to control messages from the ZBridge (originating from the mobile phone control device). **Figure 7** below shows the high-level structure of the multi-sensor node endpoint application.

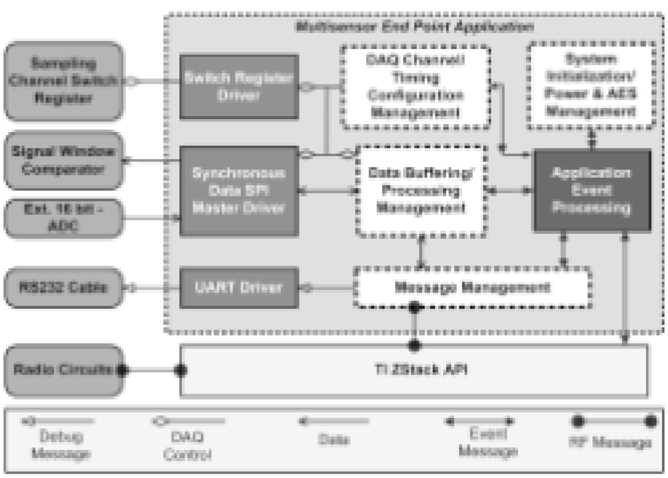

Figure 7: Multi-sensor node endpoint application firmware structure.

The operation of the multisensor application begins with receiving an OTA control configuration message from the control device. The *DAQ Channel/Timing Configuration Management* module prepares the data structure for data acquisition controls based on requests contained in the control message. Data buffer(s) and callback functions for post sampling process (signal processing) are initiated as well. The data is acquired from the sensor outputs using a switch register to select between different physiological signal channels (e.g. electrodes, accelerometer, and thermistor). The sampling period is controlled by a multi-level timer triggered through hardware timer task (not shown in the application level diagram) while sampling is done in a round-robin manner for multiple channel mode. Data is read from the high-speed high-precision (16-bits) external ADC through the *SPI driver* module configured as a master with baud rate of 115200 bps. Acquired samples are stored in a processing buffer within the *Data Buffering/Processing Management* module.

C. The Bridge Device Firmware

The ZBridge device is a bi-directional wireless data packet translator between ZigBee and Bluetooth. Figure 6 below shows the high-level firmware design of the ZBridge endpoint application.

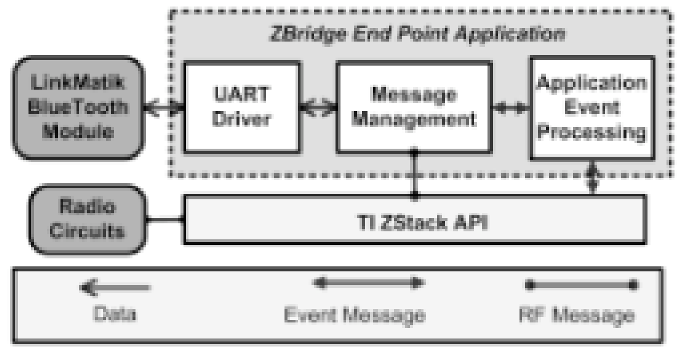

Figure 8: ZBridge endpoint application firmware architecture.

A message from the *LinkMatik BlueTooth* module is transferred to the *UART driver* and buffered on the *Message Management* module. In addition to the payload of the packet, other packet status fields such as cluster ID, network short address of the multi-sensor node, and length of the payload data are also included in the message. An event is notified within the *Application Event Processing* module after the message is buffered and the payload of the message is transferred to the multi-sensor node by its known address and cluster ID. Message transfer in the other direction is processed in a similar way.

D. Signal Processing Algorithms – Heart Rate

A key feature of the multi-sensor node is its ability to process ECG signals and detect heart rate on the node prior to wireless data transmission. Excessive wireless data transmission linked with ECG data streaming is very power consuming, so should be avoided. An efficient and compact heart rate detection algorithm is a critical component of the multi-sensor firmware.

In order to calculate the heartbeat accurately, the QRS complex of the ECG waveform must be detected for every heart beat. The algorithm applied is based on a differential method of detection of QRS complexes which recognizes the complexes based on analyses of slopes, amplitude, and width [Kohler 2002]. The raw ECG signal is bandpass filtered in order to reduce the amount of noise. It is then differentiated and averaged. The filters are designed form a class of digital filters that require only integer coefficients, which permits to avoid complicated floating point processing on the 8051 microprocessor.

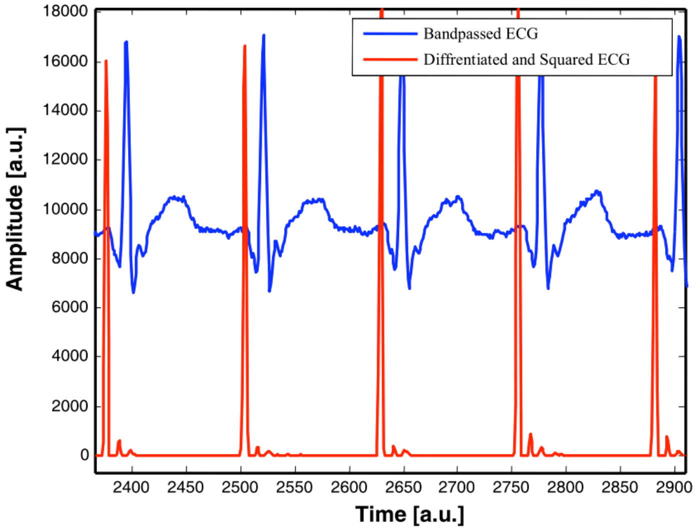

Figure 9: Few cycles of band-pass filtered ECG signal and its corresponding differentiated and squared values.

After differentiation the values are taken to the power of two. This nonlinear operation ensures that all the data points become positive and further amplifies the output of the differentiator. **Figure 9** shows the output differentiated and squared ECG versus the original input signal. The last block in heart rate detection process is the actual identification of the QRS waves and thereby calculation of the heart rate value. The number of heart beats per minute is calculated using a three beat average. Each output sample from the QRS discriminator is compared against a set threshold to detect the presence of a beat. The threshold is updated continuously based on the average of the eight previously detected QRS waves.

V. Preliminary System Results

Preliminary tests on the performance of several key elements of our system are presented in this section. Power consumption and radio communication range are presented for the ZBridge device. On the sensor side, the efficiency of the heart rate detection algorithm is evaluated. These results are critical first investigations at the system-level necessary for the validation of the full system operation, and for future clinical testing.

A. *ZBridge Power Consumption and Radio Range*

Range of use is an important factor in the usability of a wearable device. **Figure 10** presents the maximum communication range and current consumption at 3V versus transmission power (TX). It can be seen that the transmission range decrease with decreasing transmission power is much more pronounced than the decrease in power consumption. From this result, a low power level with associated communication range much higher than required is selected in our implementation allowing increased user comfort and transmission reliability.

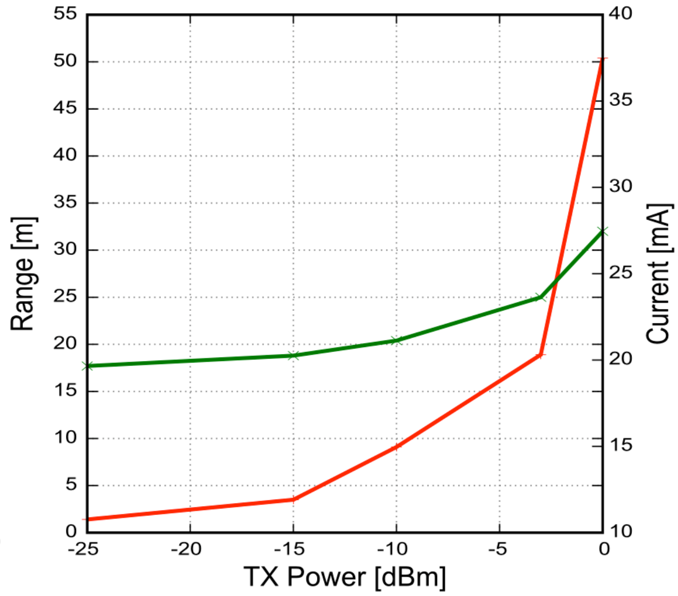

Figure 10: Communication range and current consumption of the system (at 3V) versus TX power for the ZBridge device.

B. *Sensor Node Heart-rate Calculation Performance*

The described heart rate detection algorithm was implemented on the CC2430 microcontroller. In order to validate the calculation performance, a simple test scheme was introduced. A signal was generated by a patient simulator (Fluke PS420[1]) with heart rates of 60, 80, 100, 120, 140, and 160 BPM. This signal was acquired by a commercial ECG monitoring device BURDICK EK10[2], sampled at 100Hz and stored. This data was subsequently used by the heart rate algorithm implemented on the CC2430 and the resulting heart rate was compared. **Figure 11** presents the number of iteration cycles (samplets) required by the algorithm to attain the correct heart rate (within 3% accuracy) for different pre-recorded ECGs with set heart rate values from a cold start. It is found that the higher the heart rate, the quicker the correct value is reached, which is understandable given that with higher heart rate, QRS complexes are denser within the analyzed data.

In order to further validate the feasibility of implementing the heart rate detection algorithm on the 8051 microcontroller, we measured the time necessary to perform one cycle of calculations. A cycle of calculations is performed after acquisition of each ECG digital data point (every 10ms for 100Hz sampling rate). The time needed to perform 2000 cycles was measured on a system running with 26MHz clock to be 600ms, which gives 0.3ms for one iteration. It means that time needed to perform heart rate calculation on board of the multi-sensor node is sufficiently small not to compromise its performance with other tasks.

[1] http://us.fluke.com/busen/home/default.htm
[2] http://www.burdick.com/products/electrocardio/singlechannelecgs.htm

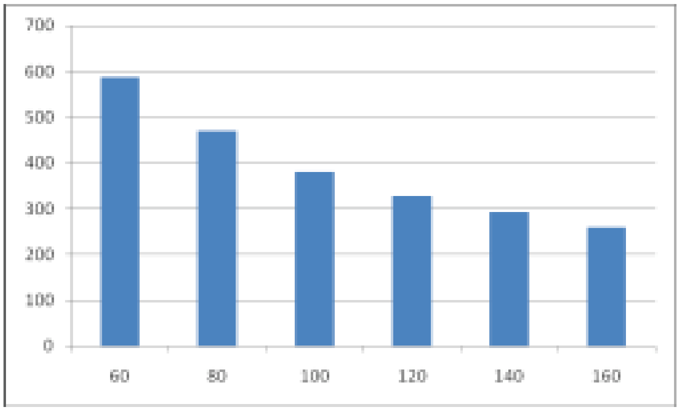

Figure 11: Number of cycles required to attain 3% accuracy of the heart rate for different heart rate values.

VI. Conclusion

A small, reliable multi-parameter system for wireless human activity and vitals monitoring may contribute to a major breakthrough in pervasive healthcare. In this paper, we presented such a system composed of a very small, flexible multisensor device communicating with a mobile phone, serving as a user interface, control, and data management device. The mechanical flexibility of the sensor greatly improves the comfort of use and the reliability of the acquired data thanks to better attachment to the body. Inclusion of a vast range of signal acquisition options in a small package without the use of a dedicated System-on-Chip is unprecedented and opens new possibilities for design options while enabling continuous monitoring of active subjects and patients in their natural environments.

During the design process, we focused on maintaining small footprint of the device by carefully balancing analog and digital signal processing as well as introducing shared analog filter chains among different sensors. We also insisted on lowering power consumption of the system in order to enable long lifetime of the system between battery recharging – a primal concern for wearable wireless devices.

The proposed device was fabricated and initial testing for key modules was conducted. We show the feasibility of using the low power 8051 microcontroller for heart rate detection from raw ECG data. We also evaluated the performance of the radio link and discussed the tradeoff between the power consumption and communication range leading to the conclusion that added comfort of having broader radio range is worth the increased power consumption.

In the future, we plan to proceed with the next phase of system testing, clinical validation, and optimizing the system's performance, especially regarding the power consumption. While some advanced energy conservation strategies are already implemented, we also plan to explore new powering options, like wireless battery recharging and human energy harvesting. We also plan to explore the possible use of flexible batteries in our system to match the overall flexibility of the sensor.

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