Mobile Multi-parametric Sensor System for Diagnosis of Epilepsy and Brain Related Disorders

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Abstract. Epilepsy is the commonest serious brain disorder, affecting 1-2% of the general population. Epileptic seizures are usually expressed with a wide range of paroxysmal recurring motor, cognitive, autonomic symptoms and EEG changes. Therefore reliable diagnosis requires state of the art monitoring and communication technologies providing real-time, accurate and continuous brain and body multi-parametric data measurements. The purpose of this paper is to present an adequate mobile system comprising all required sensor types for the everyday life monitoring of patients with epilepsy.

Keywords: epilepsy monitoring, biosensors, security and privacy**.**

1 Introduction

Epilepsy is one of the most common and devastating of the incurable neurological disorders, affecting about 1-2% of the general population. Due to its multifactorial causes and paroxysmal nature, epilepsy needs multi-parametric monitoring for purposes of accurate diagnosis, alerting, prevention, treatment follow-up and pre-surgical evaluation.

State of the art for the monitoring of epilepsy includes a series of laboratory tests. These tests can only be done in a specific unit of a specialized hospital, they are rather expensive (about 1,500 euros per day) and their diagnostic yield depends on whether the clinical event of interest occurs during the period of the monitoring (typically less than a week). Current diagnosis relies either on video EEG that records the habitual suspected event or ambulatory EEG without video. Recent research has shown that while ECG monitoring is used for real-time epileptic seizure detection [2], activity monitoring via accelerometry and GSR monitoring can also be used as extra context parameters [7-8], while monitoring epileptic patients.

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Therefore reliable diagnosis requires technologies that provide real-time, accurate and continuous brain and body multi-parametric monitoring. The assessment of those physiological signals should be ambulatory and not affect the patient's everyday life. Furthermore extra attention on security aspects should be paid.

During the past years, several hardware and software solutions for multi-parametric assessment of physiological signals have been developed. However, none of them was able to provide an integrated platform for the assessment of all the parameters needed. Furthermore the proposed systems were not appropriate to be used in everyday life. Our goal is the development of an unobtrusive sensor platform, aiming to design and develop a Personal Health System (PHS) for monitoring and analysis of epilepsy-relevant multi-parametric data, emphasizing in convenience and security issues.

In section 2 of this paper, the architecture of the whole system is introduced. The focus of this section is the description of the mobile sensor-platform for multiparametric monitoring of different vital signals related to epilepsy and the description of encryption unit for secure transmission of the data. Section 3 presents the processing of the acquired signals and their role in diagnosis of epilepsy. Then section 4 presents the initial performance results, while section 5 concludes indicating the main objectives and directions of this on-going effort.

2 System

Depending on the type of epilepsy, different brain and body parameters need to be assessed in order to have a better understanding of the patient's state of health and to adapt the medical treatment accordingly. Therefore our goal is to develop a personalized system that assists in diagnosis, prognosis and treatment of the disease. Such system should fulfill the following criteria; it should be non-invasive, mobile, continuous, unobtrusive and all possible security and privacy aspects should be taken into account. Fig. 1 shows an overview of the system.

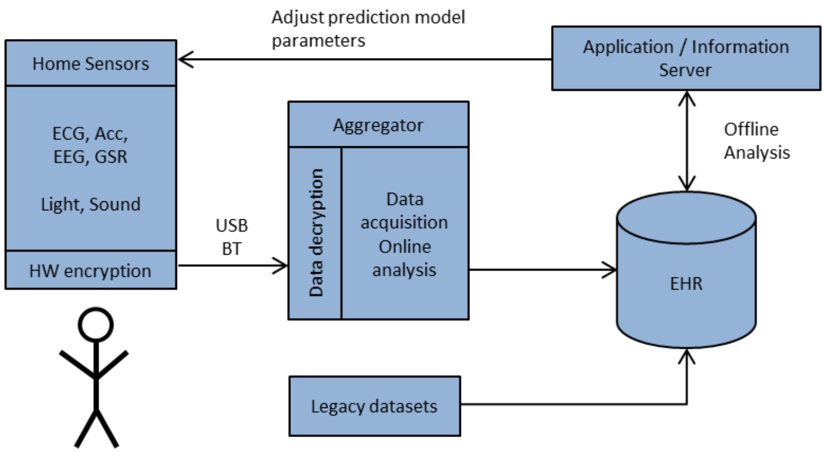

Fig. 1. System overview

The sensor platform performs the following actions: data logging, data preprocessing, data encryption and wireless transmission of the assessed data to an aggregator for further analysis. A Laptop used as an aggregator performs the data decryption (needed for the online analysis), processing and transmission to the Electronic Health Record (EHR) database. The transmission to the EHR is realized by a standardized SSL secure internet connection. EHR includes all the legacy datasets of the patient as well. The offline analysis of the data is realized on the information server. Based on the offline analysis, the prediction models may be adjusted, thus creating a personalized monitoring system.

2.1 Data Acquisition Unit

The measurement of the autonomic functions should be done by light-weight, portable, low-power sensors, specially developed for the assessment in everyday life.

Our main platform (Fig. 2) is based on a sensor platform developed by movisens (movisens GmbH, Karlsruhe, Germany) and consists of an ultra-low-power microcontroller (MSP430F1611, Texas Instruments) with an AD/DA converter, 2 UART interfaces, a 48 kB flash and a 10 kB RAM. The assessed data is encrypted and then transmitted wirelessly to the aggregator by using the Bluetooth interface. Due to the big amount of data to be transmitted, data reduction on the sensor side is fundamental. The transmitted data, following appropriate processing, are no longer raw data, thus reducing the amount of data to be transmitted. To avoid data loss in case the data transmission is not possible, the raw data is in parallel stored in a 2 GB micro SD card. The stored data can then be saved on the computer by using the USB 2.0 interface that is available. The charging of the power supply of the sensors is recognized by the USB interface as well.

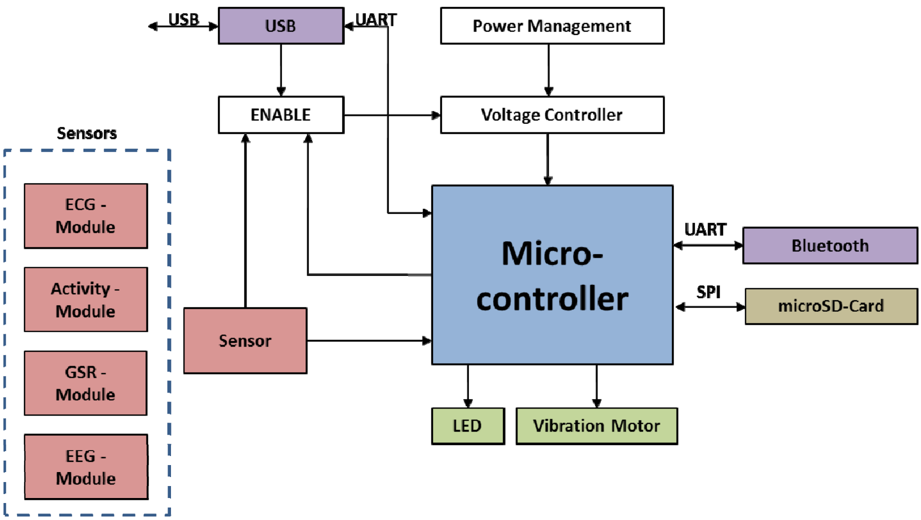

Fig. 2. Architecture of the sensor platform

The ECG module is a single channel ECG recorder with a 12 bit resolution and a sampling rate from 256 Hz to 1024 Hz. The electrodes are integrated into a wearable chest strap, which is light, small and comfortable. The electrodes are dry, allowing the everyday use of the chest strap.

The activity monitoring module consists of a triaxial acceleration sensor (adxl345, Analog Devices Inc.) with a range of ±8 g and a sampling frequency of 64 Hz. The measuring unit has an additional air pressure sensor (BMP085, Bosch GmbH) with a sampling frequency of 8 Hz and a resolution of 0.03hPa (corresponding to 15 cm).

The galvanic skin response (GSR) module measures the skin conductance with a sampling rate of 32Hz. The measurement range of the GSR module is 2μS to 100μS and its resolution is 14 bit.

Beside the above mentioned modules, the sensor platform will include an additional EEG module, which will record the brain activity.

To assess additional context parameters like sound, light or geographic position, a smartphone is used. Connection between Smartphone, Sensor and Aggregator is also realized by Bluetooth interface.

2.2 Data Encryption Unit

In wirelessly transmitting medical and highly sensitive data, security support is a prerequisite of primary importance. Respective support pertains to data privacy, data integrity and authentication of communication parties. However, provision of security features pose significant challenges in sensor network due to extremely limited resources in critical areas such as processing power, available memory and available energy. Furthermore, although Bluetooth Technology offers security features with respect to both authentication and privacy, at the same time respective weaknesses and vulnerabilities are quite well-known [10]. Additionally, significant overhead imposed by software security implementations as opposed to hardware implemented counterparts must be taken into consideration [11].

Based on these considerations, an FPGA based hardware implementation solution has been selected, aiming to provide high level security services while minimizing respective performance overhead. An ultra-low power dissipation 128bit block AES encryption cipher comprises the core encryption algorithm upon which data privacy and authentication is based.

The AES block has been power optimized by using advanced power-aware design techniques coupled with a fully serial data-path architecture. Indicatively, for Spartan-6 Xilinx FPGA technology (45 nm process, core voltage 1 Volt), the dynamic power dissipation is 6 mWatts and the quiescent power dissipation is 11 mWatts assuming 10 MHz operating frequency and a worst case I/Os & FFs toggle rate of 100%. It is also noted that the FPGA implementation is used as a proof of concept approach concerning mainly power consumption performance while other approaches such as ASIC implementation can be considered at second phase in order to satisfy unobtrusiveness requirements.

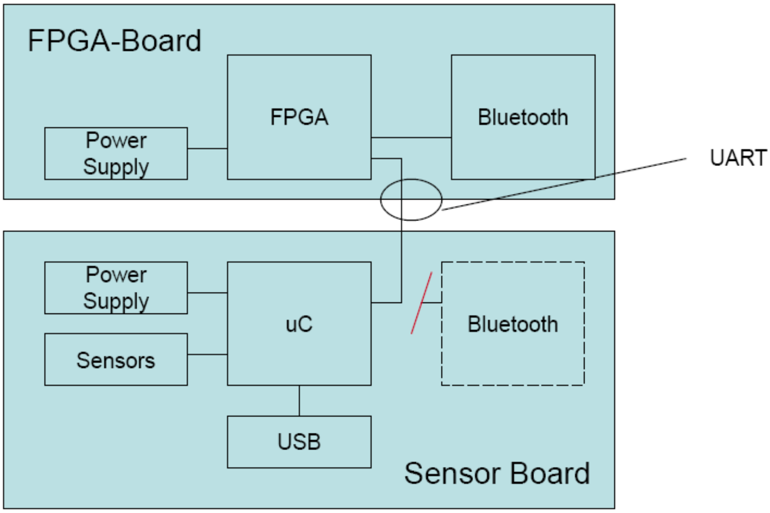

Fig. 3. Encryption and Data Acquisition Units Interconnection Design

A critical issue requiring careful consideration is the communication between the encryption unit and data acquisition unit; an abstract design of the proposed architecture is depicted in Fig. 3.

As indicated by the presented approach, the microcontroller - Bluetooth module connection is essentially interrupted and data is conveyed directly to the encryption unit. Following adequate data processing data is again directed to the Bluetooth unit to be wirelessly transmitted. An important advantage offered by this scheme is the opportunity to directly compare metrics of performance and power dissipation. This metrics consider all possible functional combinations between the hardware implemented AES cipher and Bluetooth provided security features.

Focusing on the interconnection implementation, the microcontroller unit provides the data blocks for encryption towards the FPGA platform via RS232 serial link. Therefore an adequate communication protocol is specified in order to enable a prompt implementation. Fig. 4 shows the components of the FPGA module and the communication among them.

As depicted, the data transferred over the UART link is stored in the register file. When a block of data is completed a respective status register indicates that a new data block is ready to be encrypted by the AES module.

Finally, as AES comprises one of the most prominent symmetric ciphers, appropriate encryption keys must be agreed between communicating parties. In that respect various scenarios in sensor network will be evaluated ranging from network wide keys, to pair-wise predefined keys [12]. Predefined keys appear as an appropriate approach since due to the nature of medical applications, nodes comprising a relative medical kit are expected to be also predefined. Provision of such kits are normally controlled and monitored by adequate medical facilities and personnel in order to adhere to the required privacy and ethical requirements [13].

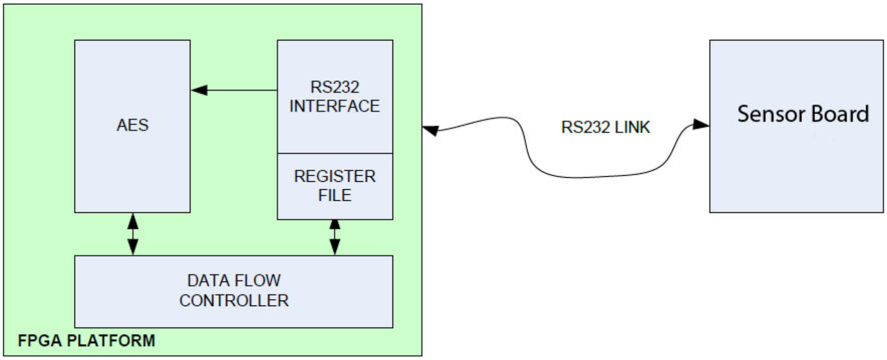

Fig. 4. UART Communication Components

3 Data Formatting and Data Processing

The data format which is being used is the unisens-format [5]. This is a universal and generic format suitable for recording and archiving sensor data from various recording systems and with various sampling frequencies.

The data acquisition on the aggregator side is performed by using xAffect [9]. xAffect is an open source software framework for online recording, processing and storage of multi sensor data. It was developed at FZI Research Center for Information Technology, Karlsruhe, Germany and can be used as a standalone application for data acquisition and visualization.

In the following significant types of measurements are presented and their role in epilepsy monitoring is depicted.

EEG monitoring is the state of the art while monitoring epileptic patients. It allows early detection of changes in the neurological status by providing dynamic information about brain function. In a clinical setting, a common practice involves examining short recordings of interictal periods. During this period, individual or isolated spikes, a sharp wave or a spike-and-wave complex are most commonly seen in epileptic patients [4].

ECG monitoring is one of the most crucial elements of monitoring in almost every disease. The ECG raw signal can be used to assess many parameters including Heart Rate (HR), Heart Rate Variability (HRV) parameters, heart rate changes and breathing rates when at rest. The above mentioned parameters have been proven useful for the measurement of autonomic functions and the automatic detection of seizures in patients with epilepsy [1, 2].

Activity sensors are useful, as they allow for the possibility to assess all the main motoric parameters. One can detect different activities (e.g. walking, jogging) or inactivity, different postures (e.g. lying left, lying prone), changes of body positions or estimate the consumed energy expenditure. Other than that, acceleration sensors also allow the detection of abnormal movements during myoclonic seizures [7] or possible falls [3] that can occur before, during or after seizures.

GSR monitoring measures the electrical conductance of the skin as it varies with moisture levels. This is a sensitive measurement of autonomic arousal and physiological state which reflects one's behavior. Studies have found that GSR biofeedback has the potential of being a potent adjunctive non-pharmacological means of reducing seizure frequency in epilepsy [6], and that seizure-induced EDA elevation is a possible sign of autonomic instability [8].

4 Results

In a first step we examined the life-time performance of the mobile sensor platform for different conditions of operation. For this, we varied the sampling frequency of different sensors, the number of online analysis performed on the mobile platform and transmission of data via Bluetooth interface. The data acquired are based on real and not simulated measurements.

On the acquisition side of the sensor module, the sampling rate for acceleration signals was varied between 32 Hz and 64 Hz, the sampling rate for ECG signal between 256 Hz and 1024 Hz. In addition to this, we added online analysis of pulse rate (bpmList) and the detection of normal R-peaks (nnList) in some cases. On the storage and transmission side of the module we changed between simple raw data acquisition and storage and additional data transmission via Bluetooth interface with different parameters. The results are presented in Table 1.

As we can see, the life time of the mobile platform depends essentially on wireless connection. The difference between wireless transmissions of different amount of data can be neglected. The use of this platform in monitoring of epileptic patients is possible regarding the results shown in this table. For all cases in which wireless connection is necessary, the future use of Bluetooth Low Energy module will provide adequate results.

Table 1. Life time performance of mobile sensor platform

Acquisition	Storage	Transmission	Life-time
acc 64 Hz, ecg 256 Hz, bpmList, nnList, press 8 Hz, temp 1 Hz	Raw data	-	2d 7h 33m
acc 32 Hz, activity, ecg 512 Hz, press 8 Hz, temp 1 Hz	Raw data	-	3d 6h 20
acc 64 Hz, ecg 1024 Hz, press 8 Hz, temp 1 Hz	Raw data	-	2d 14h 31m
acc 64 Hz, ecg 256 Hz, bpmList, nnList, press 8 Hz, temp 1 Hz	Raw data	256 Hz ECG-raw data	3h 10m
acc 64 Hz, ecg 256 Hz, bpmList, nnList, press 8 Hz, temp 1 Hz	Raw data	1 Hz HR	3h 15m
acc 64 Hz, ecg 256 Hz, bpmList, nnList, press 8 Hz, temp 1 Hz	Raw data	BT connection	3h 20m

5 Conclusion

The presented system is a complete monitoring system able to accurately acquire and assess multiple body and brain parameters. The goal of this paper was to provide a complete, secure and reliable solution for the monitoring of patients with epilepsy. The novelty of the system lies in the aspects taken into account for its realization (biomedical context, unobtrusiveness, security, software and hardware design) and its' special design to address the needs of epileptic patients.

The implementation of this solution presented here is still ongoing work.

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