Mobile monitoring of epileptic patients using a reconfigurable cyberphysical system that handles multi-parametric data acquisition and analysis

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***Abstract*— Epilepsy is one of the commonest, serious and divesting brain disorders. Although it is still an incurable disorder in most cases its symptoms can be ameliorated by life-long pharmaceutical treatment. Depending on the type of epilepsy and due to its multifactorial causes, different brain and body parameters need to be assessed continuously over a long period. This allows clinicians to have a better understanding of the patient's state of health and to be able to continuously adjust and change the medical treatment accordingly. Beside this, multi-parametric monitoring could be used for other purposes such as accurate diagnosis, detection of seizures, alerting and prevention and presurgical evaluation. The purpose of this paper is to present the architecture of the whole cyberphysical system, comprising a modular framework that is able to connect all the required sensor types and perform online data analysis for the monitoring of patients with epilepsy.**

Keywords—epilepsy; multi-parametric monitoring; EEG; ECG; GSR; Home Gateway

I. Introduction

Epilepsy is one of the commonest and most serious of the incurable neurological disorders, affecting at least 50 million people in the world [1]. Epileptic or non-epileptic seizures interfere with the life of affected people dramatically. Everyday activities like driving a car or riding a bike can become severely dangerous when having a seizure.

Clinical state-of-the-art in monitoring epileptic patients is inpatient video-EEG recording. However, this method suffers from some serious disadvantages as it is rather expensive and with low availability due to limited numbers of places for whole night recordings. In addition to this the number and type of epileptic seizures during in hospital recording could differ from normal behavior and the equipment used in clinical practice is rather inconvenient for patients. The best solution would be to enhance out-of-hospital monitoring.

Although EEG is the most important biosignal when monitoring epileptic patients, recent research has shown that ECG monitoring can also be used for real-time epileptic seizure detection [2], and that activity monitoring via accelerometry and GSR monitoring can be used as extra context parameters [3-4]. Therefore, depending on the type of epilepsy, different brain and body parameters need to be assessed in order to monitor the patient's state of health at best and to adapt the medical treatment accordingly.

Different solutions for multi-parametric assessment of physiological signals have been developed during the last years. However, none of them were able to provide an integrated platform for the assessment of all the parameters needed or the proposed system was not appropriate for use in everyday life.

This paper proposes a reconfigurable cyberphysical system that handles multi-parametric data acquisition and analysis for the mobile monitoring of epileptic patients.

II. System Architecture and Components

Since different types of epilepsy require monitoring of different brain and body parameters, our goal is to develop a personalized and reconfigurable system that assists in diagnosis, prognosis and treatment of the disease. Some of the main requirements of the system are that it should be non-invasive, mobile, continuous, unobtrusive, reconfigurable and able to perform online analysis. The system can be divided into three main components: the sensors, the Home Gateway containing the middleware and the Personal Health Record (PHR) server. Fig. 1 shows an overview of the system and its components.

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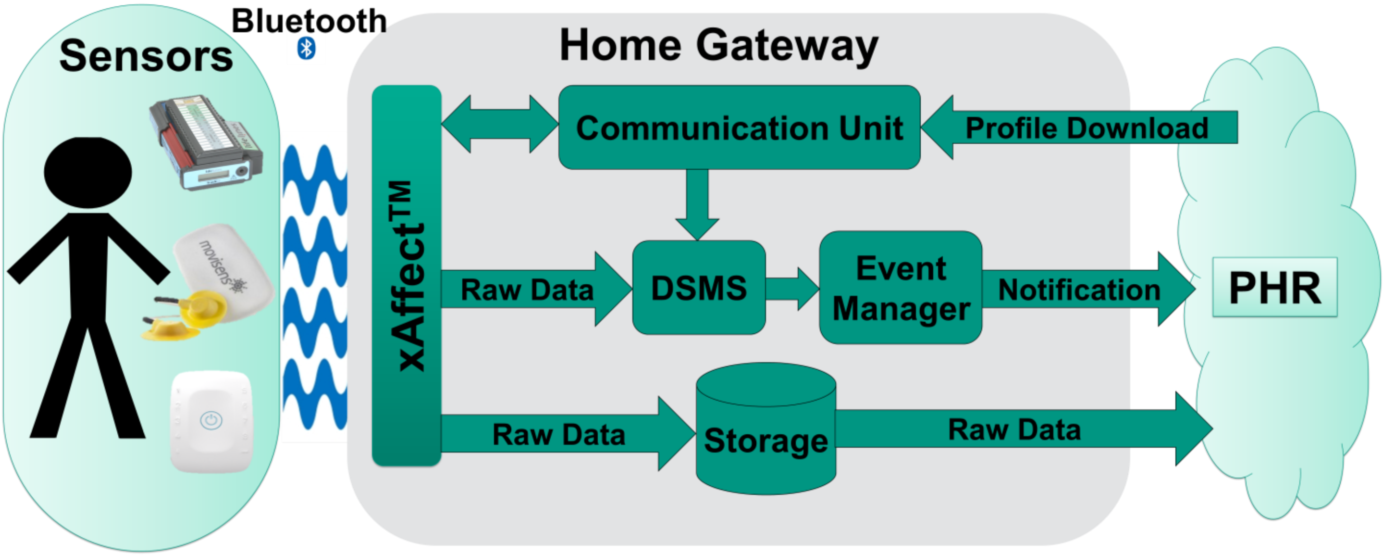

Fig. 1: System overview

The PHR server contains all the information related to the patients. When a new measurement shall be started the Home Gateway downloads a profile from the PHR. This profile contains the sensor configuration. Having this information, the middleware automatically configures the sensors and starts the measurement.

The sensors are streaming data via Bluetooth to the Home Gateway. The middleware fuses the data together, stores it, uploads it to the PHR server and also streams it to the Data Stream Management System (DSMS).

The different monitoring parameters used for multiparametric analysis include ECG, GSR, multichannel EEG and physical activity sensor (acceleration sensors) [1]. Furthermore there are some additional sensors providing context information about the measurement conditions and the patient's environment. Temperature, air pressure, body position and a push button where the patient can mark specific events of interest need to be acquired and synchronized with the physiological data and then stored in a central database. The fact that for each patient some parameters are more important than others makes it necessary to adapt the system to the patient's needs. Therefor the system is designed reconfigurable regarding the sensors. This means an individually selected set of sensors is attached to each patient profile in the PHR and the System uses only these required sensors to monitor the patient.

The DSMS runs different online algorithms to detect special events. Some examples are push button, alpha rhythm and seizure detection. These algorithms are also defined in the profile and can therefore be adapted to each patient individually.

The Event Manager handles the different events of special interest found by the algorithms in the DSMS. When an event is detected the event manager notifies the PHR directly, that can then inform the clinicians via SMS or e-mail about the patients state.

A. *Sensors*

In order to achieve the main requirement, the multi-parametric monitoring, different sensors should be integrated in the system. This includes not only the most relevant bio-signal for epilepsy monitoring, the EEG but also ECG, GSR and a push button that have be proven to be important in mobile epilepsy monitoring [2-4]. For this system the following sensors were selected.

The EEG module (Trackit™, Lifelines Ltd, Over Wallop, UK) is a mobile ambulatory device that can measure up to 32 channels with a sampling rate of 256 Hz. Each channel has an ADC resolution of 16 Bit and has a maximum differential AC input 10 mV. Depending on the number of channels, the sampling rate and the battery used the device can achieve up to 96 hours of recording.

The ECG module (ekgMove, movisens GmbH, Karlsruhe, Germany) is a single channel ECG recorder with a 12 bit resolution and a sampling rate from 256 Hz to 1024 Hz. The module can either be used with electrodes integrated into a wearable chest strap, which is light, small and comfortable or be used with conventional disposable wet electrodes. The electrodes of the chest strap are dry, allowing the everyday use. To assess the patient's physical activity, the module has also an integrated triaxial acceleration sensor (adxl345, Analog Devices Inc.) with a range of ± 8 g and a sampling frequency of 64 Hz and an air pressure sensor (BMP085, Bosch GmbH) with a sampling frequency of 8 Hz and a resolution of 0.03hPa.

The GSR module (edaMove, movisens GmbH, Karlsruhe, Germany) 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. With this one can measure both the electrodermal activity level (EDL) and responses (EDR). Furthermore the module has the same sensor set to measure physical activity integrated as the ECG module.

The push button module (bioPLUX, PluX, Arruda dos Vinhos, Portugal) is a device that collects up to 8 signals from various sensors and transmits the signals via Bluetooth to a computer, where they can be viewed in real time. The resolution of bioPLUX is 12 bits, and its sampling frequency is up to 1 kHz. For this system only one channel with a push button sensor is used.

B. *Home Gateway*

The Home Gateway consists mainly of three parts. The first part is the Data Fusion Unit that collects all the data from the sensors and fuses it to a synchronized data stream. The second part is the Communication Unit, which communicates with sensors, the PHR server and the third part, which is the DSMS. The DSMS and the Event Manager use the data stream to perform online analysis which detects events of special interest.

1) Data Fusion Unit:

To connect all the data, synchronize it and handle the data stream a lean and open framework, which can be personalized and reconfigured for each patient, is needed. xAffect is a software framework developed by the Research Center for Information Technology, Karlsruhe, Germany. It was developed in Java to fulfill real-time data processing, easy integration of different data sources, easy integration of algorithms and data logging of raw as well as derived data [5]. Libraries for some common sensors already exist in xAffect. To use a broad spectrum of biosignals, additional libraries for bioPlux and TrackIT devices from the companies bioPLUX and lifelines had to be implemented. The data format which is being used is the unisens-format. This is a universal and generic format suitable for recording and archiving sensor data from various recording systems and with various sampling frequencies [6].

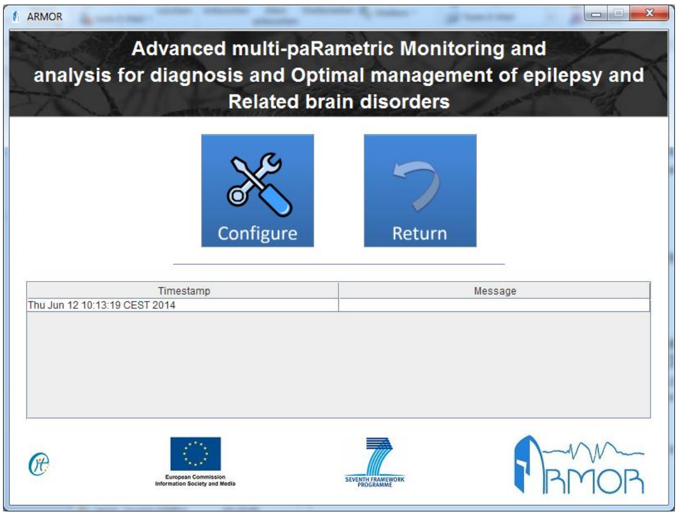

Fig. 2 GUI of monitoring system

2) Communication Unit:

The Communication Unit handles the communication with all components and with the User himself. A simple graphical user interface (GUI), shown in Fig. 2 enables the the user to set up the measurement.

In the GUI the user enters his username and password and the patient-id. With the patient-id the Communication Unit can download the personalized profile from the PHR. Afterwards the user can press the configure button to initialize the communication with the sensors. Furthermore the profile contains information about the alarm settings. This enables the Communications Unit to set up the DSMS with the customized set of alarms.

When the configuration process has finished successfully the user is able to start the measurement by pressing the record button. During the recording the data is streamed from the sensors through xAffect towards the DSMS and the storage. The Communication Unit takes the data from the storage and uploads it in junks of 30 minutes to the PHR. In case an Event occurs the data will be uploaded immediately. This ensures that when an alarm is send to a clinician the data will be ready to download and view.

The GUI also allows the User to pause or resume the measurement. This allows the subject interrupt the data acquisition and move out of the Bluetooth range of the Home Gateway.

3) Data Stream Management System (DSMS) and Event Manager:

The DSMS function takes place on-line, where real time processing of modalities is performed. The DSMS is based on Microsoft™ StreamInsight™ platform created for the development and deployment of complex event processing (CEP) applications. It’s a high-throughput stream processing architecture that uses .NET Framework-based development platform.

The development done at the DSMS allows receiving xAffect™ sensor data in real time, to provide it in a lossless way to the computation algorithms. With this, the framework is able to create own queries and policies over data.

In order to explain the data workflow within the DSMS, we need to introduce some concepts related to StreamInsight™ as following:

- Sources: They are data providers and can be implemented with adapters, IEnumerable or IObservable objects. They are in charge of collecting data, fit it into a payload, generate an appropriate timestamp (if needed) and redirect this to StreamInsight's core adding appropriate CTI (Current Time Increment) insertions. Sensor sources are IObservable objects built with information coming from xAffect through TCP sockets.

- Queries: All data from sources goes directly to StreamInsight core (in any number of streams) where it's processed in order to satisfy one or more queries (LINQ). That will produce an output that will go through to the data consumers (observers) where custom operations can be defined. It can also compute different operations depending on query needs such as aggregation, unions, max/min etc.
- Consumers: They are pieces of software which main function is to process data output from StreamInsight™ queries. They are usually implemented with the observer interface so it can be easy to notify them when new data is available.

We are achieving lossless stream between xAffect™ and DSMS by using TCP channel. This makes sure the built-in architecture of StreamInsight™ can work with the synchronized data coming from xAffect™.

The main objective of the DSMS is to deliver alarm and warning events predefined in the profile. One of the most important events is the push button detection. Other events are for example an alpha rhythm or seizure detection. The module that communicates events towards the PHR is called the Notification Manager.

C. Personal Health Record (PHR)

The PHR server is an online server were the clinicians can access all the patient related data. A customized set of sensors and also a customized set of algorithms can be defined for each patient. Furthermore all data acquired by the system is uploaded to the PHR server continuously. Hence, data can be downloaded and viewed by the clinicians almost instantly from any point where they have an internet connection. In case of events the PHR server set a marker for the time of interest and can notify immediately by sending an email or a SMS.

III. CONCLUSION

Different sets of sensors can be used customized to the needs of clinicians and patients to acquire the necessary data from a specific patient to handle his epilepsy. Furthermore the system does not acquire unnecessary data that is useless for the clinicians by reducing the hardware to a minimum set of sensors personalized for the patient.

The first tests under clinical conditions indicated that the developed system is not only more comfortable for the patients since they can move more freely but also usable for the clinicians who were in charge of the data acquisition. The key factor to usefulness seemed to be a GUI that is designed as simple as possible. Future tests have to focus also on the user feedback to show the usefulness of the device. Furthermore in the future the system should be tested not only in clinical environment but also in patients' homes to verify the reliability of the system. Furthermore the Home Gateway which is running on a laptop at the moment should be replaced with a smartphone for providing an even more comfortable monitoring.

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