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Smartphone-Centred Wearable Sensors Network for Monitoring Patients with Bipolar Disorder

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Abstract— **Bipolar Disorder is a severe form of mental illness. It is characterized by alternated episodes of mania and depression, and it is treated typically with a combination of pharmacotherapy and psychotherapy. Recognizing early warning signs of upcoming phases of mania or depression would be of great help for a personalized medical treatment. Unfortunately, this is a difficult task to be performed for both patient and doctors. In this paper we present the MONARCA wearable system, which is meant for recognizing early warning signs and predict maniac or depressive episodes. The system is a smartphone-centred and minimally invasive wearable sensors network that is being developing in the framework of the MONARCA European project.**

I. INTRODUCTION

BIPOLAR Disorder, formerly known as manic depression, is a common and severe form of mental illness [1]. It is characterized by alternated episodes of mania and depression, and, typically, its treatment is based on a combination of pharmacotherapy and psychotherapy. Unfortunately, the effectiveness of this treatment is only limited. Moreover, the pharmacotherapy can be hardly adapted to the patients because of the difficulty of recognizing their upcoming changes in state. A promising form of intervention is to teach patients to recognize and manage early warning signs (EWS) [2]. However it involves a very significant training effort and strongly depends on the patients compliance and discipline. Thus, this therapy is also of limited use only. A great improvement in managing bipolar disorder can be achieved with the use of wearable technology in support of both patients and doctors. Actually, thanks to the continuous advances in the development of technologies, such as sensing and communication, in parallel with the continuous progress of electronic device miniaturization, the wearable systems are becoming more and more a powerful support in health care. Today the wearable technology is envisioned for use in clinical applications [3] and personalized healthcare [4], where the wearable system became a part of a chain in which all the other actors, patients, healthcare centres, and doctors are in a closed loop for better understanding, monitoring, preventing and treating the illness with a personalized approach. However, although the incredible technology advances in terms of device miniaturization, low power consumption and high computational power, the main challenges that a wearable system has to face with are always the same. In fact, the more the new technologies offer, the more the demand for new features and functionalities increases. So we are still to deal with low energy consumption [5] and minimally invasive systems development [6]. While the first constraint is independent from the clinical application, the second one applies differently depending on the disease to be treated. In fact, patients suffering from a cardiovascular disease can accept better to wear some bulky sensor on the skin than patients with mental disease. In the letter case not only the sensors cannot be accepted, but they can also affect the mood of the subject producing a biasing effect on the monitored data. To make the wearable system as minimally invasive as possible there are two lines of approach: embed all sensors in a garment [7][8], or move as much sensors as possible in wearable daily life equipments [9]. In this paper we present a solution that is a combination of the two approaches, which is intended for monitoring and treating patients affected by bipolar disorder. The system is a smartphone-centred and minimally invasive wearable sensor networks that is being developing in the framework of the MONARCA European Project [10]. The goals of the project are to develop and validate solutions for multi-parametric, long term monitoring of behavioural-physiological information relevant to bipolar disorder. These solutions will be deployed through an appropriate healthcare platform providing a set of novel services for personalized management, treatment, and self-treatment of bipolar disorder. The architecture of the whole system is shown in Fig. 1. The rest of the paper is organized as follows. First we describe the MONARCA wearable system. In Section III we present the main challanges that the MONARCA system have to face with. Then, in Section IV, we briefly describe how the medical trials will be performed and finally, we present the conclusions.

II. MONARCA WEARABLE SYSTEMS

The main responsibility for the wearable system is to recognize the early warning signs in order to timely predict and prevent the occurrence of manic/depressive episodes, and to adjust the therapy accordingly. Therefore, the system must be capable of identifying, or at least has to be an aid for both patient and doctor to identify those signs that prelude the upcoming changes in patient's mood: level of patient activity,

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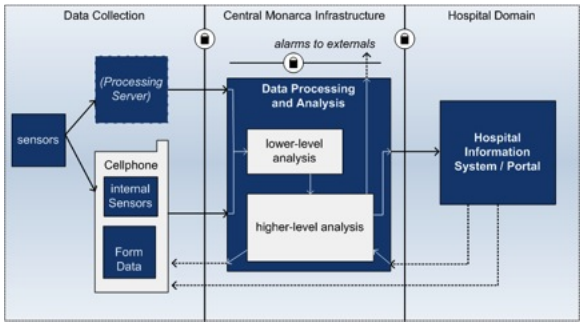

Fig. 1. Monarca system architecture overview

amount of social interaction, changes in daily routine, stress, quality of sleep, etc. So, in our case, we need more to acquire information on social and behavioural attitude of the patient than specific physiological parameters. To this aim, the MONARCA Wearable System (MWS) is centred on a smartphone, which does the most important sensing part, that is complemented with two other wearable sensors: a wrist worn sensor and a *smart sock*.

A. Smartphone

The smartphone is the core of the wearable system and it is also the means for the direct connection between patient and doctor. It is an Android based platform equipped with: GSM/UMTS/WiFi/Bluetooth communication technologies, a GPS sensor, a three-axial accelerometer sensor and a three-axial magnetometer sensor. In addition to these technologies it can provide other sort of ”sensors” that are very useful for determining the behaviour, social interaction and mental state of the patient. They are: 1) the microphone, which can be used for background noise recording and voice recording during calls, 2) the counter of calls, SMS and e-mail performed every day, and 3) the utilization of the smartphone (e.g. frenetic switches among applications, or less or no use at all).

B. Wrist worn sensor

The wrist worn sensor (WWS), developed in the project framework by Aipermon [11], is defined to be an activity logging device, which detects users movement. Movement data are stored within a non-volatile memory and transferred via Bluetooth to the smartphone. The WWS is built as a watch device and incorporates a three-dimensional accelerometer and a three-axes gyroscope sensor for angular rate sensing. It is based upon Atmel ATmega329P microcontroller using 8MHz main clock frequency. Additionally, a 32 KHz oscillator crystal will be used as auxiliary clock source. A real time clock is used for maintaining the synchronization with the smartphone even when the connectivity between them is temporarily not available. The WWS is powered by a 3.7 V LiIon rechargeable battery, which can be recharged via external power supply. This sensor gives information on arm motion and combined with the smartphone sensors is used to infer a broad range of activities such as nutrition, homemaking as well as different leisure and sports activities. Furthermore, the WWS will be a valuable source of information on sleep quality that is a strong index of patient state.

C. Smart sock

The smart sock provides Galvanic Skin Response (GSR), also known as Electrodermal Activity (EDA), and pulse signals as an indication of stress. The choice of a sock as platform is due to the fact that reliable GSR signals can only be collected at the palms (which is not practical) or at the feet [12]. Blood vessels in the lower leg can be used to derive a pulse signal using infrared pulse oximetry or capacitive methods. The measurement principle is referred to as an exosomatic quasi-constant voltage method. A constant voltage (500mV) is applied to one electrode leading to a current flowing through the skin to a second electrode. Measuring the voltage at the reference resistance allow to directly determine the skin resistance. To eliminate high-frequency noise, a 2nd order low-pass filter with a cut-off frequency of fc=5Hz is applied before A/D conversion of the measured signal. Applying an additional high-pass filter (2nd order, fc = 0.05 Hz) yields the phasic part of the EDA signal. For further noise reduction, this signal is once more low-pass filtered (2nd order, fc = 5 Hz), amplified and fed to the A/D converter. Also for the sock the communication with the smartphone is made via bluetooth connection. Given the position of this sensor on the patient’s body, the communication with the smartphone could be problematic in some period of the day. For this reason, the sock is equipped with an SD card in order to store all data every time that the connection is lost.

III. Challenges

The main challenges for MONARCA wearable system are of two kinds: the early warning signs detection, which is based on data analysis, and technical challenges that are more related to technology and resources optimization.

A. Early warning signs detection

Processing the information retrieved from the smartphone, the WWS and the smart sock, provides a good indication of the patients overall state and lead to detects indexes useful for recognizing early warning signs. The main relevant indexes are the level and repetitiveness of physical activity during the day, the level of social interaction and the level of stress and mood changes. Initially a baseline will be established that describes the typical state of the patient and the expected variations that may occur in the typical, non-episode-experiencing state. Once the baseline is established, the measured data will be continuously compared to the baseline with the view of detecting deviation of the measured parameters from the baseline. This will allow monitoring of fast changing parameters and comparison to the subjective patients state. When a tendency to move away from the baseline measurements is detected, feedback is given to the patient in order to teach him to recognize early warning signs. The feedback will be initiated not only from the objective data but also their correlation with the subjective data and clinical advice. The subjective data are retrieved from a daily questionnaire that the patient has to fill in on the smartphone. Example questions are: which meals have you taken, amount of time spent outside home and at work, hours of sleep, number of places visited, level of daily activity, level of sociability. The feedback will take the shape of a persuasive user interface running on the mobile device. It will inform the patient of detected changes in the overall state and provide motivation to address the warning signs and explain correlation between the changes in lifestyle and changes in the condition.

1) Physical activity recognition: The physical activity level is an important index of the patient state [14]. In the manic phase, for instance, people often behave recklessly, and feelings like heightened energy, creativity, and euphoria are common. Subjects experiencing a manic episode often talk very fast, sleep very little, and are hyperactive. On the contrary, when in depression people tend to move and speak slowly, sleep a lot, and gain weight. Therefore, it is very important to recognize not only the type of subject's activity, such as running, walking, driving, but also how it is performed and repeated during the day. The activity recognition is made by the analysis of data recorded from different sources. The smartphone accelerometer provides information on the overall level of activity. The localization system (GPS plus GSM base station for outdoor, and GSM base station and WiFi for indoor), is mainly used for discriminate indoor from outdoor activities. The microphone is used for fine activity recognition, based on the sound sensed [13], and can be complemented for this purpose by the WWS.

2) Social activity recognition: As for the physical activity also the social interaction is an important factor for determining the patient state. When in manic phase, people tend to spend much of the day outside, moving from place to place. Moreover, they are very active in making calls and sending SMS and e-mails. While when in depression the social activity is really minimal. An evident sign of upcoming changes in the patient state is when, for instance, the time spent outside as well as the distance from home to the places visited every day decrease progressively. Therefore, the localization system is a fundamental aid for the recognition of this early warning sign. However, it is not really important to define exactly the subject location in terms of longitude and latitude, but the type of places visited (e.g. shopping mall, cinema, restaurant), and their relative distance from the patient's home. As before the accelerometer is used for retrieving information on the overall level of activity. The microphone is used for capturing the surrounding noise for context information. In addition, a log of calls, SMS and e-mails is performed for retrieving information like the number of people contacted, and the number of repeated contacts with the same person during the day.

3) Mood detection and state assessment: Voice analysis is a powerful means for determining the patient mood [15], and this is possible by acquiring and consequently analyse the patient speeches during voice calls. Six different emotions are classified: happiness, pride, cold anger, disgust, desperation and boredom. Moreover, the smart sock and the smartphone accelerometer can contribute to stress level analysis, the former with GSR and pulse signals information, and the latter through motion pattern analysis. Finally, for a complete patient state assessment it is necessary to correlate these information with the physical and social activity level.

B. Technical challanges

Having a smartphone as the main part of the wearable system contribute to a great extent in minimizing the invasiveness of the systems since it is seamlessly integrated in the patient daily life. However, it become a great issue in the management of the energy consumption. In fact, the smartphone battery capacity has to be shared between the normal use of the phone, by the owner, and the application that works in background for monitoring and prediction. Therefore, whereas the MONARCA system well satisfy the condition of minimal invasiveness, the limitation of energy consumption is still an issue. Moreover, since we are dealing with subject's personal information and private data, the security and privacy aspects have to be taken in high consideration.

1) Energy Consumption: The smartphone that has been chosen for the first medical trial is a HTC Desire with an extended battery pack. It has been tested for long for determining how long the battery can leave during both use and monitoring. The results were not so satisfactory as hoped since the maximum time reached with all sensors running (included GPS), WiFi and 3G active, and low level of smartphone use (i.e. playing around with the functionalities but no phone calls), was only of 12 hours. Moreover, the time dropped to few hours in case of WiFi/3G connectivity not available. Therefore, a number of countermeasures have been taken. Firstly, we have used the accelerometer sensor as a trigger for starting the smartphone sensors acquisition. In fact, when the mobile phone is lying around or, generally, when the user is not moving significantly, a continuous acquisition of all sensors is a useless waste of energy. Secondly, the localization system is optimized as follows:1) when in indoor the GPS is not used and the GSM cell and WiFi are checked regularly with an inter-time correlated with the user speed (i.e. slow speed gives high inter-time and vice versa); 2) when outdoor the GPS, GSM cell and WiFi are checked regularly again depending on the user speed; 3) when the subject is driving only GPS and GSM are checked. Thirdly, the monitoring activity is adjusted with the patient state. In fact, the important thing is to recognize the early warning signs, while when the patient is already in a defined state, like manic or depression, it is less important to acquire information with high frequency (all the calls, all activity etc). This is especially true for manic state since when patients are depressed the activity is probably less the normal. Finally, the data acquired during the whole day, which are a huge amount, are sent only at the end of the day when the smartphone is plugged in with the power cord.

2) Security and Privacy: All data acquired during the day are encrypted directly inside the smartphone memory with the Advanced Encryption Standard (AES). The encryption key is chosen by the patient and the doctor together, and it is known only to them. The communication between the smartphone and the MONARCA center, instead, is done via HTTPS. All data transmitted are sent already encrypted with AES, so we have a double security layer on them. When the calls, SMS and e-mails are logged all the personal information, like for instance telephone numbers and person names, are whitened by coding them in hash values. In this way we are able to recognize and count the number of messages or calls to the same person but not the person data themselves. The voice recorded during calls, as well as the background noise recordings, are analysed immediately after their savings on the smartphone memory and then removed. However, in order to avoid any possibility to restore the speeches or the sounds recorded, before analysing them the data files are divided in small chunks and then permuted randomly.

IV. Medical trials

Instead of performing a single final trial at the end of the project, in MONARCA three medical trials have been planned. In this way we will minimize the consequences of any problems emerging during the trials. Moreover, It will allow us to incrementally improve system stability and trial methodology starting with a relatively simple setup. In addition, feedback from patients and medical personnel can be better integrated into the system development. Unfortunately, at the moment no trials have been yet performed, so we do not have any results to present. However, we want to give an idea on how the trials will be organized and performed. The trials will be conducted in three stages of increased complexity. The first one will be conducted with subjects in stationary care and with the wearable system composed solely by the smartphone. The purpose of this trials is to evaluate how the basic technology will perform, to rate the user acceptance and, finally, to produce the data needed for the development of state assessment and transition prediction algorithms. The advantage of having subjects in stationary care is that the technical support is easily organized. Moreover, the subjects are under constant observation which means that very well annotated data will be available and can be used as ground truth in comparison with the system data. Clearly the value of the data is limited since the environment is different from the every day situations in which the system will eventually be deployed. The second and third trials will be conducted with patients in ambulatory care. To provide reliable ground truth the patients will go for consultations with the doctor at least twice a week. The purpose of the second trial is to evaluate the correctness of state assessment and episode prediction algorithms. Finally, with the last trials, we want to assess the effectiveness of therapy planning, feedback and self therapy. For each trial we aim to recruit around 10 subjects with an average monitoring period of 4 to 8 weeks per patients. The exact duration of the observation and the number of subjects will be determined during the trials, depending on the quality of the data. The main concern is to get enough data from relevant episodes and phase changes to be able to adequately train the algorithms.

V. CONCLUSIONS

One of a sever form of mental illness is the Bipolar Disorder, which is characterized by alternated episodes of mania and depression. It is typically treated with a combination of pharmacotherapy and psychotherapy. Unfortunately, the pharmacotherapy can be hardly adapted to the patients because of the difficulty of recognizing their upcoming changes in state. A great improvement in managing bipolar disorder can be achieved with the use of wearable systems based on smartphone technology. The smartphone enhance the possibility to recognize physical and social activities and behavioural attitude of patients, facilitating the identification of early warning signs of upcoming manic/depressive events. This is of great importance for the adaptation and personalization of the illness treatment.

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