Rehab-aaService: A Cloud-based Motor Rehabilitation Digital Assistant

Giancarlo Fortino
University of Calabria, Italy
fortino@unical.it

Raffaele Gravina*
University of Calabria, Italy
rgravina@deis.unical.it

ABSTRACT

Body Sensor Networks (BSNs) are playing an important role in the ongoing revolution of the health-care system, introducing the domain of the so-called *m-Health*. The integration of BSN applications with Cloud-computing technologies is an emerging approach, promising to favor the diffusion of many m-Health services in real life. Among them, motor rehabilitation is one of the application areas where this is particularly true. Monitoring rehabilitation patients via communication networks and mobile computing systems is a crucial aspect since the idea of tying the opportunity to follow and monitor the patient at all post-admission stages through remote monitoring allows to substantially reduce the costs associated with the process. On the other hand, patients that can safely perform rehabilitation and be monitored remotely will get benefit in terms of comfort, physical stress, and economic cost. This paper introduces a motor rehabilitation digital assistant, called *Rehab-aaService*, based on a three-tier architecture that includes wearable motion sensor nodes, a personal mobile device, and a Cloud-based back-end supported by the BodyCloud middleware.

Keywords

Wearable sensors, BSN, Motor Rehabilitation, Cloud computing, BodyCloud.

1. INTRODUCTION

Body Sensor Networks (BSNs) [3] are specific Wireless Sensor Networks (WSNs) for monitoring of humans. BSNs are potentially a disruptive technology in several human-centered applications, including medical monitoring, fitness and sport, large-scale events management and social networking. BSNs involves a broad range of wearable sensors for physiological measurements such as heart and respiratory rate, body temperature, blood glucose, limb motions, electrocardiogram (ECG), electromyography (EMG), and electroencephalogram (EEG). Physiological signals are processed to infer higher level knowledge to enable more complex services, including physical activity recognition, heart attack early detection, emotion detection, and neurodegenerative diseases monitoring.

However, to fully expoit this emerging technology, there is the need to deal with management of a large number of cooperative and non-cooperative BSNs. Supporting pervasive applications for large communities of users is in fact a critical and complex task. The massive data that BSN networks can generate, requires a scalable and flexible platform for their collection, secure storage and processing.

Effective and efficient management of networks of BSNs cannot be accomplished uniquely relying on their limited resources.

We tackle this problem using a Cloud computing infrastructure and providing an integrated platform, namely BodyCloud, built upon the following functional requirements:

- heterogeneous wearable sensing through personal mobile devices acting as local coordinators;
- scalability in terms of processing power for diverse medical analysis;
- scalability in terms of physiological signals collection and data storage;
- global access to processing and storage functionalities;
- simple and authenticated sharing of results.

This paper presents a scalable motor rehabilitation research prototype, Rehab-aaService, that is based on BodyCloud [7]. BodyCloud is a Software-as-a-Service (SaaS) platform that provides real-time storage, online/offline management of physiological signals, data processing and analysis using software plugins hosted in the Cloud. In particular, BodyCloud has been designed to effectively support diversifies cross-disciplinary applications and processing tasks. It enables ubiquitous large-scale data sharing, collaborations among users and applications in the Cloud, and delivers Cloud-based services through sensor-rich mobile and wearable devices. In addition, BodyCloud includes data mining functionalities to enable high-level decision support based on the collected BSN data.

Rehab-aaService is a hardware/software system to assist the physical rehabilitation. It is built atop the BodyCloud platform so to support for remote and ubiquitous collection, storage and processing of data streams from non-invasive sensors worn by patients during therapy and rehabilitation.

*Corresponding author.

REHAB 2014, May 20-23, Oldenburg, Germany

DOI 10.4108/icst.pervasivehealth.2014.255273

During motor rehabilitation therapy, it is quite common to require repetitive physical exercises, for instance, to recover from a muscle strain, a limb fracture, or a surgery. Having real-time feedback about exercise performance quality allows users to independently exercise properly without the need of a continuous professional assistance. As a consequence, especially for certain types of motor traumas, the concept of *tele-rehabilitation* becomes strategical. Being able to perform rehabilitation independently (e.g. at home), is a benefit for patients in terms of physical stress and economic cost reductions. Thus, a strong motivation for this project is to optimize and manage the rehabilitation stages through hardware/software systems installed at the remote patient. Our system, therefore, proposes a novel contribution to the state-of-the-art by (i) providing an integrated hardware/software system for continuous non-invasive monitoring patients undergoing rehabilitation, and (ii) by the introduction of a Cloud-based management and analysis service, used by medical doctors and physiotherapists, with support for remote access to rehab exercises traces, improvement parameters, and other information throughout the whole rehabilitation process of their patients.

The rest of the paper is structured as follows. Section 2 discusses related work on physical rehabilitation aided by wearable sensors. Section 3 overviews the BodyCloud architecture. Section 4 describes the proposed cloud-based Motor Rehabilitation application service. Finally, in Section 5 conclusive remarks are drawn and directions of future work are briefly outlined.

2. RELATED WORK

Although the literature on physical rehabilitation assistance supported by wearable sensors is still limited, a few interesting studies have been published already. An early research [1] focuses on the therapist perspective aiming at determining the physical activity stress and the energy expenditure of therapists while practicing using a portable accelerometer sensor placed on their waist belts. In [9] authors propose the use of wearable accelerometer sensors for objectively assessing motion capabilities and activity levels of patients affected by multiple sclerosis, so not to rely uniquely on self-reports and questionnaires. However, the specific problem of supporting patients during rehabilitation exercises with the aid of wearable sensing devices and real-time visual feedbacks is being investigated only in more recent times. In [12] authors describe a rehabilitation support system based on a smartphone and a bracelet to capture patient's rehabilitation exercises. Dynamic Time Warping is used to train and recognize movements. The system is fully customizable so it allows the therapist to choose the position of the device and other parameters in order to adapt to different exercises. The proposed system, however, by relaying on a single sensing device suffers of the problem that a number of exercises cannot be monitored and relevant parameters, such as elbow and knee flexion angles, cannot be measured. RIABLO [5] is a game system realized to specifically support physical orthopedic rehabilitation. Authors suggest the use of game elements to motivate and engage the patient, while providing feedback on the correctness of the performed exercises. The system is based on five wearable devices equipped with a 3-axis accelerometer and a gyroscope, positioned on the body with elastic straps, and a pressure sensor tile connected via Bluetooth with the game

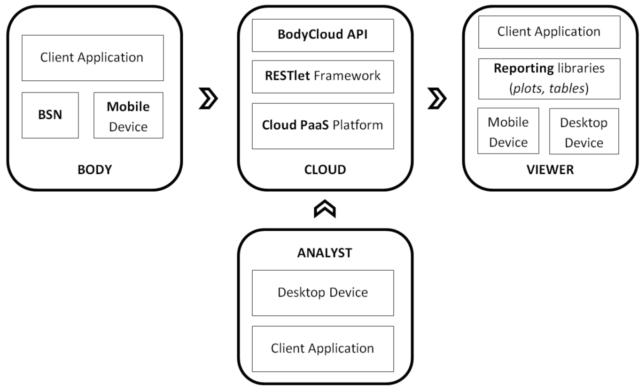

Figure 1: A simplified architectural representation of BodyCloud.

station. Another interesting project [15] uses two wearable motion sensors attached to the patient's arm or leg and a commercial Android tablet where a graphical application provides with a visual real-time feedback on the performed exercises as well as an assessment on the practice quality with respect to a reference movement previously recorded. In addition to purely academic researches, there exist some commercial solutions [4, 10] with similar functionalities to what described above. For further literature study, readers can refer to interesting surveys [11, 8] published recently.

However, none of them offers adaptable and customizable tele-rehabilitation. Rehab-aaService, instead, proposes an original contribution, responding to i) the need for integrated hardware/software systems for the continuous monitoring and follow-up of patients under rehabilitation therapy and ii) the lack of effective solutions for data collection, integration and analysis with support for data mining and statistical techniques for the management of the various rehabilitation stages. With Rehab-aaService, the stakeholders (e.g., physicians, physical therapists, patients, centers for rehabilitation and physiotherapy, gyms) are connected to each other and have integrated and interoperable access to data related to patients rehabilitation process.

3. BODYCLOUD

BodyCloud is an open platform for the integration of BSNs with a Cloud Platform-as-a-Service (PaaS) infrastructure.

As depicted in the simplified component diagram in Figure 1, the architecture is composed of four main components:

- *Body*: the component that monitors the assisted living by means of wearable sensors, and forwards the collected data to the Cloud through a personal mobile coordinator device. Data acquisition is currently handled using Android-SPINE [6, 2, 13] and wireless communications with the sensors based on Bluetooth.

- *Cloud*: the component that gives full support for specific applications through data collection, processing/-analysis, and visualization. In particular, applications are defined through specific software abstractions (Group, Modality, Workflow/Node, View). Such abstractions are supported by a RESTful web service (Server Servlet), programmed atop the Restlet Framework [14]. Every

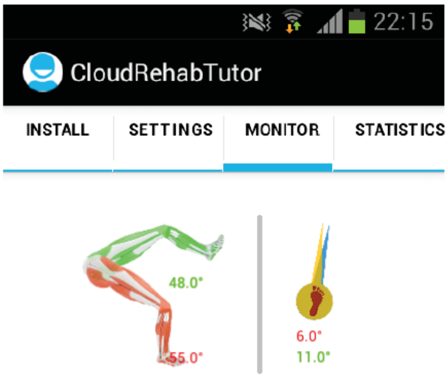

Figure 2: Rehab-aaService: live rehabilitation exercise monitoring dashboard on the mobile device.

interactions is authenticated using OAuth 2.0 protocol. The Cloud-side runs on the Google App Engine (GAE) PaaS. GAE exposes the Datastore API, used by BodyCloud to store sensory and processed data generated by the application services, and the Task Queue API, through which BodyCloud supports asynchronous execution of tasks triggered by application requests.

- *Analyst*: the component supporting BodyCloud customization/extension, in terms of development of new application services (plugins). Specifically, new services are defined in terms of the aforementioned *abstractions*, and deployed using simple HTTP PUT requests to the corresponding Cloud-side resource.
- *Viewer*: the component supporting graphical visualization of raw and processed data through flexible graphical reporting options.

4. REHAB-AASERVICE

Rehab-aaService is a Cloud-assisted motor rehabilitation assistant application, currently optimized for elbow and knee. Limbs motion measurement is performed using two tiny and lightweight wearable devices equipped with 3-axial accelerometers. Sensors are attached by means of elastic bracelets in specific positions of the limbs for acquiring accelerometer data, which are eventually processed by the BSN coordinator to estimate medical-relevant rehabilitation information such as joint (e.g. elbow and knee) flexion and extension angles. Implemented according to the software abstractions (*Group*, *Modality*, *Workflow*, *View*) introduced by BodyCloud, Rehab-aaService defines the following entities:

- *Rehab Group*: represents the group of monitored patients.
- *RehabDataFeed Modality*: allows the transmission of rehabilitation session data from the Body-side to the Cloud-side.
- *RehabDataAnalysis Modality*: based on the *RehabDataAnalysis Workflow*, analyzes individual data and provides (aggregated and statistical) information about the progress of the therapy.
- *RehabData View*: the graphical display (e.g. plots, diagrams, and tables) through which rehabilitation data are rendered at the Viewer-side.

Figure 3: Rehab-aaService: a graphical analysis of a recorded rehabilitation session on the Cloud side.

To estimate the flexion and rotation information of the limbs, the proposed system uses SPINE-enabled wearable nodes [6] equipped with 3-axis accelerometer sensors. The application configures the nodes to sample the accelerometer at a sampling rate of 30Hz so to monitors limb bending movements dynamically (green, as in the application screen-shot shown in Figure 2; it also allow to overlap the visual real-time feedback with the reference movement model, recorded by the physiotherapist during a set-up phase (orange, as in the application screen-shot shown in Figure 2). The application scenario consists of two steps, namely setup and exercise phases. During the set-up phase, the user wears two sensors on either leg or arm that needs to be exercised and performs the correct exercise under the guidance of rehabilitation professional. Meanwhile, the system records the data and stores it as reference exercise. Then, during the exercise phase, the user repeats the bending movement and is provided with a real-time feedback about how the movement is done with respect to the stored reference exercise. All the rehabilitation session data are also securely transmitted to a Cloud server using the BodyCloud infrastructure. A number of improvement indexes are reported in a separate panel, so to allow the patient to get quantitative information regarding his improvements throughout the rehab therapy. In addition, the application retrieves online the patient's rehab exercise scheduling.

The Cloud web-based front-end allows authenticated users, such as physiotherapists and doctors, to visualize detailed information about each patient's exercise sessions, to compare graphically their adherence to previously recorded reference exercise template (see Figure 3), and to create or update individual exercise scheduling programs, that are seamlessly downloaded to the patient's mobile device.

We evaluated the performance of our system in terms of joint angle estimation accuracy. Specifically, the angle measurement was performed by attaching the two sensors to the interested limb; we compared the obtained values in reference positions (with a step of 10°) against a specifically-designed protractor attached to the same limb. We therefore calculated the estimation error, defined as the absolute difference between the estimated angle and the one given by the reference medical-approved instrument:

$$\epsilon_\alpha = |\hat{\alpha} - \alpha| \quad (1)$$

Table 1 shows the results obtained, in terms of average, variance and maximum error, over a sample of 50 measurements, half obtained from the arm, half from the leg.

Joint Angle Error (°)	*Arm*	*Leg*
MEAN(ϵ_α)	4	3,5
VAR(ϵ_α)	3,76	3,24
MAX(ϵ_α)	7	5

Table 1: Joint angle estimation accuracy

The results show that the average error is less than 5°. Hower, if the sensors are not correctly worn by the patient, the precision can decrease significantly. To handle such situation, the mobile application includes a user-friendly sensor calibration.

5. CONCLUSIONS

In this paper we presented Rehab-aaService, motor rehabilitation digital assistant based on wearable motion sensors, a personal mobile device, and Cloud-based management platform. The current prototype supports arm and leg rehabilitation and has been programmed using the SPINE-Android framework for connecting the sensors to the mobile device, and atop BodyCloud for supporting the Cloud functionalities. The system includes a joint flexion/rotation angle estimation algorithm based on accelerometer data with average error less than 5°.

An interesting lesson learned of this research is that, according to our preliminary performance evaluation in terms of execution time required by our angle estimation equations, current low-to-mid range mobile devices might not have enough computing power to execute, at regular periodic basis (the system has to estimate instantaneous joint angle values at a rhythm that is driven by the sensor sampling rate), the involved math within the sensor sampling period. This alone is a strong motivation for us to have moved the algorithm. Currently, our prototype retrieves the device' CPU speed and executes the estimation algorithm locally on the mobile device (so to forward to the Cloud directly the estimated angles) if the mobile device is powerful enough, or enables Cloud-computing otherwise.

Ongoing works are currently devoted to re-engineering the system to allow for more flexibility in customizing it to different physical rehabilitation (e.g. the shoulder). In addition, we are planning a performance evaluation testbed with several real devices running the Rehab-aaService to evaluate the scalability of our Cloud back-end. Future works will also include a feature to allow the patient requesting a video chat with the physiotherapist while performing the rehab exercises, so to further improve the guided-exercise mode.

6. ACKNOWLEDGMENTS

Our thanks to Daniele Parisi and Vincenzo Pirrone for their efforts in implementing BodyCloud and to Fabrizio Granieri and Luigi Salvatore Galluzzi for their support with the Rehab-aaService prototype. This work has been partially supported by the "2007-2013 NOP for Research and Competitiveness for the Convergence Regions (Calabria, Campania, Puglia and Sicilia)" with code PON04a3 00238.

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