SenseMyHeart: A Cloud Service and API for Wearable Heart Monitors

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Abstract— **In the era of ubiquitous computing, the growing adoption of wearable systems and body sensor networks is trailing the path for new research and software for cardiovascular intensity, energy expenditure and stress and fatigue detection through cardiovascular monitoring. Several systems have received clinical-certification and provide huge amounts of reliable heart-related data in a continuous basis. PhysioNet provides equally reliable open-source software tools for ECG processing and analysis that can be combined with these devices. However, this software remains difficult to use in a mobile environment and for researchers unfamiliar with Linux-based systems. In the present paper we present an approach that aims at tackling these limitations by developing a cloud service that provides an API for a PhysioNet-based pipeline for ECG processing and Heart Rate Variability measurement. We describe the proposed solution, along with its advantages and tradeoffs. We also present some client tools (windows and Android) and several projects where the developed cloud service has been used successfully as a standard for Heart Rate and Heart Rate Variability studies in different scenarios.**

I. INTRODUCTION

Wearable sensors and systems are comfortable, non-intrusive devices that allow individuals to be monitored, directly or remotely, over extended periods of time. This technology, promoted by recent advances in small devices and ubiquitous computing, can have direct impact in citizens' quality of life. It provides clinicians and researchers with data which was often inacessible outside of a clinical environment, except by expensive and obtrusive ambulatory devices [1]. Consequently, the resulting information can greatly help clinicians in the assessment and monitoring of a patient's health status. Additionally, it provides researchers further insight into the study of complex physiological patterns and signals, trailing the path for new software in disease-prevention and prediction of cardiovascular events, which non-clinical populations can also benefit from.

In particular, wearable technology is currently being applied in the study of stress and fatigue among first responders, police officers, bus drives and also regular citizens [2–5]. Using medically-certified wearable ECG products, such as the VitalJacket® by Biodevices [6], one can record up to 72 hours of continous ECG exams. The resulting ECG data can then be processed on the fly, or stored for later analysis depending on available resources (smartphone, web-connection, battery-life). Measures of Heart Rate (HR) and Heart Rate Variability (HRV), which reflect activity of the Autonomic Nervous System (ANS), can be extracted from an ECG exam, or RR interval time series, and used to assess cardiovascular stress and intensity [7], [8].

There are several software tools for ECG processing and analysis, many of which proprietary. One open-source solution stands out however: the PhysioToolkit – a large library of software for processing and analysis of physiological signals – composed by PhysioNet [9]. This software package has been freely available for more than ten years, it is recognized worldwide and provides software for HRV processing and QRS detection that has been extensively and rigorously tested [10]. Nevertheless, using the PhysioToolkit requires a Linux-based environment and some knowledge of the bash command-line interface, which makes it difficult for inexperienced users and mobile applications to directly benefit from.

Thus, we identified the need to develop a computing infrastructure which integrated the existing software solution within a remotely accessible application or service. Such infrastructure aims to provide a standardized computational backbone to projects studying psychophysiological stress and software applications providing monitoring tools based on measurements of Heart Rate and Heart Rate Variability. Further requirements include the support for different access points within the processing pipeline, and optional inputs to be passed, such as the use of specific processing parameters and algorithms. Ultimately, the objective is to provide as much flexibility as possible to researchers and app-developers.

Taking these requirements into account, we designed and implemented a web-service which provides a flexible and scalable API in ECG processing and HRV measurement. Such solution has various advantages, but also carries a constraint. Hereafter we present and describe the proposed API and architecture, along with relevant use cases.

II. MATERIALS AND METHODS

A. PhysioNet-based Pipeline

A wearable monitoring unit consists of one or more sensors connected to a Local Processing Unit (LPU), forming a Body Sensor Network (BSN). The LPU contains either, or both, a storage device for offline monitoring and a receiver-transmitter module for online monitoring. In the case of cardiovascular systems, electrodes placed correctly on the chest will generated an ECG signal which expresses the electric activity of the heart. Each heartbeat is represented in the ECG signal by a combination of deflections, one of which represents ventricular depolarization, named QRS complex – composed by waves Q,R and S. Heart Rate (HR) and Heart

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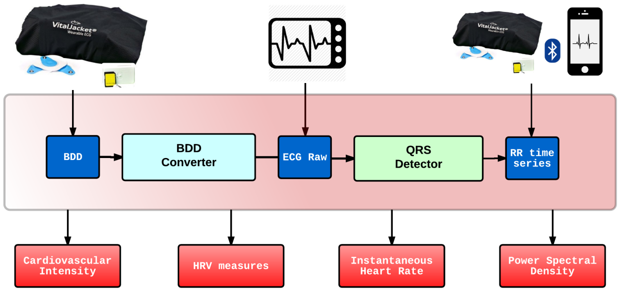


Fig. 1. Block diagram of SenseMyHeart pipeline interactions.

Rate Variability (HRV) are computed from time-differences between successive R waves, named RR intervals, which are obtained through a QRS-complex detector.

The PhysioToolkit contains the features necessary to perform each one of these steps, given a ECG in raw-format, i.e. a sample-value array with specific bit-resolution, sample frequency and A/D (Analog to Digital) gain. Yet, clinically-certified products, such as VitalJacket®, rarely transmit these signals in raw ECG format due to high sensitive nature of the data. Thus, we developed a software conversion module, in combination with Biodevices S.A., which parsed the output ECG-signal from a VitalJacket®, stored in binary files called BDD, into raw ECG format.

Furthermore, the PhysioToolkit comes in the form of a library and applications that can be executed via the command-line. Useful tools from both WFDB and HRV software toolkits [9], [10] include:

wrsamp: Reads input-text data and writes columns in specific WFDB signal file format. Used for reading input ECG-raw signals and creating a WFDB record.

sqrs, wqrs, gqrs: 3 different QRS detectors, which read a specific WFDB record and output an annotation file.

ihr: Calculates instantaneous heart rate from a WFDB record and annotation file, applying a specific tolerance and rejection criterion.

lomb: Transforms a unequally spaced time series into a power spectrum, using the Lomb periodogram technique [11].

get_hrv: Reads and filters RR intervals, which uses to calculate time and frequency domain HRV measures.

Each piece of software is self-contained and relies on file system read and write operations to successfully execute. Consequently, considerable amount of work was put into integrating the different components in a robust, cohesive and persistent pipeline. We also worked on extending these features by providing automation enhancements and adding a new method to assess cardiovascular strain – cardiovascular intensity.

We started by considering the *get_hrv* function, which computes one set of HRV measures, in time and frequency domains, over a period of time, regardless of its duration – minutes or hours. The resulting set of measures is averaged over all sub-sets obtained from 5-minute analysis windows, following the HRV Taskforce recommendations [12]. However, in the search for cardiovascular events we want to return all 5-minute window measurements and not an average representation that may hide important underlying system changes. To retrieve these results from long input exams, a great number of *get_hrv* calls is required, making any manual approach time-consuming and costly. Thus, we enhanced the process so that the entire HRV time series is obtained automatically.

Additionally, users can specify new size and overlap values for measurement windows. Default HRV measurement sets windows of 300 seconds with 0% of overlap. Window size can decrease down to 60 seconds whereas overlap can be increased to a maximum of 90%. We consider this extension important as promising results have been shown in the detection of mental stress-related events in mobile settings, using HRV measures obtained from analysis windows of 60 to 120 seconds [13].

Although low and high frequency components of HRV can be used to assess mental stress, as they reflect the behaviour of the ANS, they cannot be computed on a heartbeat-to-heartbeat basis. On the other hand, cardiovascular intensity can evaluate cardiovascular strain using one's age and basal heart rate. Cardiovascular intensity, expressed in eq. 2, can be computed using the Tanaka et al. formula, expressed in eq. 1, for determining peak heart rate and an average value of basal heart rate. This calculation requires extended knowledge of the user: age and heat rate at rest. The first can be easily obtained through a front-end application whereas the second can be estimated using a simple calibration protocol – e.g. request the person to sit still for one or two minutes following the placement of the wearable system.

$$HR_{max} = 208 - 0.7 \times age \tag{1}$$

$$CI_i = \frac{(HR_i - HR_{rest})}{(HR_{max} - HR_{rest})} \times 100\% \tag{2}$$

B. Webserver and API

To work with the PhysioNet-based pipeline, users interact with the SenseMyHeart Application Programmatic Interface (API). It provides remote session-based access to the pipeline over HTTP, using the Simple Object Access Protocol (SOAP). The HTTP webserver was designed and implemented using the gSOAP toolkit for SOAP and REST web-services [15].

The SenseMyHeart API supports methods to manage sessions, submit ECG/RR exams and return measures of cardiovascular interest. Processing methods can be issued using advanced, optional parameters in order to grant users flexible modes of operation. An illustrative interaction with the API, using pseudocode, is represented in listings 1. Keywords preceded by **soap** imply client-server communication complying with the SOAP protocol, using request-response messages in XML format. The service's definition is available in Web Services Description Language (WSDL). It is obtained automatically in response to a HTTP GET request, and thus can be easily retrieved just by knowing the service's endpoint. The wsdl content describes data schemas, soap operations and necessary message formats.

Listing 1. Example of interaction with SMH API – Pseudocode.

```
init soap_context(‘‘http://sensemyheart.fe.up.pt’’)

set Credentials
set Exam, ExamType
set Age, HRrest   # Parameters for Cardiovascular Intensity #
set Time Interval, Window Size, Window Overlap # Processing Parameters #
set Qrs Detector, Tolerance Threshold # Processing Parameters #

soap_call openSession
    input  Credentials
    output Session Token

soap_call submitExam
    input  Token, Exam, ExamType
    output Status Code

soap_call getRRIntervals
   input    Token
   optional Qrs detector
   output   RR intervals

soap_call getHrvSeries
    input    Token
    optional Time Interval, Window Size, Window Overlap, Qrs Detector
    output   Hrv Measures per Time Frame

soap_call getPowerSpectralDensity
    input    Token
    optional Time Interval, Qrs Detector
    output   Magnitude of Power Spectrum per Frequency

soap_call getIHeartRate
    input    Token
    optional Time Interval, Qrs Detector, Tolerance Threshold
    output   Instantaneous Heart Rate

soap_call getCardioIntensity
    input    Token, Age, HRrest
    optional Time Interval, Window Size, Window Overlap, Qrs Detector
    output   Cardiovascular Intensity per Time Frame

soap_call closeSession
    input  Token
    output Status Code

destroy soap_context
```

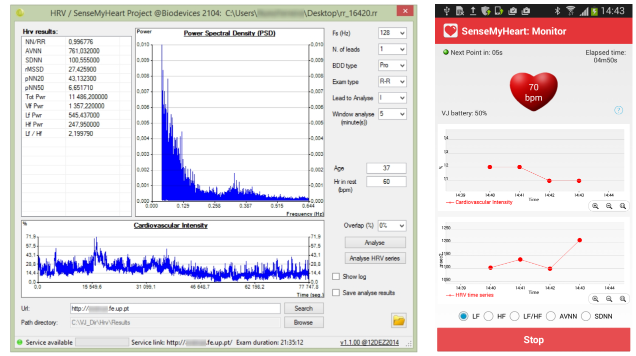
Only legitimate users are allowed to interact with the pipeline. Their credibility is established by requiring each client to authenticate using username-password credentials. Once a validated user requests to open a new session, an authentication token is issued that the user must endorse in subsequent calls to the server. All sessions are automatically terminated after 30 minutes of inactivity.

III. Results

A. Client Applications

To depict client-server proof-of-concept we developed three client applications for different environments: Android, Windows and Linux. The latter is mostly used for server back-end integration, that is, to provide an interface to other platforms, such as SenseMyCity which stores and analyses data delivered by cardiovascular devices [5]. The second application was created to assist Windows-based users in the off-line analysis of long ECG exams (several hours in duration). For instance, it has been used by researchers in combination with tools like Matlab, in the study of cardiovascular stress among police officers and surgeons, see the following section III-B.

On the other hand, the Android application is a prototype for “real-time” cardiovascular ambulatory monitoring. It uses the smartphone bluetooth interface to connect to a VitalJacket®wearable device. VitalJacket SDK (`http://www.sdk.vitaljacket.com/`) was used to read data from the device, either as raw ECG or RR intervals (using Biodevices S.A. built-in QRS detector) which was then passed to the



(a) Windows App (b) Android App

Fig. 2. Screenshots from Prototype Windows and Android Applications

webservice using a Wifi or 3G data connection. A plot of HRV measures and cardiovascular intensity was provided to users, as well as other useful indicators. It was also possible to record by voice important events triggered by VitalJacket’s push-button.

We used the prototype Android application to conduct a real live demo using a VitalJacket in order to show the potential of the service in a mobile context. The demo is available at (`https://www.youtube.com/watch?v=cikNlXsdrHs`).

B. Real Use Cases

The SCOPE project – Stress and Coping among Portuguese Police Officers – investigates the psychophysiological impact of stress among police officers originating from on-duty tasks, such as patrolling and on-site interventions [3]. A smartphone and VitalJacket®were used to record travel-activity and ECG data, respectively. The ECG exam in combination with data from VitalJacket’s accelerometer sensor was passed to SenseMyHeart’s cloud service to help distinguish between movement and threat triggered cardiac activity. Analysis of HRV measurements and geo-referentiated data resulted in a suggestion system which highlighted locations where cardiac strain might have ocurred. At the end of the shift, perceived stress was assessed against physiological observations, through a set of questions posed to officers in a questionnaire.

The VitalSurgeon project aims at detecting occurences of stress-related cardiovascular strain in neurosurgeons during intracranial Aneurysm Procedures [16]. The project started by monitoring one healthy male neurosurgeon during four intracranial aneurysm procedure, who wore a VitalJacket®during all procedures. To assess cardiovascular strain, the BDD data was obtained and passed on to the SenseMyHeart service to extract measures of cardiovascular intensity (CI) and HRV in time (AVNN, SDNN, pNN20, pNN50) and frequency domains (LF,HF,LF/HF). CI values were found to increase during most critical stages of the procedure (aneurysm clippings, and aneurysm rupture), whereas HRV was found to decrease. The LF/HF ratio is observed to increase, indicating an activation of the Sympathetic Nervous System over the Parasympathetic Nervous System, indicative of perceived stress event. These results are in accordance with previous reports in the literature.

IV. DISCUSSION

We presented a novel computing infrastructure built on top of existing and recognized software in ECG processing and HRV measurement – the PhysioToolkit. We added new features and developed a service and API that has enabled research projects to study stress under very different real work conditions using only a comfortable wearable ECG device. This approach provides clients with a meaningful layer of abstraction on PhysioToolkit's software and system dependencies. It is applicable in a variety of scenarios, from real-time to off-line monitoring of long cardiovascular exams.

By using a cloud-based service, most of the processing is done server-wise, which makes it highly suitable for mobile environments where battery power or processing resources are limited. Additionally, a client-server architecture that uses a well-defined web-protocol for machine-to-machine communication, allows developers to build their applications seamlessly throughout different platforms and operating systems. However, like all web-based services, this solution comes at the cost of an existing stable Internet connection.

Besides available network resources, quality of service relies heavily on good design of the server-side infrastructure. Scalability, load balancing, performance, availability and security are important issues that need to be further explored, taking into account the underlying tradeoffs. User feedback is also important when comes to detecting problems, adding new features and improving existing ones.

Although we opted for a SOAP webservice, as it is better equipped to provide complex and stateful operations, it requires the use of XML schemas and strongly typed messages. Consequently, a small change in the type signature results in clients built according to those specifications to break. This may be a problem if we are publishing a service for others to use. Alternatively, by using REST, message payloads get smaller and the API becomes more flexible and dynamic for client applications. However, it does not provide a solution to asynchronous communication and stateful operations whereas SOAP does.

Ultimately, the decision between SOAP or REST comes down to whether the operations should act on the state of the processing pipeline, and/or client-server communication should be performed synchronously or not. Most of our methods are in fact of type CRUD (create, read, update, delete) and communication is synchronous, but long client wait times take place if message sizes and/or processing are long and costly. Thus, we need to further take this question into analysis. A combined approach is definitely worthy of consideration.

More importantly the service is scalable to include new ECG and HRV processing algorithms, as well as to accept data collected from other sensors that bring relevant information to the problem, such as accelerometer, body temperature and GSR (Galvanic Skin Response). Particularly, these can help differentiate between movement or threat triggered cardiac-activity.

Finally, we aim at submitting this work to PhysioNetWorks for external review, so that it may integrate PhysioNet software tools and be shared openly across the community.

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