Design and implementation of a novel ECG teleconsultation platform

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Abstract: - This work presents the implementation of a novel ECG teleconsultation platform based on a 12-lead Bluetooth electrocardiograph for smartphone and tablet devices and a set of collaboration tools deployed in the cloud. The proposed apparatus comprises a fully integrated analog frontend, a microcontroller and a Bluetooth Low Energy transceiver. An application for smart devices configures the apparatus for acquisition, displays the digitized ECG samples on screen in real-time and allows to save or share the signals in the cloud. A web-based collection of collaboration tools allows, among the other features, to browse for a past exam, provide a diagnosis or leave a comment, and to create physicians' workgroups.

Key-Words: - ECG; Teleconsultation; Bluetooth Low Energy; Electrocardiograph; Collaboration Tools; Cloud Computing

1 Introduction

Smart devices and web-based collaboration tools are expected to empower next-generation teleconsultation flows. Previous works reported the prototypal implementation of Bluetooth electrocardiographs [1][2] and of cloud-based platforms for telemedicine [3][4]; however, few works investigated an integration of the two efforts.

The main contribution of this research is the proposal of an integrated ECG teleconsultation platform that takes advantage of smart devices and modern cloud services. This has been done through: i) the implementation of a cheap, compact and lightweight Bluetooth electrocardiograph; ii) the development of a *host* application for smartphone and tablet devices; iii) the deployment of a web-based collection of collaboration tools in the cloud.

2 Bluetooth electrocardiograph

The 12-lead Bluetooth electrocardiograph is a hardware and firmware subsystem based on a fully integrated analog frontend, a microcontroller and a Bluetooth Low Energy (BLE) transceiver (Fig. 1).

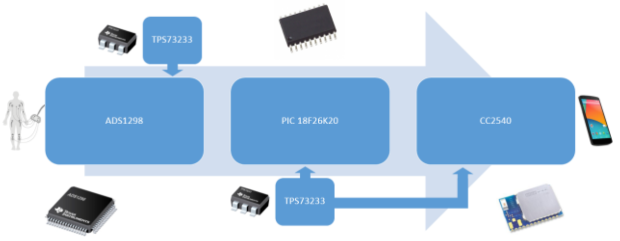

Fig. 1 – Bluetooth electrocardiograph block diagram

The selected analog frontend is the TI's ADS1298. The IC complies with the AMI EC11, EC13, IEC60601-1, IEC60601-2-27 and IEC60601-2-51 standards; integrates eight simultaneous sampling delta-sigma ($\Delta\Sigma$) Analog-to-Digital Converters (ADCs) with 24-bit resolution and eight Programmable Gain Amplifiers (PGAs); implements, among the others, the Right Leg Driver (RLD) and the Wilson Center Terminal (WCT) circuits.

A PIC 18F26K20 microcontroller runs the application firmware, a software component, written in C programming language, which configures the biopotentials' acquisition, collects digitalized samples and forwards them via a third-party BLE transceiver (based on TI's CC2540). Data exchange between the microcontroller and the ADS1298 is performed through SPI, with an interrupt-driven samples' acquisition. Instead, data exchange between the microcontroller and the BLE transceiver is performed through UART.

The analog and the digital section of the apparatus are configured for single supply operation (3.3V, 0V), a popular choice for battery-operated devices, though two separate voltage regulators are used to preserve noise characteristics. A third-party wireless-charging module, based on the Qi standard [5], has been integrated for future investigations (e.g. seal the apparatus to improve its robustness in tough environments).

The Printed Circuit Board (PCB) of the proposed apparatus (Fig. 2) (Fig. 3) measures 5x5cm^2 and has been enclosed in a convenient plastic case. An adhesive NFC tag has been glued to one of the internal faces of the case and has been programmed to let the user pair with the apparatus when in close proximity, a feature that is commonly referred to as *tap-to-pair* [6]. The apparatus has a DB15 connector to allow connection for 10-lead ECG cables (HP, Philips and Agilent compatible).

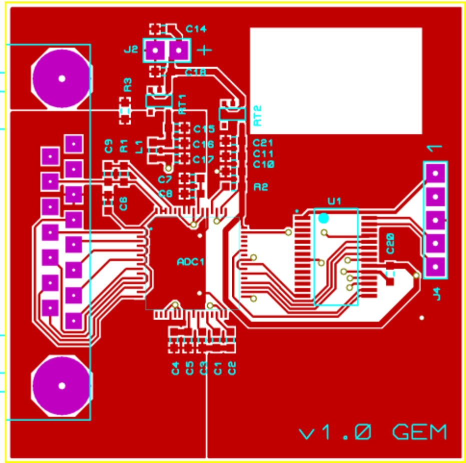

Fig. 2 – Actual layout of the apparatus (top layer)

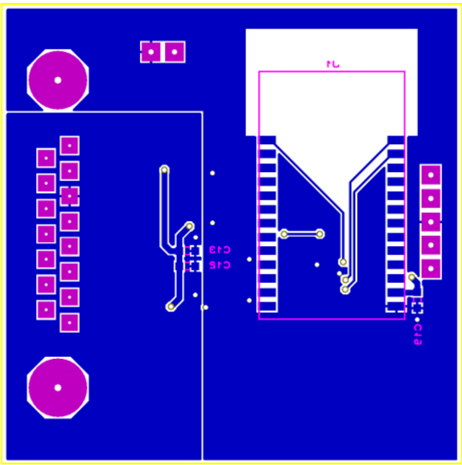

Fig. 3 – Actual layout of the apparatus (bottom layer)

The BLE transceiver has been configured to act as a *UART to BLE bridge*, emulating a Serial Port Profile (SPP). A proprietary protocol, based on a binary packet exchange, has been implemented to ensure that a consistent stream of samples is received and interpreted, and that communication errors could be identified and, possibly, corrected [7].

A MATLAB® script capable to test the whole electrocardiograph has been developed. The script configures the apparatus, and acquires and plots an internal test signal on channel 1 at a rate of 500sps; two timed loops perform the latter two tasks: the acquisition loop is executed every 100ms, the plot loop every 500ms. The acquisition loop is responsible of: i) reading the serial stream; ii) recomposing the incoming packets; iii) populating the sample buffer. The plot loop is responsible of updating a figure with a convenient set of the incoming data.

3 Application for smart devices

The application (app) for smartphone and tablet devices is a key software subsystem for the acquisition of ECG signals and for the initiation of teleconsultation flows.

The app constitutes the main user interface towards the hardware; it is capable of: i) configuring the apparatus for acquisition; ii) displaying the digitized ECG samples on screen in real-time; iii) saving or sharing the signals in the cloud. Moreover, the app conveniently processes the incoming signals through a cascade of three digital filters (high-pass, low-pass and notch). In fact, the hardware and firmware subsystem is intentionally lacking this feature, thus relying, for this task, on the compute power of the *host* smart device; though, the implications of this tradeoff may further be investigated.

The app's interaction flow has been designed to minimize the number of steps separating initialization from acquisition. The main menu allows registered users to log into the cloud platform or to immediately browse for Bluetooth devices in pairing mode (Fig. 4); if an already paired electrocardiograph is ready for connection, the app automatically shows up a convenient shortcut dialog box. After this step, the hardware, firmware and software subsystems are ready to perform the biopotentials' acquisition; additionally, a step by step tutorial mode can be activated, even assisting the correct electrode placement. Eventually, actual acquisition is performed, and the user is prompted a dialog box that allows to save further details about the exam (e.g. patient's name, age, …); then, the user can store the exam locally or in a remote workspace. As soon as an exam reaches the cloud, it becomes available for its further classification (e.g. it can be assigned to an existing patient's record) and in teleconsultation flows through web-based collaboration tools.

Current operative scenario is oriented towards acquisitions characterized by a limited duration; however, the Bluetooth electrocardiograph could even operate as a Holter monitor if paired to a different software subsystem. This unprecedented modularity of the above discussed components proves that modern apparatuses, whose functioning is based on smartphone and tablet devices, can interestingly take advantage of updatable apps to adapt to not foreseen use cases or to provide newer features.

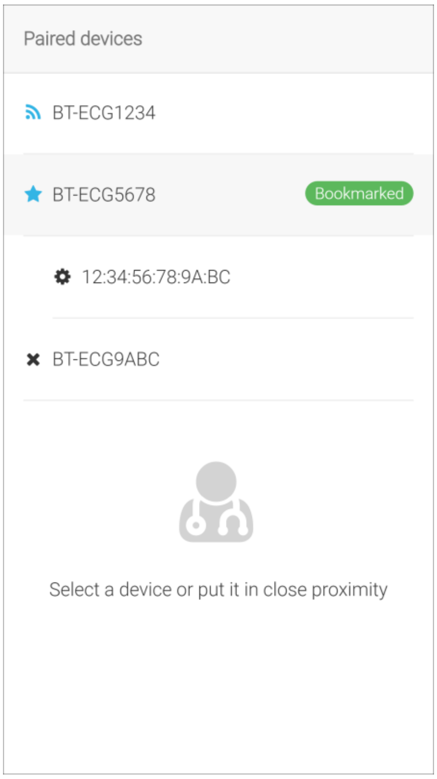

Fig. 4 – Actual graphical user interface (paired devices)

Two concurrent threads, that replicates the aforementioned MATLAB® script's behavior, manage the biopotentials' acquisition; however, in this case, the plot loop is also responsible of the digital signal processing. The signal processing class implements filters in Direct Form II and has been realized in managed code. A native code reimplementation will be investigated to increase throughput [8] and support a higher number of filter's coefficients.

The normalized frequency response that has been implemented is represented in (Fig. 5).

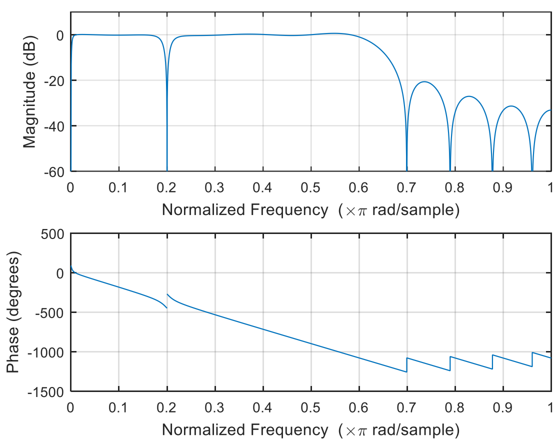

Fig. 5 - Normalized frequency response of the high-pass, low-pass and notch filters' cascade

The discrete-time high-pass filter's (HPF) transfer function is:

$$H_{HPF}(z) = \frac{1 - z^{-1}}{1 - 0.992\, z^{-1}}$$

The discrete-time notch filter's (NF) transfer function is:

$$H_{NF}(z) = \frac{0.963 - 1.558z^{-1} + 0.962z^{-2}}{1 - 1.558\, z^{-1} + 0.926\, z^{-2}}$$

The discrete-time low-pass filter's (LPF) transfer function is represented in (Fig. 6).

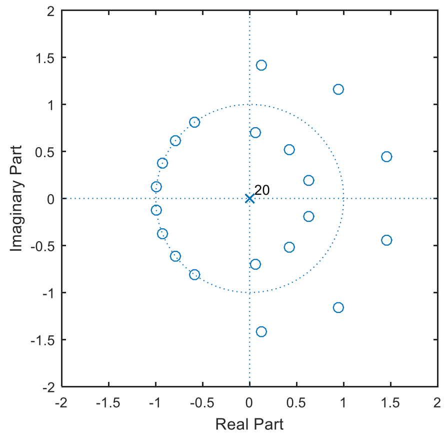

Fig. 6 – Zero-pole plot of the LPF

A two-tone signal has been processed to verify the appropriateness of the frequency response. The sum of a 0.01Hz and a 50Hz tone has been successfully suppressed (Fig. 7), respectively mimicking baseline drift and mains hum. An ECG acquisition from a patient simulator is depicted in (Fig. 8).

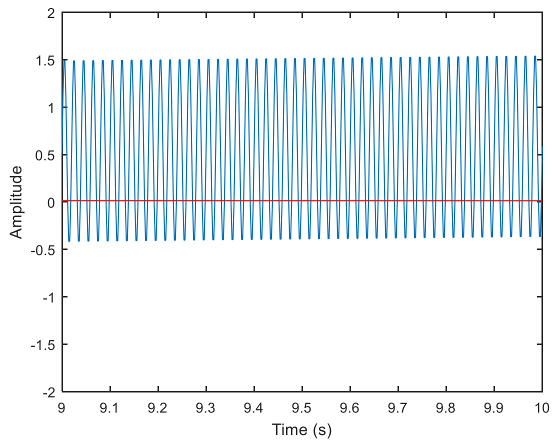

Fig. 7 – A two-tone signal, before (blue) and after (red) processing.

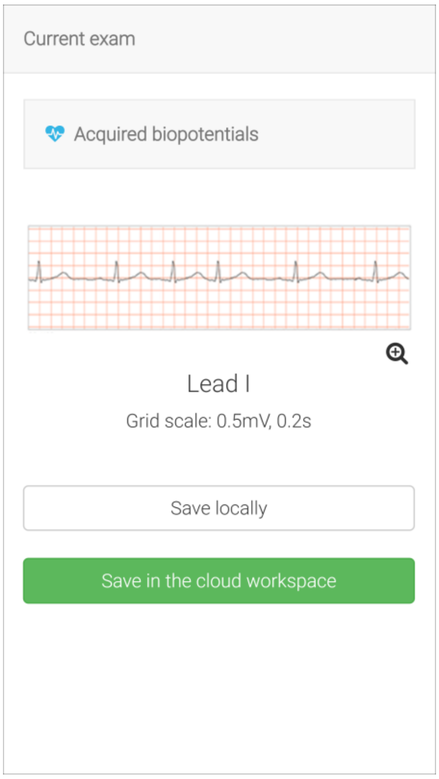

Fig. 8 – Actual graphical user interface (current exam)

4 Collaboration tools

A web-based collection of collaboration tools implements the remote platform services empowering teleconsultation flows. The overall system and software architecture (Fig. 9) comprises: i) a fault-tolerant Distributed Filesystem (DFS) based on a NoSQL Database Management System (DBMS); ii) a Relational DBMS (RDBMS); iii) an Identity Manager (IDM); iv) a RESTful API towards data; v) a Policy Enforcement Point (PEP); vi) a publish/subscribe message broker; vii) an integrated web application.

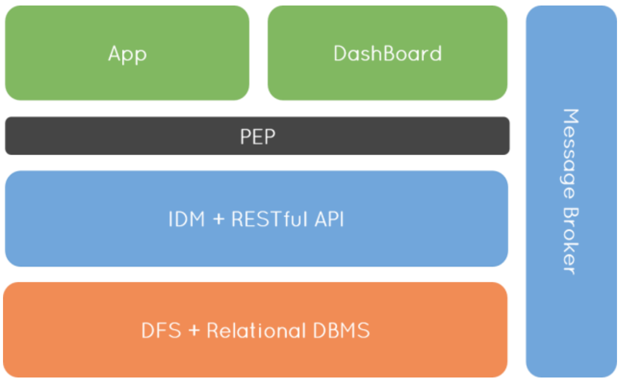

Fig. 9 – System and software architecture's diagram

In this particular implementation, the DFS is based on MongoDB, and is responsible for the acquired biopotentials' persistence; relevant metadata are stored along with actual samples, so as each document implements a self-contained piece of information. The RDBMS is based on PostgreSQL, and is responsible for structured data persistence. The IDM and PEP are based on OAuth 2.0, and are responsible for authentication and authorization procedures. The RESTful API is based on the Slim Framework; it implements the endpoint that allows creating, reading, updating and deleting remote resources and their relationships.

On top of the aforementioned components, a web application has been implemented, namely a platform component developed in HTML5, CSS3 and JavaScript (using jQuery and Bootstrap frameworks) that allows users to operate on private and shared workspaces from any modern web browser. By logging into the cloud platform, registered users can: i) manage their own patients; ii) assign exams; iii) provide diagnoses or leave notes. Users can also join workgroups and collaborate with other professionals; under this scenario, a number of users can: i) manage a shared directory of patients; ii) operate on shared exams; iii) leave notes towards collaborative diagnoses. Moreover, the workgroup's owner can assign roles and define workflows, namely predefined procedures with role-based steps. An event-driven message broker for WebSockets, based on Node.js [9]: i) orchestrates teleconsultation flows; ii) allows users to receive notifications; iii) synchronizes client-side collections.

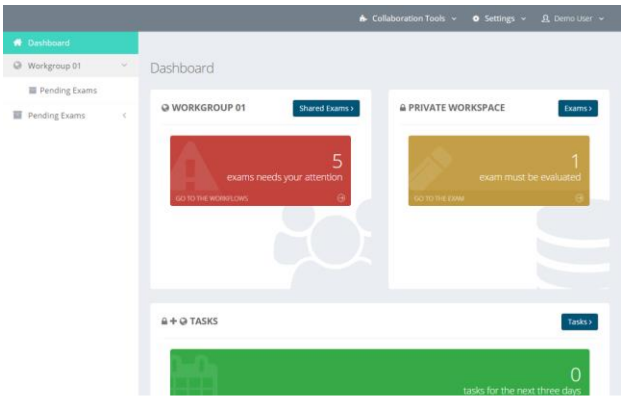

Fig. 10 – Actual web application (user's dashboard)

The above services have been deployed among three CentOS 7 virtual machines, namely a Web Application Server (for message broker and web application), a Web API Server (for authentication, authorization and RESTful endpoint) and a Database Machine (for DFS and RDBMS).

5 Conclusion

The key finding of this research is that a novel ECG teleconsultation platform can be implemented through the integration of modern apparatuses (whose functioning is based on smartphone and tablet devices) with collaboration tools deployed in the cloud. Future ECG machines can take advantage of the compute power embedded in smart devices to achieve cheapness, compactness and lightness, while delivering improved interaction schemes and functionalities, such as the opportunity to connect to collaboration tools and further services in the cloud.

It seems important to remark that, regardless of the underlying technological effort, the deployment of effective teleconsultation platforms eventually depends on cultural acceptance, and thus a careful multi-disciplinary and multi-professional co-design stage shall always be conducted.

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