Microprocessor-based simulator of surface ECG signals

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Abstract. In this work, a simulator of surface electrocardiogram recorded signals (ECG) is presented. The device, based on a microcontroller and commanded by a personal computer, produces an analog signal resembling actual ECGs, not only in time course and voltage levels, but also in source impedance. The simulator is a useful tool for electrocardiograph calibration and monitoring, to incorporate as well in educational tasks and in clinical environments for early detection of faulty behaviour.

1. Introduction

Since 1985, Bioengineering is established as a degree-level career at the School of Engineering of Universidad Nacional de Entre Ríos in Argentina. In its program, the undergraduate course Bioengineering II deals, among other things, with metrology applied to biomedical instrumentation and equipment, one of the competences that future Bioengineers must acquire. The syllabus contents of Bioengineering II include the use of transducers and signal conditioning circuits for the design and calibration of biomedical instruments. One of the fields concerning biomedical instruments -that we also choose to train students in theoretical principles and practical aspects- is surface electrocardiography (ECG).

From among the various didactic strategies opted for teaching purposes, one approach compels students to develop several theoretical-practical tasks in the Instrumentation Laboratory. One such task consists on designing and developing a protoboard (MR) level of an ECG preamplifier, capable of recording, conditioning and exhibiting ECG in one of the standard bipolar leads. Recording and signal conditioning specifications, similar to those encountered in current one-channel clinical electrocardiographs, such as preamplification, patient isolation, signal filtering, power amplification, must be satisfied by the design made by the student.

In order to tune-up the project, students perform standard electronic bench-tests, by setting each stage (offset, gain, frequency response, etc.) using conventional waveforms (sinusoidal, triangular, square) as input signals, and by revisiting the complete design, if necessary [1], [2]. After the circuit performance gives results within design specifications, the students make a field test on the entire circuit, and record their own ECGs. This final stage of the calibration procedure is necessary because

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waveforms used in bench-proofs do not completely reproduce actual ECG signal patterns, and because recording artifacts, similar to those produced in ECG cabinets under live recording conditions, need to be recognized by Bioengineering students to learn how to prevent them.

Abnormalities observed in the recording of ECG during the field test could be originated in improper electrode location, a faulty circuit, or less probably in genuine cardiac anomalies in the subject whose ECG is being recorded, borrowing the interpretation (and prevention) of anomalies in the recording, which is one of the proposals of the exercise.

Because of this, we decided to feed the tested ECG amplifier with a pure ECG signal resembling normal, abnormal, and also artifact ECG recordings, prior to the recording of a live ECG with the amplifier under test. This strategy aims at reinforcing the students’ confidence on their own capabilities to produce an efficient design. An antecedent of a device capable of generating an artificial ECG can be found in [3].

The recording of an artificial signal with known properties, similar to those expected in live recordings, and the comparison in real time between input and output signals, will permit to perceive distortions only related to the ECG amplifier. This is a useful complement to the classical bench-proofs referred to above.

2. Objectives

In the present work, we have developed a device (ECG simulator) to generate an analog signal with the most salient attributes of a live ECG recording, which is capable of being connected to the input stage of the one-channel ECG amplifiers designed by students.

3. Design and development

The leading idea was to store a digitized live ECG, select an epoch from it (i.e. a complete cardiac period), and send it to a digital-to-analog converter (DAC) at an adequate rate of refreshment to bring up a continuous analog ECG signal to the ECG amplifier through a driver amplifier. Our ECG simulator (ECGS) was provided with digital storage capacity, serial communication and DAC, and was designed based on a microcontroller and a solid state driver amplifier. The ECGS is to be configured and controlled from a personal computer (PC). Blocks diagram of the ECGS is shown in figure 1. It can be unfolded into five main stages: microcontroller (figure 2), serial communication (figure 3), EEPROM memory (figure 4), DAC (figure 5) and analog output (figure 6).

![Figure 1. Block diagram of the ECGS. Personal computer (PC), serial communication (RS232), ECGS memory (EEPROM), digital to analog converter (DAC).](image)
One cardiac period (ECG epoch) from a live human ECG in the DI lead, obtained from a normal individual, was digitized (10 bits, 500 Hz) by means of a computerized polygraph constructed at our Laboratory in an earlier stage [4], and the most significant 8 bits were stored in the hard disk (HD) of a PC. A dedicated PC-resident program sends this ECG epoch to ECGS through the PC serial port, to be stored in the ECGS memory by a dedicated program resident in the microcontroller.

Then this last program sends the ECG epoch from the memory of ECGS to the DAC of the microcontroller at the same sampling rate (500 Hz) in order to present the ECG to the output amplifier of the ECGS. The transfer output cycle is repeated until an operator interruption stops the process. The DAC output is smoothed via analogical low pass filtering (single pole, 100 Hz), and conditioned in impedance and amplitude in order to simulate the ECG signal expected at the input of an ECG amplifier.

3.1. Hardware design

The microcontroller (PIC16C877-20/P, from Microchip, U.S.A.) commands several actions in the ECGS: data management, serial communication with the PC, 8 KB EEPROM (24C64, from Microchip, U.S.A.) memory management, and 8 bit DAC (DAC0808, from National, U.S.A.) operation [5], [6]. Figure 2 shows the pin out of the microcontroller.

![Figure 2. Microcontroller module (PIC16C877-20/P) pin out. 20 MHz xtal.(Y1)](image-url)

Figure 3 shows the stage which adapts voltages between the RS232 serial port in the PC and the transmission and reception pins of the microcontroller. It is based on a voltage adapter circuit (MAX232, from Maxim, U.S.A.).

Figure 4 shows the wiring of the EEPROM. The PC, through the RS232 serial port brings the ECG epoch previously stored in the HD to the microcontroller which stores it in the EEPROM memory. The microcontroller can, in turn, read the EEPROM to send the ECG epoch to the DAC in a repetitive cycle mode. The microcontroller and the EEPROM communicate under I2C protocol.
The circuit in figure 5 illustrates the connection between the microcontroller and the DAC in order to bring the digitized ECG epoch stored in the EEPROM as an analog signal to the output stage. The amplifier (LF353H from National, U.S.A.) converts DAC output current into a voltage signal.

Figure 5. DAC wiring. DAC module (DAC 0808). Connection with microcontroller (RB0……RB7). Current-to-voltage conversion (LF353H). Connection with output stage (V1)

Figure 6. Output stage. Connection with DAC (V1). Connections with ECG (electrodes 1, 2 and 3, see text)

Figure 4. ECGS memory. 8 KB EEPROM module(24C64). Connection with microcontroller (SCL, SDA)
3.2. Software design
The program which transfers data from the PC to the ECGS was built in Delphi 6.0 (from Borland, U.S.A.). This PC resident program permits the configuration of the RS232 serial port to comply with ECGS requirements. It transfers the ECG epoch stored in the HD to the ECGS, exhibits the simulated ECG in the PC monitor and performs a transmission error-checking protocol. Figure 7 illustrates the digitized ECG which is the source signal for ECGS, as seen in the visual environment of the program, on the PC monitor.

The program resident in the microcontroller was written in C-compiler Software Development Tools (from CCS, U.S.A.). This program controls data transfer between EEPROM and MAX 232, and between EEPROM and DAC.

![Figure 7. Visual environment of ECGS.](image)

The upper trace shows the ECG epoch previously stored in HD; the lower trace shows the ECG epoch after transmission from PC, as it was recovered from EEPROM by the transmission error–checking protocol.

4. Results
In order to verify the performance of the ECGS, two simultaneous recordings of the digitized ECG shown in figure 7 were performed. The first recording, showed in figure 8, was taken from the DAC output with a precision digital oscilloscope (Scopemeter 190/C, from Fluke, U.S.A.); the second was obtained by connecting the ECGS output to the patient cable inputs of an electrocardiograph (ECGView, from Eccosur, Argentina) and recording a DI lead ECG. A fragment of the ECGView report is reproduced in figure 9.
5. Discussion

As a gross view of the ECG stored in HD (figure 7), the ECG signal driven to the electrocardiograph (figure 8) and the ECG finally recorded by the electrocardiograph (figure 9), permits recognize a very high concordance among them.

We thus conclude that the ECGS developed in this work has the capability of reproducing a stored digitized ECG trace and transforming it into an analog signal which is, in turn, suitable for being reproduced without undesired artifacts by a standard commercial electrocardiograph. Nevertheless, a quantitative comparison among the three traces could be useful in order to better characterize the performance of this ECGS.

As a result, we now have a device which can be easily installed in the teaching laboratory, and the students will have another tool for completing the calibration procedure of their ECG amplifiers.

The ability of the device to feed an electrocardiograph with normal or abnormal ECGs, and to add programmed artifacts to the recording by digitizing actual ECG records, or by loading the ECGS with synthetic ECG-like waveforms, will not only expand the possibilities of the educational tasks, but also provide a method for early detection of electrocardiograph faults.

This easy-to-operate ECGS, together with its low-cost characteristic, make it suitable for use in an Electrocardiology Department in hospitals where technicians could consequently obtain recordings of simulated ECGs with their in-use electrocardiographs and, by comparing actual recordings with the expected ECG as visualized in the PC monitor, will be able to decide on the recalibration of the electrocardiograph by the Bioengineering section of the hospital, instead of recording unsuspected wrong ECGs.
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