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Prototype of an Ambulatory Long-Term ECG Monitoring System for Real Time Detection of QRS Complex and T Wave End Based on FPGA

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***Abstract*- A prototype of an ambulatory long-term ECG monitor was developed for the simultaneous acquisition and storage of 3 quasi-orthogonal leads, and its real-time processing for the beat-to-beat detection of QRS complex and T-wave end for the measurement of heart rate and RT interval. The prototype has as its core a Field Programmable Gate Array (FPGA) of Xilinx Artix-7 embedded in a CMOD-A7 development board, it also controls and communicates with an ADS1294 circuit for the acquisition of the simultaneous ECG leads (D1, aVF, V2) and a micro-SD memory for the storage of these leads and the heart rate and RT interval beat-to-beat values. The prototype has a bandwidth of 200 Hz delimited by a digital FIR filter, a minimum CMRR of 112 dB at 60 Hz, a resolution of 0.76 µV and an average current consumption of 85 mA which allows a minimum battery life of 36 hours. The evaluation of the QRS complex and T-wave end detection algorithms implemented in the FPGA was performed with 10 records of the QT database. For the QRS complex detection the accuracy was of 97.8%. For the T-wave end the measurement error was of 5.14±7.07 ms, which was within the tolerance limits for deviations with respect of the manual measurements made by the CSE experts.**

Keywords- ECG, Holter recorder, Heart Rate, RT interval, Wavelet Transform, FPGA, ADS1294, Micro SD Memory.

I. INTRODUCCIÓN

Cardiovascular diseases are a health problem both in Mexico and worldwide and represent the leading cause of death. [1]. Thanks to advances in technology, noninvasive techniques have been developed for monitoring the electrical activity of the heart from the acquisition of the electrocardiogram (ECG). Abnormal variations in parameters such as heart rate (HR), QT interval duration and ST-segment changes are not always visible in short-duration recordings that are usually taken at rest, so continuous long-term recordings acquired by continuous ECG monitoring systems called Holter are necessary.

The evolution of the Holter monitor has been extensive over the last few years, with changes and innovations ranging from processing and storage technology, algorithms for reliable segment and interval detection, device size, and finally the number of leads [2,3]. Nowadays Field Programmable Gate Arrays (FPGA's) are a powerful processing tool due to their architecture that allows to execute processes in parallel, a quality that makes them ideal for systems that involve real time processes as is the case of this work [4,5] .

Another objective of this work is the real-time detection of the QRS complex and T-wave end (Te) for the study of two indices such as heart rate variability, which is a predictive parameter in the diagnosis of heart attacks, coronary atherosclerosis and sudden death [6]. On the other hand, the RT interval (from R wave apex to Te) is an approximate measure of the QT interval duration, whose prolongation, dispersion and alterations in the dynamics are related to the risk of developing malignant arrhythmias and sudden cardiac death [7].

Several techniques have been used for the detection of the QRS complex and Te, such as: adaptive filters [8], the use of derivatives [9], the wavelet transform [10], among other techniques, all of them are offline. The use of the continuous wavelet transform (CWT) with splines has proven to be an effective technique because it uses more scales in different frequency bands and allows a reliable detection of the QRS complex and Te discriminating the signals of interest between noise, artifacts and other waves [10].

The objectives of this work are to develop a prototype of an ambulatory long-term ECG monitor for the simultaneous acquisition and storage of quasi-orthogonal leads (D1, aVF, V2) with real-time beat-to-beat measurement of HR and RT interval using algorithms based on the CWT implemented in an FPGA.

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II. MATERIALS AND METHODS

The prototype consists of 3 fundamental elements as shown in Fig. 1, in order to meet the proposed objectives, these elements are:

- Xilinx Cmod A7 development board, which contains a low power consumption Artix-7 XC7A35T-ICPG236C family FPGA.
- Texas Instruments ADS1294 integrated circuit with low power consumption, 4 channels, 24-bit analog-to-digital converters and ECG acquisition module.
- 16 GB Kingston Class 10 micro SDHC memory.

According to the American Heart Association, the main characteristics that an electrocardiograph should meet are as follows [11]:

- Common Mode Rejection Ratio (CMRR) > 80 dB.
- Minimum bandwidth of 0.05 - 100 Hz (-3 dB).
- Resolution: 10 µV.

A. FPGA

The FPGA is an integrated circuit that can be programmed after its fabrication to function as any digital circuit, i.e. it is a programmable structure that presents an array of programmable logic blocks [12]. For this project an FPGA Artix 7 XC7A35T-1CPG236C was used immersed in a Cmod A7 development board, which is of low integration scale, and is of low power consumption since its main clock is 12 MHz.

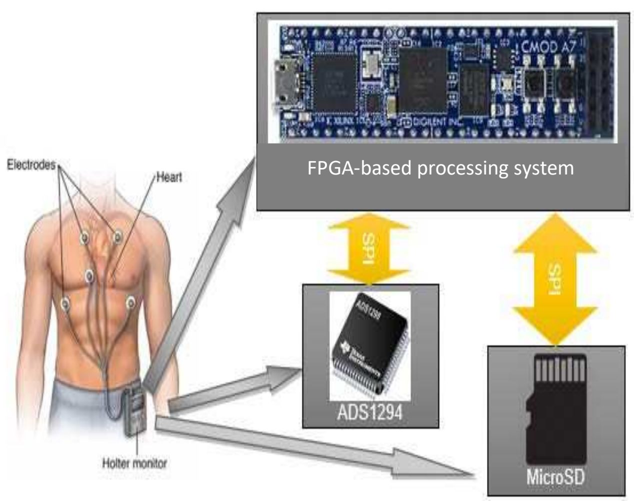

Fig. 1. Main components of the 3-channel ambulatory system.

B. ADS1294

The ADS1294 series (ADS129x) from Texas Instruments belongs to a family of multi-channel, simultaneous sampling, 24-bit resolution analog-to-digital converters (ADCs) with a delta-sigma (ΣΔ) architecture that also features internal programmable gain amplifiers (PGAs), reference and oscillator. The ADS1294 is a chip designed to address the need for signal acquisition in medical applications such as Electromyography (EMG), Electrocardiography (ECG) and Electroencephalography (EEG). [13].

The ADS1294 incorporates indispensable and specific functions for ECG acquisition such as the Wilson Central Terminal (WTC) block for precordial leads, the Goldberger terminal for augmented leads, a block to detect false electrode contact (lead-off) by using pull-up, pull-down resistors or by a current source, and the right leg circuit with a versatile system that allows to choose the average of any combination of electrodes. [13].

C. *Micro SD Memory*

A micro-SD card is a small-sized memory card that allows storing information in portable devices such as cell phones, digital cameras, electronic tablets, etc. Reliable ECG storage is one of the main qualities that a Holter should have. The card used in the design is a Kingston micro SDHC class 10 memory card with a capacity of 16 GB that achieves read speeds of 45 MB/s and 10 MB/s write speeds. [14].

D. Software implemented in the FPGA

1) General state machine

A state machine was implemented for the correct and orderly operation of all the tasks to be performed in FPGA. The state machine implemented was based on Martínez-Suárez et al. work with some modifications [15], starting from initialization of the acquisition circuit, initialization of the memory, signal acquisition, filtering, finally, processing and storage as shown in Fig. 2.

The operation of the state machine starts when the main "Inic" signal controlled by an input bit in the FPGA is activated, once the state machine is initialized the microSD memory is initialized. The next state consists of the initialization of the ADS1294 acquisition circuit, once this process is completed, the data is received and a specialized pin called "DRDY" (Data Ready) informs the main program that a data is ready.

Once the data is ready, it is sent to the digital filtering module and the ECG bandwidth is delimited by means of a digital FIR low-pass filter with a cut-off frequency of 200 Hz. Subsequently, it is sent to a module for obtaining the wavelet transform (WT) where an analysis is performed to locate the QRS complex and Te.

Finally, the 3 quasiorthogonal leads and the HR and RT interval values are stored in real time and the state machine returns to the state where it waits for the reception of new data.

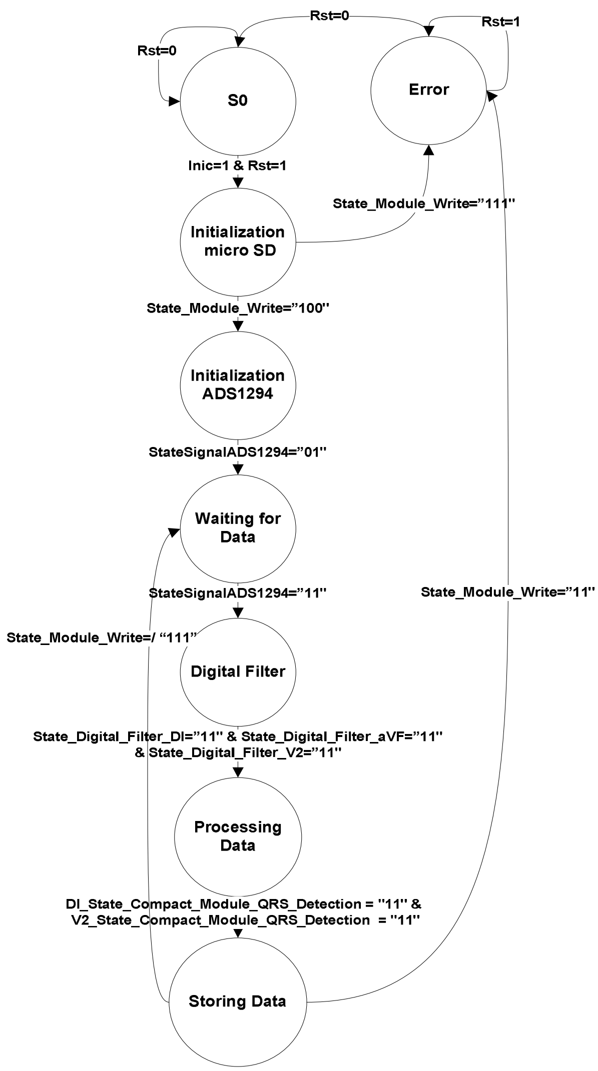

Fig. 2. General state machine implemented in FPGA.

In parallel, there is a module that displays the HR and RT interval values and refreshes the screen every time a new data is ready, in the meantime it keeps the previous values.

a) Digital Filter

For the implementation of the digital filter, the "Filter Design" tool of Matlab ® was used, which generates the coefficients of a FIR filter from specified characteristics. The selected characteristics are low pass filter, cutoff frequency at 200 Hz, order 10 of the filter and a Hamming window type. Once the characteristics were selected, the coefficients were imported and entered into the following equation:

$$y(n) = \sum_{k=0}^{N-1} b(k)x(n-k) \qquad (1)$$

Where b(k) are the FIR filter coefficients and N is the filter order.

b) QRS complex and T-wave end detection

The module consists of a main state machine that is divided into 10 states. The first 5 states were used for QRS complex detection and the last 5 states for Te detection. The module design is based on the module for the QRS complex detection of Martínez-Suárez et al. [15]. This module is based on the algorithm proposed by Alvarado-Serrano et al. [10], in which the WT is used with splines for the use of any integer scale [16]. The morphology of the ECG varies depending on the lead used, so it is possible to observe two types of QRS complexes: the QRS with negative polarity and QRS with positive polarity as shown in Fig. 3. The algorithm uses the flag "QRS_N" to classify the morphology of the QRS complex and based on that follow one series of steps or another in order to perform a correct detection.

The algorithm consists of identifying whether a maximum or minimum modulus appears first. If a maximum modulus appears first, the QRS_N flag is 1, then the algorithm looks for a QRS complex with negative polarity identifying a zero crossing, then the minimum modulus and finally a second zero crossing, on the contrary if a minimum modulus appears first, the algorithm looks for a QRS complex with positive polarity identifying the zero crossing, then the maximum modulus and finally the second zero crossing.

The same methodology is applied in the case of a positive, negative and biphasic T wave. In both cases (T wave and QRS Complex) specific waiting times are applied for the detection of the characteristic points of each wave since they have different durations. Once the QRS complex is detected, Te is searched. The value of the window depends on the duration of the previous RR interval, if the duration of the RR interval is greater than 700 ms the search window is 140 ms, otherwise its duration will be 100 ms and a process similar to that of the QRS complex is initiated, but in this case the second zero crossing generated in the WT is searched for, which determines the wave end. When the R wave peak is identified, two counters are started. The first counter is restarted until the location of a second QRS complex which represents the RR interval, the second counter is restarted until the location of Te which represents the RT interval.

III. RESULTS AND DISCUSSION

1) Digital Filter Response

To determine the bandwidth, a stimulus was generated which consisted of a sinusoidal signal which increases its frequency in steps of 5 Hz. According to Fig. 4 it is observed that at a frequency of 200 Hz a decay of -3 dB was obtained, which corresponds to the high frequency cut-off frequency of the filter, so the filter responds according to the design parameters.

a)

b)

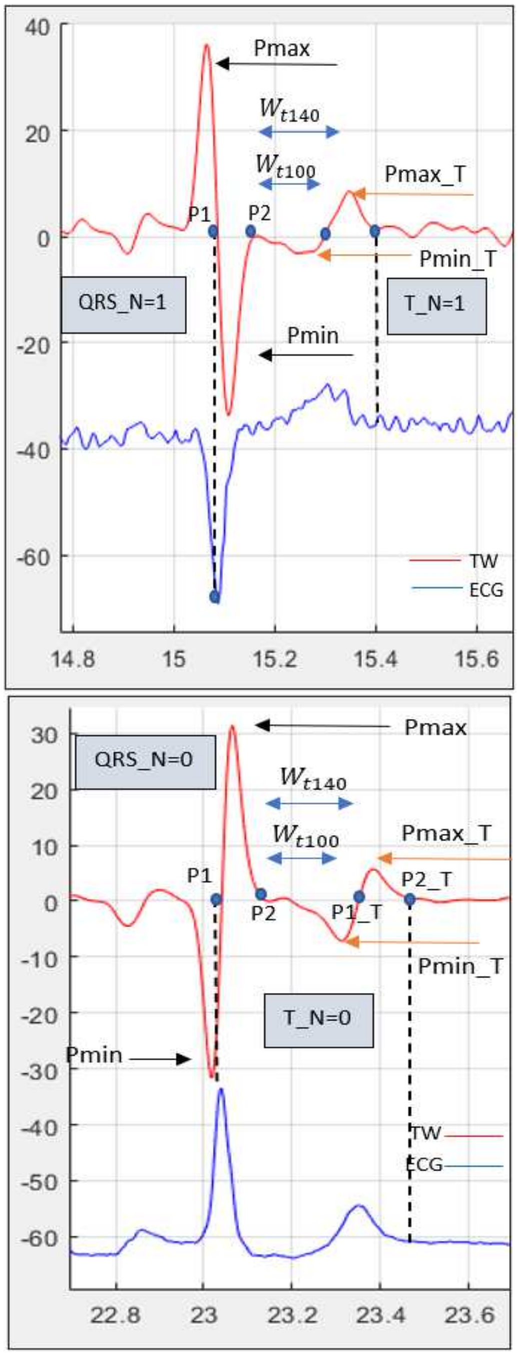

Fig. 3. a). QRS complex with negative polarity and its WT. b). QRS complex with positive polarity and its WT. In both cases a specific series of steps is followed.

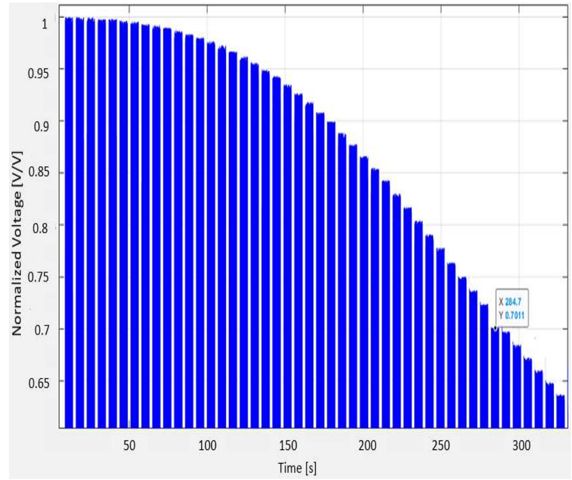

Fig. 4. Response of the digital filter implemented in the FPGA.

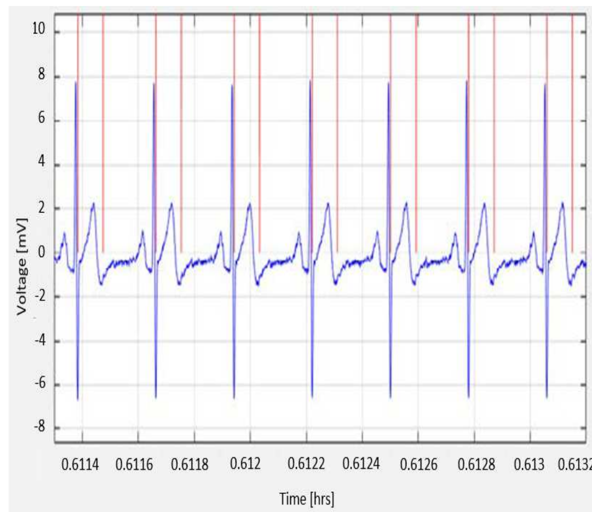

Fig. 5. QRS positive polarity and positive T wave.

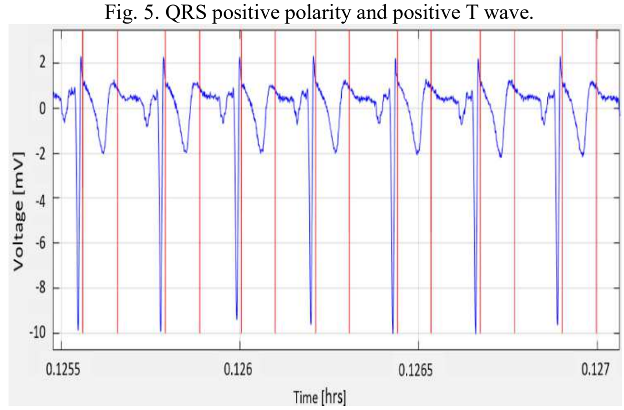

Fig. 6. QRS with negative polarity and inverted T wave.

2) QRS complex and T-wave end detection

To test the algorithm, short-duration recordings acquired by the designed prototype and from different Physionet databases that can be downloaded directly from the Physionet.org website were used [17]. The objective was to test the correct detection of both the QRS complex and Te, both with different morphologies as seen in Fig. 5 and 6.

For the validation of the algorithms implemented in the FPGA, 10 records from the QT database with a duration of 15 min with different morphologies were used [18]. The records were transformed into audio, later into electrical signals to be acquired and processed by the prototype. The selected records were: sel100, sel103, sel104, sel114, sel123, sel213, sel302, sele0104, sel0110, sel30, the results are shown in Tables 1 and 2. An accuracy of 97.8% was obtained in QRS complex detection (Table 1).

To evaluate the Te detection algorithm on the records selected from the QT database, the manual annotations made by specialists included in the database were used. The validation consisted of calculating the difference in the position of Te detection made by the proposed algorithm (WT) with that reported by the specialists (ME) in several beats of each record, obtaining the mean (m) and standard deviation (sd) (Table 2). The results of this difference were within the tolerance limits for deviations from measurements made by experts sd (CSE) [11].

TABLE 1. RESULTS OF QRS COMPLEX DETECTION.

Records	Total Beats	F.P. (QRS)	F.N. (QRS)	False detections (QRS)	
				latidos	% error
sel100	1134	6	32	38	3.35%
sel103	1048	0	0	0	0.0%
sel104	1109	5	11	16	1.44%
sel116	867	6	2	8	0.92%
sel123	756	8	0	8	1.058%
sel213	1641	13	42	55	3.35%
sel302	1501	7	45	52	3.46%
sel0104	956	2	12	14	1.46%
sele0110	906	0	6	6	0.66%
sel30	1153	10	37	47	4.07%
Total	**11071**	**57**	**187**	**244**	**2.20%**

TABLE 2. RESULTS OF T-WAVE END DETECTION.

Records	WT - ME
	m ± sd (ms)
sel100	11.33 ± 2.68
sel103	6.03 ± 14.42
sel104	12.66 ± 11.59
sel116	-1.66 ± 5.03
sel123	1.33 ± 3.78
sel213	3.66± 3.21
sel302	-3.00 ± 3.60
sel0104	5.62 ± 4.32
sele0110	7.66 ± 3.78
sel30	13.23 ± 5.29
Total average	**5.14 ± 7.07**
Tolerance limits for deviations from expert measurements [11].	
sd (CSE)	**30.6**

3) User Interface

A graphical interface designed in MATLAB was used to visualize both ECG signals and the detection of the QRS complex and T wave as well as the RT interval and heart rate variability plots and their dynamics as shown in Fig. 7.

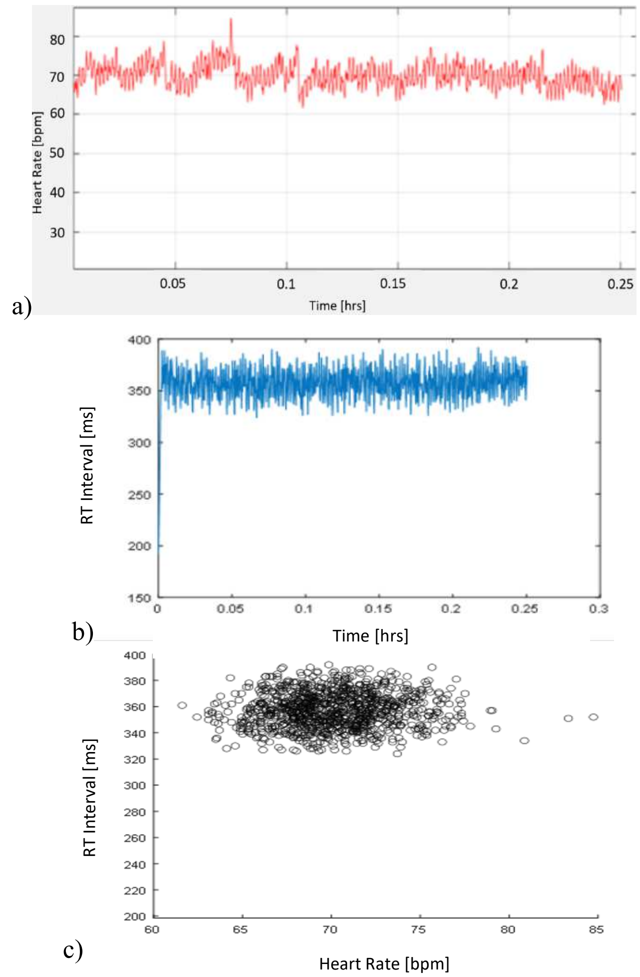

Fig. 7. Sel103 record from QT database. a). Heart rate variability. b). RT interval variability. c) Dynamics RT-HR.

4) Electronic Board Designed

The board was designed in a modular fashion so that the main elements such as the ADS1294, FPGA, Micro SD memory and LCD display could be easily removed, as this is still a prototype and improvements to the design are desired (Fig. 8).

Fig. 8. Top and bottom view of the board implemented for the prototype.

5) *Finished Prototype and Power consumption*

The final prototype has a general on/off switch for the system and 4 switches for the general system control as shown in Fig. 9. The first switch has the function of initializing the reading, processing, and storage of the data. The second switch has two functions: to display in real time the HR values and RT interval duration or to know the status of the electrodes. The third switch is to select the analysis lead, it can be DI and aVF lead. The fourth and last switch does not have a specific function and was added in case it is desired to include another function for future work. The dimensions of the prototype are: 77 mm x 102 mm x 55.40 mm with a weight of 425 g. The consumption of the device is 85 mA at 5 V which allows a minimum battery life of 36 hours. A reduction of 36% was achieved with respect to the prototype of Martínez-Suárez et al. [4].

Fig. 9. Final prototype in operation.

IV. CONCLUSIONS

The prototype is capable of simultaneously acquire and store 3 ECG leads (D1, aVF and V2) and the HR and RT interval duration beat-to-beat values of two of these leads. Also it displays in real time the HR and RT interval of one lead (either DI or aVF). The algorithms implemented in the FPGA can detect two morphologies of the QRS complex with an accuracy of over 97%, while for Te the error was of 5.14 ± 7.07 ms, which is within the tolerance limits for deviations with respect of the error suggested by the CSE specialists.

The device has a bandwidth greater than the proposed by the AHA for future applications such as late atrial and ventricular potentials. The acquisition characteristics of the prototype depend mainly on the ADS 1294 configuration, which provides a CMRR greater than 80 dB and a resolution of 671 µV, characteristics that meet the specifications of the AHA. Further validation of the algorithms is considered for the future, as only 12 records were used from Physionet databases. In addition to making the prototype lighter and reducing dimensions. The consumption of the device was reduced due to the use of a low-consumption and low-scale FPGA, added to this the ability to perform parallel processing, make the FPGA an attractive tool for use in Holter monitors.

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