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Prototype of an Ambulatory ECG Monitoring System with R Wave Detection in Real Time Based on FPGA

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***Abstract*— A prototype of an ambulatory ECG monitoring system was developed for the acquisition and storage of 3 simultaneous leads with an R wave detection algorithm based in the continuous spline wavelet transform to obtain the beat-to-beat heart rate in real time in 2 leads. The prototype has as core a 4 channel ECG front-end ADS1294, a Field Programmable Gate Array (FPGA) of Xilinx Artix-7 XC7A35T-ICPG236C in which the R wave detection algorithm was implemented, and a micro SD memory of 16 GB for data storage. The prototype has a bandwidth of 200 Hz, a minimum CMRR of 112 dB in 100 Hz, a resolution of 0.76 µV and an average current consumption of 125 mA for a minimum duration of 30 h. Evaluation of the R wave detection algorithm in aVF lead has been done with 30 min records of 5 subjects at rest, with an accuracy of 99.4%.**

Keywords—ECG, Heart Rate, Wavelet Transform, FPGA, VHDL, ADS1294, micro SD memory

I. Introduction

Cardiovascular diseases (CVDs) are among the leading causes of death worldwide according to the World Health Organization (WHO) [1]. Therefore, the use and development of noninvasive techniques as electrocardiography is a useful tool for diagnosis and treatment in patients with CVDs as the ischemia and infarction. Because heart diseases sometimes present with random symptoms that do not always occur in short-term electrocardiogram (ECG) records, a long-term continuous ECG record is necessary [2].

As a solution to this problem from the 50s of the twentieth century to the present day continuous ambulatory monitoring systems called Holter are developed, which acquire the ECG for periods of 24 or 48 hours while the patients performs their daily activities [3]. Besides the recording of cardiac arrhythmias, one of the clinical uses of Holter is the evaluation of the RR interval or heart rate changes for the analysis of the heart rate variability (HRV), which is useful for assessing autonomic nervous responses during daily activities and risk of cardiovascular death or arrhythmic events [4,5].

The development of Holter monitors continues today with the advancement of Field Programmable Gate Array (FPGA) technology [6,7], and various algorithms have been implemented for the real-time analysis of the ECG, as QRS complex detection to determine the heart rate [8–11]. In this work, we presented the development of a long-term ECG ambulatory monitoring system based on FPGA for the acquisition and storage of D1, aVF and V2 leads, and the R wave detection to obtain the beat-to-beat heart rate in real time [12].

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II. Materials and Methods

The proposed prototype has as core a 4 channel ECG front-end ADS1294, an FPGA of Xilinx XC7A35T-ICPG236C of the Artix-7 family and a micro SD memory of 16 GB (Figure 1). The programming was developed in VHDL with the software Vivado from the manufacturer Xilinx.

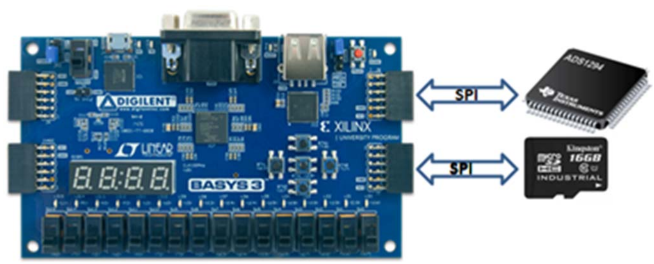


Fig. 1. Main components of the prototype of ambulatory ECG monitoring system of 3 leads with R wave detection in real time.

A. ADS1294

The ADS1294 from Texas Instrument belongs to a family of analog-digital converters (ADC) delta-sigma ($\Delta\Sigma$) multidirectional and simultaneous sampling with a resolution of 24 bits, amplifiers with programmable amplification factor, internal reference and a built-in oscillator. The 4 channel ADS1294 incorporates all the features that are commonly required in ECG applications with high levels of integration and exceptional performance [13].

In the prototype implemented, ADS1294 amplifies the input signal of 3 channels (corresponding to leads D1, aVF and V2), 12 times, generates the Wilson's terminal for the precordial lead V2, the Goldberger network for the augmented lead aVF, and digitize them. The signals of each lead are sampled at a frequency of 1 kHz and a 16 bits resolution. Once the signals are digitized, they will be sent through the SPI communication standard to FPGA.

B. Micro SD memory

A micro SD card is a small memory that stores information on portable devices such as mobile phones, digital cameras or tablets. The card used is a Kingston micro SDHC Class 10 brand with a capacity of 16 GB that reach read speeds of 45 MB/s and 10 MB/s of writing. The dimensions of the micro SD card used are 11 mm x 15 mm x 1 mm [14].

Its technical specifications allow a wide flexibility to be used in working temperature and storage ranging from -40°C to +85°C, with a relative humidity of 95% in service conditions at a temperature of 25°C and in storage conditions at a temperature of 40°C. The Kingston micro SDHC memory card can be removed and/or inserted without turning off the host system, but does not have a mechanical write protection switch.

C. *Basys3 development card*

The Basys3 board is a digital circuit development platform, which thanks to its high capacity FPGA (Xilinx XC7A35T-1CPG236C) and collection of peripherals such as USB, VGA, LEDs, switches and others, supports designs that go from simple combinatorial circuits to complex sequential circuits, such as microcontrollers and integrated processors. This allows the realization of a large number of designs without the need for any additional hardware. The Basys3 board also includes enough non-dedicated FPGA input / output pins to allow the expansion of designs. The Basys3 board uses as a development tool exclusively the Vivado design environment, which is available for free on the official website of Xilinx [15].

In the design of the prototype of Holter monitor, the FPGA will carry out as fundamental function, the processing of the information obtained from the ADS1294. Among the different tasks that include the processing of the signal is the implementation of the continuous wavelet transform, the detection of the R wave and the transfer of obtained data through the SPI communication standard to the micro SD memory for its storage.

D. *Software implemented in the FPGA*

In order to take advantage of the advantages offered by FPGAs in parallel programming, four modules were established as the core of the prototype:

• Data receiver module sent by the ADS1294

This module is intended to carry out all the requests of the ADS1294. These include configuring the operating mode, receiving and reporting the arrival of new data for later storage in the data buffer, and controlling when the ADS1294 is active among other options.

• Module for obtaining heart rate

This module has the purpose of process the information received by the "Data receiver module", and implement a R wave detection algorithm based in the continuous spline wavelet transform to obtain the beat-to-beat heart rate developed by Alvarado et al. [16]. This algorithm was evaluated with 8 ECG data files of the MIT-BIH arrhythmia database with an accuracy of 99.5%.

• Module for storing data in the micro SD memory card

This module manages the buffer, performs the configuration of the memory as well as sending the data for storage in the SDHC memory.

• Module for the visualization of the heart rate

This module is supported by 3 lamps of 7 segments to show the results obtained in the "Module for obtaining the heart rate".

Each module interacts with each other as shown in Fig. 2. To interconnect these modules, a state machine was created with the structure shown in Fig. 3.

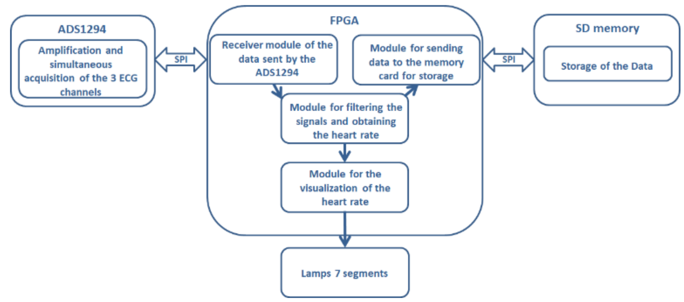


Fig. 2. Block diagram of the prototype of ambulatory ECG monitoring system of 3 leads with R wave detection in real time.

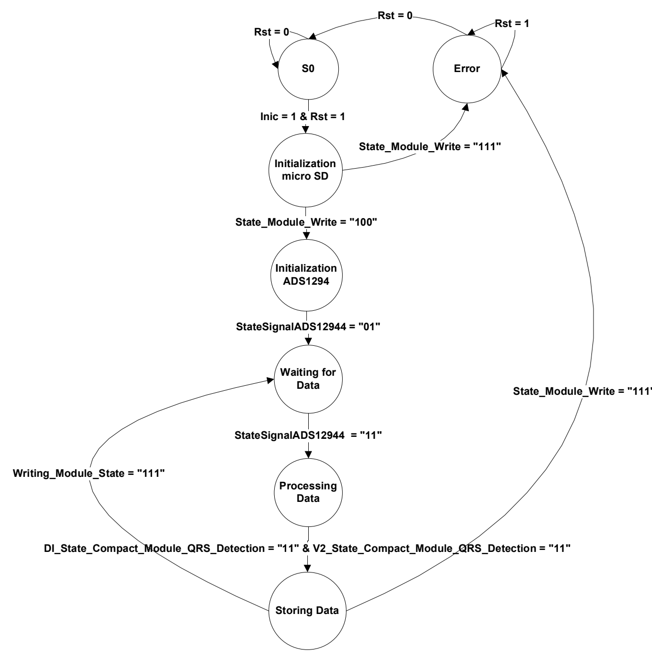


Fig. 3 General state machine (Note: When the signal Rst = 0 the next state is always S0, it was not included to better understand the diagram).

For the operation of this state machine, the first step is to wait for the order to start the system by means of the "Inic" input signal, later it starts the initialization of the micro SD memory by surveying the process by means of the signal “State_Module_Writing”.

If an error occurs in the initialization process, the system is blocked until the system is restarted using the "Rst" signal. If there is no problem with the micro SD memory, the next step is the initialization of the ADS1294. Once this process is finished, the system is ready to begin receiving, processing and writing data.

To know when a new data is available, the signal "StateSignalADS1294" is surveyed, once the existence of a new data has been confirmed, the next step is to send the information in the module to obtain the heart rate. When the results are ready, they are sent to the module for storing data on the memory card with the information obtained from the ADS1294. To finish the cycle, it is surveyed if there is a problem in the writing or if the memory is full. If there is no error, the system is waiting for a new data to repeat the process. If a system error occurs or if the memory is full, it is blocked until the system is restarted using the "Rst" signal.

III. Results and Discussion

The developed prototype of ambulatory ECG monitor is shown in Fig. 4. Its dimensions in cm are 16 x 6.3 x 9.7 with a weight of 700 g. To evaluate the performance of the prototype the following parameters were measured: bandwidth, Common Mode Rejection Ratio (CMRR), resolution, percentage of false R wave detections, power consumption and duration of the batteries used.

Fig. 4. Prototype of ambulatory ECG monitoring system of 3 leads with R wave detection in real time.

A. Bandwidth

To determine the bandwidth of the prototype implemented, the acquisition channels were stimulated with a sinusoidal signal containing a sweep of frequencies from 0 Hz to 500 Hz with increases of 5 Hz between each interval, an amplitude of 40 mVpp and 0 V offset. Each interval has a duration of 5 s and between the intervals there are delays of 2 s. The differential gain, ideally, is 12 analogically introduced by ADS1294 and 8 digitally introduced by the FPGA, obtaining a total of 96.

The data obtained from the stimulus signal were normalized and as shown in Fig. 5, from 200 Hz approximately output signal is less than 70.7%.

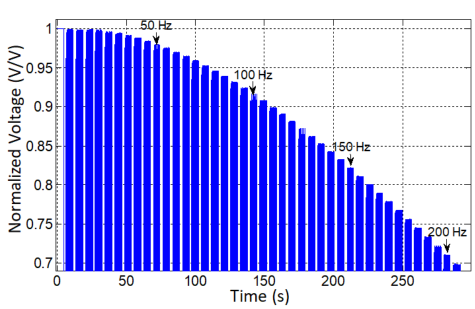


Fig. 5. Normalized output voltage of the prototype in the frequency range from 0 Hz to 200 Hz for the calculus of the bandwidth.

The bandwidth of 200 Hz fulfills the requirements for the bandwidths recommended by the American Heart Association of 100 Hz for an ECG in adults, and of 150 Hz for an ECG in children [17].

B. CMRR

The CMRR obtained is shown in Fig. 6. CMRR ranges from 113 dB for the frequency of 0 Hz to 110 dB for the 200 Hz frequency exceeding the minimum CMRR of 80 dB recommended by the American Heart Association [17].

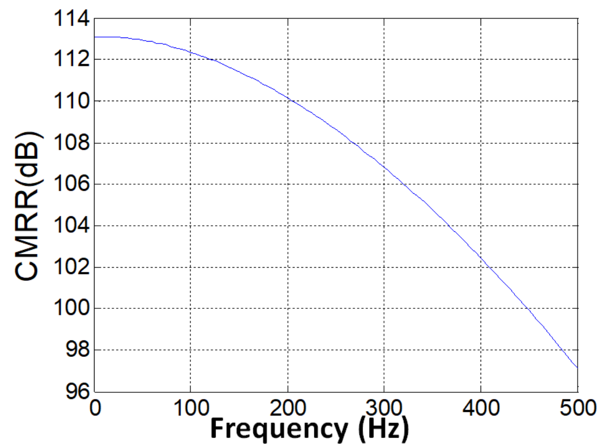


Fig. 6. CMRR obtained in the prototype.

C. Resolution

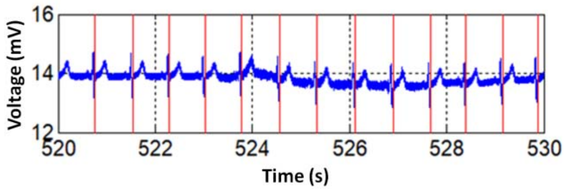
To determine the resolution in the prototype implemented, the measurement margin was determined in the first instance. To do this, the prototype was stimulated with a sinusoidal signal at a frequency of 5 Hz, in which the peak-to-peak voltage (Vpp) was progressively increased. The output signal begins to present alterations in the negative range when the signal exceeds 47 mVpp and offset of 0 V, obtaining a lower measurement range detectable by the -23.5 mV device. In the case of the positive range when the stimulus signal exceeds 52.8 mVpp, the alterations in the output signal begin, obtaining an upper measurement margin of 26.4 mV, obtaining a measurement margin of 49.9 mVpp.

Once the real measurement range of the device was determined, it was divided into 2n, (where n = 16), obtaining a device resolution of approximately 761.4 nVpp. The resolution obtained is considerably lower than the required 10 µV [17], obtaining a signal with more details for analysis.

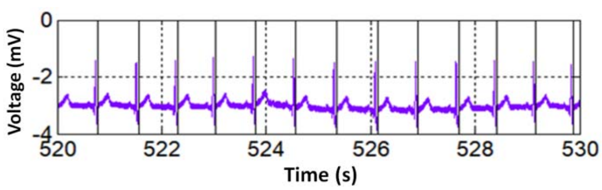
D. Percentage of false R wave detections

To evaluate the R wave detection algorithm implemented in the ambulatory monitor prototype, ECG recordings of 30 min of 5 healthy subjects at rest in DI and aVF leads were used. The first minute of these records was eliminated, which is the time the module uses to calibrate itself. ECG excerpts of the two leads and the result of the R wave detection of a subject is shown in Figure 7.

Table I shows the results obtained in the R wave detection performed in the aVF lead in the 5 subjects. From this table, 10694 beats were analyzed with 62 false detections for an accuracy of 99.4% (error=0.58%). The table II shows an analysis of the RR interval variability, in where the subject 3 has the greatest variability, and the subject 5 has the lowest variability.



a)



b)

Fig. 7. ECG excerpts with R wave detection obtained from subject 4. a). DI lead. b). aVF lead.

TABLE I. EVALUATION OF THE R WAVE DETECTION IN THE AVF LEAD

Subject	Beats	False Positive	False Negative	False Detections
1	2136	0	11	11
2	2001	0	1	1
3	2050	0	20	20
4	2292	0	0	0
5	2215	0	30	30
Total	10694	0	62	62

TABLE II. STATISTICAL ANALYSIS OF RR INTERVAL VARIABILITY IN 30 MIN RECORDS

Subject	Mean value RR interval (s)	Standard deviation RR interval (s)
1	0.869	0.11
2	0.785	0.08
3	0.819	0.12
4	0.759	0.07
5	0.809	0.06

E. Power consumption and battery life

The consumption of the device at rest is 0.1 mA, when the FPGA is initialized, the current consumption rises for a few seconds to 155 mA until the configuration of the prototype ends, which does not exceed 10 s. Once the device configuration is complete, the current stabilizes at 125 mA in normal operation. Once in operation, the prototype is powered at a voltage of 5 V, which resulted in a power consumption of 625 mW/h.

The device has two rechargeable batteries (HQS-606090p) connected in parallel with a voltage of 3.7 V and 4000 mA/h each, which through the TP4351B component raises the voltage to 5 V. These batteries have an ideal power of 29.6 W/h, which allows a theoretical operating duration of the device of 47.36 h. In practice, the device does not have that performance, since it is only possible with an ideal energy transfer, which could be verified in a duration test. In the duration test, a 30 h device performance was achieved, exceeding the minimum 24 h continuous operation requirement.

IV. CONCLUSIONS

In this work, a prototype of an ambulatory ECG monitoring system for the acquisition and storage of 3 simultaneous leads, with an R wave detection algorithm based in the continuous spline wavelet transform to obtain the beat-to-beat heart rate in real time in 2 leads, and the visualization of the results obtained was developed. To achieve this goal were implemented in the VHDL hardware description language, the communication protocols of the FPGA with the ADS1294 and with the micro SD memory.

The prototype developed fulfills the requirements of high CMRR, bandwidth, resolution and long-term, and the R wave detection algorithm tested on five 30 min recordings has an accuracy of 99.4%. In comparison with a commercial device, the main advantages is that the proposed prototype detects and stores the beat-to-beat heart rate in real time, has a higher resolution and a higher sampling rate. Therefore, it can be used for clinical diagnosis and for the long-term analysis of the RR interval or heart rate variability (HRV). As future work, the objectives will be to reduce the size, weight and power consumption of the prototype.

REFERENCES

[1] World Health Organization (WHO). (24/5/2018). “The top 10 causes of death,” In: News, Fact sheets, Detail, Available from: https://www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death [Accessed: 19/3/ 2019]

[2] M. H. Crawford, S. J. Bernstein, P. C. Deedwania et al. “ACC/AHA guidelines for ambulatory electrocardiography,” J. Am. Coll. Cardiol., vol. 34, no. 3, pp. 912–948, 1999.

[3] H. L. Kennedy, “The history, science, and innovation of Holter technology,” Ann. Noninvasive Electrocardiol., vol. 11, no. 1, pp. 85–94, 2006.

[4] H.L. Kennedy, “Use of long-term (Holter) electrocardiographic recordings,” in: Cardiac Electrophysiology: From Cell to Bedside, D.P. Zipes and J. Jalife, Eds. Philadelphia: Saunders, 2004, pp. 772–787.

[5] R.E. Kleiger, P.K. Stein, J.T. Bigger Jr., “Heart rate variability: measurement and clinical utility,” Ann. Noninvasive Electrocardiol, vol. 10, no. 1, pp. 88–101, 2005.

[6] L. Du, Y. Yan, W. Wu, Q. Mei, Y. Luo, Y. Li, L. Wang, “Towards a smart Holter system with high performance analogue front-end and enhanced digital processing,” in Proc. 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Osaka, Japan, pp. 1210–1213.

[7] S. Zhang, Y. Ma, L. Tian, “Design of a dual-core Holter Systerm Based on STM32 and FPGA,” in Proc. 2nd International Conference on Computer Science and Electronics Engineering (ICCSEE 2013), Hangzhou, China, pp. 1486–1489.

[8] A. Shukla and L. Macchiarulo, “A fast and accurate FPGA based QRS detection system,” in Proc. 2008 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS), Vancouver, BC, Canada, pp. 4828–4831.

[9] R. Stojanović, D. Karadaglić, M. Mirković, D. Milošević, "A FPGA system for QRS complex detection based on integer wavelet transform," Measurement Science Review, vol. 11, no. 4, pp. 131–138, 2011.

[10] H.K. Chatterjee, R. Gupta, J.N. Bera, M. Mitra, "An FPGA implementation of real-time QRS detection," in Proc. 2011 2nd International Conference on Computer and Communication Technology (ICCCT-2011), Allahabad, India, pp. 274–279.

[11] T. Li, Yi. Ma, Yu. Ma, X. Lu, "The real-time R-wave detection based on FPGA," in Proc. 2014 7th International Conference on BioMedical Engineering and Informatics (BMEI 2014), Dalian, China, pp. 393–398.

[12] F. Martínez-Suárez, "Prototype of a Long-Term ECG Ambulatory Monitor of 3 leads with QRS complex detection in real-time using the wavelet transform implemented on FPGA," Master's Thesis, Bioelectronics Section, Department of Electrical Engineering, Cinvestav, Mexico City, Mexico, 2018, (In Spanish).

[13] Low-Power, 8-Channel, 24-Bit Analog Front-End for Biopotential Measurements ADS1294/6/8, Texas Instruments Inc., SBAS459D May 2010.

[14] Tarjeta microSDHC / microSDXC Clase 10 UHS-I, Kingston Technology Corporation, 2017.

[15] Basys3 ™ FPGA Board Reference Manual, Digilent Inc., 2014.

[16] C. Alvarado, J. Arregui, J. Ramos, R. Pallàs-Areny, "Automatic detection of ECG ventricular activity waves using continuous spline wavelet transform," in Proc. 2005 2nd. International Conference on Electrical and Electronics Engineering (ICEEE), Mexico City, Mexico, pp. 189–192.

[17] J. J. Bailey, A. S. Berson, A. Garson Jr., L.G. Horan, P.W. Macfalane, D.W. Mortara, C. Zywietz, "Recommendations for standardization and specifications in automated electrocardiography: bandwidth and digital signal processing," Circulation, vol. 81, no. 2, pp. 730–739, 1990.