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Ambulatory Electrocardiogram Prototype

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Abstract

The use of electrocardiogram nowadays, is very important in diagnosis of heart disease. The emergent increase of portable technology provides medical monitoring of vital signs allowing freedom of movement and watching during normal activity of the patient. In this study, it is described the development of a prototype of an ambulatory cardiac monitoring system using 3 leads. The systems consists on conversion of an analog signal, having been previously processed and conditioned, into digital ECG signal and after processed with a microcontroller (MCU). The heartbeat rate can be observed in an LCD display. The LCD display is also used as the interface during the setup process. All digital data stream can be stored on a SD memory card allowing the ECG signal to be accessed later on a PC.

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1. Introduction

More and more cardiac diseases are more and more the main cause of globally concern, mostly as a consequence of eating habits and lifestyle. Although widely studied, electrocardiogram is one of the bio potentials most studied ever. The electrical events detected at body surface, become a good way to analyze the performance and the physiological function of the heart [1].

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Technological advances in medicine has been a great asset, being applied in the prevention, diagnosis and monitoring of many diseases. An ambulatory electrocardiogram records all the electrical activity of the heart while the daily life is preformed ("Ambulatory-freedom of movements"). The ambulatory monitoring may also be known as, Holter, or an electrocardiogram that can register the cardiac history for a period of 24 hours.

The Holter detects each abnormality during the execution of activities. Several cases of arrhythmias occur when least expected. The importance of irregular heartbeat is dependent on several factors such as: the ECG pattern produced, the frequency and the duration of events, the frequency and the duration of events combined with other symptoms detected at same time [1-3]. The continuous monitoring for a long time period provide registry of all heart activity during physical activities of daily life.

The normal electrocardiogram is formed by P wave, QRS complex and T and U waves as can be seen in Fig. 1. The P waves represent the atrial depolarization being, at a normal electrocardiogram, an initial small deflection in each cardiac cycle. It has an apex with normal duration, which varies from 0.09 to 0.11 seconds [4]. The QRS complex, has fast deflections produced during the ventricular depolarization. The ascending deflection is the R wave, and any descendant deflection proceeding the R wave is called the S wave. The normal duration (between Q and S) does not exceed the 0.09 seconds. In the heart of the human being, the ventricular repolarization occurs in the same sequence as the depolarization. The T wave represents the ventricular repolarization and has a mean duration of 0.20 seconds.

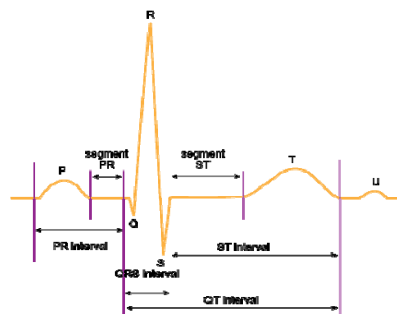


Fig. 1. P, QRS and T complex of one cycle of ECG signal.

The amplitude of the potentials captured by the electrodes varies with the type of electrodes used and its location in the body. Silver/silver chloride (Ag/AgCl) electrodes placed on the chest near the heart can capture potentials up to 5 mV. However, if the electrodes are placed in members, such as pulse, the typical value is 1 mV. Typical amplitudes are around 1 mV for R wave until a minimum S wave, between 0.1 to 0.3 mV for the P wave, and finally these values are between 0.2 and 0.3 mV for the T wave.

Concerning the quantity and electrodes localization in the body surface, this is dependent of the type of exam and diagnosis required. For this type of exam there is a standard convention in the placement of electrodes when ECG exam is performed, called standard bipolar limb lead [5-7].

In this project we proposed the use of three leads to be placed on the chest in order to obtain greater accuracy in the signal, although low-frequency noise caused by movement of the members can occur [2] and [8].

The motivation which led to this project achievement was the possibility of designing a low cost prototype capable of overcoming several requirements, such as the ability to perform cardiac monitoring operations and at the same time of diagnosis, which allows that entities such as schools, or rehabilitation clinics have the possibility to incorporate this type of devices. As expenses decrease, the technicians can more easily monitor their athletes or patients, combining the possibility of transferring data to a terminal via wifi, which allows that highly qualified medical staff and the area of cardiology can access them remotely and give a more accurate diagnosis, without being needed the patient presence.

2. Development

The signal acquisition is made through Silver/silver chloride disposable electrodes connected to the configuration illustrated in Fig. 2.

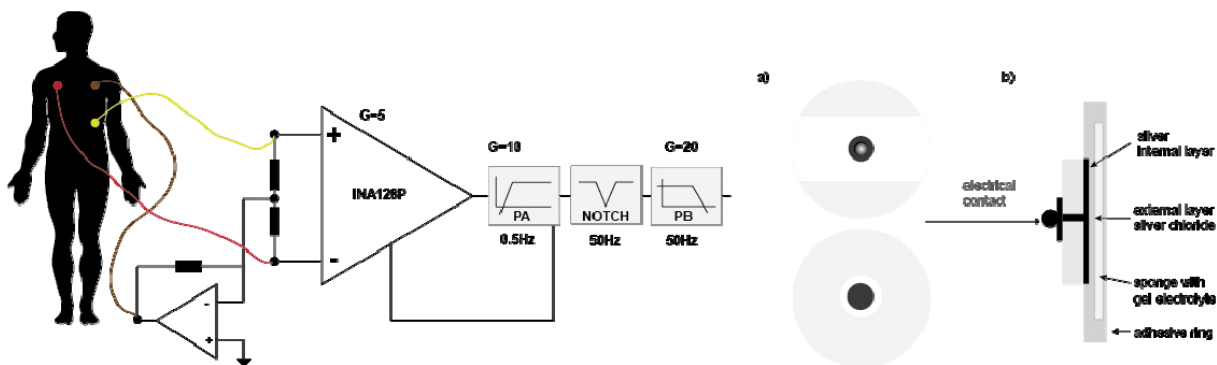


Fig. 2 - Signal acquisition in differential mode. a) - Silver Chloride Electrode. b)- Structure of an Electrode.

The instrumentation amplifier (INA128) receives the input signals captured by the electrodes with configuration lead II [1-2], placed in the left and right chest to obtain the signal in differential mode. A third electrode is placed near the floating rib. According to the nature of the acquired signal, about 5 mV, it is required a gain of about 1000 times, which is implemented in three amplification stages. The first stage is done in the instrumentation amplifier, with a gain of 5, the second stage, with a gain of 10, corresponding to an active high-pass filter with a cutoff frequency of 0.5 Hz. The last amplification stage, with a gain of 20 is obtained with an active low-pass filter with a cutoff frequency of 50Hz, that matches the maximum frequency used in cardiac signal monitoring, Fig. 3.

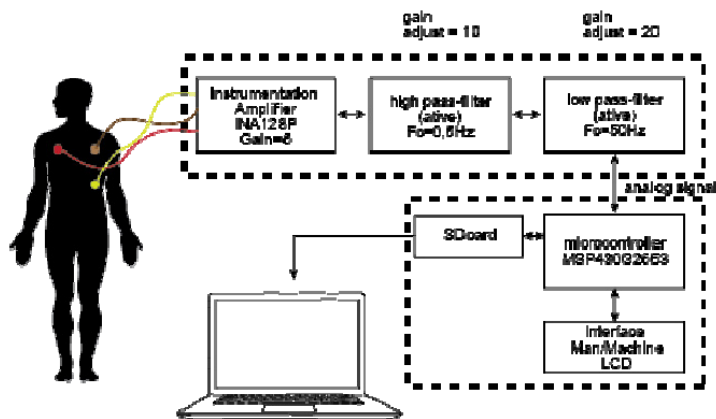


Fig. 3 - Detailed prototype diagram in development blocks.

Fig. 4 presents the electronic circuit of the first stage (Instrumentation amplifier) that is supplied through a single supply voltage (5V), by a device portable monitoring.

Although the instrumentation amplifier (INA128P) is double supply with symmetrical voltages, there is the possibility to operate with 0-5 V of the available single supply. It is needed that the part of the circuit in which it operates has their all ground points to 2.5V (half of 5V). Obtaining a virtual ground, requires the development of an extra circuit block (U5), making the main circuit more complex.

$$V_{out} = \left(\frac{R_{21}}{R_{20} + R_{21}} \right) V_{in} \tag{1}$$

The voltage divider (Eq. 1), with R_{20} and R_{21} both with $3.3k\Omega$, gives the required $2.5V$. In order to stabilize the voltage a buffer has implemented, providing in its output a standardized and stable voltage. Therefore the $2.5V$ voltage line is connected to the non-inverting input of operational amplifier (U1) and to the reference pin of INA128P. The INA128P is connected with two gain resistors (R_4 and R_5), with equal value, any DC component in common mode present at the two inputs will change the DC level at the junction of resistors. The signal between these resistances is the average of the two signals captured by the electrodes connected on the chest. Afterwards, it passes through a voltage follower U2, with its output applied to U1, The circuit with U1 is an inverter amplifier supplied by the floating rib electrode. The gain of this scheme is given by Eq. 2.

$$G_{U1} = -\frac{R_2}{R_3} \tag{2}$$

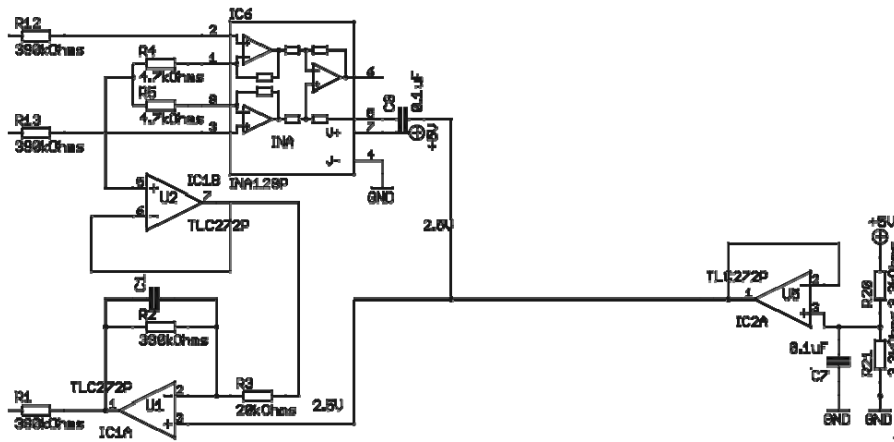


Fig. 4 - ECG analogue signal conditioning.

Using R_3 and R_2 with $20k\Omega$ and $390k\Omega$, respectively, by equation 2 gives the gain of 19,5.

The complete configuration of Fig. 4 creates a negative re-alimentation, which leads the voltage in the common-mode to a lower value, increasing the common mode rejection. The instrumentation amplifier has a gain given by Eq. 3.

$$G_{INA128} = 1 + \frac{50k\Omega}{R_4 + R_5} \tag{3}$$

INA128P datasheet, gives the values for R_4 and R_5 for an approximate gain of 5. The gain could be obtained from a single gain resistor connected between the input 1 and 8 of the amplifier. The inexistence of the exact value of gain resistor, suggests the use of a serial association of R_4 and R_5 with common resistor values of $4.7k\Omega$, getting a gain of 6,32.

2.1. Signal conditioning

The signal obtained with the scheme shown in Fig. 4, has the characteristic of varying its baseline with body movement, requiring a high-pass (HP) filter to attenuate the respective fluctuations. Another noise that overlaps with

desired signal is the main noise of 50Hz, with significant amplitude compared to the desired signal, requiring a notch or a low-pass (LP) filter that attenuate this frequency component.

Regarding the frequencies that are intended to filter, two second order Sallen-Key filters were implemented, a high-pass followed by a low-pass as illustrated in Fig. 5. The output signal of the instrumentation amplifier (pin 6) is connected to the input of the second order high-pass filter (Op-Amp U3).

In order to delimit the cut-off frequency between 0.5 for HP filter and 50 Hz for LP filter, the bandwidth (BW) can be determined by $BW = f_{c2} - f_{c1} = 50 - 0.5 = 49.5\text{Hz}$. The center frequency or resonance can be calculated in two ways, by geometric mean or using the arithmetic mean, if the bandwidth is too small relative to the center frequency it's possible to use the arithmetic mean for calculate the approximate resonance frequency, where $f_0 = (f_{c2} + f_{c1})/2 = 25.25\text{Hz}$ and the Q factor, $Q = f_0/BW$, therefore it's equal to 0.51.

Considering the high-pass filter (U3), choosing, for calculation purposes, the same values for capacitors C_2 and $C_3 = 3.6 \mu\text{F}$, assigning the value of 33kΩ to R_{10} resistor, Eq. 4 gives $R_9 = 240 \text{ k}\Omega$.

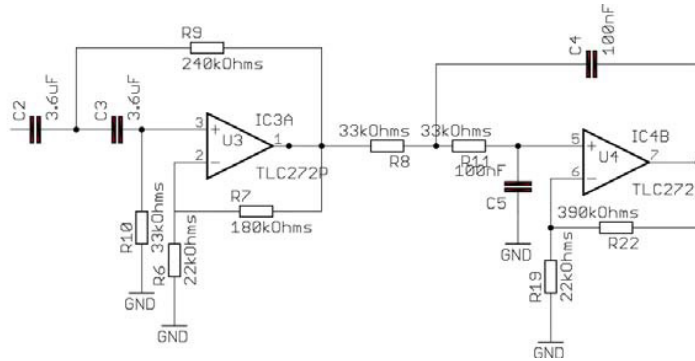


Fig. 5 - Sallen Key filters chain: High Pass and Low Pass.

$$Q = \frac{\sqrt{R_{10} R_9 C_2 C_3}}{R_9 (C_2 + C_3)} \tag{4}$$

$$f_c = \frac{1}{2\pi\sqrt{R_{10} R_9 C_2 C_3}} \tag{5}$$

The closest commercial values available is $C_2 = C_3 = 3.3\mu\text{F}$, $R_9 = 240\text{k}\Omega$ and $R_{10} = 33\text{k}\Omega$, which with the Eq. 5, forms new parameters $f_0 = 25.27\text{Hz}$, $Q = 0.5109$ and $BW = 49.46$.

For these values the real cutoff frequency was slightly modified to $f_c = f_0 - BW/2 = 0.54\text{Hz}$.

The low-pass filter with the Op-Amp U4, will remove the 50 Hz component and will work also as anti-aliasing filter for later conversion ADC.

Choosing values for $R_8 = R_{11} = 33 \text{ k}\Omega$, the capacitors should have a capacity $C_4 = C_5 = 100 \text{ nF}$. This way, the cutoff frequency is now 48,23 Hz.

Fig 6 presents the frequency response of low-pass and high-pass filters.

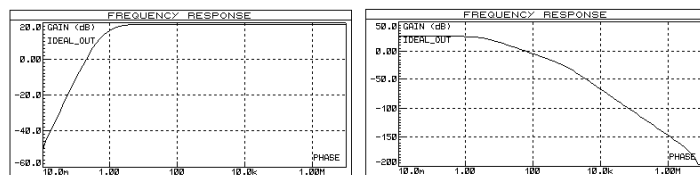


Fig. 6 - Frequency response of the High Pass and Low Pass filters.

2.2. Amplification

The gain of both filters are applied to amplify the signal. In the high-pass filter (U3) with the feedback of the inverting input it is possible to achieve a gain in the order of 10. Likewise the low-pass filter (U4) reaches a gain approximate to 20. Eq. 6 and 7 were used for the calculation of respective gains Eq. 8 gives the total gain of the circuit $G=1000$.

$$G = \frac{R_6 + R_7}{R_6} \quad (6)$$

$$G = \frac{R_{19} + R_{22}}{R_{19}} \quad (7)$$

$$G_{total} = G_{INA} \times G_{HP} \times G_{LP} \Leftrightarrow G_{total} \quad (8)$$

2.3. MicroController

Although the signal acquisition is a fundamental part of the design, the microcontroller plays in this step, an important role in decision of some processes, becoming this way the brain of all operation. The need to acquire, process and store the ECG signal requires the microcontroller to be programmed (C language).

The MSP430G2553 of Texas Instruments is a low-power device, engaged to a set of peripherals for several applications. The architecture, combined with 5 V supply and low levels consumption is optimized to maximize battery life in portable applications.

To perform the acquisition and processing, the microcontroller has several ports that can be used to convert analog to digital signals (ADC). This block will be responsible for the conversion of the ECG analog signal to a binary sequence (digital signal). Through the microcontroller the signal is stored and processed immediately. An LCD device (see Fig. 3) was used to implement a man/machine interface that allows the user to set the date and time of the start of the acquisition. After insertion of these data, the microcontroller uses the ADC channels, to start conversion, processing the signal and storing in an SDcard, in a text file in ASCII format. While this processing is done, the patient can visualize some information on the LCD. Namely, the average heart rate determined by the microcontroller during a short period.

2.4. Visualization and Storage

The visualization in a 2 lines LCD implements the man/machine interface. The display will allow the initialization of some variables for the monitoring process like set the clock, set the onset and offset monitoring time and show some information during the cardiac monitoring phase like the beat rate or other details to be developed.

The transfer of data between a handheld device and a PC has become increasingly simple with the appearance of memory cards such as SD (Secure Digital), MMC (Multimedia Card) among others. For data to be clearly legible on the PC it should be stored using a file system supported by operating system. The DOS file allocation table and the file system (FAT) is used. The SD card can be controlled via the SPI mode (see Fig. 7) that allows a serial communication. This transmission can be implemented as a peripheral of MSP430. Files are stored in the SD card in *.txt format, with ASCII code.

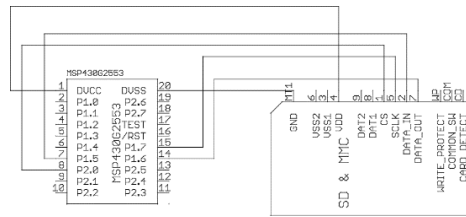


Fig. 7 - SD card-connection scheme via SPI.

2.5. Firmware

The microcontroller MSP430G2553 has a development board, Launchpad, allowing the microcontroller to be programmed by an interface that is used to compile the program. The compiled program code is transferred through an interface known as JTAG. A variety of compilers are available for the MSP430 family devices. The Code Composer Studio (CCS) was selected.

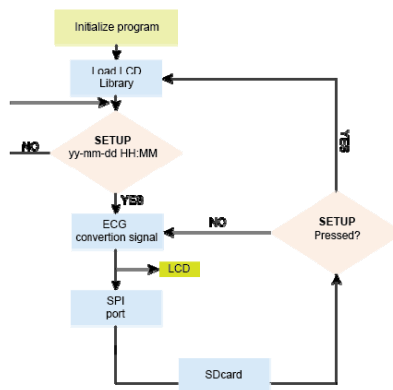


Fig. 8 - System Operation Flowchart.

The project development of firmware, is composed of source file, header file and library file. Each of these files are an integral part of the program when compiled. Fig. 8 illustrates the flowchart of the main cycle of the program code. By default, when starting a program debugging, the *main.c* file will start running. This is the main file, and the remaining files should be attached. The hardware has assembled with three buttons. The SETUP button, causes a state machine trigger. Then, the parameters, like date and hour or others, can be adjusted by the user. The other two buttons (+ and -) allow the increase or decrease of initial values. The SETUP button allows the user to change the state.

3. Discussion

During acquisition of the electrocardiogram signal, various amplification tests and filtration were performed in order to remove noise. The single supply 0 and +5 V power, introduced additional complexity in selection of the electronic integrated circuits. But the use of symmetric power would result in inefficiency, once this should be a mobile device. INA128P can work with single supply since the circuit in which it operates has their ground point to 2.5V (half of 5V). There is also need to make the capacitive decoupling DC of the remaining parts of the circuit.

In the stages with high pass and low pass filters the main difficulties relay with the available components values, in particular resistors and capacitors. The difference between the calculated values and the commercially available resistors and capacitors values, lead to several iterations to determine and find resistors and capacitors.

The MSP430 microcontroller can perform A/D conversion with 10 bits, therefore, the binary number that represents the result of the conversion may vary over the range 0-1024.

The microcontroller program was made with the help of the CCS application. One of the difficulties was the control of the sampling frequency. The sampling frequency is set to 200 kHz that is too much for this application, turning too heavy the whole process of sending data through the SPI. The sampling frequency should be reduced to about 200 Hz by a decimation operation with $M=1000$.

The configuration of the serial port to be used as debug allowed to observe the data storage in SD card. The high sampling rate also difficult the correct writing on the memory card.

4. Conclusions

The paper presented the development detail of a system to record the EEG signal with three leads in a portable device. The system has an LCD to allow the interface with user and present directly some basic information about the ECG signal. An SD card allows to store the ECG data over several days.

The three leads are connected to an instrumentation amplifier (INA128) that is connected to a high-pass and low-pass Sallen-Key filters to keep the bandwidth between 0.5 and 50 Hz of the ECG. The three stages of amplification gives a gain about 1000. The signal is then converted into digital by the microcontroller (MSP430). The signal is stored in an SD memory card and some information can be presented on the LCD.

In the future, some changes are expected, so that the unfamiliar users with the medical area are able to access information, including the implementation of an application that allows to reveal several changes related to heart rhythm, signaling possible cardiac arrhythmias such as bradycardia or tachycardia. The addition of a wifi module will allow the patient to be remotely monitored since there is an access point, which can be a wifi network, or mobile device with Internet access.

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