Paper

Design and Implementation of an Embedded System for Ambulatory Cardiac Monitoring

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Abstract—Cardiac monitoring in the environment of the subject is one of the major fields of telemedicine. In this paper we present a prototype of embedded system for acquisition, storage, display on LCD or PC and transfer via GSM alarm warning in case of arrhythmias, which allows a great opportunity for rapid intervention of the physician. In terms of hardware, we have designed and implemented our system with a modular approach to facilitate development and debugging. Thus the system comprises three modules: analog module, digital module microcontroller-based for certain pretreatment, and a GSM communication module. Of course, there is appropriate software behind the material described. The system has the following features: low cost, ease to implement and versatility.

Keywords*—*arrhythmia, ECG, embedded system, GSM communication, heart rate, telemedicine.

1. Introduction

In recent years, technological development especially in microelectronics and software engineering have allowed the emergence of powerful processors (microprocessors, microcontrollers, digital signal processors, FPGA, etc.) for embedded systems, sophisticated personal computers (PC) and communications networks with varied standards (TCP/IP, GSM, Bluetooth, Wi-Fi, ZigBee, etc.). The hospital industry benefits from these assets and produces more reliable equipments, user friendly and accessible to a wide range of social strata, allowing, among other things, saving more lives and creating valuable data for research and diagnostic.

An interesting scenario is to monitor people with heart disease who may at any time be subject to a heart attack. In this context, the system we have designed and implemented is a simple prototype example of an embedded system for such scenario.

Without claiming to be exhaustive, we report that a number of studies have concerned the ECG signal (Electrocardiogram), based on standard databases [1], or by developing a standard ECG acquisition module or dedicated ASIC [2]–[4]. Other researches suggested software solutions for signal processing to reduce noise and classification of cardiovascular diseases [5], [6], remote monitoring via Bluetooth [7] or via an RF module integrated into a microcontroller [8].

This work concerns an embedded system based on standard and cheap components, built around the microcontroller PIC16F876 for the acquisition of the ECG, its storage, visualization and detection of arrhythmias with alert message transmission via GSM.

2. System Description

Figure 1 shows the block diagram of the system inspired, among others, by the application note from Analog Devices [9], common reference for many projects of this kind. The system presented is designed with a modular approach to facilitate the development and debugging. Thus, it includes three modules:

- acquisition module,
- microcontroller-based digital module,
- GSM communication module.

The ECG signal is the measure on the body surface (skin), of the electrical potential generated by the heart's electrical activity. Reading it allows an accurate evaluation of the performances of the heart.

As shown in Fig. 2, the ECG is characterized principally by 5 waves reflecting the different functions of the heart during a cardiac cycle; these waves are called by the successive letters of the alphabet P, Q, R, S and T [10].

It is then question to acquire the ECG signal typically characterized by a maximum amplitude of 1 mV and a bandwidth of 0.05 Hz to 100 Hz; also, a such signal is normally subject to several sources of noise: bad contacts and movement of the electrodes, contraction muscles, electromagnetic interference by inductive coupling, and 50 Hz or 60 Hz power line through capacitive coupling; this latter source is by far the most dominant.

Like any embedded system, our application has a hardware aspect and a software aspect. In turn the hardware consists of an analog part and a digital part.

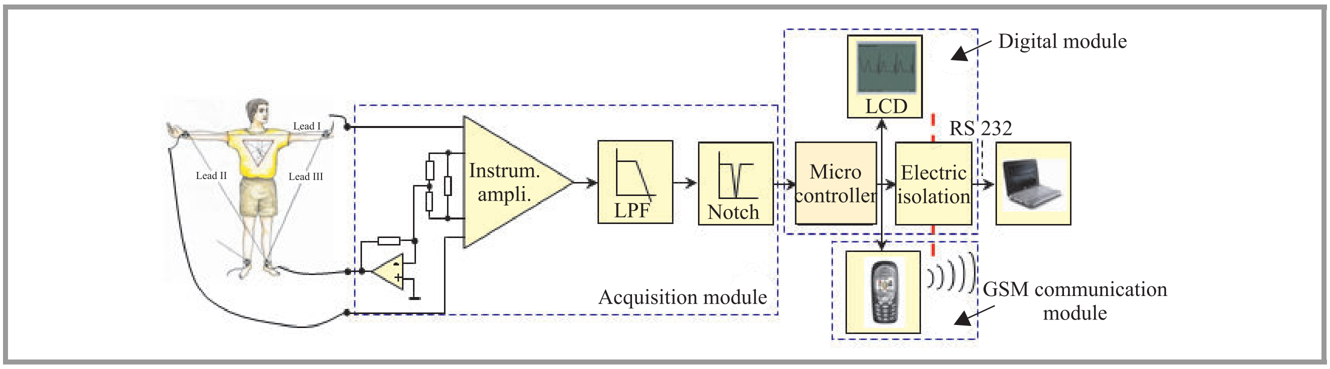


Fig. 1. Block diagram of the system.

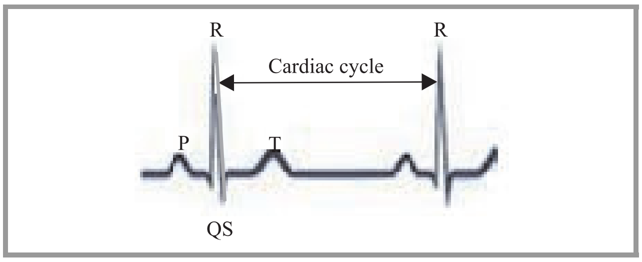


Fig. 2. The ECG waves.

2.1. Hardware Aspect

2.1.1. Analog Part

The analog module has two stages:

- an instrumentation amplifier,
- an analog filter.

As in most wearable ECG, our system uses lead II of the Einthoven's triangle, which is enough for a quick review. The two electrodes of this lead II, connected to the arms or on the chest, are applied to a differential instrumentation amplifier (IA) that we have achieved with cheap conventional operational amplifiers with acceptable performances, particularly a relative good Common Mode Rejection Ratio (CMRR), see Fig. 3.

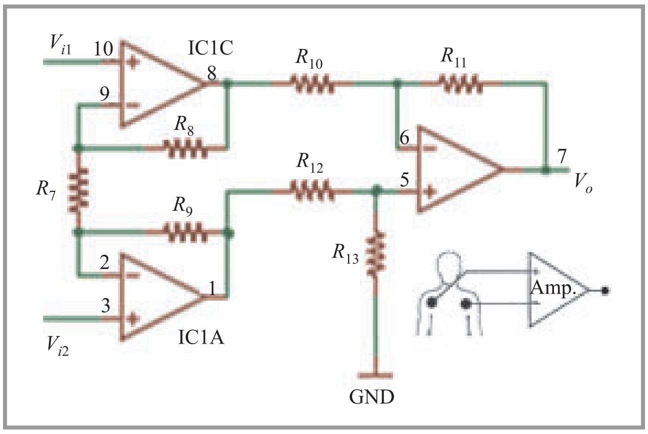


Fig. 3. Instrumentation amplifief with the LM324.

The amplification is expressed as:

$$V_0 = \left(1 + \frac{2R}{R_7}\right)(V_{i1} - V_{i2})$$

where R is the value of all the resistors except R_7.

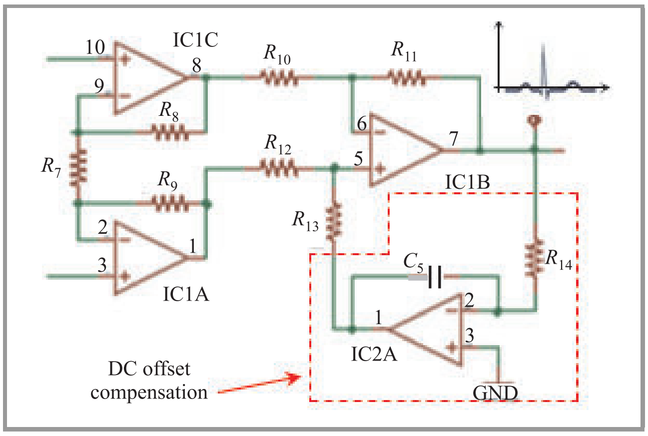


Fig. 4. DC offset compensation (baseline wander).

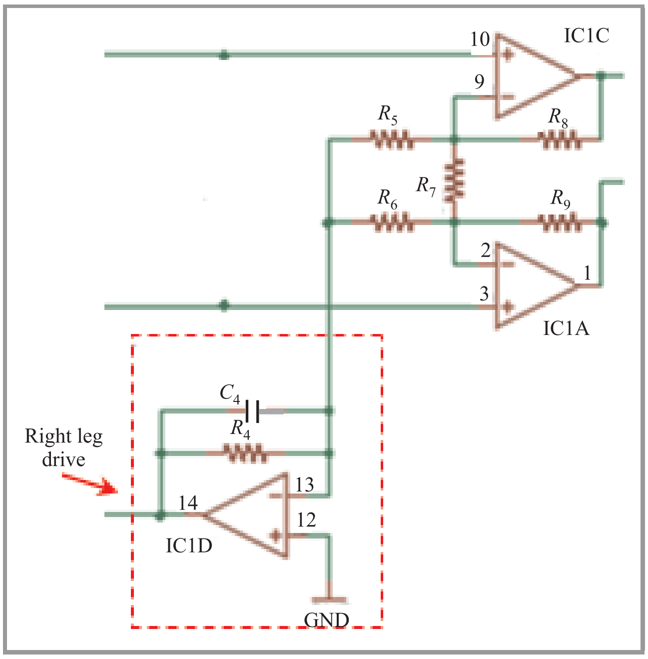


Fig. 5. Right Leg Drive.

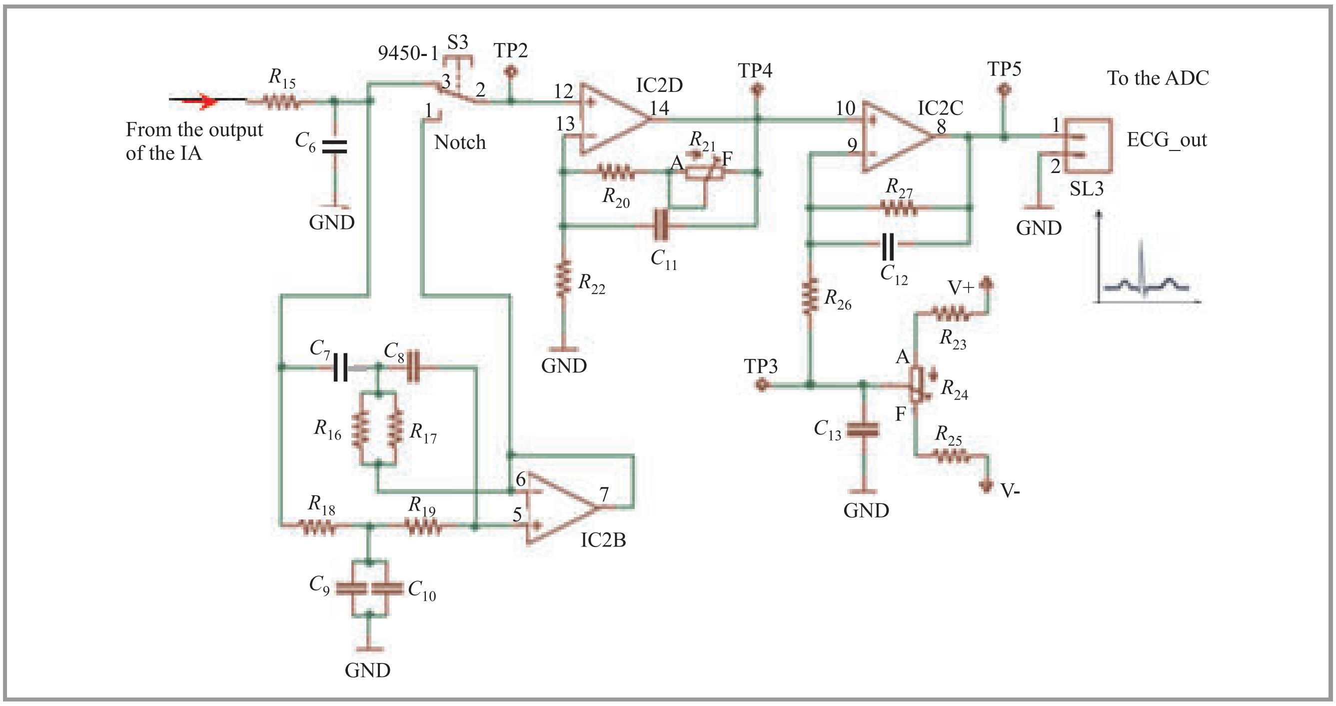


Fig. 6. Filters structure.

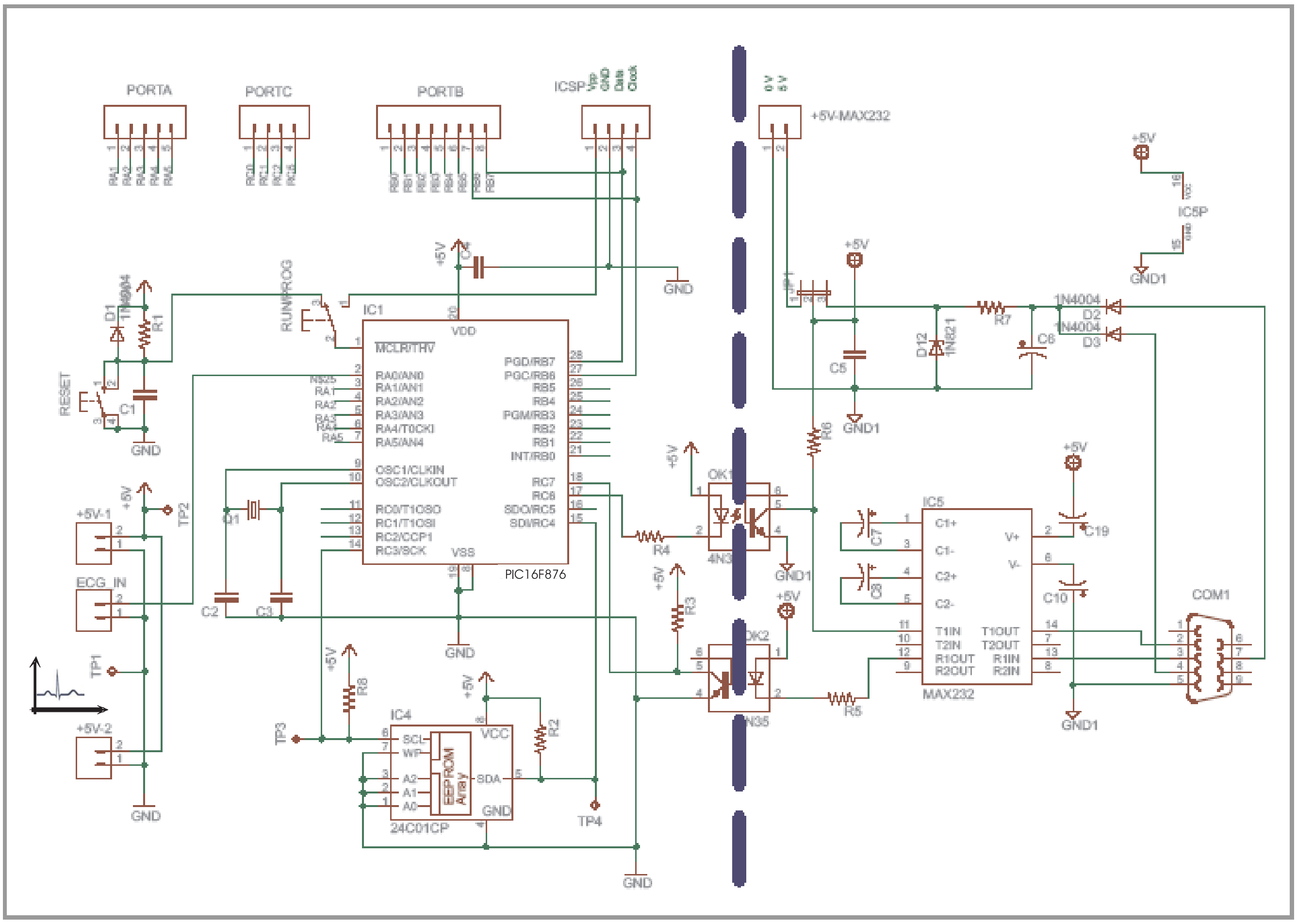


Fig. 7. Digital module.

To avoid the effect of baseline wander (isoelectric line drift), caused among others by electrodes movement, we add a control loop which detect the DC component due to this phenomenon by a low pass filter (RC circuit) and inject that component to the input, that is the reaction with IC2A in Fig. 4 [11]; thus, the final result is that the output signal of IA is adjusted automatically to a null DC component.

As in the modern electrocardiograph [12], the reference electrode is connected, with feedback, to the right leg via an amplifier to reduce common mode noise, a principle commonly known by the “Right leg drive”. Figure 5 depicts the implementation of such a circuit.

The amplification stage is followed by an analog active filtering stage (Fig. 6). Thus, the different types of noise are first reduced by low pass filter (R_{15}, C_6) with band pass up 70 Hz and an optional notch filter for 50 Hz power line noise (IC2B). This latter operates only if the 50 Hz noise is at a high level; indeed, the 50 Hz frequency is natural component of the ECG’s spectrum.

The system is battery powered, which contributes efficiently to improve the noise immunity, particularly against the 50 Hz power line noise. The last stage (IC2C) of this analog module is an anti-aliasing low pass active filter (Shannon sampling theorem), with adjustable DC offset, via R_{24}, allowing the output of this stage having an amplitude comprised between 0 and 5 V, which is required by the built-in analog to digital converter (ADC) of the microcontroller. The global amplification of the entire measuring chain is around 1000, as typically required.

2.1.2. Digital Part

The output signal of the analog module is then applied to the ADC of this digital module, and it is sampled at frequency of 200 Hz respecting the condition of Shannon. As shown in Fig. 7 this module includes primarily:

- a microchip PIC16F876 microcontroller, as hard core of this structure,
- an I2C EEPROM for storing samples of the digitized ECG,
- RS232 interface for communication with PC with galvanic isolation; the same interface is used for GSM communication,
- a graphic display LCD for displaying the signal and heart rate.

The choice of the PIC16F876 [13] is dictated by, among other things, its popularity, its price/quality ratio and the abundance of documentation and development tools. Thus, the analog signal ECG drives an analog input of the μC (RA0) configured in unipolar mode; the sampling frequency F_S is chosen equal to 200 Hz ($T_S = 5$ ms), principally because of the response time of EEPROM [14], which is around 3 ms. The EEPROM communicates with I2C protocol [15].

The sampled signal is saved in the I2C EEPROM, 24LC256, with a storage capacity of 256 kbits, that is 32 kbytes (IC4). Thus, with F_S of 200 Hz, we can record up to 2 mn 43 s for a further off-line treatment:

$$T_S = \frac{32 \times 1024}{200} = 163.84 \text{ s} \approx 2 \text{ min } 43 \text{ s}$$

The μC have built-in RS232 interface that permits serial communication with a PC or GSM, via his serial port. A classic MAX232 [16] achieves the RS232/ TTL conversion (physical layer protocol). With this point to point link, we transmit the sampled ECG to the PC for storage in hard disk and treatment in real-time or off-line (filtering, analysis, displaying, etc.).

The LCD displays the ECG signal and heart rate; we have used a popular and cheap graphic LCD. This is a mobile phone spare part available on the market, the Nokia 3310 which have acceptable features [17]:

- resolution of (84 × 48 pixels as shown in Fig. 8), it can display up 6 lines of 14 characters in the form of a matrix of (8 × 5) pixels with a good contrast,
- easy to drive as illustrated in Fig. 9,
- consumption of 110 μA under 3.3 V,
- controled by Philips PCD8544 [18].

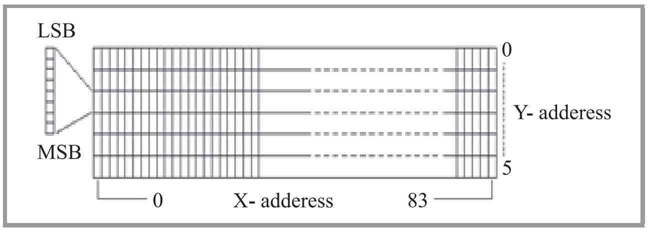


Fig. 8. LCD RAM addressing.

Personal safety is a central point for medical equipment; in fact, the subject is in direct contact with electrical voltages, and care should be taken to protect him by ensuring that the currents flowing by him respect the standards such as those of the AAMI (Association for the Advancement of Medical Instrumentation) [19]. In all cases, the currents must not exceed a value of 50 μA. In order to comply with this standard, among the techniques used for the safety of the subject, we have chosen (Fig. 10):

- using the battery power (±(3–9) V) for the entire analog and digital circuitry,
- galvanic isolation with infrared optocoupler, between the digital module and the PC, which is normally powered from the mains (220 V, 50Hz),
- clipping by diodes and current limiting in case of any electrical accident (direct contact of the line with the circuitry).

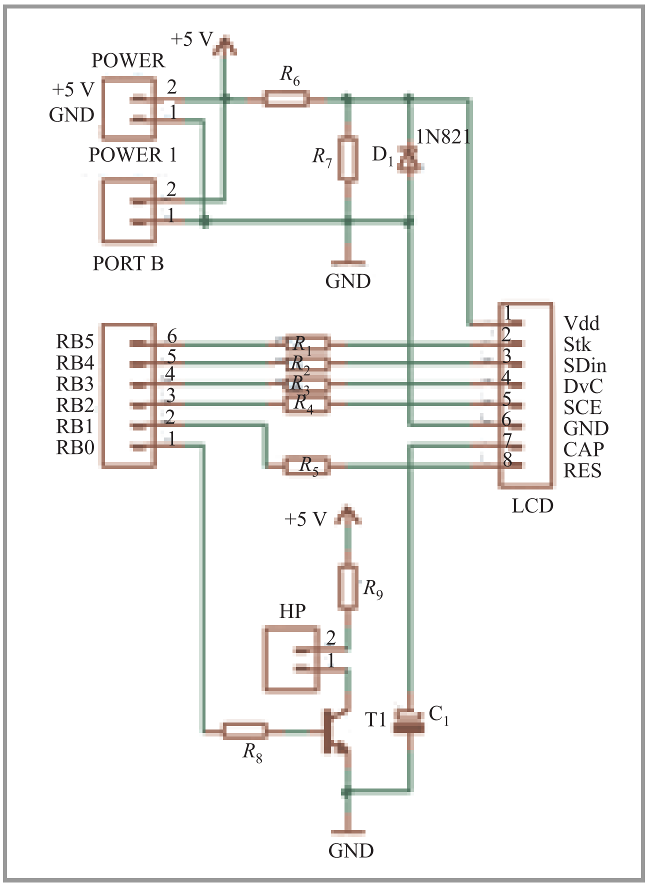


Fig. 9. ILCD control.

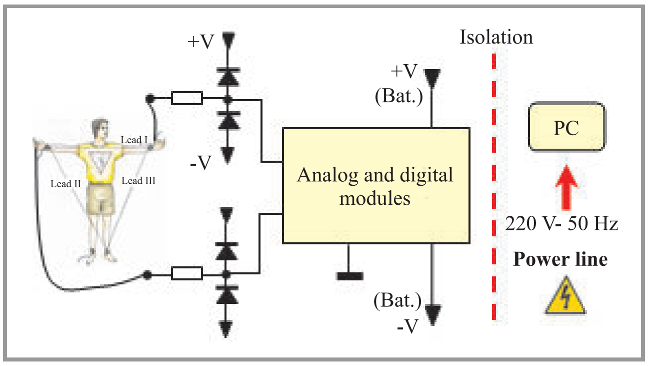


Fig. 10. Subject safety.

2.2. Software Aspect

This section treats the software aspect of our application; thus, we discuss the used software structures: the development tools, the various programs developed for microcontroller and PC.

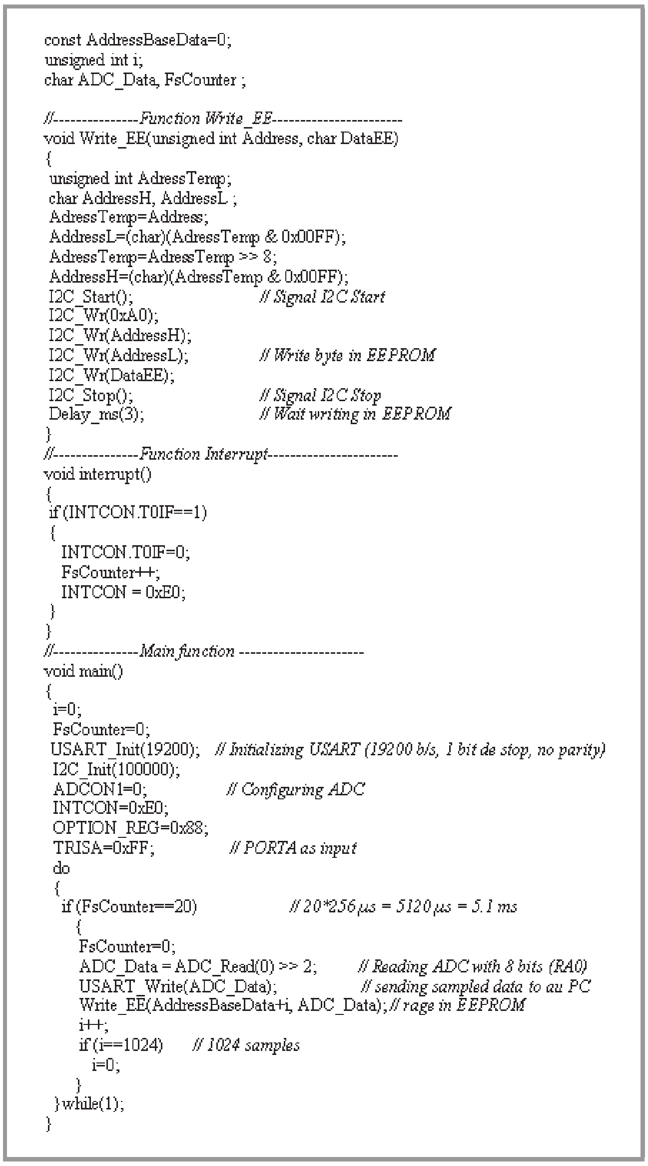
2.2.1. μC Side

We opted for the following tools:

- The C compiler mikroC of MikroElektronika for all programs on the microcontroller, because such a compiler is rich in libraries for standard peripherals (keyboard, displays, EEPROM, etc.).
- The environment Microsoft Visual Basic (VB6) for the graphical user interface (GUI) on PC; in fact, this environment is one of the most used in the development of Windows applications.
- The MATLAB software for the calculation of digital filters.

It is then question to write a code that manages information related to all the devices that we have already briefly described in the hardware aspect of the system:

- acquisition of the ECG signal,
- storage sampled data in EEPROM,
- serial asynchronous communication,
- LCD display,
- audio signal,
- human/machine interface (buttons/LEDs).



```
const AddressBaseData=0;
unsigned int i;
char ADC_Data, FsCounter ;

//---------------Function Write_EE----------------------
void Write_EE(unsigned int Address, char DataEE)
{
 unsigned int AdressTemp;
 char AddressH, AddressL ;
 AdressTemp=Address;
 AddressL=(char)(AdressTemp & 0x00FF);
 AdressTemp=AdressTemp >> 8;
 AddressH=(char)(AdressTemp & 0x00FF);
 I2C_Start();                   // Signal I2C Start
 I2C_Wr(0xA0);
 I2C_Wr(AddressH);
 I2C_Wr(AddressL);              // Write byte in EEPROM
 I2C_Wr(DataEE);
 I2C_Stop();                    // Signal I2C Stop
 Delay_ms(3);                   // Wait writing in EEPROM
}
//---------------Function Interrupt----------------------
void interrupt()
{
 if (INTCON.T0IF==1)
 {
   INTCON.T0IF=0;
   FsCounter++;
   INTCON = 0xE0;
 }
}
//---------------Main function ----------------------
void main()
{
 i=0;
 FsCounter=0;
 USART_Init(19200);   // Initializing USART (19200 b/s, 1 bit de stop, no parity)
 I2C_Init(100000);
 ADCON1=0;             // Configuring ADC
 INTCON=0xE0;
 OPTION_REG=0x88;
 TRISA=0xFF;           // PORTA as input
 do
 {
  if (FsCounter==20)                 // 20*256 µs = 5120 µs = 5.1 ms
    {
     FsCounter=0;
     ADC_Data = ADC_Read(0) >> 2;        // Reading ADC with 8 bits (RA0)
     USART_Write(ADC_Data);              // sending sampled data to au PC
     Write_EE(AddressBaseData+i, ADC_Data);// rage in EEPROM
     i++;
     if (i==1024)      // 1024 samples
       i=0;
    }
 }while(1);
}
```

Fig. 11. Acquisition, storage and sending to PC.

After many attempts to process all these tasks in real time, we finally realized that, having regard to the modest structure of the chosen microcontroller: small capacity of RAM (368 bytes), relative low speed (4 MHz), etc., the program must be implemented under a real-time operating system (RTOS).
So, in this work, we have developed all the tasks separately with success; we describe briefly the code of some of these tasks.

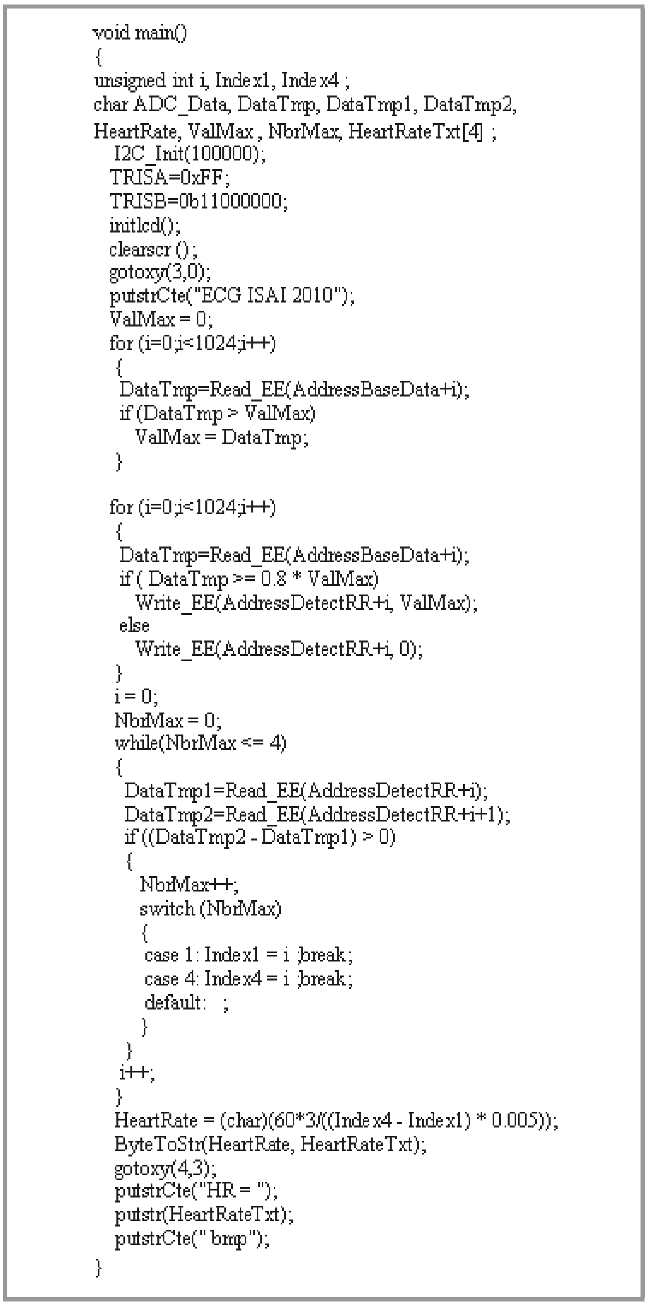
- **Acquisition of ECG, storage and sending to the PC**. In this program, we use the predefined basic functions of mikroC compiler:
  - *interrupt ()* to intercept the timer 0 interrupt setting the sampling period at 200 Hz,
  - *ADC_Read ()* to read the ADC,
  - *USART_Write ()* to send the sample acquired to the PC,
  - *I2C_Start (), I2C_Wr () and I2C_Stop ()* we have encapsulated in *Write_EE function ()* to write a byte to an address in the EEPROM.

  Figure 11 provides the corresponding complete C code.

- **Measurement and display of heart rate**. For this case, although the most common choice is the well known and more efficient algorithm of Pan/Tompkins [20], we opted for a simpler algorithm, an off-line simple thresholding algorithm after high pass filtering discriminating the R wave, based on [21] which is an average calculation of 3 RR cycles:
  - read the ECG signal from the EEPROM,
  - detect the maximum value of the ECG signal, that is detecting the R wave of the QRS complex (Max),
  - compare each value of the threshold (0.7 × Max) to avoid the influence of the P wave, which typically has a value (0.4 × Max) and produce a logic signal, the result of the comparison and store in EEPROM,
  - detect rising edge of the logic signal and count up 4 occurrences of this event, which corresponds to three cycles of the RR interval of the ECG,
  - identify the indices 1 (Index1) and 4 (Index4),
  - deduce the cardiac cycle, knowing that $T_S = 0.005$ s:

  $$\text{heart rate} = \frac{60 \times 3}{(\text{Index4} - \text{Index1}) \times 0.005}$$

  Figure 12 provides the corresponding complete C code.



```
void main()
{
unsigned int i, Index1, Index4 ;
char ADC_Data, DataTmp, DataTmp1, DataTmp2,
HeartRate, ValMax , NbrMax, HeartRateTxt[4] ;
   I2C_Init(100000);
  TRISA=0xFF;
  TRISB=0b11000000;
  initlcd();
  clearscr () ;
  gotoxy(3,0);
  putstrCte("ECG ISAI 2010");
  ValMax = 0;
  for (i=0;i<1024;i++)
   {
    DataTmp=Read_EE(AddressBaseData+i);
    if (DataTmp > ValMax)
      ValMax = DataTmp;
   }

  for (i=0;i<1024;i++)
   {
    DataTmp=Read_EE(AddressBaseData+i);
    if ( DataTmp >= 0.8 * ValMax)
      Write_EE(AddressDetectRR+i, ValMax);
    else
      Write_EE(AddressDetectRR+i, 0);
   }
   i = 0;
   NbrMax = 0;
   while(NbrMax <= 4)
   {
    DataTmp1=Read_EE(AddressDetectRR+i);
    DataTmp2=Read_EE(AddressDetectRR+i+1);
    if ((DataTmp2 - DataTmp1) > 0)
     {
       NbrMax++;
       switch (NbrMax)
        {
         case 1: Index1 = i ;break;
         case 4: Index4 = i ;break;
         default:   ;
        }
     }
    i++;
   }
   HeartRate = (char)(60*3/((Index4 - Index1) * 0.005));
   ByteToStr(HeartRate, HeartRateTxt);
   gotoxy(4,3);
   putstrCte("HR = ");
   putstr(HeartRateTxt);
   putstrCte(" bmp");
}
```

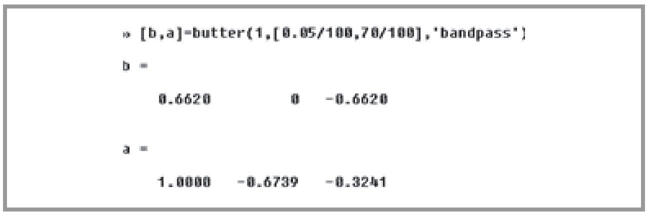
Fig. 12. Measure and display of heart rate.

2.2.2. PC Side

The program of this human/machine interface (HMI) on the PC we have developed in VB6 environment allows to:

- Communicate with the μC through the serial port.
- Display the original ECG signal (noisy signal) and filtered signal.
- Calculate and display the heart rate.
- Display signals related to the measurement of heart rate (threshold, QRS binary signal, etc.).
- Record the signal on hard drive for archiving and the possibility of further processing.

- Communicate by e-mail with the GSM protocol "AT Commands" for arrhythmia warning.



```
» [b,a]=butter(1,[0.05/100,70/100],'bandpass')
b =

    0.6620         0   -0.6620

a =

    1.0000   -0.6739   -0.3241
```

Fig. 13. IIR design with *butter*.

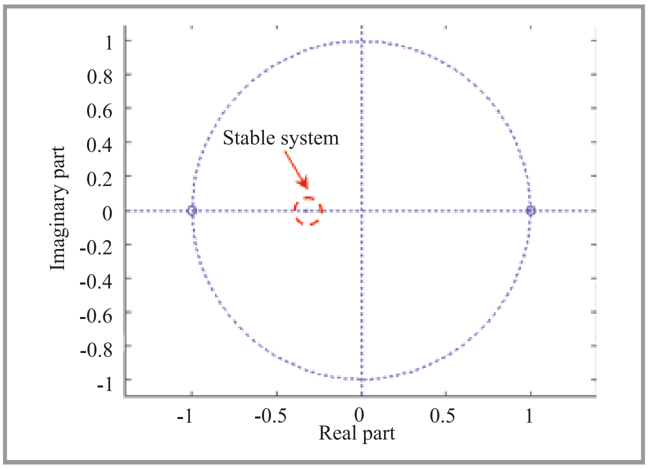


Fig. 14. IIR stability with *zplane*.

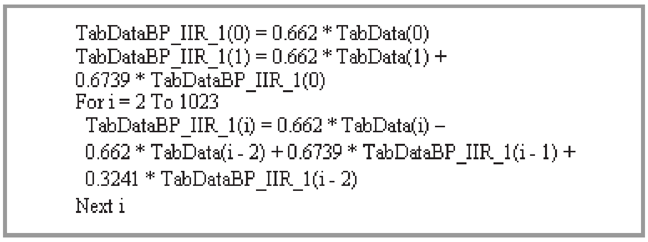
In what follows, omitting the code purely related to the HMI, we discuss only the application's core, i.e., digital filtering [22]–[24], measurement of cardiac rhythm and GSM communication.

So, we used the MATLAB functions *butter* and *zplane* (Figs. 13 and 14), respectively for coefficients determining of the transfer function and providing graphic display of poles and zeros, which allows to check the stability of the IIR filters.

Thus the transfer function and the difference equation of this IIR filter are found to be, respectively:

$$H(z) - \frac{Y(z)}{X(z)} = \frac{0.662 - 0.662z^{-2}}{1 - 0.6739z^{-1} - 0.3241z^{-2}}$$

$$y(n) = 0.662x(n) - 0.662x(n-2) + 0.6739y(n-1) + 0.3241y(n-2)\,.$$



```
TabDataBP_IIR_1(0) = 0.662 * TabData(0)
TabDataBP_IIR_1(1) = 0.662 * TabData(1) +
0.6739 * TabDataBP_IIR_1(0)
For i = 2 To 1023
 TabDataBP_IIR_1(i) = 0.662 * TabData(i) –
 0.662 * TabData(i - 2) + 0.6739 * TabDataBP_IIR_1(i - 1) +
 0.3241 * TabDataBP_IIR_1(i - 2)
Next i
```

Fig. 15. VB program sequence.

The sequence of the following VB program (Fig. 15) provides an extract of the complete implementation of such an IIR filter.

2.3. GSM Communication

Radio frequency (RF) communication allows removing the gene of the patient caused by cables; on other hand, it permits to transmit important data over long distances. In our application, we are interested in transmitting an alarm warning of arrhythmia. As stated in the medical documents [25], the heart normal rhythm at rest is between 50 and 100 bpm (beats per minute), otherwise there is arrhythmia:

- < 50: bradycardia,
- > 100: tachycardia.

There are several wireless communication standards (GSM, Bluetooth, Wi-Fi, ZigBee, etc.). All use the microwave band. We have chosen GSM technology for practical considerations. Indeed, the GSM (Global System for Mobile Communications) has become ubiquitous in recent years. With the wide variety of GSM devices in the world market, standardization was necessary. Thus, the protocol "AT Commands" was normalized by ETSI (European Telecommunications Standards Institute), allowing different systems to communicate via this protocol, for example, an embedded system μC-based can generate an alarm message by SMS (Short Message Service). So, such communication has 3 layers:

- physical layer: RS232,
- link layer: asynchronous serial communication protocol character-based,
- application layer: AT protocol.

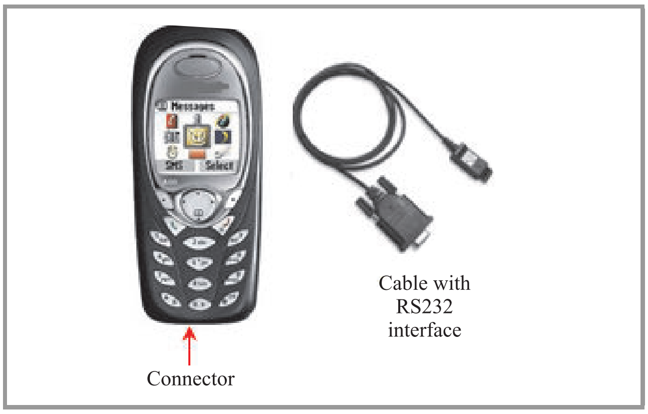
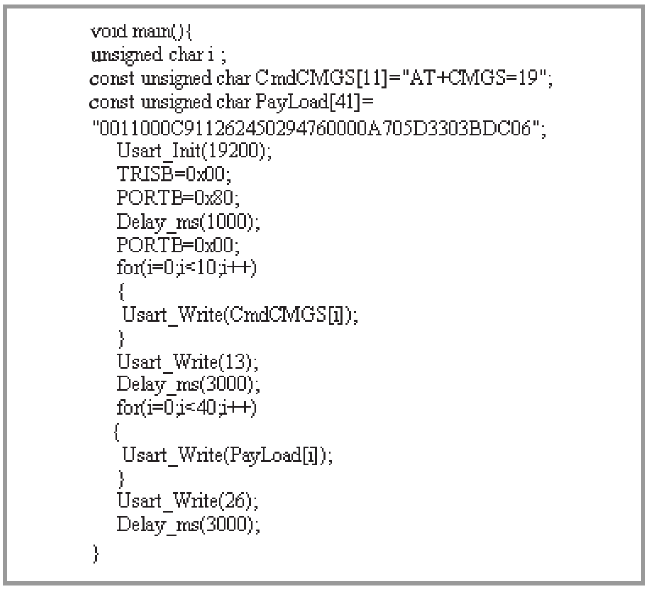


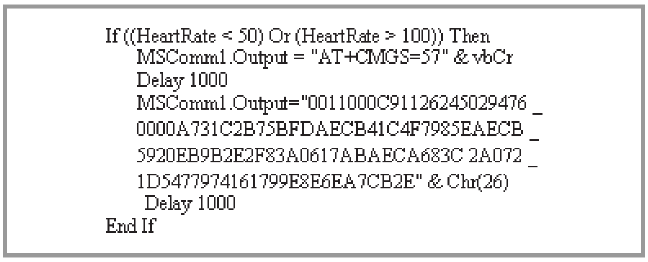
Fig. 16. Used GSM phone.

We have used the Siemens A60 GSM phone with embedded RS232 interface in cable (Fig. 16), allowing direct connection between GSM and PC or μC.



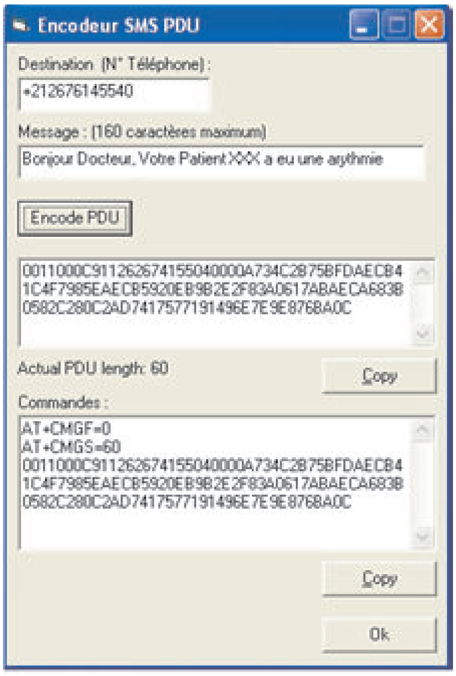
```
void main(){
unsigned char i ;
const unsigned char CmdCMGS[11]="AT+CMGS=19";
const unsigned char PayLoad[41]=
"0011000C9112624502947600000A705D3303BDC06";
    Usart_Init(19200);
    TRISB=0x00;
    PORTB=0x80;
    Delay_ms(1000);
    PORTB=0x00;
    for(i=0;i<10;i++)
     {
      Usart_Write(CmdCMGS[i]);
     }
    Usart_Write(13);
    Delay_ms(3000);
    for(i=0;i<40;i++)
    {
      Usart_Write(PayLoad[i]);
     }
    Usart_Write(26);
    Delay_ms(3000);
}
```

Fig. 17. C code for sending SMS.



```
If ((HeartRate < 50) Or (HeartRate > 100)) Then
    MSComm1.Output = "AT+CMGS=57" & vbCr
    Delay 1000
    MSComm1.Output="0011000C91126245029476 _
    0000A731C2B75BFDAECB41C4F7985EAECB _
    5920EB9B2E2F83A0617ABAECA683C 2A072 _
    1D5477974161799E8E6EA7CB2E" & Chr(26)
     Delay 1000
End If
```

Fig. 18. VB code for sending SMS.



Destination (N° Téléphone) : +212676145540

Message : (160 caractères maximum) Bonjour Docteur, Votre Patient XXX a eu une arythmie

```
0011000C9112626741550400000A734C2B75BFDAECB4
1C4F7985EAECB5920EB9B2E2F83A0617ABAECA683B
0582C280C2AD7417577191496E7E9E8768A0C
```

Actual PDU length: 60

Commandes :

```
AT+CMGF=0
AT+CMGS=60
0011000C9112626741550400000A734C2B75BFDAECB4
1C4F7985EAECB5920EB9B2E2F83A0617ABAECA683B
0582C280C2AD7417577191496E7E9E8768A0C
```

Fig. 19. PDU encoding.

AT commands form a protocol for controlling modems, mobile phone, GPRS, etc. This allows configuring, dialing numbers, sending messages, etc. [26], [27].

In our application, we need sending SMS; so, we use the commands “AT”, “AT + CMGF” and “AT + CMGS”. Any AT command starts with two characters ”AT” (ATtension), and finally the control character “Carriage Return” symbolized by <CR>. The following simple description gives the basic syntax of the three commands we have handled in our application.

The “AT” command is a status request used for testing if a compatible modem is connected and that the serial interface is working properly. This is like the well known “ping” command for communication test in the TCP/IP world.

The “AT+CMGF” command is used to set input and output format of SMS messages. Two modes are available:

- text mode: reading and sending SMS is done in plain text,
- PDU (Protocol Description Unit) mode: reading and sending SMS is done in a special encoded format. This mode compresses data to transmit allowing gain in time and space.

The “AT+CMGS” command enables the user to send SMS messages. A message can contain up to 160 7-bit characters. The transmission format is as follows:

“AT+CGMS=Message lenght”<CR> “PDU Message”<Ctrl+Z>

The PDU message is the text message to transmit after coding in PDU format (compression). We developed a program for μC that has remained at the stage of debugging (Fig. 17). In return, we transcribe the same program in VB6 (Figs. 18, 19), using with adaptation an open source implementation for PDU encoding algorithm [28]. Obviously, the GSM is connected to the PC serial port; the program gives a good result.

3. Summary

The ECG signal is captured by the analog module and sampled and digitized by the digital module, stored in EEPROM and treated (IIR and FIR filtering, measurement of heart rate by simple algorithm and communication with GSM). Figure 20 shows the results display on PC (unfiltered signal, filtered signal, heart rate). The signal can be recorded on hard disk and later reloaded for study purposes.

Compared with the works quoted in the introduction paragraph, briefly reflecting the state of the art, our project is prototype equipment having the following features: low cost, easy to implement and versatile. In fact, the hardware is made with cheap and well known components; regarding the software, it is also developed in known and widely disseminated environments. On one hand, this could contribute, on the commercial point of view, to democratize such often expensive equipment, especially in developing countries, which may help in diagnosis and improves

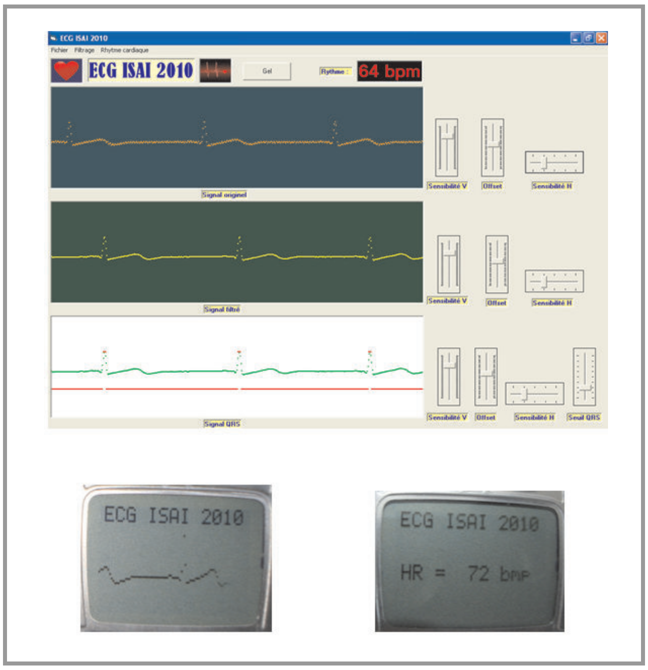


Fig. 20. Results display.

the level of health care; on the other hand, this could help novice researchers to touch closely and to be well acquainted with the different problems of biomedical engineering (hardware and software), in general and particularly for the cardiac signal (ECG). Furthermore, the system is naturally open and versatile. So, it can be certainly improved with dedicated hardware and reliable software.

4. Conclusions

We have developed an embedded system that can be used as ECG display equipment and arrhythmia monitor for patients at risk for heart attack. The system can be improved by using more specific components such as instrumentation amplifiers with better performances, dedicated microcontrollers with more speed and RAM space and RF technologies more suited to the medical context, such as the ZigBee standard.
Furthermore, the system has many tasks to be programmed, which requires a real-time operating system; this offers the opportunity of a certain parallelism in treatment. In this context of multitasking, a future study is underway to implement the system in a modern FPGA because of his reconfigurable characteristic. This approach represents the current trend thanks to the continuous development in the microelectronics science; it allows programming tasks with hardware parallelism [29]. The future work has as start point, like for any cardiac signal processing, the QRS detection with the efficient Pan/Tompkins algorithm.

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