Sensing - Low-Cost EKG Pulsometer

AN2284

Author: Serhiy Matviyenko
Associated Project: Yes
Associated Part Family: CY8C24xxxA, CY8C27xxx
GET FREE SAMPLES HERE
Software Version: PSoC® Designer™ 4.2
Associated Application Notes: AN2158

Application Note Abstract

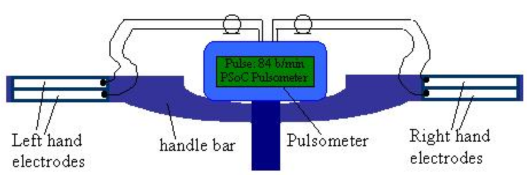
This Application Note describes the EKG Pulsometer. Pulsometers can be used in the medical sector of sports training to monitor pulse rates, or embedded in various sports training equipment.

Introduction

Pulse rate measurement plays a very important part in medical applications and athletic and sports training.

There are several methods to measure pulse rates. The electrical signal detection method has been used in this proposed application. This method requires the placement of two or more electrodes on human hands. Figure 1 shows an example of the EKG Pulsometer electrodes attached to an exercise bicycle. Analysis of the electrocardiogram (EKG) from the electrodes provides a quantitative description of the heart's electrical activity and is routinely used in hospitals as a tool to identify cardiac disorders.

Figure 1. Pulsometer Electrodes Attached to an Exercise Bicycle

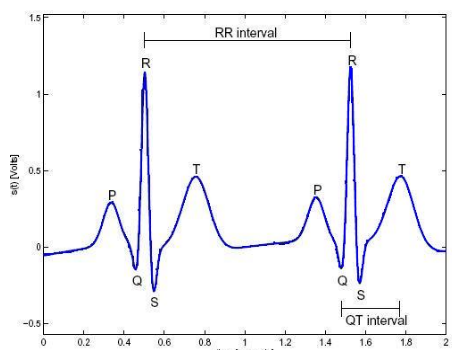


The EKG signal is characterized by six peaks and valleys labeled with successive letters of the alphabet (P, Q, R, S, T, and U). See Figure 2.

The average heart rate is calculated by measuring the time interval, RR interval, between two consecutive R peaks (Figure 2), taking the average reciprocal of this value over a fixed time period (usually 15, 30 or 60 seconds) and then scaling to units of beats-per-minute (bpm).

A typical EKG is can invariably be corrupted by such things as electrical interference from surrounding equipment, measurement (or electrode contact) noise, electromyogram noise (muscle contraction), movement artifacts, baseline drift and respiratory artefacts, and instrument noise (such as artifacts from the ADC conversion). A variety of signal-processing techniques can be employed to filter the raw EKG signal prior to feature extraction and diagnosis of medical disorders.

Figure 2. EKG Signal



Before calculating a heart rate we must process the EKG in the analog (amplification, common mode voltage suppression and filtering) and digital (digital filtering) domains. Most of the functions in this application are performed by PSoC device in realtime.

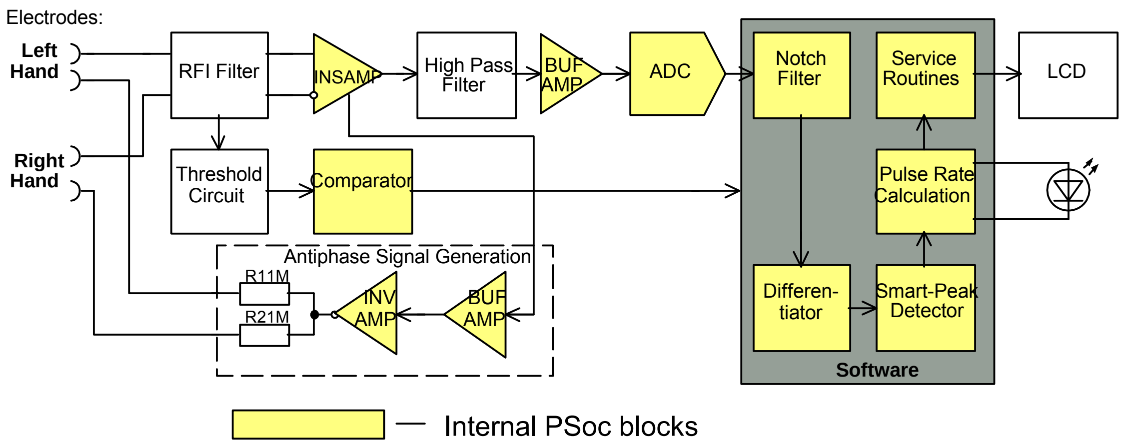
The Pulsometer technical specifications are given in Table 1.

[+] Feedback

Table 1. Pulsometer Specifications

Item	Item Value
Pulse Measurement Method	Electrical signal detection: measuring the RR interval of the EKG
Power Supply Voltage	5V
Power Consumption	<1 mA in sleep mode 30 mA in active mode
Measured Pulse Range	45 - 260 beats per minute
Measurement Time	11 pulse intervals or 15 – 3 sec.
Pulse Calculation Method	Measuring time interval between adjacent beats
Number of electrodes	4 (first and second – for left hand; third and fourth – for right hand)
Display Type	16x2 graphic LCD
Service Features	- Automatic measurement starting when user places hands on electrodes - Automatic measurement stopping when user removes hands from electrodes - LED flashes when beat is detected - EKG signal transmission to PC via RS232 interface - Automatic wakeup and sleep when no signal

Figure 3. Pulsometer Block Diagram



Pulsometer Block Diagram

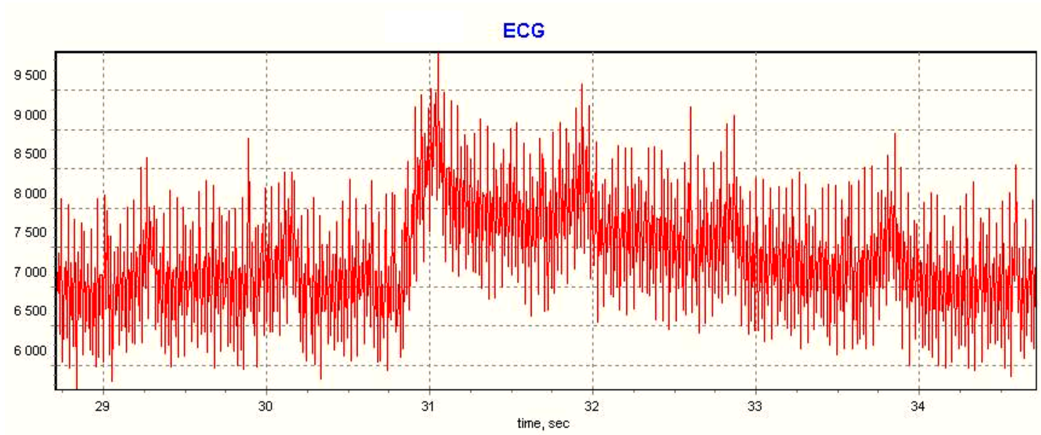
Figure 3 depicts the Pulsometer flowchart. The EKG signal passes through the RFI filter (to cut inducted RF signals) to the input of the high common-mode-rejection ratio (CMRR) instrumentation amplifier (INSAMP).

The main purpose of the INSAMP is to reject the CMRR voltage (a ~300 mV common-mode component from the potential between the electrodes and skin, power-line interference and other noise sources) and pre-amplification of the differential EKG signal. To improve noise immunity, an antiphase signal is used.

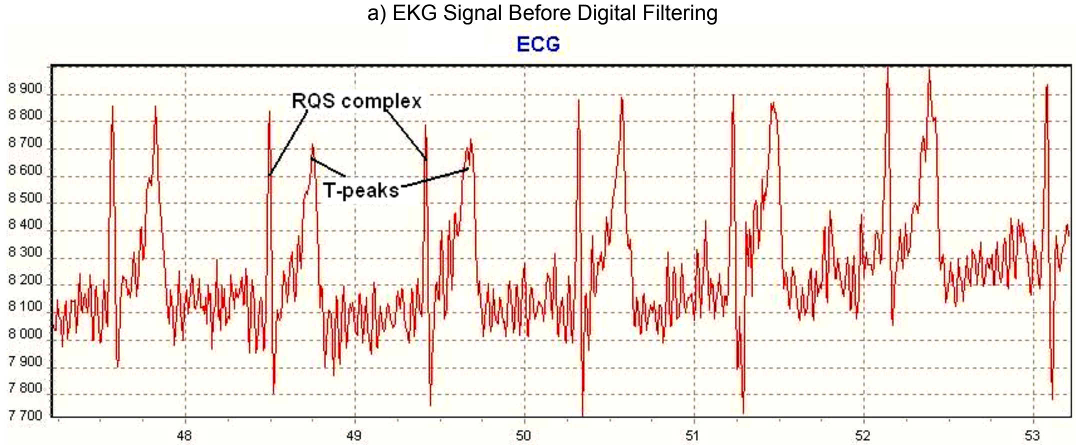
This circuit consists of a buffer amplifier (BUF AMP) and an inverting amplifier (INV AMP) that applies an inverted version of the common-mode signal to the hands, with the aim of canceling the interference. On the output of this circuit there is a voltage level shift occurs to automatically detect the moment hands are placed on the electrodes. The threshold circuit and comparator detect this moment.

From the output of the INSAMP, the EKG signal passes through a high pass filter and is buffered by the BUF AMP. Then the signal is digitized via a 14-bit incremental ADC.

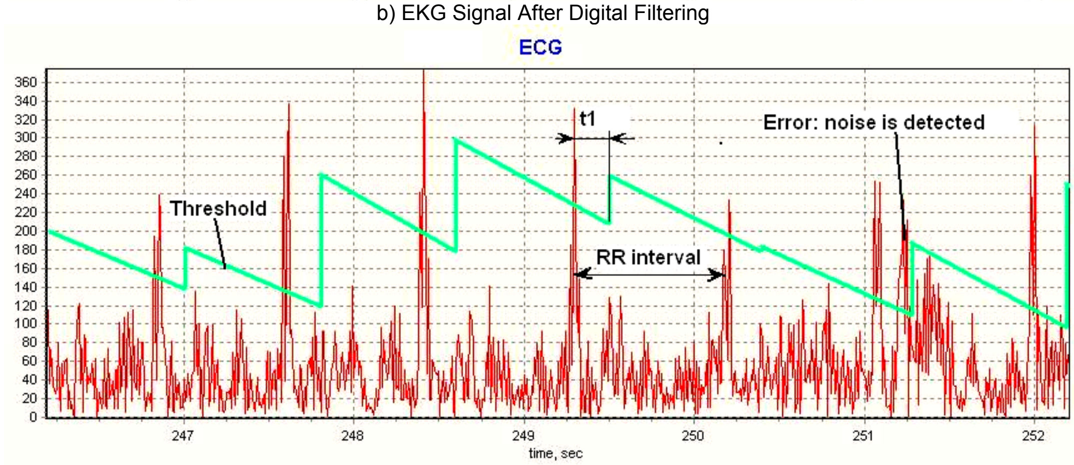
Figure 4. EKG Signal Before and After Digital Processing



a) EKG Signal Before Digital Filtering



b) EKG Signal After Digital Filtering



c) First Derivative of the EKG Signal Used to Calculate Pulse Rate

Processing the ADC data stream is implemented in firmware. The PSoC device's digital filtering processes the acquired EKG signal. For power-line 50-Hz interference suppression, a second-order infinite impulse-response (IIR) notch filter is employed. After digital filtering, the pure EKG signal passes through the differentiator, where the RQS complex is picked out. Pulse beats are detected by a smart peak detector with a threshold level that is automatically adjusted to increase the noise resistance.

The Figure 4 shows the EKG signal before (a) and after (b) digital filtering. In Figure 4 (c) the first derivative of the

EKG signal that is used to calculate pulse rate, is shown. Here, you can see how the threshold adaptive algorithm works. Note that all the diagrams are measured in different time intervals.

The software reads and digitally filters the ADC data. It also calculates the pulse rate and displays it and other state information on the LCD.

For external pulse wave signal processing and debugging, the EKG samples can be sent via a RS232 port.

Device Schematic

The Pulsometer schematic is shown in Figure 5. The noisy EKG signal from the human hands passes through the RFI filter (R5, R6, C1 – C3) to the input of the embedded INSAMP, which has a CMRR of ~60 dB. The gain of the INSAMP is 16. From the output, the EKG signal passes through a high pass filter (C4, R9) and is fed in via PSoC port P0[6] to the input BUF AMP. Then the signal is digitized via a 14-bit incremental ADC.

The common-mode voltage is derived from the INSAMP's internal resistors. The inverted amplified value of this voltage from port P0[4] via resistors R7 and R8 is applied to the hands, with the aim of suppressing the power-line interference.

In addition to applying inverted common-mode voltage to a human, the resistors R7, R8, R3, and R4 play a part of the threshold circuit to detect the moment hands are placed on the electrodes.

Let's see how this circuit works. Primarily, the voltage drop on resistor R3 or R4 is equal to a very small value $\sim(R4 \cdot I_b)$, where I_b is the INSAMP's input bias current. When hands are placed on the electrodes, the potential on resistor R4 rises up to >Vcc/2.

This voltage passes through the low pass filter (R1, R2, C4) to P0[5] and on to the input of the comparator. The comparator enables heart rate calculation.

The values of resistors R1 through R8 comply with the Association for the Advancement of Medical Instrumentation (AAMI) standards for safe current levels. These standards require that the RMS ground currents or fault current from the electronics must be less than 50 µA.

The calculated pulse rate is displayed on the low-cost LCD. D1 is an LED that flashes every time a beat is detected.

The optional RS232 optoisolated level translator U2 can be used to send ADC data to the external PC.

PSoC Internals

The PSoC internal user module placement is shown in Figure 6. Here, the analog blocks are shown. The voltage from the external RFI filter passes through ports P0[0] and P0[1] to the INSAMP's input (ACB00, ACB01 and ASC10 blocks). From the INSAMP's output, the amplified EKG signal is fed out via the P0[3] to the external high pass filter. The main purpose of the high pass filter is to remove DC components. From the output of the high pass filter, the EKG signal is fed out via P0[6] to the input BUF AMP (ACB03 block). The output BUF AMP is connected to the ADC, which is placed in ASD13. ADC resolution is set to 14 bits and sampling rate is Fs = 121.81 Hz.

The low-power comparator is placed in the ACB02 block. Sleep mode is used to reduce power consumption. The sleep interval is set to 1 sec. Every 1 sec the software reads the state of the comparator bus via the CMO_CR0 register and allows the pulse rate to calculate when (CMP_CR0 & 0x20) = 0x20. Otherwise, the software switches off all the analog blocks (ARF_CR &= 0xF8 and ABF_CR0 &= 0xE3), puts P0[4] into Strong drive mode (corresponding bits of PRT0DM0, PRT0DM1 and PRT0DM2 registers), and sets logical 1 to P0[4]. The Pulsometer then returns to sleep mode.

PSoC's analog ground (AGND) is set to 2.5V and fed out via the analog driver of the fourth column to P0[2]. Note that because the analog block ACB03 is already used by BUF AMP, we must set the corresponding bits in register ACB03CR2 to enable the AGND output on the fourth column to use the TestMux.

The common-mode voltage is derived from INSAMP's NON_INV block. This voltage is inverted and amplified by the low pass filter (ASD11 and ASC21 blocks) and fed out via the ASC12 block to P0[4] to be applied to the hands.

Figure 5. External Hardware Schematic

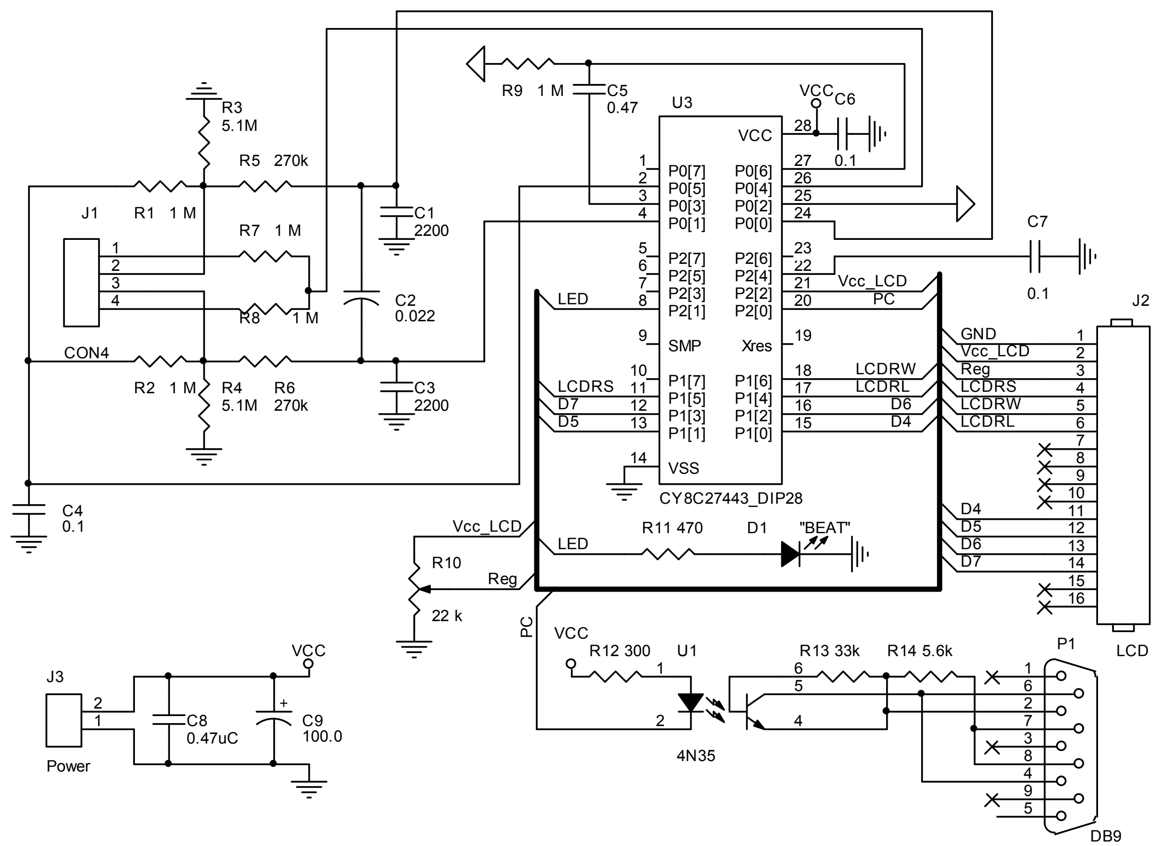
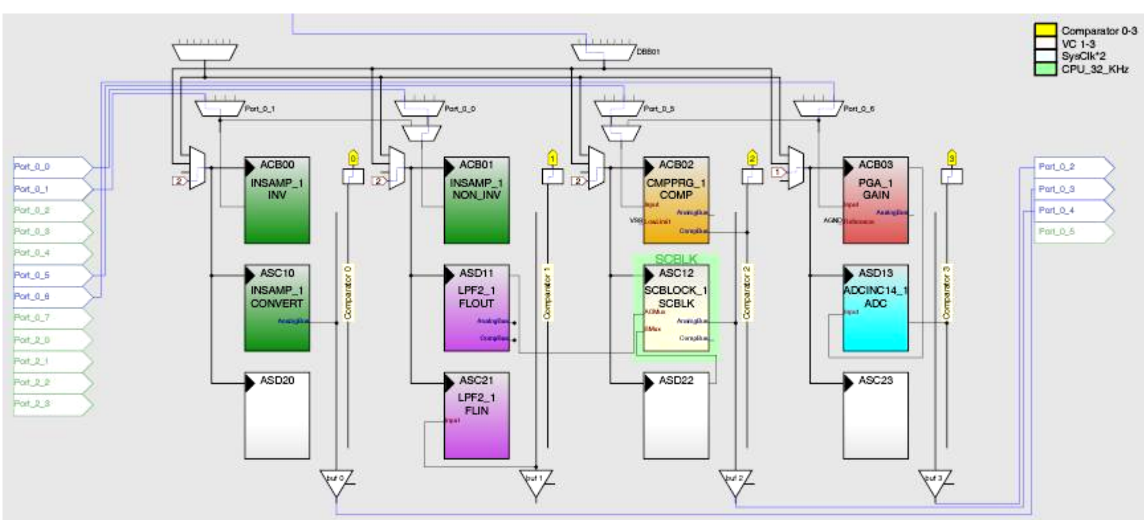


Figure 6. PSoC Internal User Module Configuration



The Software

The Pulsometer software reads and digitally filters the ADC data. It also calculates the pulse rate and displays it and other state information on the LCD. Figure 7 illustrates the realtime signal-processing algorithm. The ADC samples are filtered by a cascade of five second-order IIR notch filters. These filters are designed to suppress the 50-Hz interference and each has the following transfer function with the notch width of 6 Hz:

$$H(z) = \frac{0.75(1+z^{-2}) + 1.332103z^{-1}}{1+1.332103z^{-1} + 0.5z^{-2}} \qquad \text{Equation 1}$$

To obtain the first derivative of the EKG signal, which is used to calculate pulse rate, the first-order IIR high pass filter with cutoff frequency Fc = 30 Hz is used:

$$H(z) = \frac{0.5(1 - z^{-1})}{1 - 0.015625z^{-1}} \qquad \text{Equation 2}$$

To implement these two equations in 'C' code in fixed-point representation we must scale the filter's coefficients by 65536 and then verify if the filters remain stable (that is all the poles lie within the unit circle of the z-plane). The quantized filter Hq is stable if:

$$\lim_{n\to\infty} h(n) = 0 \qquad \text{Equation 3}$$

h(*n*) is the impulse response of the quantized filter. MATLAB® has been used to study stability of the quantized filter.

Following are the filters written in 'C':

IIR second-order notch filter:

```
diff1 = (x + xn_2) <<16;

y = ((diff1>>1)+(diff1>>2)+87301*(xn_1 -
yn_1) -((yn_2<<16)>>1));

xn_2 = xn_1;

xn_1 = x;

yn_2 = yn_1;

yn_1 = y;
```

IIR first-order high pass filter:

```
y=((((x-
x_hpf1_1)<<16)>>1)+(y_hpf1_1<<10))>>16;

x_hpf1_1 = x;

y_hpf1_1 = y;
```

The division of 65536 is done by shifting 16 bits right.

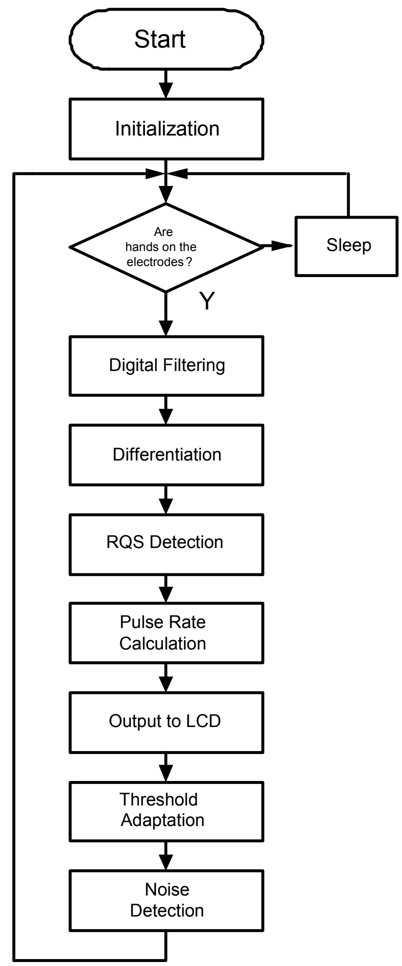
The filtered and differentiated EKG signal is used for RQS complex detection. The RQS complex is detected when the absolute magnitude of the differentiated EKG signal is higher than the threshold value. At that moment, the current RR-interval is calculated:

$$RR = g\_time - g\_time\_old \qquad \text{Equation 4}$$

g_time is the value of time counter, which is incremented with every cycle of ADC conversion. g_time_old is the value of time counter at the moment of previous RQS complex detection.

After calculating 11 RQS complexes, the array of nine RR intervals passes through the median filter, which gives the nearest-to-integrated duration value of the RR interval. The RR interval duration then passes via a fourth-order averaging filter, is scaled to beats-per-minute, and displayed on the LCD.

Figure 7. Real-time Pulse-Calculating Algorithm



To reduce the detection of false beats, after every detected RQS complex, the algorithm performs the automatic threshold level adjustment and noise detection in 320 msec:

- The maximum of the absolute value is searched at an interval of t1 = 200 ms after the detected complex. The threshold value is updated with 0.75*max(abs(E)), where E is the differentiated EKG (see Figure 4c).
- The threshold value decreases at a slow rate after 200 ms. The decrease stops when a pre-defined threshold value is reached.
- If E is greater than the threshold value during the interval between t1 (200 ms) and t2 (240 ms) following the last QRS complex detection, then noise is detected and we increase the threshold value and count the current RR interval again.

Also, a program for viewing EKG signals on a PC was developed and shows the EKG signal in Figure 4.

The developed EKG Pulsometer was tested with a professional Pulsometer. The tests showed errors less than ±2 bpm.

Suggested Improvements

It is a good idea to generate a beep via the piezoelectric speaker when a beat detected. Also, it is possible to use a Flash-card to log pulse rates or Cypress WirelessUSB technology to send the EKG and measured pulse rate values to a PC.

Summary

The low-cost EKG Pulsometer was developed. It can be used in medical applications, sports training, and home appliances. Note that the proposed Pulsometer shows good results measuring pulse rate without using the costly external high CMRR instrumentation amplifier. In comparison to a discrete element solution it costs less and consumes less board space. This Pulsometer complements our Optical Pulsometer, described in AN2158 “Optical PulsOmeter with PSoC.”

About the Author

Name: Serhiy Matviyenko
Title: Research Engineer
Background: Serhiy Matviyenko earned a physical and biomedical electronics diploma in 2003 from National University "Lvivska Polytechnika" and is presently working as a research engineer at National University "Lvivska Polytechnika" (Lviv, Ukraine). His interests include electronic device design.
Contact: matvs@ukr.net

In March of 2007, Cypress recataloged all of its Application Notes using a new documentation number and revision code. This new documentation number and revision code (001-xxxxx, beginning with rev. **), located in the footer of the document, will be used in all subsequent revisions.

Cypress Semiconductor
198 Champion Court
San Jose, CA 95134-1709
Phone: 408-943-2600
Fax: 408-943-4730
http://www.cypress.com/