SMART HEART MONITORING SYSTEM

Justin Loop, Mequanint Moges
University of Houston
College of Technology
jtloop@uh.edu, mmoges@uh.edu

Abstract

The recent technological advances in wireless communications have made it possible to create sensor devices that can monitor systems or patients from a remote location. Examples of these can include, but are not limited to, control systems from an industrial plant, remote control of vehicles, and hospital patient monitoring systems.

Because of the growth in population all over the world, the demand for hospital care is on the rise. A simple solution to this problem is to have patients be monitored non-intrusively. By utilizing wireless technology, and coupling it with the newest sensor technology, a method of monitoring a patient remotely can be established.

The National Science Foundation- Research Experience for Undergraduate students (NSF-REU) of the College of Technology has sponsored the first step of this process: the design and implementation of a wireless electronic stethoscope. Specifically, this project involves the design of a signal conditioning system in order to process the low level heartbeat (audio) signals from an electronic stethoscope for wireless communications utilizing the latest of Cypress's CyFi wireless technology. With this device, one can tell the physiological state of health of a person. Essentially, sounds taken from the heart can tell the health of the heart, whether the heart's beat is healthy, or has an abnormal condition such as a murmur or unsteady rhythm. It can also tell the stress level of the patient. Having a stethoscope reading transmitted through a wireless communication system to an observing body is a great solution for rapid response and immediate intervention if necessary.

Introduction

The purpose of the research behind the Smart Heart Monitoring System sponsored by the National Science Foundation's Research Experience for Undergraduates was to marry two technologies together for a more intelligent and rapid patient response system which may be deployed and implemented in the medical industry. Presently, a problem exists where a patient admitted to a hospital or clinic and deemed, or diagnosed, to have a condition or problem requiring additional monitoring by medical staff has no other option other than to stay in the hospital's care. This may become a financial burden for a patient. This could also lead to an overcrowding problem for the hospital. Overcrowding of hospitals has become an emerging threat to patient care in the United States [1]. When a patient is admitted, space, manpower, and equipment may not be as utilized as wisely as it otherwise could be. In the case where a hospital's emergency room may be approaching maximum capacity, and taking patient's comfort and stress levels into consideration, the motivation for new innovations is inevitable. This research entails the creation of a non-invasive system that reports a person's medical status continuously and communicates wirelessly to a central computer that can monitor and store statistics, raise certain flags based on certain criteria, and allow for better utilization of medical manpower and tools.

Heart Monitoring Analysis

Heart monitoring analysis begins by taking audio samples, otherwise known as auscultations, from the heart externally, via an electronic stethoscope. Each individual amplitude, audio frequency, and cardiac pulse can determine the state of health of a person. The amplitude of the audio signal taken from a heart beat can be measured against previously sampled amplitude levels from the same heart to determine the intensity from which that heart is beating. This intensity can determine whether the heart is beating normally, too hard, or too soft. Essentially, understanding this can determine and measure the strength, the stress, and the exertion of the heart in relation to the size of the body.

Filtering the specific audio frequencies exhibited by the heart from other physiological auscultations will allow doctors to focus their attention solely on pulmonary functions, thus detect heart-specific irregularities.

The frequency at which the heart beats can differentiate between either a healthy or abnormal/malfunctioning heart. One such condition is called tachycardia, which can cause the heart to beat faster that the 100 Beats per Minute (BPM) for no apparent reason. Tachycardia is a dangerous condition in that it could be a sign of heart disease [2].

A slow heart beat is also another very important reason to monitor heart auscultations. In the case where a heart is beating too slow, the result is that the body is not getting enough blood, thus unwarily exhibiting fatigue or dizziness. This can be brought on by a number of causes including variations in activity, diet, medication, and/or age [3].

Having the ability to monitor these conditions any time, a doctor can be acutely aware of how a person's heart is operating and can diagnose a problem more appropriately.

Theory of Operation

The Smart Heart Monitoring System is composed of three main parts: input, signal conditioning and processing, and communication. The input is comprised of a microphone circuit. The microphone circuit converts the audio energy into electrical energy. The electrical energy created by the microphone requires conditioning and processing. This is executed by Cypress's microcontroller system known as the Programmable System on a Chip (PSoC). Once the signal is conditioned and processed into digital form, it is transmitted via wireless means. The wireless communication is accomplished by using Cypress's CyFi wireless technology. At the receiving end of this transmission is a hub attached to a computer. The hub will retrieve that data so that the adjoining computer can further process the information for databasing and statistical analysis.

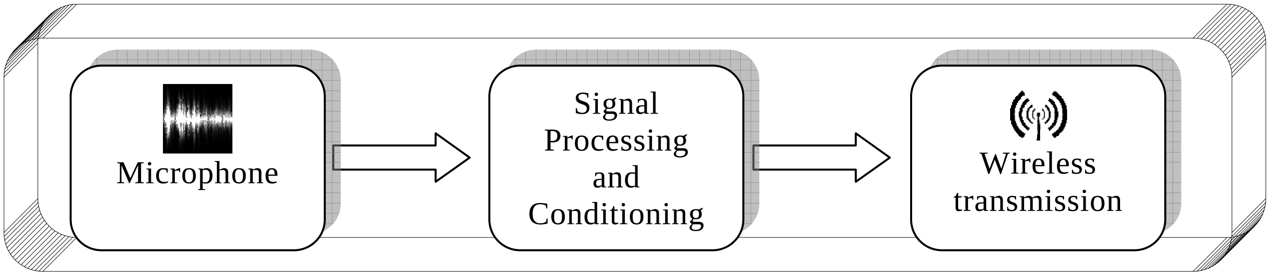

Figure 1: PSoC Top-level block diagram

Programmable System on a Chip

The data that is acquired from the microphone is conditioned using Cypress's Programmable System on a Chip (PSOC), version 1. The PSoC is a very adept 8 bit microcontroller that encompasses a complete complement of analog and digital peripherals based on the Harvard architecture. The PSoC is what is known as a Mixed-Signal Array with an On-Chip Controller. Its sole purpose is to replace the traditional MCU-based systems that would normally have several external components that would ordinarily make up the system.

The PSoC includes a fast CPU (up to 4 million instructions per second), Flash memory, SRAM, and configurable inputs and outputs. The architecture of the PSoC is comprised of several areas: PSoC core, digital systems, analog systems, and system resources. It has global busing that allows device resources to mesh for complete system integration. It can have up to eight input/output ports interconnecting with global digital and analog internal buses, allowing full access to 16 configurable digital peripherals and 12 configurable analog peripherals. The user has the option of using the 3.3 volt low power setting, or the 5.0 volt normal setting. This architecture allows the user to create customized peripheral configurations to match the requirements of each individual application [4].

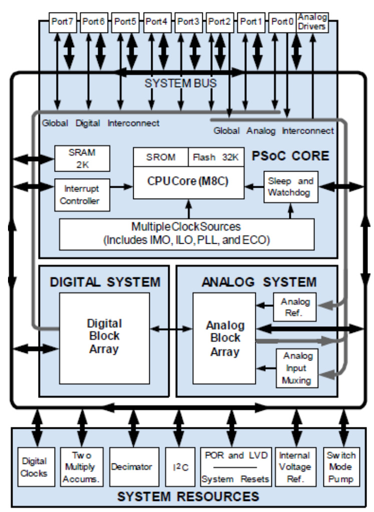

Figure 2: PSoC Top-level block diagram

The PSoC is programmed based on a modular concept. For the particular function that the system is intended to do, the firmware programmer will choose the appropriate module(s) and use the command line to dictate how the system will work. For example, if one needs a pulse width modulator (PWM), the firmware engineer would choose the PWM module in the desktop workspace in the PSoC Designer software provided by Cypress, select the appropriate properties in the associated window, and then program its functionality in the code editor within the PSoC Designer.

The PSoC consists of several different digital functions. These include, but are not limited to, Timers, Counters, and PWMs. Each of these components has a selectable range from 8 to 32 bits. Digital functions of the PSOC also include various communication protocols. These protocols include:

Up to 4 full duplex **UARTs**	Multiple **Serial Peripheral Interface (SPI)** - Master - Slave	**Inter-Integrated Circuit (I^2C)** - Master - Slave

Table 1: Communication types for PSoC

A very important aspect of the PSoC is the many analog features offered such as:

ADCs	**DACs**	**Amplifiers**	**Filters**
Up to 14-bit resolution - Incremental - Delta Sigma - Dual - TriADC - SAR	Up to 9 bit resolution	- Inverting - Comparator - Instrumentation - Programmable gain	- Band pass - Low pass

Table 2: Analog features

By having as much of the analog system available on board the same chip as the processor saves space, which also equates to weight. For the Smart Heart Monitoring System, this is a crucial component, as the specification requires a small footprint of the entire system. The alternative is to have the various analog conditioning elements external to the microcontroller making the footprint of the entire device much larger than it needs to be. This also makes for troubleshooting difficulties.

By exploiting the fact that the PSoC couples analog components with digital components on a single microchip, miniaturization of the Smart Heart Monitor System was a viable goal for this system; and, it also ensures compatibility between the components.

In the Smart Heart Monitoring System, the PSoC is the data acquisition system. It performs signal conditioning of the raw signal from an audio input device that is attached to the head of a stethoscope. The signal conditioning performed entails amplification, filtering and then quantization for computer communication.

5.1 Sensor

A microphone is used in the Smart Heart Monitoring System to capture the audio signal. It is an omnidirectional electret condenser microphone manufactured by PRI Audio. Its operating voltage is 5 volts with a sensitivity of – 46 dB +/- 3 dB. With its superb sensitivity and its miniature size of 4.5 millimeters deep with a diameter or 9.7 millimeters along with its low power usage makes this microphone perfect for this application.

5.2 Amplification

The PSoC allows for many different types of amplification techniques. For the Smart Heart Monitoring System, two Programmable Gain Amplifiers (PGA) were cascaded within the PSoC for a total gain of 96 to boost the signal coming from the audio input device to a desirable level.

The PGA's feedback is a function of a string of resistors measured in "units." There are a total of 16 units available. The resistance values are defined as:

$$R_1 = a \cdot R \quad R_f = (16 - a) \cdot R$$
$$a = \left\{\tfrac{1}{3}, \tfrac{2}{3}, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16\right\} \tag{1}$$

The gain for the PGA is defined by the equation:

$$\frac{V_{out}}{V_{in}} = Gain = \frac{R_f + R_i}{R_i} \tag{2}$$

By combining the two equations above, the results will render:

$$Gain = \frac{16}{a} \tag{3}$$

Once this signal is amplified to a useful level, filtering can commence.

5.3 Filtering

The PSoC offers several different types of filters to choose from. Used in this case was an onboard two-pole low pass filter. By utilizing the filter design wizard embedded in the PSoC Designer software, this particular filter type was configured to accept only signals lower than 1000 Hz. Signals above 1000 Hz will get discarded. Because a human heart's audio frequency is less than 100 Hz, and also depending on the sex and age of the person being monitored, emphasis must be given to the spectrum listed above. All frequencies over the value listed above should be disregarded (for the case in which one only wants to monitor the heart).

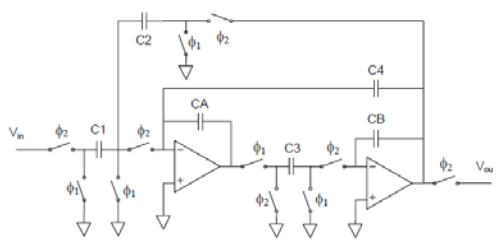

Figure 3: Low Pass Filter Block Diagram

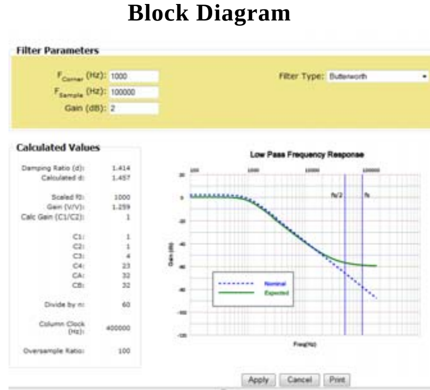

Figure 4: Filter Design Wizard

The Two-Pole Low Pass Filter selected is configured with a gain of two, which complements the already 96 gain from the cascaded amplifiers. The user has the option to have any of the following filter configurations: Butterworth, Bessel, Chebyshev, as well as a custom design.

Through various testing, it was determined that the Smart Heart Monitor would utilize the Butterworth configuration for best overall performance.

Filters for the PSoC operate on the principle of charge vice resistance. Resistance is simulated via switched capacitors. The two-pole low pass filter has the response of:

$$\frac{V_{OUT}}{V_{IN}} = \frac{G(\omega_n \omega_0)^2}{s^2 + s\omega_n \omega_0 d + (\omega_n \omega_0)^2} \qquad \textbf{4}$$

The Low Pass Filter, two-pole, (LPF2) implements a general purpose biquad, or second order state, low pass filter. The corner frequencies and damping ratios are functions of the system clock and the ratios of the capacitor values selected [6].

5.4 Analog to Digital Conversion

Of the many components that the PSoC has to offer, one of the more significant ones is the analog to digital converter (ADC). This allows the signal to be quantized for further processing. There are several ADCs that the PSoC has to offer. Among them is the DELSIG8 (8 bit delta sigma) ADC.

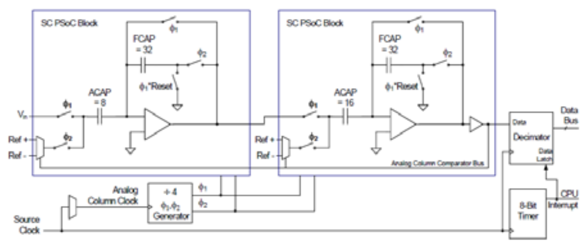

Figure 5: DELSIG8 ADC Block Diagram

A DELSIG8 has an 8 bit resolution formatted in 2's compliment that can support sample rates from 1.8 kilosamples per second (ksps) up to 31 ksps. The sample rate is determined by a clock that is configured in the properties menu chosen by the programmer. The DELSIG8 allows for either a first order or second order modulator. The Smart Heart Monitor is configured to have the second order modulator for improved performance [7].

The decimator is an important component of the DELSIG8 ADC. It is a digital Finite Impulse Response (FIR) filter whose purpose is to convert the density stream into digital data. Cypress argues that the utilization of a decimator is more resourceful than alternatively using external FIR filters.

As shown in [8], the authors define decimation as a function that downsamples the input signal. It has the benefits of higher signal to noise ratio and lower power consumption. It is an averaging function that accumulates N bits and averages them to give an output value. Decimation for digital signals is similar to sampling for analog signals. The most economical method of implementation of a decimation function is to pick one sample out of K samples. This is the method used in PSoC, by use of a hold register and clocking it at the decimation frequency.

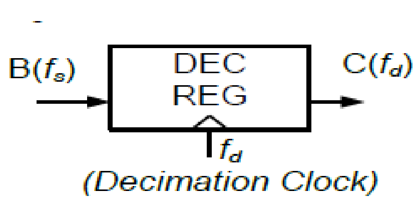

Figure 6: Decimation Function

The decimator in the PSoC incorporates a sinc^2 filter, which is a low pass digital filter. Its single purpose is to attenuate such possible problems as quantization, interference, and anti-aliasing noise [8]. Coupling a decimator with an ADC allows for much more accuracy when quantizing a signal.

The ADC used in the Smart Heart Monitoring System oversamples the audio heart sound based on a 100 Hz audio signal. It oversamples the audio frequency 39 times. The effective sample rate is a function of the equation below:

$$SampleRate = \frac{DataClock}{256} \quad (5)$$

The data clock is reduced such that the sample rate of the ADC is approximately 3,900 samples per second. Oversampling at this rate would maintain high resolution of the heart's audio and save on memory in case one wants to record data onto a medium.

The data outputted from the ADC is an 8 bit hexadecimal value whose quantized steps are 20 mV for a 0 to 5 volt input. Essentially, there will be 256 quantization steps when reading a heartbeat.

Once the ADC has sampled and quantized the signal, the data will get coded into an 8 bit code and then stored into a buffer. Once the data is available in the buffer, the SPI protocol will be invoked for data transfer to the CyFi transceiver chip.

Wireless Communication using Cypress's CyFi

CyFi is a low power wireless solution that works on the star network principle via its star network protocol stack CYFISNP. This protocol entails a single hub per up to 250 general purpose nodes. The CyFi protocol stack provides two way communications between the hub and the various nodes. It has a dynamic data rate of up to 1 Mbps. The output power varies in accordance with the channel noise level and packet loss rate. Operational frequencies are from 2.400 GHz to 2.483 GHz.

A CyFi node is a PSoC device that reports data wirelessly to a hub; whereas, a CyFi hub is a PSoC device that receives, as well as transmits, data wirelessly from one or more nodes. Every node will have an address assigned to it that makes it unique.

Each node within a system will be assigned an 8 bit device ID assigned by the hub. This ID will identify the node amongst others when data is being sent. IDs can be assigned on-the-fly, or they may be preassigned by the user.

The CyFi protocol has four modes from which it will operate: bind, connect, data, and ping. The CyFi must begin with the bind process to secure a connection to

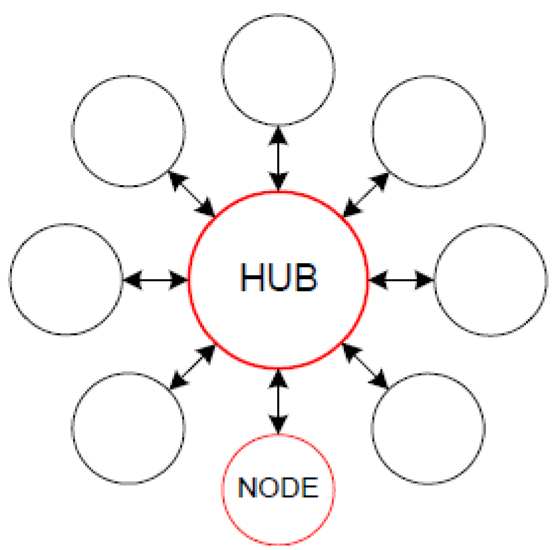

Figure 7: CyFi Block Diagram

the hub. Once a connection has been established, then the CYFISNP will begin the pinging process. Although a ping can originate from a node, typically the ping process is done by the hub so that is can gather data about the environment from which it is working in. From that, the CYFISNP will make a decision whether to keep the current setup, or change the wireless connection either by changing the channel and/or reducing the data rate. Once a solid connection has been established, meaning that the signal does not fall below the noise threshold governed by the pingRssiThreshold within the CYFISNP protocol, the CyFi will switch to data mode for information broadcast. However, if it does fail the aforementioned threshold, a series of channel switches and/or a speed drop will occur. The speed of the signal could drop to 250 kbps for more reliable data transfer [9].

The Smart Heart Monitor uses CyFi to transport the data taken from the sensor to the local hub for further processing. The receiving point may be either a computer or a routing device.

Cypress Semiconductor has created a generic all-purpose Sense and Control Dashboard program enabling the ability to monitor CyFi units from a remote computer. Basically, the hub would be connecting to the computer via USB allowing for data communication to take place between the CYFISNP and the computer. The Sensor and Control Dashboard allows the flexibility of customization for the user defined application. The Sense and Control Dashboard is used in the Smart Heart Monitoring System for analytical purposes.

Results

In order to analyze a heartbeat, it is necessary to understand the information that will be given by the sensor. In order to do so, analysis of the heartbeat must take place in both the time and frequency domain. Once the parameters are defined, then signal conditioning and processing can take place.

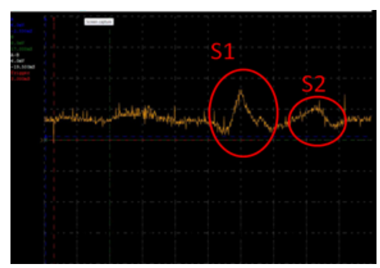

Figure 8: Heartbeat in the time domain

By understanding the heart beat in the time domain (Figure 8), the heart's intensity (amplitude), rate, and number of beats per cycle can be analyzed.

By understanding the frequency domain (Figure 9), the PSoC system can concentrate specifically on the heart's audio frequency and filter all unwanted frequencies out. Seen here was that the audio frequency taken from the heart was very near 40Hz.

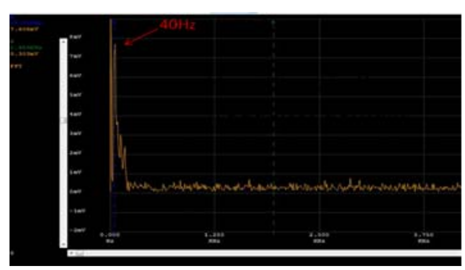

Figure 9: Heartbeat in the frequency domain

Once the analysis is complete, the circuit can be built and the PSoC system can be configured.

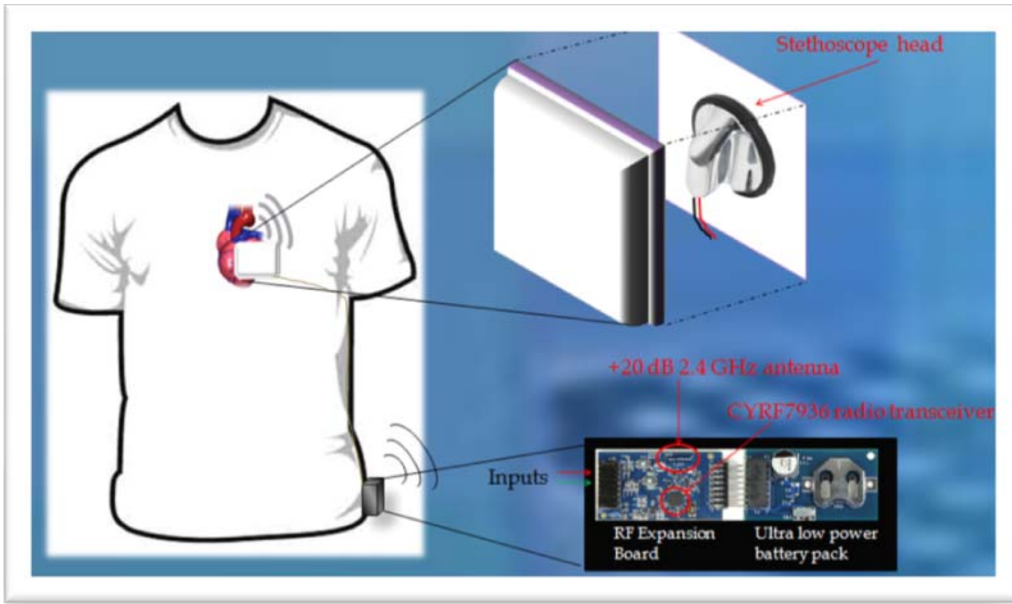

Figure 10: Full system

Conclusion

The Programmable System on a Chip is a very capable micro-controller. Being able to integrate the wireless component allows for technologies to exist never before thought of; hence, the idea of the Smart Heart Monitor System. With the Smart Heart Monitoring System, that ability to monitor patients from a remote location is feasible, and at a low cost. Thanks to the National Science Foundation's Research for Undergraduate Experience, the exploration to make such as device was initiated. With this technology, patients can be constantly monitored non-intrusively and remotely. If an indication of a health problem exists from a patient monitored by this device, the doctor or medical staff can be alerted of the issue and take the appropriate action.

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