Chapter 5

Ambulatory ECG signal acquisition system

The electrocardiogram (ECG) is most important diagnostic tool in cardiac malfunction. If we look at the price of the cardiac monitors commercially available in the market, we can find that the main constraint in their widespread usage is their cost. The cost of the instruments for ECG acquisition and necessity of ECG recorder for clinical diagnosis, reduction in equipment cost can make significant improvement in the health care monitoring. Advancement in the field of electronics, communication and information technology opens the door for possibilities to economize the ECG acquisition and portability of the system. Such portable system can be wearable by human body.

The aim of this research work is to develop a low cost module for ambulatory ECG acquisition which allows the patient to do the daily activity. The system is portable and battery operated that can be interfaced to PC through wireless channel, so that it can be wearable. As we have discussed the importance of physical movement detection of the subject, the acquired ambulatory ECG signal can be analyze with the movement detection signal and useful information can be derived. The acquisition of physical movement detection along with ambulatory ECG is to be recorded on base station for off line signal processing. Ambulatory ECG signal is acquired while subject is in his/her daily activity. So, the AECG signal acquisition system should be wireless connectivity or on board data storage capability.

5.1 System design of ECG signal acquisition

The output signal of interest is ECG of the order of 1-2 mV in amplitude occupying a frequency range of 0.05Hz to 150 Hz [3] for the wearable system. The wearable system requirement in this research work is discussed in the earlier chapter. Keeping in mind all those requirements we need to find out the latest technological solution for optimizing performance of the wearable ECG system. This section describes the design of circuit block of the instrument to fulfill the project objectives. The signal must be amplified properly to derived proper signal quality. The human body exists in lot of noisy environment. The noise there exists are power line interference noise of 50 Hz,
muscular noise, base line shift due to respiration and physical artifacts noise caused due to physical movement of the body for wearable systems.

![Figure 5.1 Block diagram of wearable ECG acquisition](image)

The wearable ECG system block diagram is shown in Figure 5.1. As shown in block diagram the amplification of the signal without introduction of additional noise and matching the impedance of the skin electrode interface with the impedance of recorder to avoid loading effect. An important factor common to all amplifier is the first stage, or preamplifier. This stage must have low noise, because its output must be amplified through the remaining stages of the amplifier, and any noise is amplified along with signal. It must also be coupled directly to the electrodes to provide optimal low frequency response as well as to minimize charging effects on coupling capacitors from input bias current. Even without coupling capacitors it can polarize the electrodes, resulting in polarization over potentials that produce a large dc offset voltage at the amplifiers input. This is why preamplifier often has relatively low voltage gains. The offset potential is coupled directly to the input, so it could saturate high gain preamplifiers, cutting out the signal altogether. To eliminate the saturating effects of this dc potential, the preamplifier can be capacitor-coupled to the remaining amplifier stages. Also, the preamplifier must have very high input impedance, because it represents the load on the electrodes. The first and foremost requirement in ECG acquisition is the electrodes. The electrodes discussion with various types of electrodes available in the market is discussed below.
5.1.1 Electrodes

The electrodes are one of the most important components of the system. It is the interface of the ECG acquisition system with the body skin and act as a transducer to convert the ionic current into electronic current. As we have discussed in earlier chapter, the ECG signal is captured with a pair of Ag/Agcl electrodes used for making electrical contact with the skin on specific locations on the body. Obtaining accurate data from an electrocardiogram depends partially on the specific electrode placement and site preparation [43]. In any measurement system, input impedance of the recording instrument must be many times greater than the impedance of the source. The same goes for a bioelectric recorder and the reason behind this procedure is the prevention of ‘loading’ of the recorder on the electrode bio-electric generator system. High impedance can be caused by excess dry skin, long hair, or the presence of scar tissue, and has the detrimental effect of adding noise to the signal of interest. Proper skin preparation must take place so that the least amount of impedance is present and optimal skin contact is obtained. Electrode gel can then be applied to the electrode in order to further increase its performance.

One of the most frequently used forms of bio-potential sensing electrodes is the metal plate electrode. In its simplest form, it consists of a metallic conductor in contact with the skin. An electrolyte soaked pad or gel is used to establish and maintain the contact. There are other types of foam electrodes available which are pre-gelled and disposable. Since in our application its long term ambulatory monitoring requirement and ease in use for wearable system pre-gelled foam type electrodes as shown in Figure 5.2 is used here in this application.

![Figure 5.2 a foam pad type electrode](image)
5.1.2 Instrumentation amplifier

As we have discussed in the introduction chapter that the ECG acquisition contaminated lots of noise caused due to various reason. Also, this noise is in the spectral overlap and amplitude with the ECG signal itself. Since the signal acquisition with noise superimposed on ECG signal, a differential amplifier with high Common Mode Rejection Ratio (CMRR) is preferable to remove the noise at the input terminal itself. The best suited amplifier for such application is instrumentation amplifier. The instrumentation amplifier with good CMRR around 100 db is selected for such application.

The differential amplifier used in the front end of this application is an INA321 instrumentation amplifier that has perfectly matched and balanced integrated gain resistors. The INA321 family is a series of rail-to-rail output, micro power CMOS instrumentation amplifiers that offer wide-range, single-supply, as well as bipolar-supply operation. The INA321 family provides low-cost, low-noise amplification of differential signals with micro power current consumption of 40µA and shutdown current of less than 1µA. INA321 provide CMRR of approximately 94 dB extended up to 3 kHz, the INA321 rejects the common-mode noise signals including the line frequency and its harmonics. The INA321 reduces common-mode error over frequency and with CMRR remaining high up to 3 kHz, line noise and line harmonics are rejected.

The ECG signal conditioning circuit is required to have proper frequency band signal is achieved at the output. Figure 5.3 shows the INA321 configured to serve as a low-cost ECG amplifier [46]. The input signals are obtained from the left and right arms of the patient. The common-mode voltage is set by two 2MΩ resistors. This potential, through a buffer, provides an optional right leg drive. The base line wandering effect is rectified by right leg drive circuit as shown in Figure 5.3. The output of the signal conditioning circuit contains still noise like power line interference need to be rectified. The cut off frequency can be change to by changing capacitor of the low pass filter connected after instrumentation amplifier.
Since our goal is to design small and portable wearable system design, we are optimally utilized the various circuitry integrated on chip microcontroller. In this design ultra low power microcontroller MSP430 is chosen for utilizing its mixed signal architecture. The MSP430 having three on chip operational amplifier can utilized to form amplifier and filters in the analog design. It is also having multichannel analog to digital convertor (ADC) as well as digital to Analog (DAC) for data conversion. In this design of signal conditioning circuit of ECG signal acquisition the on chip analog and digital peripherals are used to optimized the component count of the system. The ECG hardware on MSP430 microcontroller is discussed as under.

5.1.3 ECG hardware system on MSP430 Microcontroller

As we have discussed in chapter 3, in MSP430 microcontroller there are three operational amplifiers OA0-OA2. In this design op amp OA0 is used to have low pass filter circuit as shown in Figure 5.4 [34]. The low pass filter here acts as an anti-aliasing filter which restricts the signal of higher frequency to the further stages of the circuitry. The base line wandering effect that we have discussed earlier is implemented using OA1 output driven by on chip DAC controlled through software of MSP430 microcontroller. The integrator output of OA1 is feedback from the INA321 amplifier to maintain the
output DC offset to zero level. Since this circuit does not require third op amp as seen in schematic diagram of Figure 5.3 for the right leg drive we have only 2 leads electrodes are required to attached with the body that is right arm and left arm (lead II) configuration.

![Diagram](image)

**Figure 5.4 Signal conditioning circuit block diagram using on chip op amp of MSP430**

The amplified output generated from the signal conditioning circuit is then fed to the on chip 12-bit Analog to Digital converter (ADC) of MSP430 microcontroller. The ADC sampling frequency is controlled through timer of the microcontroller. The timer of the microcontroller can be programmed to change the sampling frequency of the on chip ADC. The digitized output of the ADC chip contains noise like line frequency 50 Hz, artifacts noise and muscular noise. Since in our application the system is operated through 3 V DC supply, the line frequency noise filter is not required. However the ECG output in the 50 Hz noisy environment the signal quality is degraded.

The microcontroller is operated through 3 V DC supply and INA321 is also working on single supply 3 V DC. The button cell battery is used to drive both controller and INA321 chip. The programming of MSP430 microcontroller is done with the JTAG connector. The JTAG connection is taken out from the board of the system so, that it can be programmed on board by the TI USB programmer. There is a provision for UART connection out from the board. The ECG signal derived from the circuit is transmitted to the wireless channel. The Zig-Bee wireless channel module is interfaced with this board via UART connection and then module transmit ECG to base station located to the nearby location. The role of software in this design is discussed in the next section of this chapter.
5.2 Software algorithm

The development in the software technology offers lot of facility for the programmer to program the microcontroller quit easily. The MSP430 microcontroller can program in higher level language C by using development tools. IAR workbench tool which we have discussed in the third chapter is used here to program MSP430 microcontroller. The library function are already available that can be included in the design to simplify the software developments. The functions for controlling of ADC, Timer, UART, digital amplification and filtering are used in the design.

![Flow chart of software algorithm for MSP430](image)

Figure 5.5 flow chart of software algorithm for MSP430

The Flow chart of the software algorithm is as shown in Figure 5.5. The software algorithm start with the initialization of the various hardware block of the controller is when it is powered. In the initialization routine the software started the various parameter to the peripherals like, timer for sampling frequency of ADC, baud rate for URAT, DAC input configuration etc. The operational amplifier in this design to fulfill the signal conditioning circuit to interface with various external connections is initialized. The DAC
1 is used for generating constant reference voltage is enabling in initialization phase. The timer is also required to set parameter for triggering of ADC sampling frequency for 512 Hz. The ADC is turning on with interrupt mode to take sample after software interrupt generated. The DAC1 initialized to have constant bias voltage of 1.5 V for amplifier blocks. Later the UART port of MSP430 is initialized to have the parameter like 115.2 K bps, 8-bit character, no parity bit and modulation parameter.

After initialization is over the program will generate start pulse for ADC to take samples from the OA0 output of MSP430 controller. The data available from the ADC requires filtering of high frequency noise like artifacts and low frequency 50 Hz line frequency noise. First the output of ADC is passed through the function subprogram of low pass filter to filter the line frequency noise. The attenuation of the signal is improved in this filtering to have signal amplitude to have desire level. Then the output data of low pass filter are passed through high pass filter to remove muscular artifacts noise. The digital filter can easily implemented in software by providing filter coefficient in the lookup table of the program. The various software tools are available on the internet to calculate the filter coefficient.

The digitized data from the high pass filter is then transmitted from the UART port facility of MSP430 microcontroller. In this design the baud rate at which the ECG data are coming at the rate 15200 bps. The UART port of microcontroller is connected with the UART of Zig-Bee module. The Zig-Bee module receives the ECG data and transmits it to the air within 2 to 4 meter distance of Zig-Bee range. The Zig-Bee wireless receiver is attached to the base station that receives the data of digital ECG on its virtual com port through USB. The LabView GUI program is developed on base station for displaying ECG signal in real time graphical window. The received data can also be recorded into base station memory for further offline processing and printing.

5.3 PCB design of the wearable ECG system

The wearable system requires portability to have ambulatory condition. The circuit components are chosen SMD (surface mount) for size constrain of the wearable design. The printed circuit board (PCB) is design by keeping in mind the physical dimension is as possible as small of the system. The PCB is design using PCB design software ORCAD. The complete schematic diagram is shown in the Figure 5.6. The PCB is double sided SMD components with plated through holes (PTH). The PCB board for this design is
optimally design such that the noise is rectified through strong ground plane provided on board.

Figure 5.6 the Schematic diagram of ECG circuit

The dimension of the PCB board is 9.0 cm x 3.5 cm which is well suited for wearable systems. Most of the circuit blocks on the PCB have mixed signals (i.e. analog and digital) and consequently special care was needed in the layout design. Since the analog and digital signal meeting, there is a great possibility of analog supply being corrupted by digital switching noise. Even in the digital parts, proper decoupling of power supply of each chip is essential. Also the supply routing should be done carefully. The analog ground and digital ground is routed separately. The picture of both the top and bottom layer layout diagrams is shown in Figure 5.7.
The top layer of the PCB for ECG acquisition is shown in Figure 5.8. The top layer mask is also shown in Figure 5.9. The bottom layer diagram and bottom layer mask diagram of the developed PCB is shown in Figure 5.10 and Figure 5.11 respectively.
Figure 5.9 Top layer mask of the PCB for wearable ECG

Figure 5.10 Bottom layer layout diagram for wearable ECG
There is a provision for wireless Zig-Bee module on the PCB to have wireless channel. As discussed earlier the digital values of ECG signal is available through UART standard pins. The UART connection of MSP430 is connected to Zig-Bee connector on board itself, so no extra jumper is required for the same.

### 5.4 Wireless channel

The ambulatory signal is acquired by wearable system discussed earlier. The digital data are required to transmit wirelessly to the base station via wireless channel in wearable system. The acquired data on wearable system now uses UART port to transmit serially at the baud rate of 115.2 kbps. In this design the Zig-Bee wireless module is interfaced with the system to transmit data to the base station. On the base station the receiver Zig-Bee module is interfaced with USB port to receive the data and transmitted through wearable system. The received data serial port is display on the GUI developed in LabView software running on the base station. The discussion on GUI developed in LabView for display the ECG signal in real time is given later in this chapter. The detail discussion on wireless Zig-Bee module is given earlier in chapter 3.

### 5.5 LabView GUI for ECG acquisition

The LabView based GUI software is developed on base station to receive the wireless transmitted data from wearable ECG system. The wireless module is interfaced with base station via USB port. The LabVIEW program is responsible to read serial port...
continuously and display on the real time graphical window designed in LabView. The various parameter of com-port setting is also given as tab window as per user requirement. The parameter like baud rate, sampling time etc. can be change as per user requirements. The snap shot of the LabView front panel window is shown in the Figure 5.12. The block diagram of the front panel window is shown in Figure 5.13.

![Figure 5.12 front panel GUI developed in LabVIEW](image1)

![Figure 5.13 Block diagram of front panel GUI](image2)
The front panel on GUI window developed for ECG signal is shown in Figure 5.1. In the above LabView window there is a front view of the GUI developed for various serial ports setting as per requirements. Initially when the Zig-Bee USB module is interface with PC, it initialize the virtual com port, that port number, we have to select from the list of the text box called VISA resource name. The various baud rates can also be selected by baud rate setting shown in the figure of LabView window. Data width setting is also possible through data bits fields. Various other options are also available but as a default case we need to only change the com port setting each time when we started the application.

5.6 Experimental results of ECG hardware system

The main objective of the system is to acquire the ambulatory ECG signal data. Here we show the ECG plots of the data acquired by the ECG hardware through the sensor electrodes from the body during various different types of body movement activities. For example in Figure 5.15, there is signal plotted during standing still position of a person wearing the sensor node of ECG acquisition. The signal value in the plot are nearly a good quality ECG signal with various points on ECG are visible like P, Q, R, S and T segments as expected for a stand still condition.
Figure 5.15 Ambulatory ECG signal acquired during standing still position.

In Figure 5.16, the ECG signal shown for up and down movement of right arm and accelerometer sensor attached to the left arm wrist.

Figure 5.16 Ambulatory ECG signal when repetitive movements of right arm in vertical plane

Similarly, in Figure 5.17, the ECG signal plotted which are acquired during slow motion walking of the subject.
Finally, we performed the experiments for several other physical activities like walking, running, climbing stairs etc. that may occur in routine life and found that these activities can easily be sensed from the acceleration signal measurements from different parts of the body, like hands, legs, waist, chest, shoulders, and head etc.

5.7 Specification of the developed system

The system specification is described in shown in appendix A. From the table we can see the developed wearable system can be used to monitor and record ambulatory ECG signal. The system can also be used for biotelemetry application in medical instrumentation. In the next chapter we will discussed about integrating of such wearable system with physical movement detection system for simultaneous acquisition of signals. The multiple accelerometers can be interfaced with such system for simultaneous movement detection of the body for further offline analysis.

5.8 Summary

In this chapter it is presented that a system for sensing ambulatory ECG signal wirelessly acquired on the based station computer located to nearby distance. The developed wearable ECG system is demonstrated to the medical officer and the observation report from the officer is given in the Appendix B. The system is able to
capture the ambulatory ECG signal that is when subject is performing routine life activity. Moreover, it is based on a ultra low power mixed signal microcontroller that can be configured for analog and digital processing of the signals and transmission of the acquired data in real time. The ambulatory ECG signal recorded on the base station memory. The recorded signal can be processed off line to recognize the daily activity of the subject from AECG signal itself. The developed wearable system can also be used to have remote monitoring of the subject from the remote location for bio-telemetry application. This is important contribution of this research work.