Chapter 4

Physical movement detection system

ECG signals are widely employed as a non-invasive tool for cardiac monitoring. However, the quality of the ECG signal is severely affected by the physical movement of the patient. Hence it is necessary to sense the body movement during ambulatory or mobile cardiac monitoring for determining the quality of ECG signal and also to know the physiological effects of the physical activity [4-8]. In, [4-5], authors have proposed various methods for recognition and transition detection of body movement from the ECG signal itself. Based on recent research trends, in [9], a survey of ambulatory ECG monitoring has been presented and it is concluded from this study that physical activity related information is very useful for ambulatory ECG monitoring. Thus it is required to sense body movement for correlating it with the ECG signals while ambulatory health monitoring. The presented body movement sensing system is very light-weight, small size and hence suitable for wearable and mobile applications.

4.1 System design

As we have discussed in earlier that the physical movement detection is essential in ambulatory analysis of the wearable systems. Wearable systems require acquisition of required parameter through sensor attached to the body. As we have discussed in earlier chapter that the physical movement of the subject can be sensed by accelerometer sensor. Usually, a movement sensing system has multiple accelerometer sensors attached to a central unit. This requires interfacing of several analog and digital integrated circuits. The integration of multiple-chips increases the cost and size of the design and results in a poor reliability which is a major concern in the health monitoring system. As a preferred option, PSoC (Programmable System on Chip) can be used for designing a dedicated health monitoring system. One such PSoC based system has been developed for temperature monitoring in [42] with a single temperature sensor interfaced with PSoC. In this chapter we will discuss a design of body movement sensing system with multiple acceleration sensors interfaced with a PSoC. Thus the proposed PSoC based system is a multi-channel system and it is configured in a different manner from the PSoC based temperature sensing system given in [42]. One can also used this reserved channel for any other
physiological signal with appropriate sensors. The proposed body movement sensing system consists of the following components:

1. Accelerometer sensors
2. Signal conditioning, Tri-Channel ADC and Microprocessor (built-in PSoC)
3. LCD Display
4. Connectivity to a personal computer through Zig-Bee wireless channel
5. GUI for computer interface and data logging.

A block diagram of the system is shown in Figure 4.1. The overall system is controlled through PSoC based microcontroller which controls all the operation of the wearable system. For a very compact design, this microcontroller should have sufficient programmable ROM, and data RAM, parallel I/O ports, serial port, and a programmable timer/counter in order to handle all the operations, without requiring additional chips. As we have discussed earlier, in this design a Programmable System on Chip (PSoC) from cypress semiconductor for physical movement detection system is used. The discussion on PSoC based microcontroller is described in the subsection later in detail.

![Figure 4.1 Block diagram of the PSoC system for sensing body movement](image-url)
4.2 Accelerometer sensors

The accelerometer sensors available in the market with different configuration i.e. the form of output signal analog or digital. A 3-axis accelerometer is a single chip that can measure the acceleration signals in three perpendicular directions called axis. There are two types of sensor available one sensor gives the 3-axis output in form of analog voltage and other gives directly digital output. The analog voltage generated with respect to movement of the sensor of very low voltage. The amplification is required for such low voltage to measure by instrumentation systems. While another type of accelerometer sensor directly gives digital equivalent of movement detection that does not require signal conditioning. In this design analog output accelerometer sensor MMA7361L, 3-axis accelerometer manufacture by Freescale semiconductors is used. MMA7361L can be configured for two different sensitivity values [39]. We have configured it for the acceleration range of -1.5g to 1.5g. The sensor provides three analog channel output corresponding to 3-axis. The detail discussion on accelerometer sensor is discussed in following section.

The MMA7361L is a low power, low profile capacitive micro machined accelerometer from Freescale Semiconductor featuring signal conditioning, a 1-pole low pass filter, temperature compensation, self test, 0g-Detect which detects linear freefall, and g-Select which allows for the selection between 2 sensitivities. The internal block diagram of MMA7361L sensor is shown in Figure 4.2.

![Figure 4.2 Block diagram of MMA7361L Accelerometer](Courtesy: datasheet of MMA7361L Accelerometer from Freescale semiconductor©)
The basic features of MMA7361L accelerometer sensor is given as follows [39].

**Basic Features of MMA7361L Accelerometer**

- Low Current Consumption: 400 µA, Sleep Mode: 3 µA
- Low Voltage Operation: 2.2 V – 3.6 V
- High Sensitivity (800 mV/g @ 1.5g), Selectable Sensitivity (±1.5g, ±6g)
- Fast Turn On Time (0.5 ms Enable Response Time)
- Self Test for Freefall Detect Diagnosis
- 0g-Detect for Freefall Protection
- Signal Conditioning with Low Pass Filter
- Robust Design, High Shocks Survivability
- RoHS Compliant
- Low Cost

The accelerometer sensor is MEMS (Micro Electro Mechanical System) based integrated surface-micromachined system. The device consists of a surface micromachined capacitive sensing cell (g-cell) and a signal conditioning of Application Specific Integrated Circuit (ASIC) contained in a single package. As shown in Figure 4.3 the g-cell is a mechanical structure formed from semiconductor materials (polysilicon) using semiconductor fabrication technology processes. It can be modeled as a set of beams attached to a moveable central mass that move between fixed beams. The movable beams can be deflected from their rest position by subjecting the system to acceleration. The g-cell beams form two back-to-back capacitors array. As the center beam moves with acceleration, the distance between the beams changes and each capacitor's value will change, \( C = Aε/D \). Where A is the area of the beam, \( ε \) is the dielectric constant, and D is the distance between the beams.

The ASIC uses switched capacitor techniques to measure the g-cell capacitors and extract the acceleration data from the difference between the two capacitors as shown in
Figure 4.3. The ASIC also signal conditions and filters (switched capacitor) the signal, providing a high level output voltage that is radiometric and proportional to acceleration of the chip.

![Figure 4.3 Accelerometer sensor basic mechanisms](Courtesy: datasheet of MMA7361L Accelerometer from Freescale semiconductor©)

As shown in the block diagram of MMA7361L accelerometer having various pins as output and input configuration of the acceleration. The generalized discussions of such pins are described as below.

**0g-Detect**

In the default condition this pin has active low configuration. The sensor offers a 0g-Detect feature that provides a logic high signal when all three axes are at 0 g. This feature enables the application of Linear Freefall protection if the signal is connected to an interrupt pin or a poled I/O pins on a microcontroller. The system can take reference to set some parameters for 0 g condition.

**Self Test**

The surface micro-machined accelerometer chip is very small with thin pins and need efficient soldering technique. The sensor provides a self test feature that allows the verification of the mechanical and electrical integrity of the accelerometer at any time before or after installation. User can use self test to verify the solderability to confirm that the part was mounted to the PCB correctly.
g-Select

The g-Select feature allows for the selection between two sensitivities. Depending on the logic input placed on pin 10, the device internal gain will be changed allowing it to function with a 1.5g or 6g sensitivity (Table 4.1). This feature is ideal when a product has applications requiring two different sensitivities for optimum performance. The sensitivity can be changed at anytime during the operation of the product. The g-Select pin can be left unconnected for applications requiring only 1.5 g sensitivity as the device has an internal pull-down to keep it at that sensitivity (800mV/g).

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<thead>
<tr>
<th>g-Select</th>
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<th>Sensitivity</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>1.5g</td>
<td>800 mV/g</td>
</tr>
<tr>
<td>1</td>
<td>6g</td>
<td>206 mV/g</td>
</tr>
</tbody>
</table>

Sleep Mode

The 3 axis accelerometer provides a Sleep Mode that is ideal for battery operated products. When Sleep Mode is active, the device outputs are turned off, providing significant reduction of operating current. A low input signal on pin 7 (Sleep Mode) will place the device in this mode and reduce the current to 3 µA typ. For lower power consumption, it is recommended to set g-Select to 1.5g mode. By placing a high input signal on pin 7, the device will resume to normal mode of operation.

Filtering

The 3 axis accelerometer contains an onboard single-pole switched capacitor filter. Due to the filter is realized using switched capacitor techniques, there is no requirement for external passive components (resistors and capacitors) to set the cut-off frequency.

Ratiometricity

Ratiometricity simply means the output offset voltage and sensitivity will scale linearly with applied supply voltage. That is, as supply voltage is increased, the sensitivity
and offset increase linearly; as supply voltage decreases, offset and sensitivity decrease linearly. This is a key feature when interfacing to a microcontroller or an A/D converter because it provides system level cancellation of supply induced errors in the analog to digital conversion process.

4.2.1 Accelerometer sensor module design

The tiny accelerometer chip requires 3 V DC as power supply and other necessary accessories like input-output connector, input supply connector on the compact printed circuit board (PCB). The various electronic components need to be interfaced with the accelerometer sensor IC. Since in the wearable system design the size of a system is major concern, the PCB for this designed module is compact.

The schematic diagram of the developed sensor module is shown in Figure 4.4. The sensor chip is operated with 3V DC power supply need very steady regulated 3V supply. In the circuit diagram the regulator IC LM 317 with necessary resistance connection is used to convert 5 V DC to 3 V DC supply. So, input DC supply needed for this module is 5 V DC which is standard in portable system design. The accelerometer sensor chip is of mixed signal IC, there is high speed digital switching creates noise in analog signal conditioning. To remove such noise from power supply a decoupling capacitor is connected between power supply line and ground track. The output is connected with three individual parallel capacitors to stabilize the analog voltage for further processing of each channel. As seen in the schematic diagram of Figure 4.4, the accelerometer output channels x, y and z is taken out on P3 header connector. The various input signaling like 0g-select, g-select, self test, and sleep are provided with the input pin connector P4 header. The complete accelerometer sensor module bill of material with footprints for PCB is given in the Table 4.2.

4.2.2 PCB design of accelerometer sensor module

The layout diagram of the developed accelerometer sensor module is shown in Figure 4.5. The layout diagram is double sided PCB board with all components placements are such that the size of the PCB module is small. The dimension of developed sensor module is 3.5 cm X 2.8 cm. A picture of an acceleration sensor module is shown in Figure 4.6. This module should be tightly attached to limb or body-part while
experimenting for movement detection by the subject. The developed accelerometer sensor module is now ready to interface with the PSoC based wearable system. The PSoC based implementation of signal conditioning circuit is discussed in the following sections.

![Figure 4.4 Schematic diagram of accelerometer sensor module](image)

<table>
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<tr>
<th>Comment</th>
<th>Description</th>
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<th>Footprint</th>
<th>LibRef</th>
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<td>2</td>
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<td>1</td>
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<td>HDR1X4</td>
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<td>1</td>
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</tbody>
</table>

Table 4.2 Bill of Materials (BOM) for accelerometer sensor module
4.3 PSoC based signal conditioning for accelerometer sensor

As we have discussed the importance of system on chip for wearable system design. The Programmable System on Chip (PSoC) is suitable for wearable system for low chip count and low power consumption. Generally for analog signal measurement by instrumentation requires signal conditioning circuit for achieving proper signal level for ADC input range. In this case the PSoC provide the mixed signal peripheral approach to configure its hardware circuitry. So, one can provide single chip solution for signal conditioning and signal processing. In this design of physical movement detection of the subject accelerometer sensor module is directly interfaced with the PSoC chip. The PSoC chip CY8C29466 IC from cypres semiconductor is used in this design for physical
movement detection sensor module. The following paragraph discussed about the PSoC based implementation for accelerometer sensor interfacing for developed wearable system.

4.3.1 Analog and digital modules on PSoC

In this design signal conditioning for accelerometer sensor for physical movement detection is on chip of PSoC. The signal conditioning block contains PGA (Programmable Gain Amplifier) which will amplify the accelerometer analog output as per the property setting by the user of PSoC PGA block. The amplified analog output of the 3-axis accelerometer sensor requires analog to digital conversion for digital processor for signal processing. Another important analog to digital convertor peripheral in PSoC is Tri-Channel ADC [33]. The Tri-Channel ADC is good choice for sensor having 3-axis analog output requirements where simultaneous sampling of 3 channel analog signal is taken for conversion into digital by ADC.

The output signals from the accelerometer sensor modules as discussed in the previous subsection are input to the signal conditioning block. The signal conditioning block processes the analog signals by providing the required amplification and pre-filtering before analog to digital conversion (ADC). The signal conditioning is built in PSoC and configured very easily through PSoC designer software tool. Since each accelerometer sensor module has three channels, the PSoC is also configured in three channels when a single acceleration module is connected. For multi-sensor system we have configured the PSoC for appropriate number of channels in similar modular manner. The ADCs are configured for 12-bit resolution and sampling rate of 75Hz. The data in digital form from the ADCs are then transmitted through UART.

As discussed in the design consideration chapter the analog and digital peripherals are need to be included into project created by PSoC designer software tool and then the configuration is programmed into PSoC chip by the PSoC programmer. The snap shot of PSoC designer window after project design in this tool is shown in Figure 4.7.
4.3.2 PSoC Programming

The programming of the PSoC chip through PSoC designer software tool is discussed in the 3rd chapter of this thesis. After configuration of analog and digital modules into PSoC the programming in C is possible into main file of the source directory of the created project. The various functions are already available as library file in C that can be used in our design. The firmware developed for physical movement detection system is explained below.

The firmware for the system is implemented on PSoC M8C microcontroller programming which is responsible for controlling overall systems module. The PSoC can be configured by using PSoC designer software from cypress semiconductor. The flowchart of the system firmware is shown in Figure 4.8. As soon as the PSoC power turn on it should initialized the configured hardware block according to the sequence of initialization instructions. After initialization and power on the various peripheral it check whether data from ADC output is available or not, if available then there is a instruction to read the ADC value into the declared variable. The available data are serially transmitted via configured UART port of the PSoC. Available data is then received by base station.
through USB to UART convertor or Zig-Bee wireless channel. The discussion on Zig-Bee wireless channel is discussed in detail in this chapter later.

![Flow chart of the firmware](image)

**Figure 4.8 Flow chart of the firmware**

The Programmable System on Chip (PSoC) based central controller unit is responsible for overall system resources through software which is running on the PSoC controller. The PSoC microcontroller is handling the data received from various sensor nodes e.g. AECG node, 3-axis accelerometer node. The analog signal available from both the sensor node is converted into digital data by on chip ADC configured into PSoC controller by PSoC designer software tool.

The acceleration values are also displayed on a 16x2 LCD interfaced with PSoC. PSoC is programmed for performing these tasks of displaying and transmission. The acquired data is transmitted through a serial interface to base station in RS-232 standard. A GUI developed in LabVIEW program is developed for displaying the results on PC screen.
in real time. The GUI is prepared using LabVIEW®. The received data on pc can be stored in a file in excel format for data recording.

4.3.3 PCB design of PSoC based system

The programmed PSoC IC is now ready to insert into the PCB board of the developed system. To have complete system in operation we need to have a PCB of the wearable system for physical movement detection. The various connections are needed on PCB to have system working with battery. The schematic diagram of PSoC based system is shown in Figure 4.9. In this schematic design we can see the JTAG programming interfaced with the PSoC programmer. The header P5 is used to connect the PSoC to the programmer. There is LCD display connection on 14 pin header connected with PSoC chip to display the required information through PSOC programming.

The complete bill of material for the PSoC based wearable system is given in Table 4.3. The layout diagram of the developed system of PSoC based wearable system is shown in Figure 4.10. The dimension of the PCB is 6.5 cm X 8.1 cm. The picture of PSoC based physical movement detection system is shown in Figure 4.11.

![Figure 4.9 Schematic diagram of PSoC based wearable system](image)
Table 4.3 Bill of Material for PSoC based wearable system

<table>
<thead>
<tr>
<th>Comment</th>
<th>Description</th>
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<th>Footprint</th>
<th>LibRef</th>
<th>Quantity</th>
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<td>Header 2</td>
<td>1</td>
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<td>XTAL</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 4.10 Layout diagram of PSoC based wearable system
4.4 Wireless connectivity

The physical movement accelerometer signals are acquired by wearable system discussed earlier. Digital data are required to transmit wirelessly to the base station computer via wireless channel in wearable system. The acquired data on wearable system now uses UART port to transmit serially to the outside systems. 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 transmitted through wearable system. The received data serial port is displayed on the GUI developed in LabVIEW® software running on the base station. The discussion on GUI developed in LabVIEW® is given later in this chapter. The detail discussion on wireless Zig-Bee module is given in the following section.

4.4.1 Zig-Bee wireless module

The Zig-Bee module OEM RF module is used in this design which is shown in Figure 4.12. The Zig-Bee is standardized by IEEE 802.15.4 OEM RF (wireless communication module using wire antenna) modules are useful in transferring low data rates and where low-power consumption is necessary. These modules operate in the unlicensed 2.4 GHz industrial, scientific, and medical (ISM) band. The snap shot of such module is shown in Figure 4.6.
The OEM RF Modules were standardized to meet IEEE 802.15.4 standards and support the unique needs of low-cost, low-power wireless sensor networks. The modules require minimal power and provide reliable delivery of data between devices. The modules operate within the ISM 2.4 GHz frequency band and are pin-for-pin compatible with each other. The 802.15.4 OEM RF (wireless communication module using wire antenna) module is used for embedded solutions providing wireless end-point connectivity to devices. This is an ideal module for robots to PC or robots to robots communication. This module can give range of 30 meters indoor or 100 meters outdoor. This wireless device can be directly connected to the serial port (at 3.3V level) of your microcontroller. By using a logic level translator it can also be interfaced to 5V logic (TTL) devices having serial interface. This module supports data rates of up to 115kbps. It has indoor range of 30 meters and outdoor RF line-of-sight range of up to 100 meters. These modules use the IEEE 802.15.4 networking protocol for fast point-to-multipoint or peer-to-peer networking. They are designed for high-throughput applications requiring low latency and predictable communication timing. This OEM RF Modules interface to a host device through a logic-level asynchronous serial port. Through its serial port, the module can communicate with any logic and voltage compatible UART; or through a level translator to any serial device.

### 4.4.2 UART Data Flow

Devices that have a UART interface can connect directly to the pins of the RF module as shown in the Figure 4.13. System Data Flow Diagram in a UART-interfaced environment (Low asserted signals distinguished with horizontal line over signal name.)
The LabVIEW® based GUI software is developed on base station to receive the wireless transmitted data from physical movement detection 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® window is shown in the Figure 4.14.

The front panel on GUI window developed for ECG signal is shown in Figure 4.15. 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.

Figure 4.15 LabVIEW front panels for real time graphical data display

The block diagram of the front panel GUI developed for acquisition of accelerometer signal and real time display is shown in Figure 4.16.

Figure 4.16 LabVIEW block diagram window for accelerometer data acquisition
4.6 Experiment result of body movement data acquisition

The main objective of the system is to acquire the body movement data. Here we show the plots of the data acquired by the PSoC through the acceleration sensors during various different types of body movement activities. For example in Figure 4.17, there is 3-axis acceleration signals plotted during standing still position of a person wearing the sensor at back of the waist. The signal values in the plots are nearly a constant as expected for a stand still condition. The differences among the levels of the 3-axis signals are attributed to the static gravitational acceleration. The sensor axis nearly aligned with the gravitational axis exhibits the highest acceleration level due to gravity.

![Figure 4.17 3-axis acceleration signals acquired during standing still position. The sensor attached on back of waist.](image)

Next, we have acquired data to represent movement of any limb. In Figure 4.18, 3-axis acceleration signals are shown for repetitive movement of a hand in azimuth plane. These acceleration signals are acquired from the sensor tightly attached on the wrist. We can observe that there is a cycle in acceleration signals corresponding to each repetition of the movement and nearly four repetition of same type of hand movement are performed here.
Similarly, in Figure 4.19, the acceleration signals from a sensor attached to the wrist are plotted which are acquired during repetitive up-down movements of the hand. Here also the cyclic nature of the acceleration signal is visible because of repetitive actions of hand.

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.
4.7 Summary

In this chapter we have discussed a system for sensing acceleration caused due to body movement. The system is able to capture the body movements that are performed in routine life. Moreover, it is based on a single programmable chip that can be configured for analog and digital processing of the signals and transmission of the acquired data in real time. The acceleration sensor module can be attached separately on any part of the body for sensing the movement of that body-part. Various routine physical activities can be characterized and recognized from the acquired acceleration signal using the presented system. Though the body movement can easily be recognized with several acceleration sensors tightly attached to the body, it is cumbersome for a person to wear so many sensors. Therefore, it is preferred to attach fewer sensors at selected body parts that represent the body movements distinctly.