A SYNERGISTIC WEARABLE HEALTH MONITORING SYSTEM USING CELLULAR NETWORK TECHNOLOGY

By

Nagarjuna Pamidi

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APPROVED:

Dr. Dejan Raskovic, Committee Chair
Dr. Denise Thorsen, Committee Member
Dr. Jason B. McNeely, Committee Member
Dr. Charles E. Mayer, Chair
Department of Electrical and Computer Engineering
Dr. Doug J. Goering, Dean
College of Engineering and Mines
Dr. Michael Castellini, *Dean of the Graduate School*

Abstract

This thesis presents a synergistic approach to healthcare applications by integrating a wearable health monitoring system into a smart home system. By exploiting synergy within each system and between these two systems, this thesis shows that the efficiency of the health care can be increased while providing the added advantage of utmost user-friendly environment. Initially, a wearable health monitoring prototype system was developed for vital sign data collection and processing. The developed system used biosensor integration to distinguish amongst multiple physical activities and to compare the variations in physiological conditions according to physical activity of the user. Afterward, system learning techniques were established for accomplishing the scalability of the health monitoring system. The resulting system is able to monitor different users without the need for explicitly changing the thresholds for the individual user.

The health monitoring was further improved through integration with the smart home system to exploit synergy between various physiological sensors and to reduce false alarms generated by the system. A cellular communication interface was developed for transmitting the collected data to a remote caregiver and also to store the time-stamped data on the online web server. A web interface was developed to allow monitoring user's health and activity data, along with their surrounding environment.

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Chapter 1 Introduction

The global elderly population is growing dramatically [1]. The Agency for Healthcare Research and Quality (AHRQ) has conducted research on health care expenditure and proclaimed that older people are amongst the highest-spending percentiles [2]. The National Health Expenditure (NHE) fact sheet has shown similar results, stating that people 65 years and older accounted for 34 percent of total healthcare expenses in 2012 [3]. In 2013, the elderly population spent $34 billion on injuries related to falling, and these spendings are expected to reach $67.7 billion by 2020 [4]. Increasing healthcare costs have encouraged the growth of research in wearable systems for personal health monitoring. It is anticipated that monitoring senior citizens' health and lifestyle in their living environment will lower the need for frequent visits to a hospital. A growing body of research demonstrates the importance of continuous physiological status monitoring to reduce health care expenditures [5-11].

1.1 Wearable Health Monitoring Systems

The objective of wearable health monitoring systems is to minimize medical expenses by providing inexpensive substitutes for physiological data monitoring. Wearable systems are intended to deliver continuous monitoring of health and activity data without interrupting the lifestyle of the person wearing it. The wearable systems use on-body, miniaturized biomedical sensors to observe multiple physiological signals such as heart activity, brain electrical activity, muscle activity, respiration rate, lung volume, galvanic skin response (GSR), oxygen saturation (SpO_2), skin conductivity, body core temperature, blood pressure, blood glucose level, sweat conductivity and pH levels. In addition to the bio-signals, physical activity and living environmental conditions are also monitored for better understanding of the modulations in physiological conditions [12].

The collected medical data is transmitted to a local server using either wireless communications or a wired link [13]. Most current health monitoring systems use smartphones [14] and personal computers as gateways or local servers. In the past, researchers have also used personal digital assistants (PDA) [13] as gateways. Typically, local servers are responsible for processing the gathered data, providing real-time feedback to the user and distant caregivers, while raising alarms during vital sign abnormalities and storing the collected data in a medical web server. Healthcare professionals and informal caregivers are intended to have access to this online health information. Remote healthcare professionals can then use the online data to suggest to the user any appropriate changes needed to be made in medication intake, adjustments in physical activities, and to provide immediate help during critical conditions. Besides wearable systems, researchers have also used smart homes to track the well-being of the elderly [10] [11]. In the past, the health status of inhabitants was supervised by monitoring the use of household furniture and electronic appliances [10].

1.2 Smart Home Systems

Smart home systems (or automated home systems) aim to improve healthy lifestyle of home occupants by facilitating comfort and security in an energy efficient environment. By 2022, the smart home market is expected to reach $121 billion [15]. Advances in smart appliances are affected by improved power efficiency and reduced carbon emission [15]. Due to the evolution of internet of things (IoT), most of the home appliances are becoming smarter and more automated alongside the advantages of remote access [16]. Several industries are actively producing appliances to support smart homes. Nest Labs Learning Thermostat [17], LIFX Smart Bulb [18], August Smart Lock [19] and Amazon Echo [20] are few examples of most advanced and automated electrical appliances that are available in 2016. However, all these appliances run on their platform requiring users to run multiple apps to control individual smart appliances. Future technology is expected to support diverse home appliances through a single platform; researchers at the University of Alaska Fairbanks designed a medium access control (MAC) protocol to integrate multiple smart appliances into a single platform [21]. Furthermore, automatically adjusting the smart home environment according to given medical conditions of inhabitants would increase healthcare proficiency by providing comfort and safety in a living environment, which further improves the life expectancy.

1.3 Possible Improvements in Healthcare Applications

Wearable systems for medical applications continuously monitor physiological conditions of the user. On the other hand, smart home systems continue to grow their abilities to automate the home environment. However, integration between these two different systems still needs to address improvements for achieving effective results in health care, while maintaining a user-friendly living environment.

1.4 Contribution of Thesis

Some of the major contributions of this thesis are:

1. Development of a wearable health monitoring platform to allow research on physiological data collection and processing and system synergy.
2. Implementation of sensor synergy techniques for actively monitoring physiological conditions and physical activity.

3. Development of an interface that can accept sensors with various interfaces (I2C, SPI, UART, and analog), which cover a broad range of physiological sensors.
4. Further development of the wearable health monitoring system to interface with a smart home system through a wireless communication network.
5. Development of an interface to support the use of a camera module to assist emergency crews and to reduce false alarms by providing visual information about the user.
6. Development of an interface for embedded 3G cellular communications for possibly transmitting the collected physiological data anywhere on the Earth.
7. Development of a web interface to store (and provide online access to) the collected data from the system.

1.5 System Overview

The purpose of this thesis is to develop a wearable health monitoring prototype system to facilitate the research on wearable health monitoring systems by collecting physiological statistics, such as heart rate, body temperature, and physical activity data. Initially, the wearable system utilized microelectromechanical (MEMS) sensor fusion techniques to detect events such as resting, sitting, walking, running, stairs climbing, rope jumping and falls. Afterward, the wearable system would use the sensor synergy and system learning techniques to learn and store the collected physiological data, which is stored according to the user's level of activity. Then, the system monitors the user by continuously comparing newly collected data to the previously stored baseline data, in order to detect improvements or deterioration in user's physiological condition. Consequently, the system is able to provide a local feedback to the user, as well as to a distant caregiver regarding changes in vital signs. Initial testing of the developed wearable system was performed on multiple users for reliability and efficiency in data collection. The wearable system was further improved so that it could be integrated into a smart home system through an RF wireless communication network.

The smart home system is equipped with environmental sensors to collect temperature, humidity, and barometric pressure data from the surroundings of the user. It also includes a 3G cellular module to deliver quick notifications regarding the health and safety of the user, as well as to save the user's physiological data on a web server. The system also supports a JPEG color camera for emergency scenarios. In such cases a photo taken by a strategically placed camera can provide a better understanding of the user condition and their surrounding by sending a picture using the 3G cellular network. Through the Internet, the user's private healthcare professionals and informal caregivers have access to quick notifications and online data. Consequently, the home system receives commands to adjust its environment using data synergy between wearable sensors and smart home sensors.

1.6 Thesis Organization

Chapter 2 presents an overview of health monitoring systems and smart home systems developed by researchers and technological industries.

Chapter 3 describes system architecture, functionalities, and components used for achieving multiple tasks.

Chapter 4 provides details on the hardware implementation of the heterogeneous systems.

Chapter 5 describes custom software design for sensor data collection and annotation. It also provides a brief description of online data storage using cellular network technology.

Chapter 6 describes data processing techniques used for monitoring relevant physiological conditions and system synergy techniques for improving health care.

Chapter 7 presents system results collected from multiple users to provide accuracy of the system. Based on collected results, improvements made to the system are briefly explained.

Chapter 8 gives a brief conclusion of the system and provides future directions to further improve the system.

Chapter 2 Literature Review

With the evolution of technology, hardware size is decreasing as software capabilities increase. Advanced digital communication, low-power consumption, and embedded device miniaturization offered a better opportunity to wearable technology to interact with the human body. Healthcare wearable systems reduce medical expenses by providing effective alternatives for continuous physiological data monitoring [22]. With this intention, numerous health monitoring prototypes and commercial products are developed by both researchers and technology manufacturing industries. This chapter provides an overview of health monitoring prototype systems and wearable commercial products that are oriented towards medical applications.

2.1 Prototypes Systems Developed by Academia

In the literature, researchers used several sensors for monitoring physiological parameters. Table 1 presents an overview of the type of biosensors and corresponding measurable vital signs. In addition to the bio-signals, researchers also determined external artifacts that amplify the physiological conditions. Conditions that externally affect humans' physiological behaviors includes physical activity and surrounding environment. The user's physical activity, body orientation, and gait-phase are determined using microelectromechanical (MEMS) based sensors such as accelerometers and gyroscopes. On the other hand, environmental sensors are used to examine environmental conditions such as ambient temperature, humidity, atmospheric pressure, noise, and air quality. Raskovic et al. [12] listed a table (refer to Table 2) that provides general information regarding the set of physiological parameters to be examined, corresponding to given medical condition.

Table 1: Biosensors and physiological parameters

Sensor	Vital Sign
Electrocardiogram (ECG or EKG)	Heart activity
Electroencephalography (EEG)	Brain electrical activity
Electromyography (EMG)	Muscle activity
Photoplethysmography (PPG)	Blood pulse activity
Pulse Oximeter	Oxygen Saturation (SpO_2)
Respiratory inductive plethysmography (RIP)	Lung volume and respiration rate
Thermistor	Skin Temperature
Electrochemical sensor	Sweat Sodium (Na) concentration
Pressure sensors (cuff-based)	Blood Pressure
Skin Electrodes	Galvanic Skin Response
Glucose sensor	Blood glucose levels

2.1.1 Systems Based on Custom Microcontroller Platform

In 2003, researchers at the University of Alabama in Huntsville developed a sensor network system based on Body Area Network (BAN) to evaluate stress levels using heart rate variability measurements [13]. The developed system relies on a 3-tier network. A Polar Heartrate Monitoring sensor was used to collect physiological parameters from the user. An iPAQ PDA was used as a mobile gateway to collect the measured physiological data from the on-body sensor and to transmit toward a personal computer. The on-body sensor network system was able to gather and store the heart rate data for prolonged monitoring periods of up to 60 hours. The stored data was downloaded wirelessly without interrupting the user's activities. Researchers tested this system with several users who were going through stressful military training. Their preliminary results showed that people with better stress tolerance had significant differences in their heart rate variabilities.

Table 2: Medical conditions and physiological parameters

Medical Condition	Physiological Sensors
Cardiac Arrhythmias/Heart Failure	Heart rate/ECG, blood pressure, activity
Asthma	Respiration rate, peak flow, oxygen saturation
Cardiac Rehabilitation	Heart rate/ECG, activity, environmental sensors
Postoperative Rehabilitation	Heart rate/ECG, temperature, activity
Diabetes	Blood glucose level, activity, temperature
Obesity/Weight loss programs	Heart rate, activity
Epilepsy	EEG, gait (gyroscope, accelerometer)
Parkinson Disease	Gait, tremor, activity (gyroscope, accelerometer)

The AMON system [23] was developed in 2004. The AMON was a wrist-worn device, which was designed for monitoring and detecting medical emergencies in cardiac/respiratory patients. The system was capable of collecting multiple physiological parameters such as blood pressure, oxygen saturation (SpO_2), skin temperature and ECG. In addition to vital sign monitoring, it was also equipped with a 2-axis accelerometer for physical activity detection to reduce false alarms by comparing activity and elevated physiological data. Furthermore, the system was also equipped with a GSM (global system for mobile communication) based cellular link to provide a communication channel between patient and distant health care providers using short message system (SMS) and TCP/IP protocol communications. Finally, researchers developed a JAVA server based software platform for secure medical data access by healthcare professionals. Reliability of the system was validated by performing medical tests on 33 users. Although results were less reliable and few users expressed problems regarding wearability, the general idea behind the AMON system was well received by all the users, as they expressed a feeling of security from wearing such a device.

AutoSense [24], designed in 2011, was a wearable system designed for stress assessment. It was used to find the causes and consequences of stress by collecting data from cardiovascular, respiratory, and thermoregulatory systems. AutoSense was equipped with six sensors to collect heart rate, lung volume and breathing rate, galvanic skin response, skin temperature, ambient temperature and physical activity. A Bluetooth communication link was also designed for the establishment of wireless communication with a smartphone. The mobile phone used a software framework to compute collected data from the AutoSense system and to provide inferences related to stress and behavioral aspects of activity and conversations. Results obtained from scientific and field tests represented the effectiveness of AutoSense in inferring stress. Henceforth, AutoSense is actively used in multiple studies [25] [26] to investigate stress-related human behaviors and health conditions.

In 2005, the Stanford University, in collaboration with NASA, developed a system called LifeGuard [27]. It was similar to the multiparameter measuring systems that are mentioned above; however, it was specially designed for terrestrial applications where real-time physiological monitoring was crucial. LifeGuard was equipped with a crew physiologic observation device (CPOD), which incorporated external sensors for collecting and continuously streaming multiple vital signs data using Bluetooth technology. In addition to vital sign monitoring, LifeGuard was also equipped with a piezo buzzer to alert the user regarding low-battery life, abnormal levels in SpO_2 and heart rate, and sensor malfunctions. The durability of the system was examined by conducting studies in extreme environments. During testing, the LifeGuard system was able to detect and correct various software and hardware issues.

2.1.2 Textile-Based Systems

WEALTHY [28] and BIOTEX [29] were textile-based wearable health monitoring systems. WEALTHY was designed in 2005, it used conductive and piezoresistive yarns to connect multiple sensors into a knitted garment. The textile system equipped with sensors for monitoring physiological parameters (ECG, respiration rate, temperature, and activity) and a portable patient unit (PPU). The PPU was responsible for sensor signal processing, local decision making, wireless communication and providing user feedback. PPU offered a simple user interface using two LEDs, a buzzer, and a switch for manually triggering alarms. WEALTHY used GPRS technology to wirelessly transmit the collected sensor data to a remote monitoring center. Overall, WEALTHY was a washable and reusable textile system with accurate vital sign monitoring capabilities.

Five years later (in 2010), BIOTEX [29] was designed. It had the ability to gather data by examining human secreted chemicals like sweat. A sensor system was integrated into a wearable fabric to collect and measure the pH, sodium concentration and conductivity of sweat. Examining sweat samples provides noninvasive information regarding hydration status, electrolyte balance and physiological condition [29]. In addition to sweat loss examination, BIOTEX was also incorporated with physiological (sweat rate, ECG, respiration and blood oximetry) monitoring sensors to correlate changes in sweat excretions with vital sign modulations. The collected sensor data was either transmitted through a Bluetooth link to a laptop or saved to an on-chip SD card recorder. Developers tested the BIOTEX textile system on multiple subjects during cycling with a 60-minute workout interval with similar environmental conditions. Results showed that sweat composition was not consistent during continuous workout intervals. Consequently, further research was suggested for gathering the right amount of the sweat composition for efficient results.

2.1.3 Smartphone Based Systems

Smartphones are being extensively integrated into the healthcare industry. With innovative digital technology, compact size and cloud computing, smartphones provide a functional means of collecting healthcare data. By adopting smartphones, health systems can synthesize benefits from components such as microprocessors, memory, battery and user interface (keyboard and screen) [30] [31]. Smartphones also support the low-power wearable health monitoring systems by offloading the computation from the wearable systems [32].

With the benefits provided by smartphone in mind, in 2010 MIT media lab researchers developed Heartphone [30], a smartphone based photoplethysmograph (PPG) system to monitor heart rhythms in cardiovascular patients. Heartphone was equipped with photosensors at each earbud in a pair of earphones. PPG signals collected from the sensors were processed using band pass filters to filter AC components and electrical noise. The raw PPG data was transmitted to a smartphone for further processing and visualization. Optionally, the system was able to forward collected data to a laptop using 2.4 GHz radio transceivers. The Heartphone had proven its accuracy by providing comparable results collected from 31 participants. Use of earphones provided a feature for checking the heart rate while listening to music; this further helped to monitor human behavior while engaged in different activities and with various styles of music.

2.1.4 Systems for Detecting Activity

In addition to implementing health monitoring systems for medical applications, various studies were also conducted for monitoring and determining falls and physical activity. The growing elderly population and amount of medical expenditure, especially injuries related to falls [3] [4], shows the need for physical activity assessment to reduce the fall's damage by providing immediate help. Physical activity determination is also a common factor in many medical rehabilitation applications such as knee and hip replacement [9], as well as heart surgery [5]. As mentioned previously, the modulations in physiological conditions are also analyzed in combination with physical activity level [23] [24].

MEMS-based sensors have been widely used for determining the physical activity. Smartphones are also used to determine human falls [33] and physical activity [34]. Researchers conducted various studies [35] [36] and proposed ideal sensor placement on the human body for reliable data collection, without disturbing the user's daily activities. Furthermore, researchers determined the body posture and physical activity using multiple approaches such as mean, standard deviation, correlation and mean crossing [37], time-frequency analysis [38], threshold evaluation and peak detection [39], dynamic sliding window techniques [40], angular velocity transformation [41], motion history image analysis from video cameras [42] and smart home-based smart textiles [43].

2.1.5 Smart Home Based Systems

Smart home systems (or autonomous home systems) are changing the way humans interact with homes and home appliances. Smart homes deliver more comfortable, secured, automated and power efficient environments. The individual smart home system has a different setup based on their end goals, such as appliance automation, elder/disabled monitoring and rehabilitation, tele-medication, and emergency assistance [44]. Using multiple approaches such as artificial intelligence, system learning, multimedia computing, and robotics, researchers developed several systems [45] [46] for inhabitant activity monitoring in order to reduce power consumption. Moreover, researchers also used smart homes to track smart appliances for estimating the well-being of the elderly [10] [11].

In 1999, Georgia Institute of Technology developed The Aware Home project [46] to support the elderly living environment and to conduct studies. The Aware Home featured a smart floor and sensors to detect lost objects. The smart floor was equipped with force-sensitive load tiles to track footsteps and localization of the user inside the home. It used Hidden Markov Models (HMM) and vector averaging methods for assessing the user's current position. Whereas radio frequency tags were used to find lost objects such as keys, wallets, glasses and remote controller. The system constantly monitored occupants' medical condition and activity using video and audio observation methods.

The University of Texas at Arlington developed the MavHome (Managing an Intelligent Versatile Home) [45] system in 2003. The MavHome was targeted to maximize comfort and productivity of its inhabitants while minimizing operational cost. MavHome extensively used prediction algorithms to observe resident activities, identify patterns and to determine future endeavors. It also integrated technologies from the database to store the history of activity data, robotics to control certain home appliances and mobile computing for offline data processing [45]. The performance was evaluated by collecting and comparing the MavHome ability to predict human activities for home automation. With the data gathered over a period of 30 days, MavHome demonstrated its effectiveness to reduce human interactions.

In 2012, Suryadevara et al. [10] developed a ZigBee-based two-tier home system for estimating the physical activity and well-being of elder people living alone. They used sensors for determining the daily use of electrical appliance and force sensors and contact sensors for monitoring use of household furnitures such as a couch, toilet, kitchen, and bed. The wellness of the elderly was calculated by monitoring inactive or over-usage of appliances and furniture.

Experimental results showed that the system was accurately determining elderly wellness by tracking the home appliances.

Both academic institutions and industries have shown greater interest in developing health monitoring systems and smart home systems. Companies like Apple™, Google™, Samsung ™, Xiaomi™, and Fitbit™ are actively developing new trends in wearable technology for both productivity improvements and healthcare applications. More trends in commercial health monitoring systems and smart home systems are discussed further.

2.2 Commercially Available Medical and Smart Home Devices

In 2016, $24 billion worth of wearable medical devices are expected to be sold due to increasing awareness and the demand for 24/7 health monitoring [47]; as a matter of fact, 2016 has been declared as "Year of the Wearable" [48]. By 2020, revenue growth of wearable medical devices is expected to reach $104 billion [49]. Technological industries are primarily targeting three areas in the market [47]: patient monitoring, home healthcare, and health and fitness.

Most of the commercial wearable medical devices use smart sensors to track body movements and vital signs; collected data is typically sent to a smartphone where it is stored and annotated. Further, the collected medical data can be presented to a health care professional to help diagnose the given medical condition.

Smartphones, smartwatches, and smart wristbands are widely used to track footsteps and heart rate activity. Smart watches and wristbands use PPG technology to monitor heart rate, whereas Under Armor [50], Polar [51] and Garmin [52] use chest strap electrodes for tracking heart rate for fitness and health. Furthermore, iRhythm developed a ZIO XT Patch [53] for monitoring the heart activity continuously over a period of two weeks before recharging or changing the battery. The ZIO Patch is lightweight, water resistant, and wirelessly transmits collected data to a smartphone for further data analysis.

Wearable medical devices are not only used for physical activity assessments but are also used for treating several medical conditions; several companies used new technological trends to produce innovative ways in wearable medical technology.

Activity is a key parameter in helping to treat several medical conditions. Pressure ulcers were frequently developed in hospitalized patients due to prolonged periods of inactivity [54]. Leaf Health Care developed a wireless sensor [54] to track patient's activity in a hospital environment. Leaf Health Sensor monitors patients' body postures and automatically alerts the hospital unit to provide assisted mobility to an inactive patient. Chrono Therapeutics is releasing a smart device [55] to help people for stopping smoking. The smart device uses motion algorithms to sense if the user is craving for nicotine; if it detects cravings, it then delivers medication to reduce nicotine dependency. Furthermore, developers also determined body posture to reduce bad habits of slouching to maintain perfect body posture. UpRight [56] and Lumo [57] are a few trending devices used to detect body posture to maintain upright posture and reduce back pain.

Google is developing a smart contact lens [58] embedded with a tiny glucose sensor and a wireless chip antenna. Google contact lenses are used to measure blood glucose levels in diabetic patients from their tears. This product is still in the testing phase and it is expected to reach the market soon. On the other hand, Abbott Diabetes Care company introduced a new wearable system, called FreeStyle Libre System [59] to monitor glucose levels continuously. The Libre system introduces a needleless and painless method to read glucose data; it detects glucose levels by monitoring the sweat samples from the back of the arm. It also provides an app to read data and display for further treatment and care.

Cyrcadia Health's iTBra [60] is a smart device that keeps track of breast health. The smart bra is equipped with sensors to continuously monitor the heat changes in breast tissues for detecting early symptoms of cancer. It connects with any smartphone and the through internet connection it provides feedback in real-time. The effectiveness of the iTBra was tested on 500 participants and results showed 87% success rate of determining possible cancer [61].

HealthPatch® MD [62] is a multi-vital-sign monitoring device, which comes with a sensor and disposable skin patch. It is equipped with ECG electrodes, thermistor and an accelerometer for detecting vital signs, biosignals, and physical activity. The biosensor is also incorporated with a Bluetooth wireless radio to provide a real-time feedback through a smartphone. It also offers a decent battery life of up to 4 days.

The Proteus Digital Health [63] discovered an innovative way to monitor important vital signs through smart sensors embedded into a pill. When the user consumes the digital pill, it starts collecting the vital signs inside the body which are then transmitted to a skin patch attached to the torso. The skin patch will further process the data, subsequently sending it to a smartphone app. Distant doctors will have access to this data allowing them to actively monitor patients' vital signs at home, how they are responding to the treatment, and suggest appropriate changes in their activity and medication intake.

BioRing [64] is a smart wearable ring, equipped with a 3-axis accelerometer, optical heart rate sensors, and a bio-impedance sensor. It actively calculates an amount of calories consumed, sleep activity, stress levels, water intake, heart rate and physical activity. It estimates the number of calories spent based on physical activity to provide real-time feedback for further actions. Additionally, it also sends reminders to maintain balanced hydration and glucose levels.

Consequently, smart home systems are also advancing to make a home smarter by automatically adjusting its environment. Currently, industries are targeting to make almost all the home appliances automated through internet connectivity for remote access; this adds a level of comfort and security that will also reduce the power consumption. Smart appliances include: smart thermostats [17] which learn and adjust heat according to occupancy, smart light bulbs [18] which provide millions of colors with adjustable intensities, security systems [19] to automatically lock and unlock doors those can be controlled remotely, and a smart entertainment system [20] that connects to Wi-Fi and comes with a personal assistant that streams audio and video according to user’s intentions.

However, smart wearable medical devices and smart home appliance mentioned above fail to connect to each other for assisting the user based on their medical and physical conditions. To the best of our knowledge, there are no existing technologies that provide compatibility between the patient physiological condition and home environmental conditions. This thesis introduces a synergistic system to monitor the user's physiological condition continuously and assist them by adjusting the smart home environment according to the changes in their vital signs and level of physical activity.

Chapter 3 System Architecture

This chapter describes the general architecture of the proposed system. This chapter also provides details on the functionalities of subsystems and the sensors used. The general architecture of the proposed system is shown in Figure 1. The system consists of a wearable health monitoring system and a smart home system. These two individual systems are connected to a central hub through a star-topology based wireless communication link, as shown in Figure 2. The wearable system for health monitoring contains sensors to collect physiological and physical activity data. Furthermore, the health monitoring system is responsible for processing, local decision making and forwarding the collected data to a central hub. By processing data locally, the wearable system can reduce the power consumed for wireless transmissions. On the other hand, the smart home system is accountable for gathering and adjusting the environmental parameters such as temperature, humidity, and barometric pressure, and validating the user condition during critical situations.

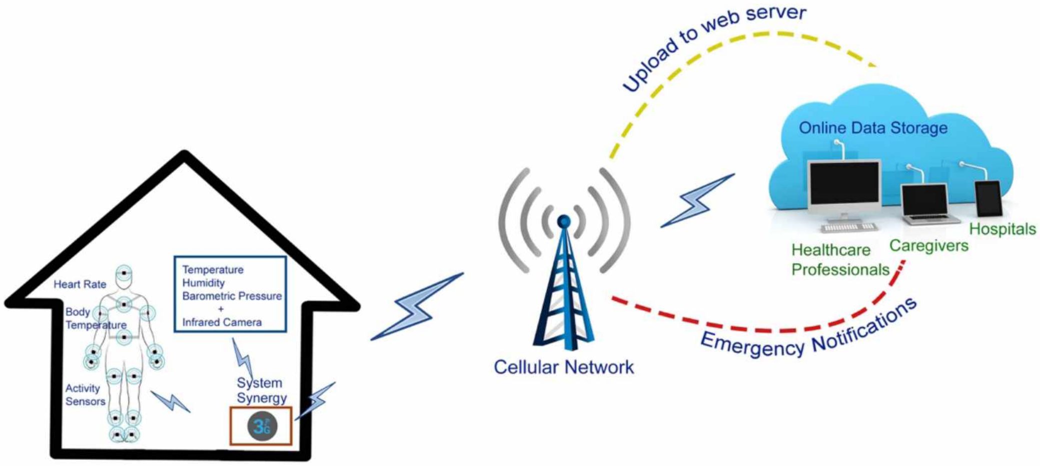


Figure 1: System Architecture of the Synergistic Wearable Health Monitoring System

The central hub is accountable for integrating the health monitoring system and the smart home system, and extracting synergy from the system to adjust the home environment based on the physiological condition of the user. Moreover, the central hub is responsible for reporting the physiological status of the user on a daily basis, raising alarms during emergency situations, and storing the collected data to a web server.

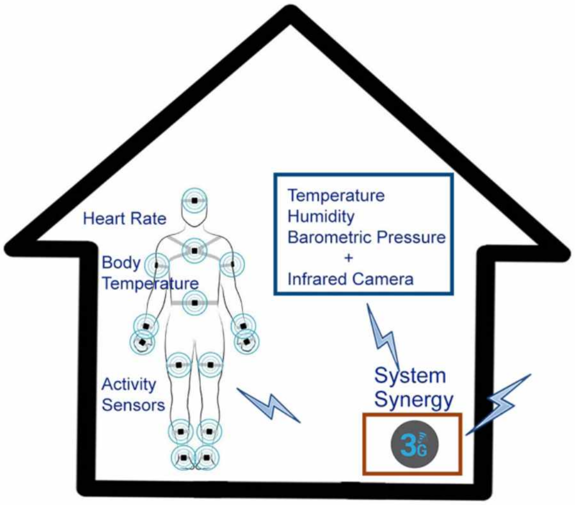


Figure 2: Integration of Wearable Health Monitoring Systems and Smart Home System

3.1 Wearable Health Monitoring System

Our wearable health monitoring system is capable of integrating multiple types of sensors, depending on the medical application. These wearable sensors must satisfy conditions such as miniaturized size, weightlessness, unobtrusiveness, low-power consumption for extended periods of use, and user-based calibration support. The goal of this thesis is to monitor at-home elderly and patients with cardiac rehabilitation. As a result, the wearable medical system is equipped with sensors to support heart surgery rehabilitation applications. Therefore, the biosensors must be responsible for monitoring the physiological parameters such as heart activity, body temperature, and physical activity. Figure 3 shows a user wearing the developed wearable prototype system for health and activity monitoring. Sections from 3.1.1 to 3.1.3 provide detailed description of functionalities of the wearable health monitoring system.

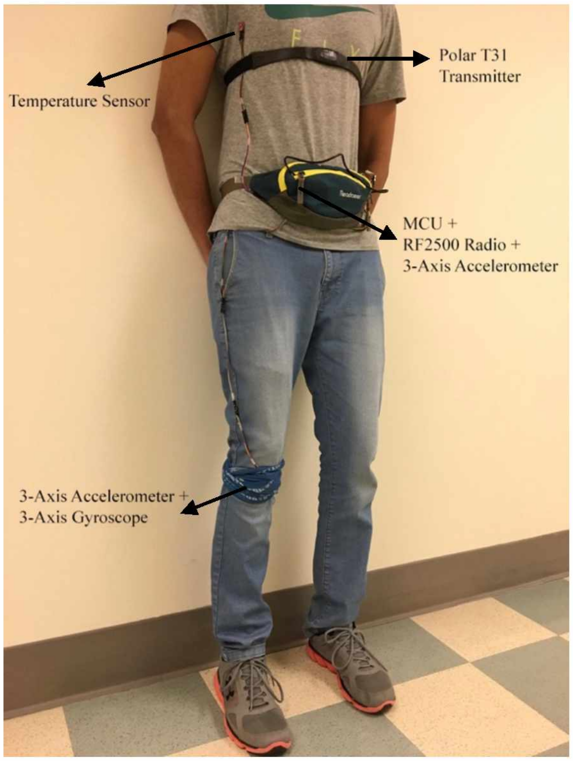


Figure 3: A user wearing the wearable health monitoring prototype system

3.1.1 Heart Activity

When a patient is going through a cardiac rehabilitation, continuously measuring their heart activity and providing feedback would help the user to stay healthy. Cardiac patients are required to maintain their heart rate within a normal window. The proposed system's goal is to constantly monitor the user's heart activity without disturbing their day-to-day operations, and report abnormalities to distant caregivers. Based on collected heart rate data, healthcare professionals or caregivers provide further instructions to help the user's rehabilitation process.

Figure 4: Polar T31 transmitter (left) and HRMI breakout (right)

Placing a wearable sensor around the chest minimizes the daily activity interruption and maximize the sensor's capability to read accurate heart rate data. These kinds of sensors are generally considered to be more reliable and less obtrusive for prolonged use than the ones based on photoplethysmography. An off-the-shelf Polar heart rate sensor (T31 transmitter) [65] is used to detect the heart activity and to transmit the measured ECG data through Bluetooth wireless communication technology. The transmitted data is received using a Polar Heart Rate Monitor Interface (HRMI) [66] receiver, where the received ECG is automatically converted into heart rate data measured in beats per minute (BPM). Figure 4 shows the Polar heart rate transmitter and receiver. The HRMI communicates with an external microcontroller using the UART (Universal Asynchronous Receiver Transmitter) communication protocol.

3.1.2 Body Temperature

Body temperature is an important parameter for estimating the user's activity level and their ability to keep heat within a healthy window. Abnormal body temperatures often indicate a possible illness. Hence, by measuring the body temperature of the user, well-being can be estimated; as mentioned previously, caregivers can provide assistance if the measured parameter is abnormal. A Si7021 [67] temperature sensor is used to measure the body temperature. The sensor is placed close to the armpit. However, the sensor only provides relevant temperature changes in the body's environment. In the future, this can easily be replaced by a medically accurate body core temperature sensor. Figure 5 shows the Si7021 temperature sensor breakout. The Si7021 sensor uses I2C serial communication protocols for communicating with a host microcontroller.

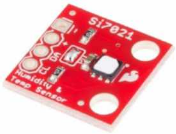


Figure 5: Si7021 - Temperature and Humidity Sensor Breakout

3.1.3 Physical Activity

Vital sign modulations are commonly observed along with the physical activity. Also, daily based physical activities are necessary for those who are going through rehabilitation. Cardiac patients should neither elevate their heart rate by over exercising, nor stay inactive. Hence, by actively monitoring the physical activity levels, the system can help the user maintain a healthy and safe lifestyle.

The proposed wearable system actively monitors the physical activity and relates it to changes in physiological conditions. MEMS-based 3-axis accelerometers (ADXL345) [68] and a 3-axis gyroscope (ITG3200) [69] sensors (shown in Figure 6) are used to determine body posture and different physical activities. These sensors use I2C serial communication protocols for data collection.

Figure 6: Breakout of ADXL345 (left) and ITG3200 (right) sensors

Activity detection sensors are placed around the waist and at the shank. Studies [6] [70] show that this proposed sensor placement would accurately read the data regarding estimated physical activity. Further, energy expenditure can be determined based on the level of physical activity. Also, since falls are most common in the elderly population, detecting falls and reporting the emergency scenario immediately to a health care provider would provide on-time information to emergency services and hopefully help reduce the harm caused to elderly users. Therefore, the system also incorporates fall detection capabilities.

3.2 Smart Home System

Hospitalization is almost unavoidably stressful, so most patients seek to stay in their home. However, the patients often require continuous surveillance and their living environments should maintain certain hospital standards. The above-mentioned health monitoring system continuously monitors the physiological conditions. On the other hand, a smart home system is required to maintain the user's surrounding environment according to their vital signs and the level of physical activity. Smart home system can improve health care at home by facilitating comfort and security.

Figure 7: BMP085 (left) and SHT75 (middle) breakouts, and RGB LED (right)

The proposed smart home system is accountable for continuously monitoring the environmental conditions inside the home, as well as maintaining the home environment according to the physiological status of the user. The home system consists of environmental sensors SHT75

[71] and BMP085 [72] to measure home environment data for temperature and humidity, and barometric pressure, respectively. In addition to the climatic parameters, the smart home system is also equipped with a red and green and blue (RGB) light emitting diode (LED) [73] to emulate changing the intensity and color of the light based on the user's physiological conditions and physical status. Studies show that surrounding colors have significant impact on human behavior [74], in fact, they also help to reduce stress. Figure 7 shows the sensors used for the smart home system; these components are connected to a master microcontroller that periodically samples and processes the collected data.

3.3 Central Hub

When integrating heterogeneous systems, a central system (or a central hub) is required for sensor data fusion, and to preserve the integration between cross-functional systems. Also, a central hub can maintain synchronization between the systems mentioned above for successfully exchanging the data without packet collisions. Henceforth, the wearable health monitoring system and the smart home system are connected to a central system through a wireless network (see section 3.4). The central hub receives information from both systems and extracts synergy to estimate the environmental effects on the user's physiological state, and to provide a better user-friendly home environment.

In addition to data fusion, the central hub is also equipped with a JPEG infrared color camera [75] for taking pictures during emergencies, and an embedded 3G cellular module from Adafruit [76] for delivering information to distant caregivers.

3.3.1 A Safety Feature to Reference Emergencies

When an older adult accidentally falls on a hard surface, it is sometimes impossible for them to call for help. Research shows that approximately 33 percent of elder people experience fall injuries every year [4]. The proposed health monitoring system is tasked with detecting falls and abnormalities in vital signals. The central hub is responsible for receiving commands during such incidents, and capturing a photo using an infrared camera. Infrared technology provides the ability to determine the user's status in dark conditions. The system provides more knowledge on user's current situation by capturing and eventually sending the picture during an incident. In a real world application, the smart home system would typically require more than one camera for tracking the user's location. In this thesis, only one camera is used with the central hub to demonstrate its functionalities and advantages. In a production system, multiple cameras throughout the household would be acting as special nodes within the smart home sensor network. Figure 8 shows the JPEG color camera; it uses UART serial communication protocol for processing the commands to capture a photo and to transfer it.

Figure 8: JPEG infrared color camera breakout

3.3.2 Cellular Communication Link

Home healthcare often requires a communication network to deliver patient's physiological data continuously, so that distant healthcare professionals can communicate with the patient regarding suggestions for medications and daily physical exercise to improve the at-home patient's health condition. Also, if distant caregivers are able to see abnormal vital signs data in near real time, they can often respond quickly and provide immediate help to a patient. Cellular communication technology has the ability to provide quick notifications such as short message services (SMS) and multimedia messaging services (MMS) to almost any location where people commonly live. Also, a cellular link can provide an internet connection for securely storing the medical data in the cloud.

An embedded 3G cellular module (shown in Figure 9) is integrated into the central hub. The central hub continuously collects the physiological and environmental data, and uploads to a web server (www.monitormyelder.website/data) which is specially developed for this thesis. Also, the central hub sends daily energy expenditure (physical activity data) and physiological data (heart rate and body temperature) as an SMS notification to the user and distant caregivers.

Figure 9: 3G cellular module breakout

Furthermore, the central hub triggers the camera during emergencies to take a current picture of the user. It sends the captured photo as an MMS through the cellular network. The healthcare providers and emergency responders (MMS receivers) will have a better understanding of the level of injury and also the location of the user inside a house.

3.4 Wireless Communication Network

Wireless communication provides an efficient and unobtrusive of transfer the information between two points, even if those two points are in relative motion. Radio link based wireless communication networks have added a new dimension to communication schemes with advantages of mobility. To provide continuous health care, the wearable system should not be physically bound, because it limits the daily user activities.

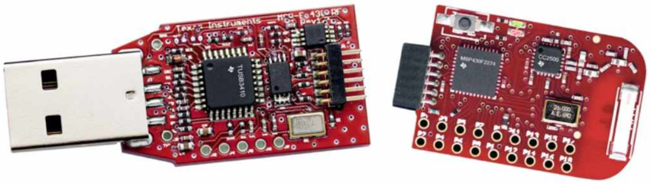


Figure 10: eZ430-RF2500 development tool breakout

Connecting various independent systems through a wireless communication provides an opportunity for the user to freely move around the house. Also, multiple smart home devices can be connected to the network to provide the most user-friendly environment. A star-topology based wireless communication link is established to connect the proposed wearable health monitoring system and smart home system to the central hub (as shown in Figure 2). Multi-channel low power transceivers (CC2500) [77] are used for building the wireless link. The CC2500 transceivers use 2.5 GHz ISM bands for wireless communications. Figure 10 shows development tool (eZ430-RF2500) for the CC2500 transceivers. Using this RF based communication link data is exchanged between the proposed components. The proposed systems can consequently represent as nodes as well (e.g.: wearable health-monitoring node/wearable node, smart home node/home node, and central hub node/central node), since all the systems include sensors and wireless communication interface.

Chapter 4 Hardware Implementation

In this thesis, a prototype system is implemented for sensor data collection and system integration. This chapter provides an overview of the hardware integration.

4.1 Microcontroller Components

The nodes for this thesis are based on MSP430 16-bit microcontrollers by Texas Instruments. The Texas Instruments MSP430 family of ultra-low-power microcontrollers is specially designed for extended battery operations. These devices feature a 16-bit RISC CPU and 16-bit registers to support high-performance computations [78]. They also support timers, analog-to-digital converters (ADC), universal serial communication interfaces (USCIs), a real-time clock (RTC) module, direct memory access (DMA) and flash read/write operations.

Various MSP430 microcontroller units (MCUs) and evaluation boards based on them are used for building the required nodes. The smart home node and the central hub node should support various sensor systems for controlling various smart home appliances. Hence, MSP430F5438A MCUs are used for building these two nodes; these MCUs support multiple serial communication peripherals for adding numerous sensor systems. Experimenter boards based on these microcontrollers are used for central nodes because they have several useful peripherals, such as switches, LCD screens, expansion ports, etc. On the other hand, the wearable node must suffice wearability requirements through light weight and small size. Hence, an MSP430F5529 MCU based LaunchPad is used for building the wearable node due to its simplicity and small size. All other hardware components and their functionalities (transceivers and sensors) are described in Chapter 3. Section 4.2 describes the hardware interface between the components of each system.

4.1.1 Texas Instruments MSP-EXP430F5438A

The smart home system and the central hub system requires a platform with a user interface for successfully displaying the collected physiological and environmental information, and receiving the feedback from the user. Also, these systems should integrate with a platform that supports future integration of additional sensor systems.

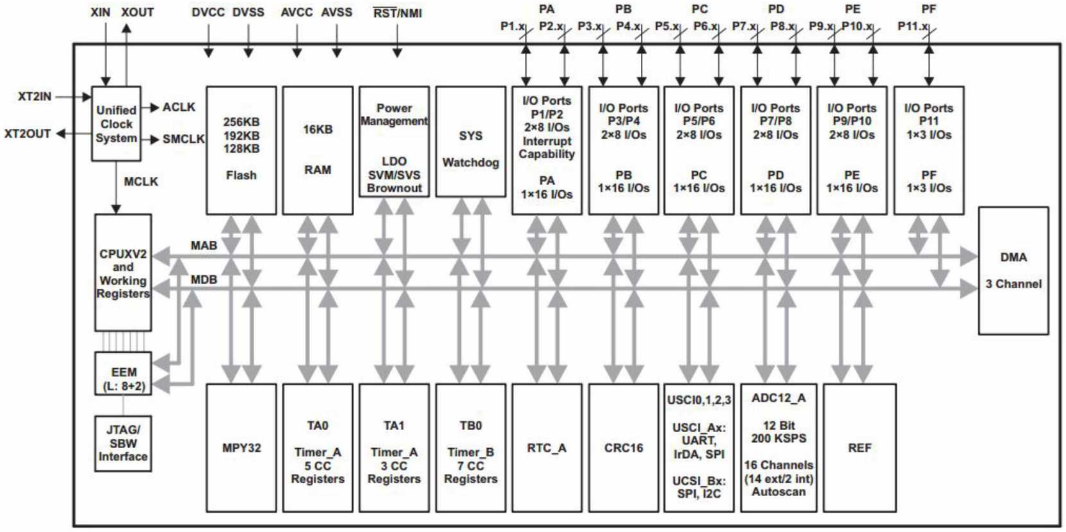


Figure 11: MSP430F5438A functional block diagram

The MSP430F5438A microcontroller features 256 KB flash, 16 KB SRAM, 16-bit timers, 8 USCI modules to support UART, SPI and I2C serial communications, 12-bit ADC with internal reference voltage, low supply voltage (3.6 V to 1.8 V) and up to 25 MHz system clock [79]. It consumes only 1.2 µA in the lowest low-power mode; it wakes up from a low-power mode as fast as 3.5 µs. The functional block diagram of MSP430F5438A is shown in Figure 11.

The MSP430F5438A experimental board (MSP-EXP430F5438A) is a MCU development board for the MSP430F5438A [80] (shown in Figure 12). It provides pin-outs for externally connecting multiple sensors and RF transceivers. It also includes LEDs, switches, a joystick, a microphone, an audio output and a 16 segment LCD for the user interface. In this thesis timers, USCI modules, low-power modes, and user interface are extensively used for communicating with sensor systems and RF transceivers, and for providing user feedback.

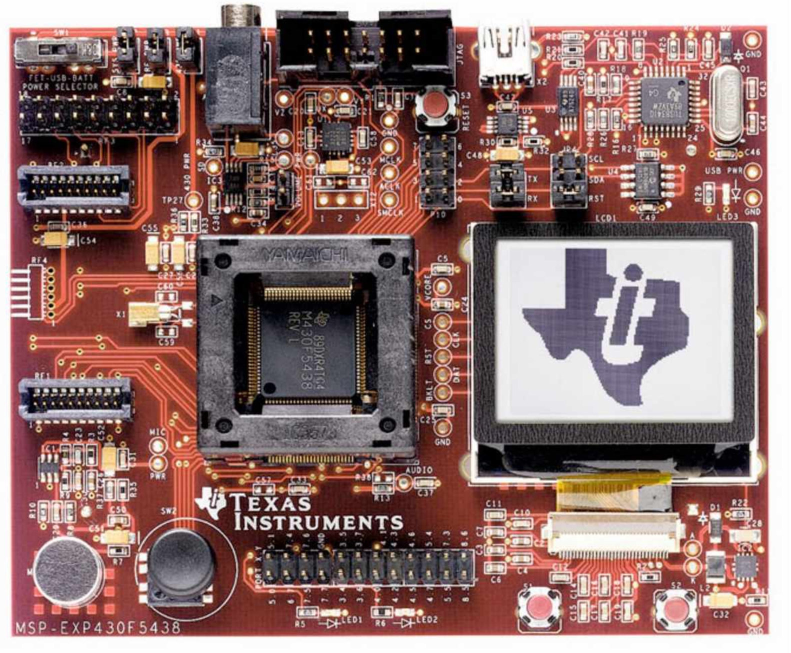


Figure 12: MSP-EXP430F5438A breakout board

4.1.2 Texas Instruments MSP-EXP430F5529LP

Wearable systems are designed based on a given application. For the research described in this thesis the system should support several biosensors and a transceiver (refer to the 3.1.1, 3.1.2, 3.1.3, and 3.4 sections). Hence, for this particular application the associated MCU platform must contain one SPI module to support RF transceiver, one I2C module to support sensors (ADXL345, ITG3200 and Si7021), two different UART modules to communicate with a Polar heart rate receiver and to transfer the collected data to a PC for further data analysis. Moreover, the required MCU platform must contain an onboard 5 V supply voltage to communicate with the HRMI receiver. The MSP-EXP430F5529LP LaunchPad satisfies all the requirements of the wearable system (for this thesis), including small physical dimensions and weight.

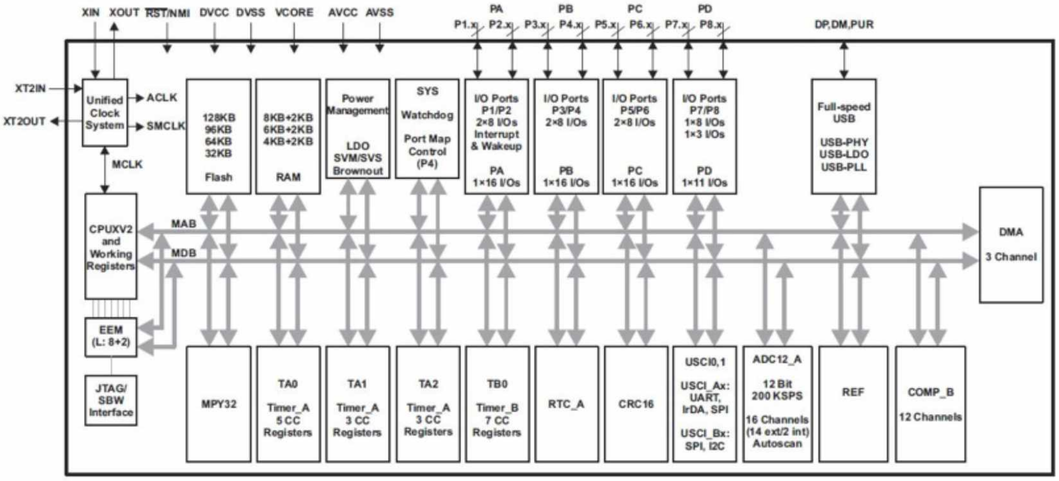


Figure 13: MSP430F5529 functional block diagram

The MSP-EXP430F5529LP includes the MSP430F5529 16-bit MCU with USB support; it has similar clock speed, voltage supply, power consumption and wake-up capabilities as MSP430F5438A (section 4.1.1). However, the MSP430F5529 only supports 128KB Flash, 8KB RAM, and 4 USCI modules [81]. The LaunchPad development board supports a broad range of voltage supplies (up to 5 V), pin-outs for booster packs to add external sensor systems, external LCD displays, and motor controllers. It is also equipped with user interfaces such as LEDs and switches, and on-board emulation for programming and debugging. Figure 13 shows the functional block diagram of the MSP430F5529 and Figure 14 shows the MSP-EXP430F5529LP LaunchPad breakout board.

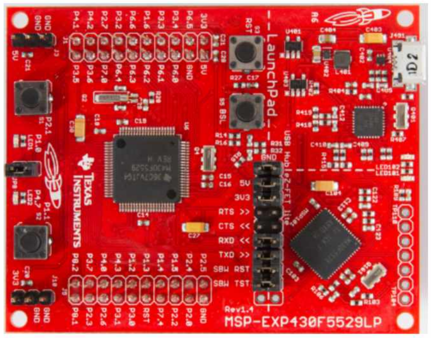


Figure 14: MSP-EXP430F5529LP LaunchPad breakout board

4.2 Hardware Integration

4.2.1 Integrating the MSP430 and eZ430-RF2500

The MSP430 microcontrollers support multiple serial communication modes. The eZ430-RF2500 transceiver uses the serial peripheral interface (SPI) communication method for exchanging data. SPI is a synchronous communication protocol that uses the serial clock for data-in and data-out; power consumption of the transceiver system can be reduced by using SPI synchronous communications. The MSP430 easily integrates with the transceiver using a 3-wire SPI serial interface where the MSP430 acts as an SPI master for controlling the serial clock for both data in and data out. The relevant connections are between the MSP430 and the transceiver are master in slave out (*MISO*), master out slave in (*MOSI*), serial clock (*CLK*), and chip select (*CS*). Both MSP430 microcontrollers (MSP430F5438A and MSP430F5529) use the *USCI_B0* SPI serial communication module for communicating with the transceiver. The external wire connections between microcontroller and transceiver are shown in Figure 15 below.

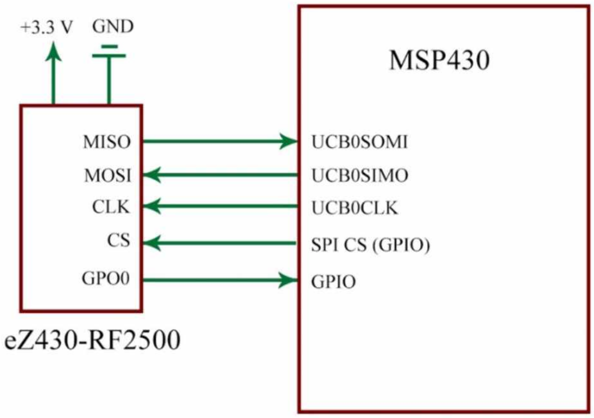


Figure 15: SPI Connections between the MSP430 and eZ430-RF2500

4.2.2 Integrating the Wearable Health Monitoring System Components

The wearable health monitoring system contains several lightweight, tiny, and inexpensive hardware components. These are:

1. MSP-EXP430F5529LP LaunchPad
2. eZ430-RF2500 transceiver
3. Polar T31 transmitter
4. HRMI receiver
5. Si7021 temperature sensor
6. Two ADXL345 3-axis accelerometers
7. ITG3200 3-axis gyroscope

The Polar T31 transmitter and the HRMI receiver are connected through Bluetooth wireless communication technology. So, there is no need for physical wire connection between these Polar devices. However, the HRMI receiver and the remaining hardware components of the health monitoring system are connected to the MSP430F5529 MCU through wired connections to avoid using multiple microcontrollers and radios, and therefore increasing the weight and the complexity of the system. Figure 16 shows how the microcontroller and other hardware components are interfaced to create a wearable health monitoring system. The listed components use different serial communication protocols; the MSP430 successfully collaborates with all hardware components through 4 differently configured USCI modules. Hardware integration of the health monitoring system is explained in detail below.

The HRMI receives ECG data from the Polar transmitter and converts it into heart rate data (beats per minute). HRMI uses the universal asynchronous receiver/transmitter (UART) communication mode. UART uses two external pins for asynchronously transmitting and receiving at a given baud rate. The transmit (*TX*) pin of the HRMI should be connected to the receive (*RX*) pin of an external microcontroller, and vice-versa. The MSP430F5529 is attached to the HRMI through the *USCI_A0* module, and the data is transferred between them at 38400 baud rate. In this system, only HRMI requires a 5 V input power supply, so it uses the inbuilt 5 V pin from the launchpad.

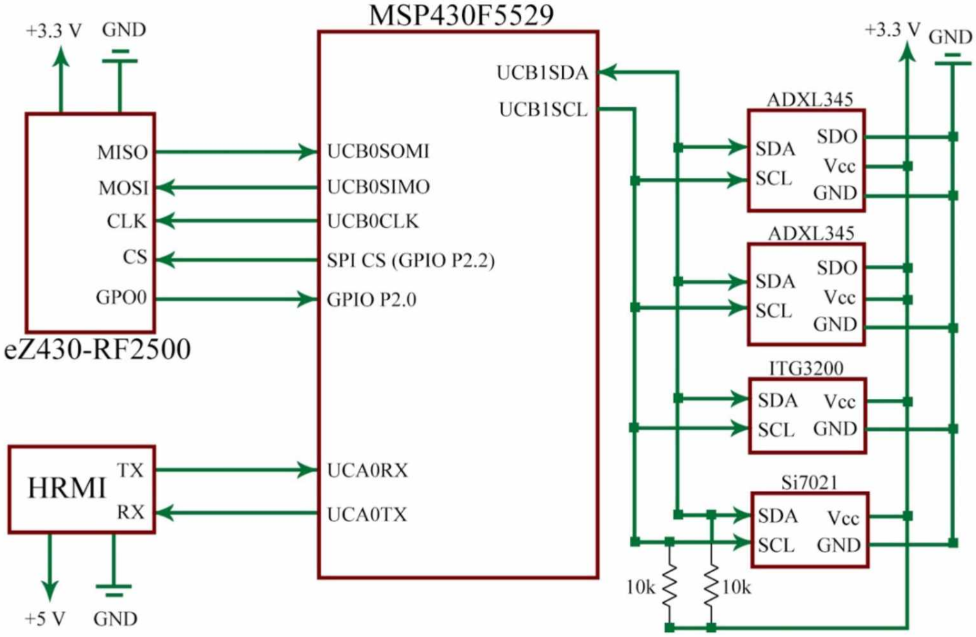


Figure 16: Integration of the wearable health monitoring system

On the other hand, sensors such as ADXL345, ITG3200, and Si7021, support I2C (inter-integrated circuit) communications to interface with any I2C capable microcontroller. I2C is a synchronous serial communication interface that allows multiple sensor devices (I2C supported) to integrate through a single I2C bus. It uses a slave address for reading (R) and writing (W) operations. Hence, all the I2C supported sensors are connected through two-wire I2C interfaces as shown in Figure 16.

In this system, two 3-axis accelerometers are used (ADXL345) for measuring different activities of the user. However, these two ADXL345 sensors are connected to the same I2C bus. Because the ADXL354 provides two different slave addresses, *SDO* pin chooses the slave address by simply connecting the to either *Vcc* or *GND*. Hence, one of the ADXL345 sensor's *SDO* pin is tied to the *Vcc* whereas the other is connected to the *GND*. To the MSP430, ADXL345 components are two different sensors with two different slave addresses.

The two essential connections of the I2C communication are serial data (*SDA*) and serial clock (*SCL*). These two pins are connected to a 3.3 V power supply using an external 10 k Ω pull-up resistors. The MSP430F5529 microcontroller (I2C master) provides a serial clock for synchronous communications. On the other hand, *SDA* is bidirectional, both master and slave can use this pin for reading and writing operations. In this system, the MSP430 uses *USCI_B1* module for interfacing with the I2C supported sensors.

The transceiver interface is discussed in section 4.2.1.

4.2.3 Integrating the Smart Home System Components

The smart home system is accountable for collecting environmental conditions such as temperature, humidity, and barometric pressure. Hence, environmental sensors (listed below) are used for continuously monitoring the smart home environment. The hardware components of the smart home system are:

1. MSP-EXP430F5438A
2. SHT75 temperature and humidity sensor
3. BMP085 barometric pressure sensor
4. Common cathode RGB LED
5. eZ430-RF2500 transceiver

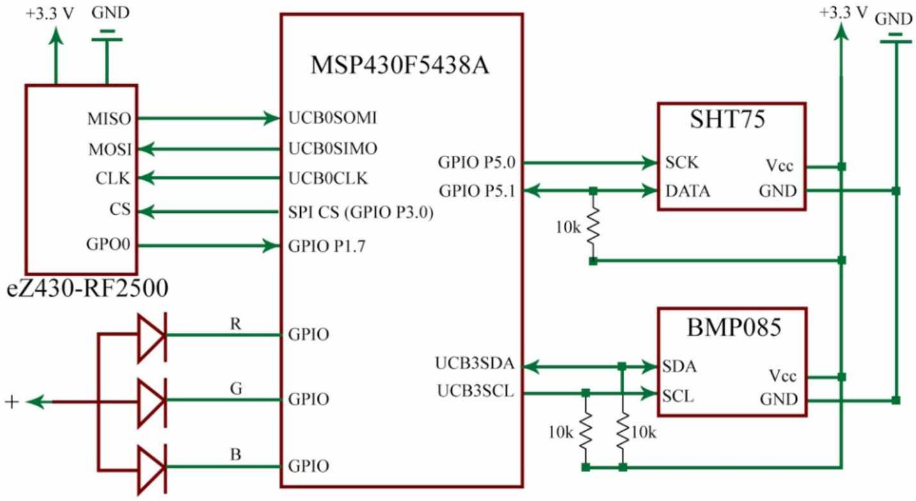


Figure 17: Integration of the smart home system

The temperature and humidity sensor (SHT75) uses two general purpose input/output (GPIO) pins for digitally communicating with the MSP430F5438A microcontroller. The MCU must generate the serial clock by alternating the GPIO pin. On the other hand, the *data* pin is bi-directional, it is shared between the MCU and the SHT75 sensor. The MSP430 sends commands to read the data from the sensor; the *data* pin is connected to the 3.3 V power supply using a 10 k ohm pull-up resistor. The RGB LED uses three different GPIO pins for three different colors. Pulse-width modulation (PWM) can be used to generate mixed colors.

The barometric pressure sensor (BMP085) communicates with the MSP430 using I2C communication protocols. The MSP430 serves as an I2C master using the *USCI_B3* module. In the future, more sensors can be integrated into the smart home system, because the MSP430 supports multiple serial communication modules.

The eZ430-RF2500 integration is discussed in section 4.2.1. Figure 17 represents the pin connections and integration of the smart home system. Figure 19 shows the smart home system hardware components.

4.2.4 Integrating the Central Hub Components

In this thesis, the central hub plays a vital role in integrating the cross-functional systems. The data collected from the health monitoring systems and smart home system are forwarded to the central hub for data fusion and data storing purposes. Further, the central hub also promises a security feature for collecting the current picture of the user during emergencies. Hence, the central hub is equipped with the following devices:

1. MSP-EXP430F5438A
2. 3G cellular module
3. JPEG color camera
4. eZ430-RF2500

The JPEG color camera and the 3G cellular modules are used for providing security and for storing the valuable information on the web server, respectively. Both of these devices use UART communication for interfacing with any external microcontrollers. Unlike I2C, UART does not support multiple device communications using the single bus. The MSP430F5438A supports 4 UART modules, providing additional serial communication modules for future expansion of the system. The MSP430 uses the *USCI_A1* UART module, with 115200 baud rate for communicating with the JPEG color camera. The camera requires 5 V power supply. Hence, a 3.3 V to 5 V logical converter is used for powering and supporting the communication between the MSP430 and the camera.

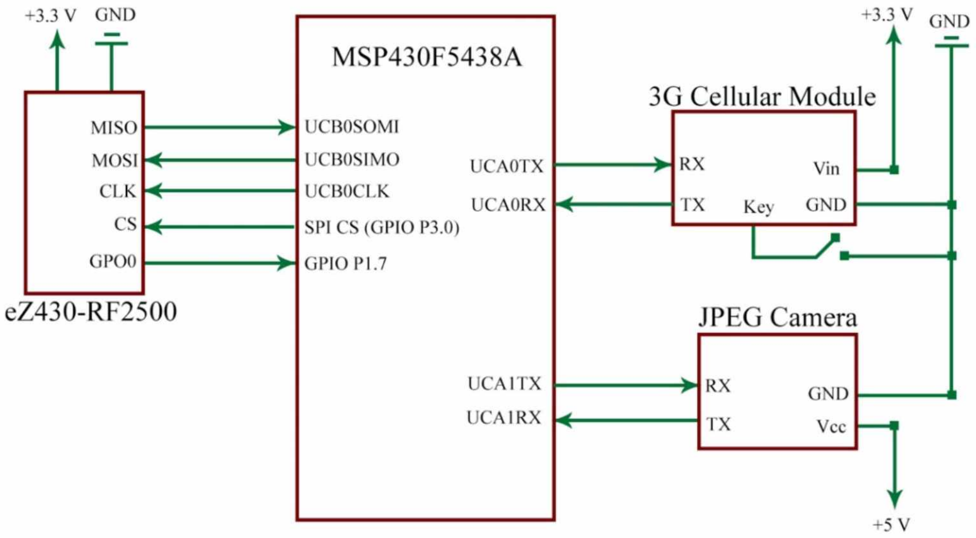


Figure 18: Integration of the central hub system

The 3G cellular module is externally connected to a lithium ion (Li-Po) battery. The 3G module requires 2 A current supply while establishing the cellular communications. However, the *Vin* pin is connected to the MSP430 3.3 V power supply for UART communication. The 3G module automatically configures the inbuilt logic level converter, based on the given *Vin* voltage. Moreover, the *key* pin is necessary for the 3G module; it should tie to the ground for 3 or 4 seconds to power on or off. This pin can be controlled through software to save power consumption of the system by turning off the cellular module when required. The MSP430 is connected to the 3G module through the *USCI_A0* UART interface with an 115200 baud rate.

Figure 18 represents the schematic for hardware integration of the central hub system, Figure 20 shows the central hub system hardware components. Interfacing the MSP430 and the transceiver (eZ430-RF2500) is discussed in section 4.2.1.

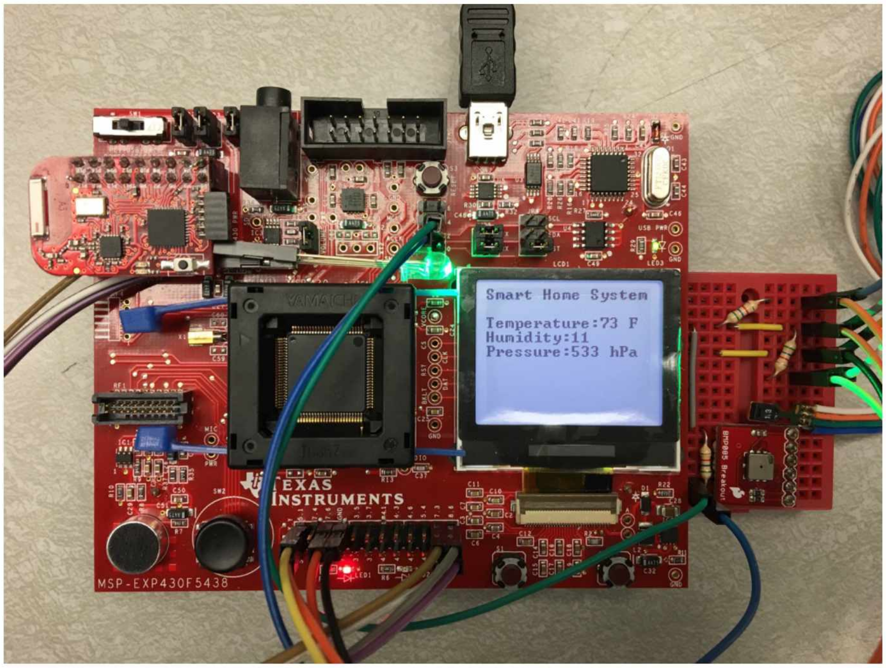


Figure 19: Smart home system hardware integration

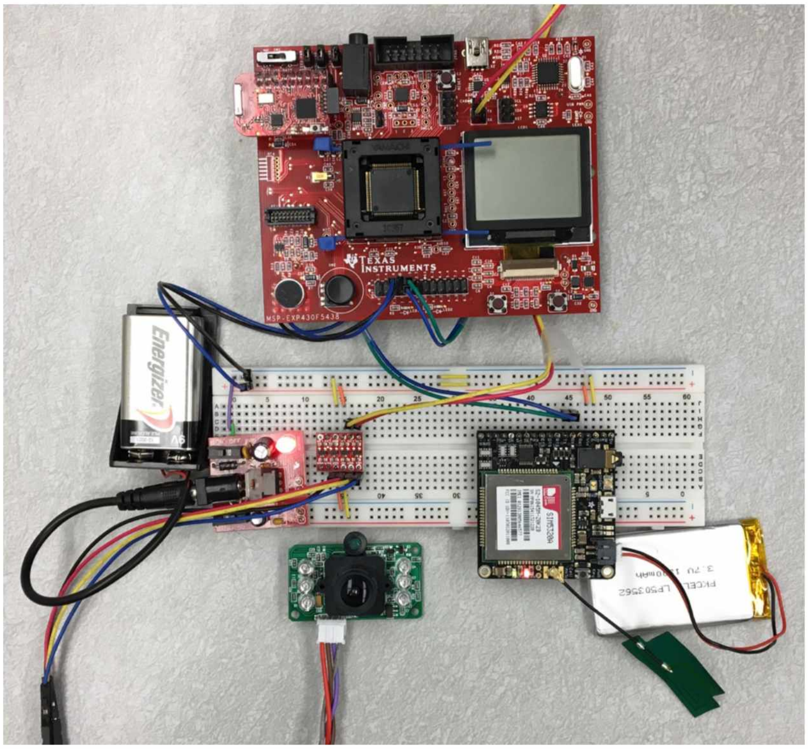


Figure 20: Central hub system hardware integration

Chapter 5 System Software Design

Application-oriented software design is an important part of developing a hardware prototype. In this thesis, several independent systems are integrated through custom software design to work together as a unit for providing a better quality of health care. Also, by designing an intelligent software, power consumption of the system can be reduced to provide extended operation. Furthermore, the software also supports an interactive user interface through hardware components such as LCD, switches, and LEDs. This chapter describes the software design for the sensor systems and other modules used in this thesis. It also describes a custom protocol design for the wireless communication network, used to achieve system integration.

5.1 Sensor Software Setup

Sensors provide valuable physiological data from the user and also from their surroundings. The systems that are mentioned previously interact with multiple sensors through several communication interfaces. To extract useful features, each sensor is operated at different sampling frequency. Consequently, the sensors require their unique way to interface with the host microcontroller for data collection. Following sections provide details on sensor setup for successfully collecting the data.

5.1.1 Polar Heart Rate Monitor Interface

The HRMI receiver collects ECG data from the Polar T31 transmitter through Bluetooth wireless technology. It automatically converts the collected ECG data into heart rate (beats per minutes – BPM) by measuring the time from one heart beat to the next [82]. The HRMI receives both raw data and averaged (removes erroneous data) data from the transmitter, and stores it in a

32-entry history buffer. However, the MSP430 is responsible for choosing which type of data to be received; in this system, the software is adjusted to read averaged ECG data which allows it to provide error free data. Furthermore, the MSP430 is responsible for reading the data from the HRMI through UART communication interface. The MSP430 uses the *USCI_A1* UART module for communicating with the HRMI. The maximum baud rate supported by the HRMI is 38400, hence, the MSP430's *USCI_A1* register is adjusted to appropriate baud rate. The MSP430 reads data with 1 Hz sampling frequency; it sends a command ('*G3*') to get the heart rate data from the HRMI history buffer. Data provided by the HRMI is in *ASCII* format, which the MSP430 system converts into *unsigned integer* format for further data processing.

5.1.2 Body Temperature Sensor (Si7021)

The MSP430 and the Si7021 sensor communicate through *USCI_B1* I2C interface. Unlike other sensors, the Si7021 requires a random time for temperature conversions [83], meanwhile the host microcontroller can either wait until the conversion is completed or continue requesting the data until the sensor returns the measured data. The MSP430 sends a measured temperature command (*0xE3*) every second, and waits by stretching its clock until the conversion data is returned from the sensor. The temperature sensor contains an on-chip non-volatile memory for calibration data. Consequently, there is no need for user calibration for this sensor. However, the collected 16-bit sensor data is converted into temperature (°C) using Equation (1) [83], further, the temperature data can be converted into °F if needed.

$$Temperature\ (°C) = \frac{Sensor_{output} + 175.72}{65536} - 46.85 \qquad (1)$$

5.1.3 Three Axis Accelerometer

The 3-axis accelerometers (ADXL345) are used to detect dynamic acceleration rate of the user. By observing the dynamic acceleration, multiple physical activities are measured. These sensors communicate with the MCU through *USCI_B1* I2C interface with 64 Hz sampling frequency. The ADXL345 comes with software adjustable *g* range, and user selectable sensitivity of up to 13-bit resolution. The ADXL345's *g* range is adjusted by setting appropriate bits in a *DATA_FORMAT* register as shown in Table 3 below [84]. In this thesis, ±16 *g* range with 10-bit resolution is selected for initial testing of the user impacts. However, data read from the ADXL345 sensor has an overhead associated with it. The ADXL345 sensor overhead is removed by using Equation (2); for this setup, the collected sensor data is multiplied with a scalar 0.03125.

$$Accelerometer_{Raw_{data}} = Sensor_{output} * \left(\frac{g_{range}}{2^{bit_{resolution}}}\right) \tag{2}$$

Table 3: Accelerometer (ADXL345) *g* range settings

Setting		**g Range**
D1	**D0**	
0	0	±2g
0	1	±4g
1	0	±8g
1	1	±16g

5.1.4 Three Axis Gyroscope

The ITG3200 is used to detect different kinds of physical activities by measuring angular velocity of the user's leg movement. The MSP430 reads data from the sensor through *USCI_B1* I2C interface at 64 Hz sampling frequency. The ITG3200 can detect up to ±2000 °/sec angular rotations [85]. However, it has a linear drift related with it and the magnitude of the drift changes with surrounding temperature. Hence, user calibration is required to remove the linear drift from sensor readings. The health monitoring system automatically calibrates the sensor upon each reboot, but the user is responsible for keeping the sensor stable. In addition, it has a sensitivity of 14.365 LSBs per °/sec. Equation (3) is used to gather raw data in °/sec by removing linear drift and sensitivity from the collected data from ITG3200 sensor.

$$Gyroscope_{Raw_{data}} = \frac{Sensor_{output} - Linear_{drift}}{14.375} \tag{3}$$

5.1.5 Temperature and Humidity Sensor

The temperature and humidity sensor (SHT75) uses digital communication to interact with a host microcontroller. The SHT75 requires a serial clock for synchronous data in and data out operations [86]. This sensor does not support any standard serial communications (UART, SIP, and I2C). Hence the MSP430 uses two GPIO pins for reading the sensor data (*DATA*), and for providing the clock (*CLK*) by alternating the GPIO at 1 MHz frequency.

To initiate a transmission, the MSP430 issues a Transmission Start sequence as shown in Figure 21. The Transmission Start sequence consists of a lowering of the *DATA* pin while *SCK* pin is high, followed by a low pulse on *SCK* pin and raising the *DATA* pin while *SCK* pin is still high. The following command consists of SHT75 address bits (‘*000*’) and command bits for reading either relative humidity ('*00101*') or temperature ('*00011*') data. Next, the SHT75 pulls the *DATA* pin low for indicating the proper reception as shown in Figure 21. In this figure, the bold lines on the *DATA* pin are controlled by the SHT75 sensor, and the plain lines are controlled by the MSP430.

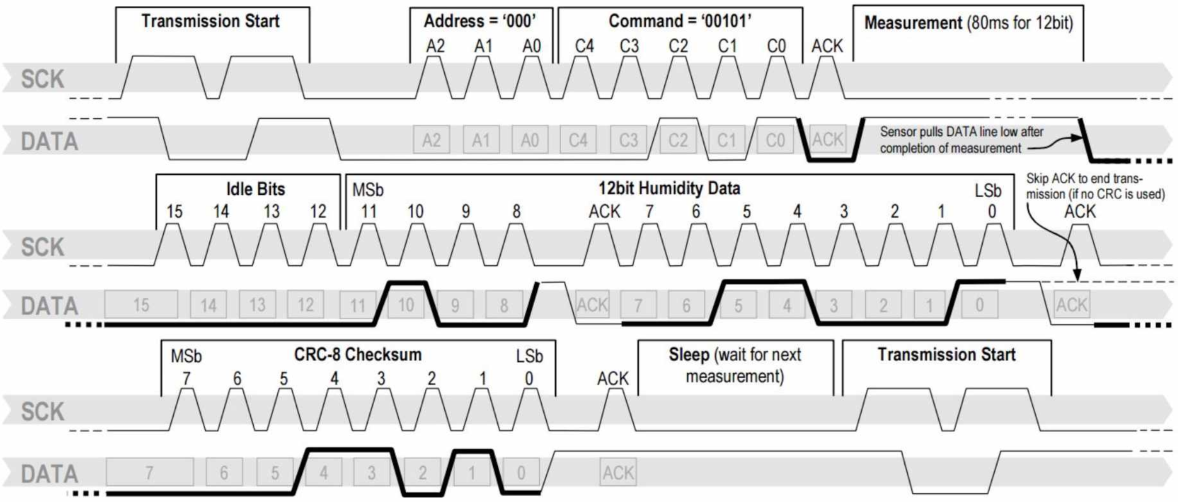


Figure 21: SHT75 measurement sequences [86]

After the measurement is completed, the sensor signals Data Ready by pulling the *DATA* pin low. Next, the MSP430 re-initiates the *SCK* for reading the sensor output data. The humidity readout (SO_{RH}) is converted into relative humidity by using Equation (4). And, Equation (5) is used to convert the temperature readout (SO_T) [86].

$$RH_{linear} = c_1 + c_2 * SO_{RH} + c_3 * SO_{RH}^2 \tag{4}$$

$$T = d_1 + d_2 * SO_T \tag{5}$$

Constants in the above equations are provided in the sensor datasheet [86]; these are:

$c_1 = -2.0468$

$c_2 = 0.0367$

$c_3 = 0.0000015955$

$d_1 = -39.4$

$d_2 = 0.018$

5.1.6 Digital Pressure Sensor

The digital pressure sensor (BMP085) [87] and the MSP430 communicate through *USCI_B3* I2C interface. The BMP085 contains 176 bit of calibration data which is stored in its E^2PROM to compensate pressure offsets [87]. The pressure sensor also supports software adjustable over sampling settings (oss) to mitigate power consumption. In ultra-low power mode, the sensor consumes only 3 µA but it is associated with more RMS noise. On the other hand, ultra-high resolution mode has less RMS noise but the power consumption is comparably high. Hence, a standard mode (oss = 1) is selected for reducing the RMS noise while allowing low-power consumption (5 µA).

The pressure data is sampled once every minute with the assumption that the home atmosphere does not change abruptly. Figure 22 shows a flow chart for reading the uncompensated data and calculating the pressure using the sensor's calibration data. Initially, the MSP430 reads the calibration data from E^2PROM and locally stores it for further calculations. Next, it reads the uncompensated temperature (UT) data followed by the uncompensated pressure (UP) data. Subsequently, the pressure data is calculated by using list of equations as shown in Figure 22. The pressure is calculated in Pa (= 0.01 hPa).

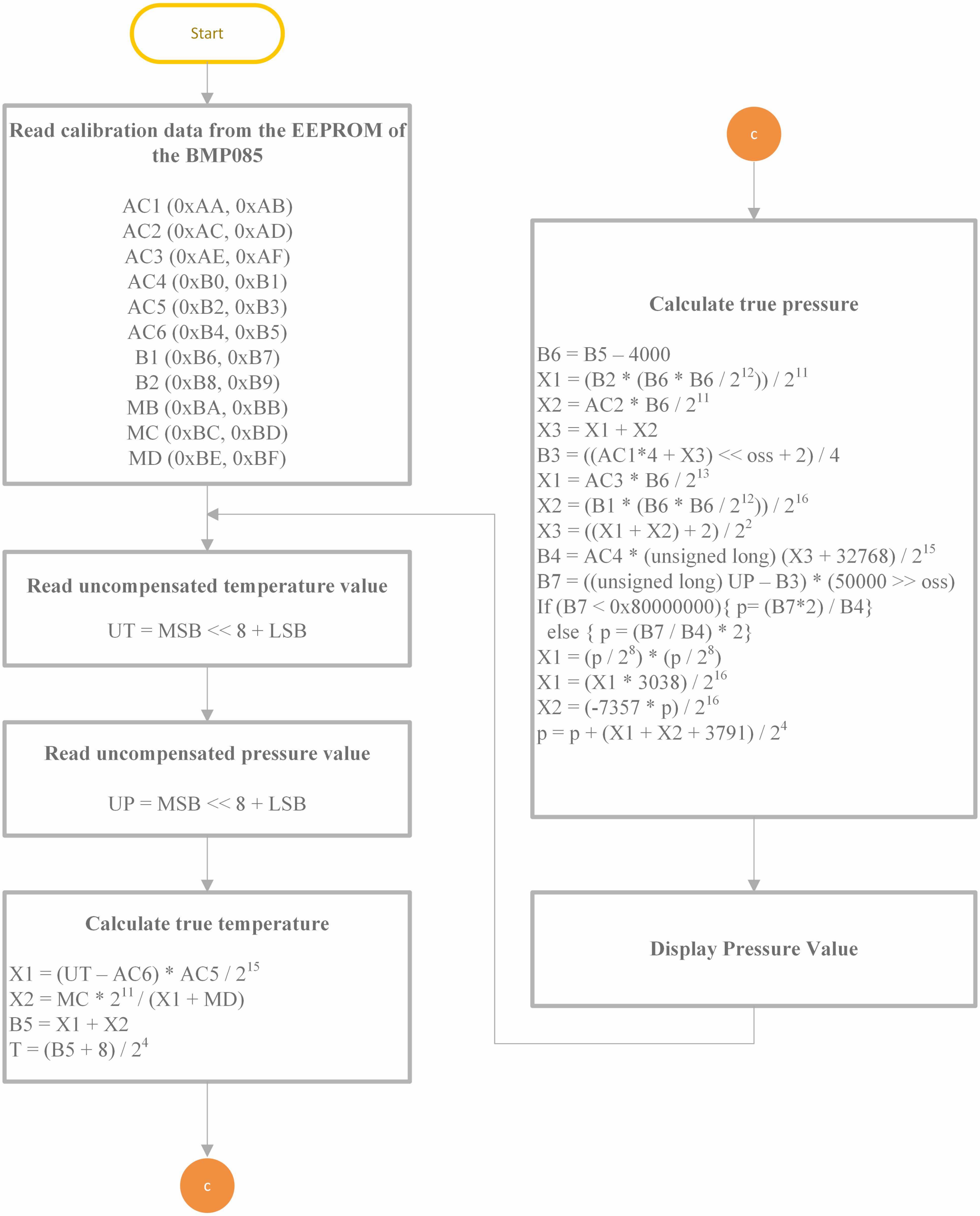


Figure 22: Calculation of pressure for BMP085 sensor [87]

5.2 JPEG Color Camera

The host microcontroller follows several steps, as shown in Figure 24, for taking a picture using LinkSprite's JPEG color camera [88]. The camera supports adjustable image size, compression ratio, and baud rate. It comes with a default baud rate of 38400 bps. However, after initialization the MSP430 sends a command to change the camera's baud rate to 115200 for supporting faster communications and to read photos captured from the camera with file size of up to 500 KB.

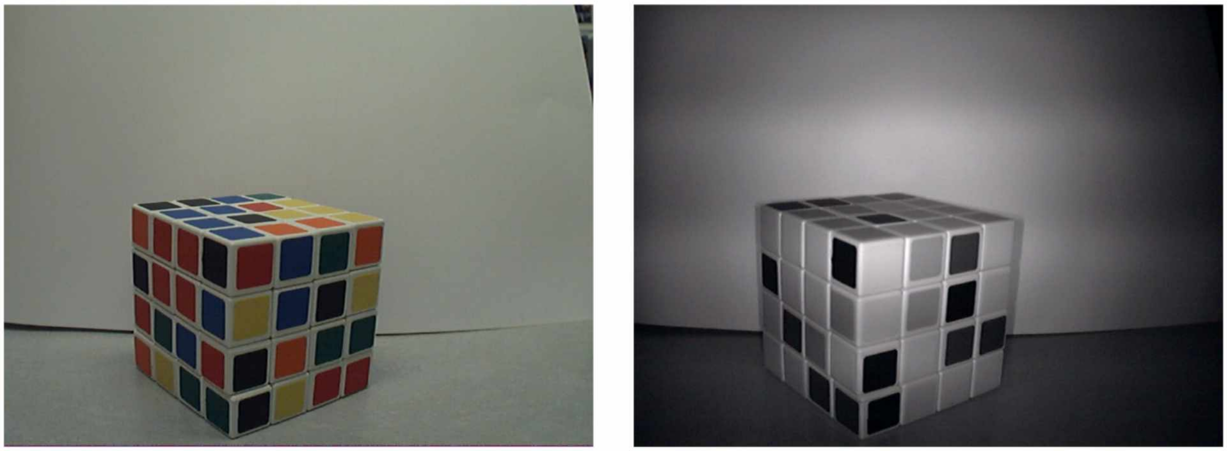


Figure 23: Output of JPEG color camera in bright light (left) and dark conditions(right)

After setting the camera to custom baud rate, the MSP430 microcontroller waits for external commands to capture a photo. Upon request, the MSP430 sends a command to start taking picture as shown in Figure 24. Afterward, the JPEG file size is received from the camera. Subsequently, the MSP430 starts reading chunks of the picture file content. The JPEG contains headers such as "*FF D8*" being the start of image, and "*FF D9*" is end of image [89]. Hence, the microcontroller continues reading captured picture frames until it receives end of the JPEG file (*FF D9*). The MSP430 then sends a command to stop picture taking, and the collected photo data is consequently transferred to the 3G module for sending the multimedia message through cellular network. Figure 23 shows the output image (example) from the camera.

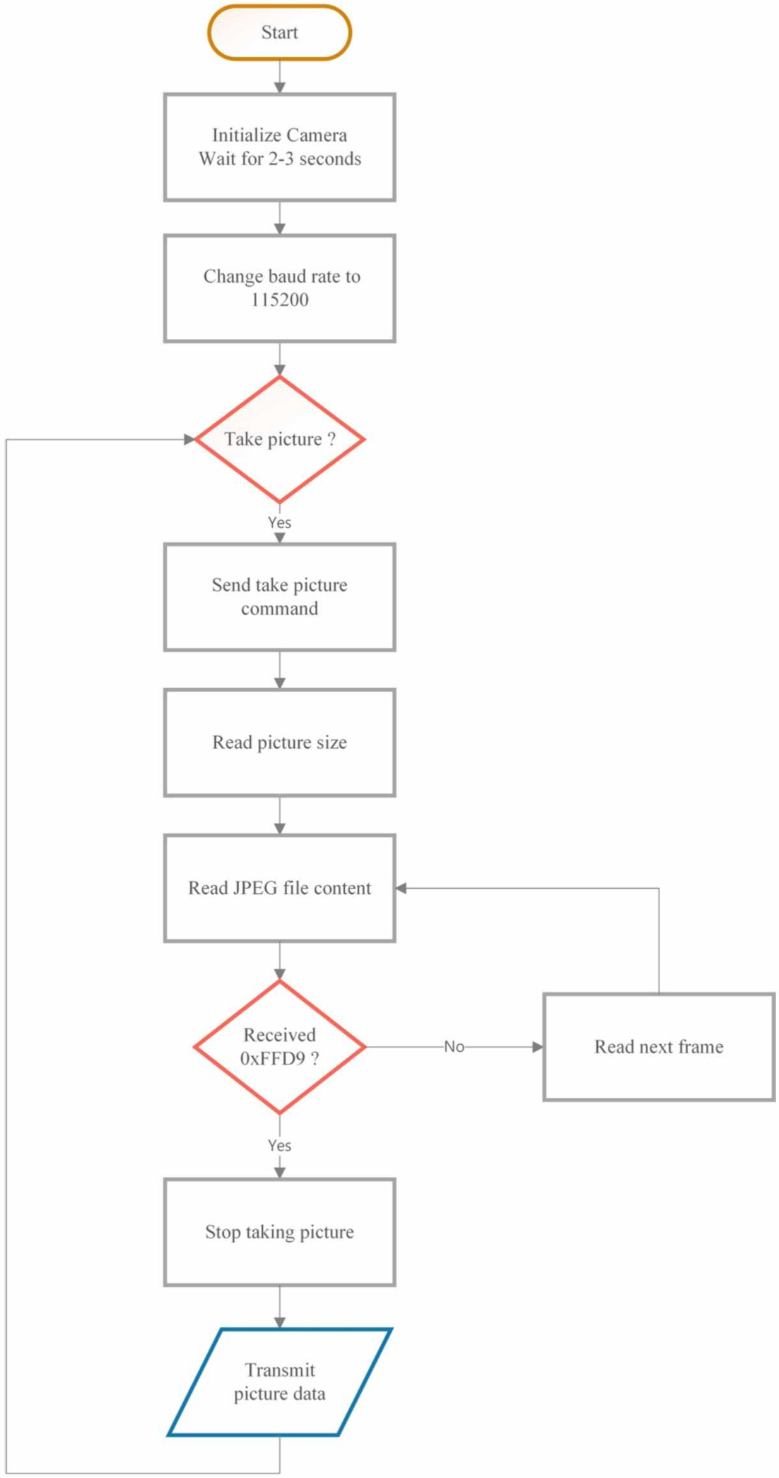
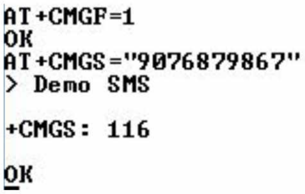


Figure 24: Flow chart for capturing a picture from JPEG color camera

5.3 3G Cellular Module

The 3G module uses AT commands for establishing the communication link and sending data through cellular network technology. Different cellular modules support their own set of AT commands; the FONA 3G module's [90] AT command set are provided in the user manual [91]. The module interfaces with MSP430 through UART communication protocols. Therefore, human interference is not required for sending any information from the cellular module. The 3G cellular module currently supports multiple functions such as sending and receiving SMS, MMS, calls, connection to the internet through 3G network, GPS, and storing multimedia files.

The cellular module receives appropriate AT commands from the MSP430 microcontroller to send data using the requested component (SMS or MMS or HTTP). A text SMS is selected using the *AT+CMGF = 1* command. Next, the recipient phone number is written into the module using *AT+CMGS = "recipient"* command. Then, text is written into the cellular module; the MSP430 initiates SMS transferring by sending *ASCII* character for *substitute* (or *ctrl + z*). After successful transmission, the cellular module acknowledges with *OK* as shown in Figure 25.



```
AT+CMGF=1
OK
AT+CMGS="9076879867"
> Demo SMS

+CMGS: 116

OK
```

Figure 25: An example sequence used to send an SMS from the 3G cellular module

Subsequently, to send an MMS, carrier (AT&T in this example) supported MMS settings must be stored into the cellular module as shown in the Figure 26. To send any multimedia related messages an internet connection is required. So, an access point name (APN) is loaded into the cellular module, then, the internet connection is activated using *AT+CGACT = 1,1* command. By setting a command (*AT+CMMSEDIT = 1*), the cellular module enters into MMS editing mode.

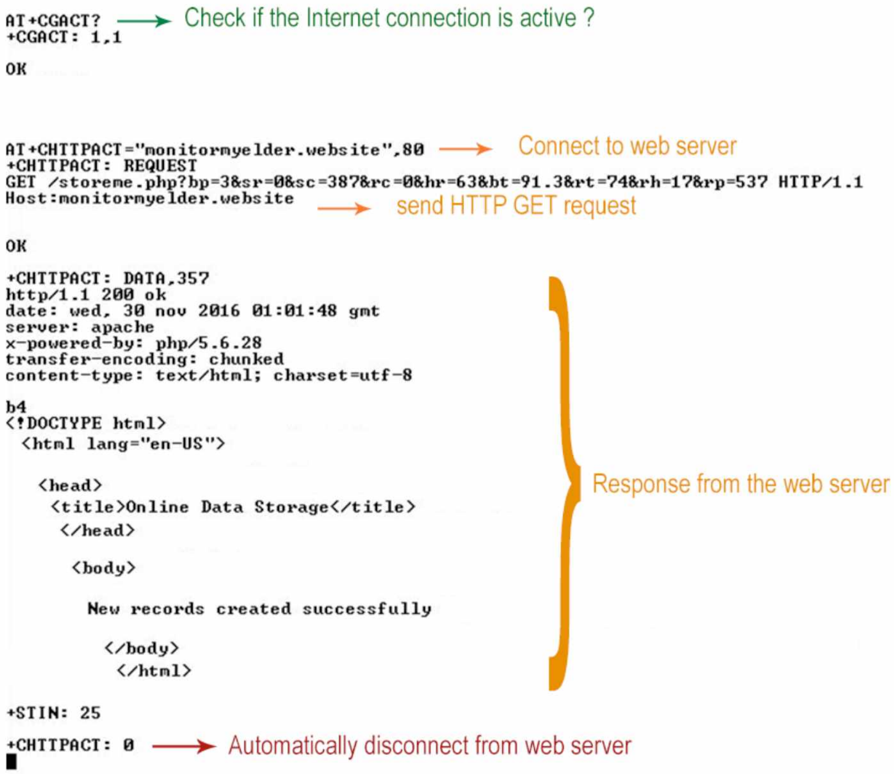
Afterwards, a title subject is written to give a brief description to MMS receiver. Subsequent command indicates type of multimedia, its size, and a file name. In this example, a picture multimedia is chosen, and image size (in bytes) is read from the camera. Then, the MSP430 collects picture data from the camera and transfer it to the cellular module. After complete image is downloaded, the recipient's contact information is provided to send MMS. After the MMS being sent, the MMS editing mode is terminated using *AT+CMMSEDIT=0* command.

```
AT+CGDCONT=1,"IP","Broadband"
OK
AT+CMMSCURL="mmsc.mobile.att.net"
OK
AT+CMMSPROTO=1,"172.26.39.1",80
OK
AT+CMMSSENDCFG=6,3,0,0,2,4
OK
AT+CGSOCKCONT=1,"IP","Broadband"
OK
AT+CGACT=1,1
OK

AT+CMMSEDIT=1
OK
AT+CMMSDOWN="TITLE",11
>Demo Alert!
OK
AT+CMMSDOWN="PIC",49768,"image01.jpg"
> ÷ ▮$J2
          QQ █
        .
        .
        .
        .

]:]D
$┬▒3<^╘╤/=±2╬2IL╒?β─|▮ ╙█Ω5·yøó≤_µ
                                 <╕┼~

█╖
ⁿ¥||╘6▮??°σIΣ<╓oµυpWk*X<?τ╨╦4β─╥ⁿ9α2 "'

3»≡S·«!θ∞σ ╥ⁿ╘╕»/Γ┐╠├╤≡_▌┘<·▄±°╘'─C≤▓╧
^▀├▮/≥∞½M▮≈║╟ⁿ±  ┘
OK
AT+CMMSSEND="npamidi@alaska.edu"
OK

+STIN: 25

AT+CMMSEDIT=0
OK
```

Figure 26: An example of sending a picture MMS from the 3G cellular module

The 3G module also supports online data storage through HTTP connections. Initially, the system checks if the internet connection is active by using *AT+CGACT?* command. If the internet connection is inactive, the microcontroller requests internet connection through *AT+CGACT=1,1* command. Afterwards, HTTP connection is activated using *AT+HTTPACT* command as shown in the Figure 27. Once the connection is established, user physiological and environmental data is stored in web server using HTTP GET requests. Eventually, the web server responses with successful data storage message and the cellular module automatically terminates the HTTP connection.

In addition, the cellular module also supports a global clock which can be used as a reference for maintaining time synchronization in a wireless communication network.



```
AT+CGACT?
+CGACT: 1,1

OK


AT+CHTTPACT="monitormyelder.website",80
+CHTTPACT: REQUEST
GET /storeme.php?bp=3&sr=0&sc=387&rc=0&hr=63&bt=91.3&rt=74&rh=17&rp=537 HTTP/1.1
Host:monitormyelder.website

OK

+CHTTPACT: DATA,357
http/1.1 200 ok
date: wed, 30 nov 2016 01:01:48 gmt
server: apache
x-powered-by: php/5.6.28
transfer-encoding: chunked
content-type: text/html; charset=utf-8

b4
<!DOCTYPE html>
 <html lang="en-US">

   <head>
    <title>Online Data Storage</title>
     </head>

      <body>

        New records created successfully

          </body>
           </html>

+STIN: 25

+CHTTPACT: 0
```

Check if the Internet connection is active ?

Connect to web server

send HTTP GET request

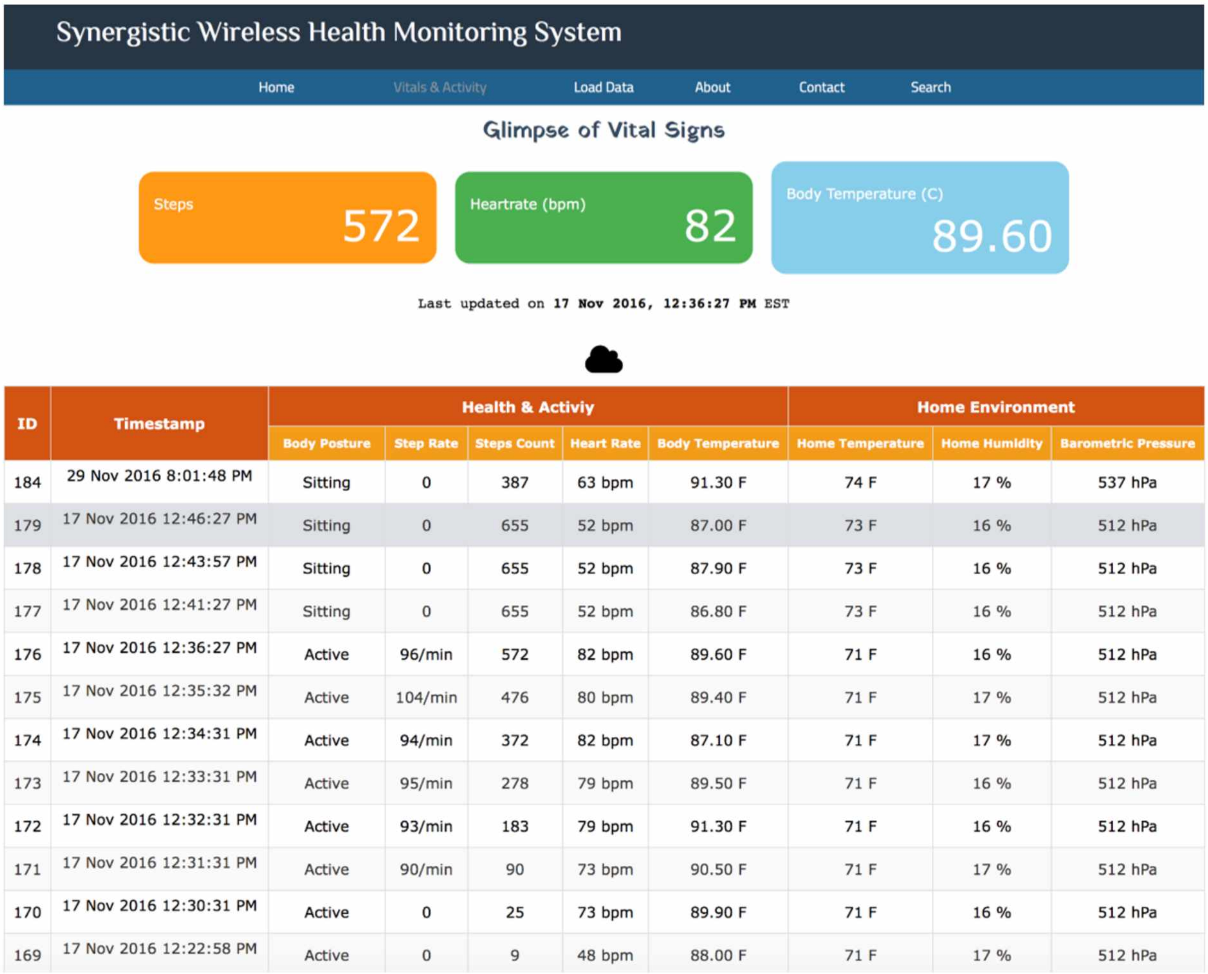
Response from the web server

Automatically disconnect from web server

Figure 27: An example of storing data on web server using the 3G cellular module

5.4 Web Interface

A web page (www.monitormyelder.website) is designed for storing and displaying the collected data during preliminary research. Scripting languages such as HTML5, MySQL, PHP are primarily used to design the web page and to store the data securely. MySQL server collects the uploaded data, sorts it out, and displays it in a meaningful HTML5 web format. In the future, a two-way communication will be established between the web page and the designed system, so that the healthcare professionals will have access to more information. Figure 28 shows a screenshot of the developed webpage.



Synergistic Wireless Health Monitoring System

Glimpse of Vital Signs

Steps 572

Heartrate (bpm) 82

Body Temperature (C) 89.60

Last updated on **17 Nov 2016, 12:36:27 PM** EST

ID	Timestamp	Health & Activiy					Home Environment		
		Body Posture	Step Rate	Steps Count	Heart Rate	Body Temperature	Home Temperature	Home Humidity	Barometric Pressure
184	29 Nov 2016 8:01:48 PM	Sitting	0	387	63 bpm	91.30 F	74 F	17 %	537 hPa
179	17 Nov 2016 12:46:27 PM	Sitting	0	655	52 bpm	87.00 F	73 F	16 %	512 hPa
178	17 Nov 2016 12:43:57 PM	Sitting	0	655	52 bpm	87.90 F	73 F	16 %	512 hPa
177	17 Nov 2016 12:41:27 PM	Sitting	0	655	52 bpm	86.80 F	73 F	16 %	512 hPa
176	17 Nov 2016 12:36:27 PM	Active	96/min	572	82 bpm	89.60 F	71 F	16 %	512 hPa
175	17 Nov 2016 12:35:32 PM	Active	104/min	476	80 bpm	89.40 F	71 F	17 %	512 hPa
174	17 Nov 2016 12:34:31 PM	Active	94/min	372	82 bpm	87.10 F	71 F	17 %	512 hPa
173	17 Nov 2016 12:33:31 PM	Active	95/min	278	79 bpm	89.50 F	71 F	16 %	512 hPa
172	17 Nov 2016 12:32:31 PM	Active	93/min	183	79 bpm	91.30 F	71 F	16 %	512 hPa
171	17 Nov 2016 12:31:31 PM	Active	90/min	90	73 bpm	90.50 F	71 F	17 %	512 hPa
170	17 Nov 2016 12:30:31 PM	Active	0	25	73 bpm	89.90 F	71 F	16 %	512 hPa
169	17 Nov 2016 12:22:58 PM	Active	0	9	48 bpm	88.00 F	71 F	17 %	512 hPa

Figure 28: Screenshot of the web interface

5.5 Wireless Packet Design

A star-topology based wireless communication network is designed for connecting the heterogeneous systems. The wireless transceivers are initially developed using drivers provided by Texas Instruments. However, the provided drivers have certain limitations; for example, the transceivers are not configured to a specific wireless topology. Hence, the network is further advanced to maintain a star topology based wireless network. Subsequently, custom wireless packets are designed to differentiate between the packet data type as shown in Figure 29.

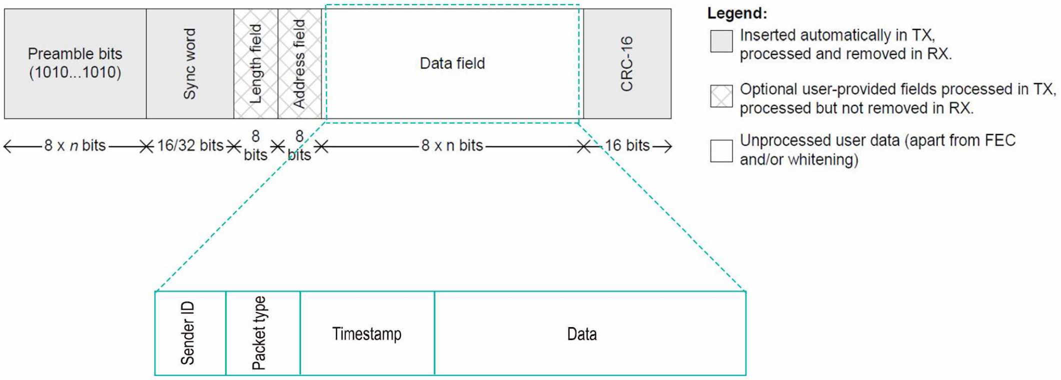


Figure 29: Wireless packet custom data field design [92]

The designed packets are of variable length. First byte in unprocessed data field represents the sender ID. Each node is associated with a unique ID, so that the receiver can distinguish between the senders. The second byte contains the packet type field. Individual nodes perform different tasks based on a given packet type. Table 4 shows all possible packet types used in the developed network. The smart home node and the health monitoring node are initially registered to the central hub by sending '*R*' packet type. The acknowledgement (*ACK*) packets are used to indicate successful packet transmission. If the user, who is wearing the health monitoring node walks out of the network then there will be no data exchange (no *ACK*), hence the health monitoring system temporarily stores the packets in flash memory. When the network is available again, the health monitoring system re-sends an *R* type packet for registering into the network and subsequently sends the stored data packet upon reconnection.

Table 4: Custom wireless packet types

Packet Type Byte	Packet Representation
A	Acknowledgement
R	Register network
Q	Request data
S	Smart home data
H	Health and activity data
E	Emergency
C	Change status

Central hub uses a *Q* packet type to periodically request the updated data from the nodes (if nodes did not send data for a while). The smart home node and the health monitoring node use *S* and *H* data packets to send updated data to the central hub, respectively. If the health monitoring system detects any emergency scenario, then it sends an *E* data packet to indicate a possible threat to the user. Central hub uses *C* packets to instruct the smart home system to change its environment according to the user status. Data bytes from 3 to 5 carry a timestamp. Finally, the rest of the data packet contains its associated information.

5.6 Annotating the Collected Data

Sensors used for the health monitoring system produce a very large amount of physiological data within a small time window. Data analysis using a serial terminal or an integrated development environment (IDE) is difficult; most of the biological data is better understood using graphical presentation. Hence, the sensor data is directly transferred to a laptop through USB. The laptop uses MATLAB, which is designed with adjustable baud rate to read serial data transmitted from the MSP430. By graphically annotating the collected sensor data, the MATLAB supported initial data analysis for identifying important physiological data.

5.7 System Flow Charts

Figure 30 – 32 show the software design for the wearable health monitoring system, the smart home system, and the central hub system respectively.

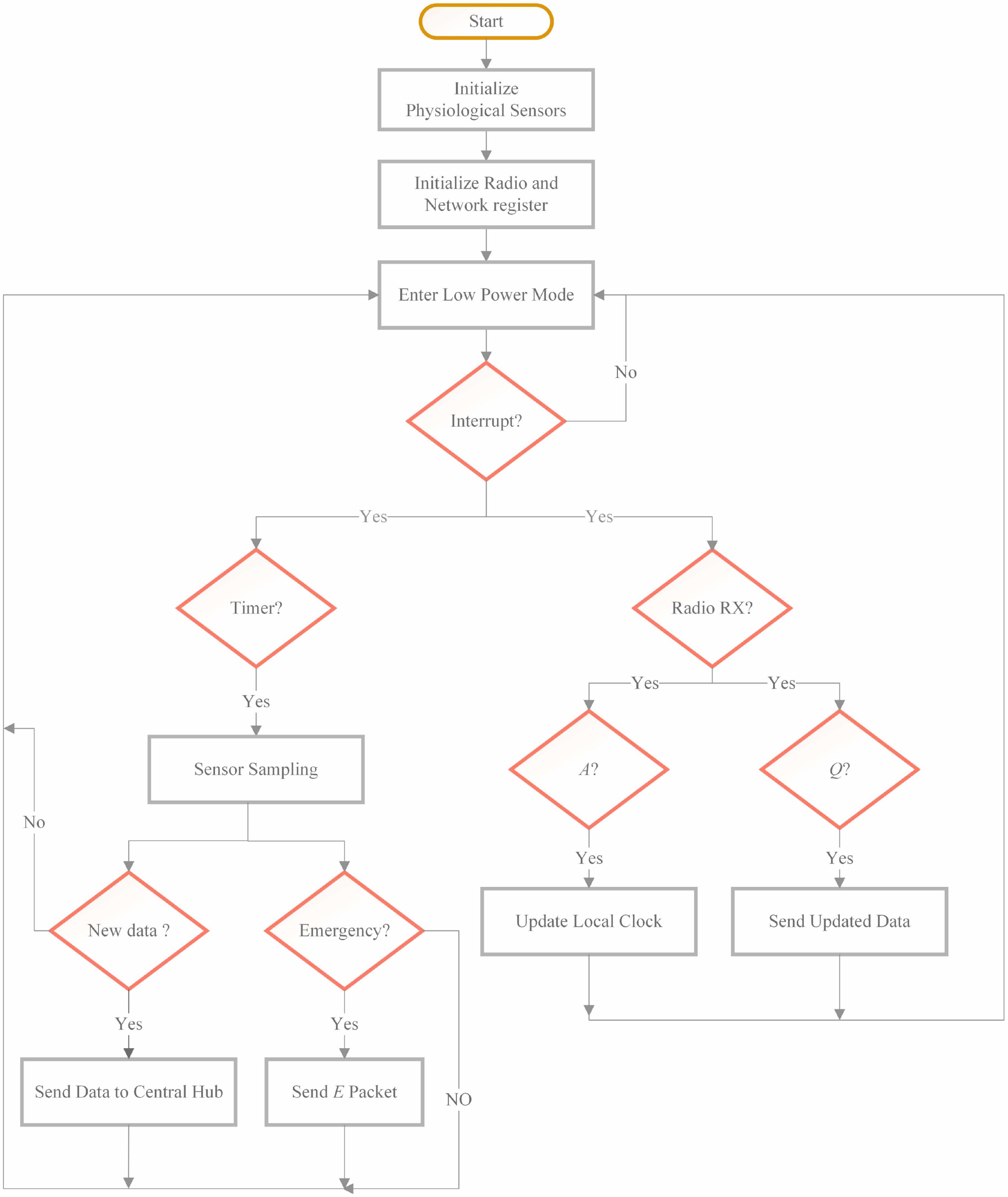


Figure 30: Wearable health monitoring system software flow chart

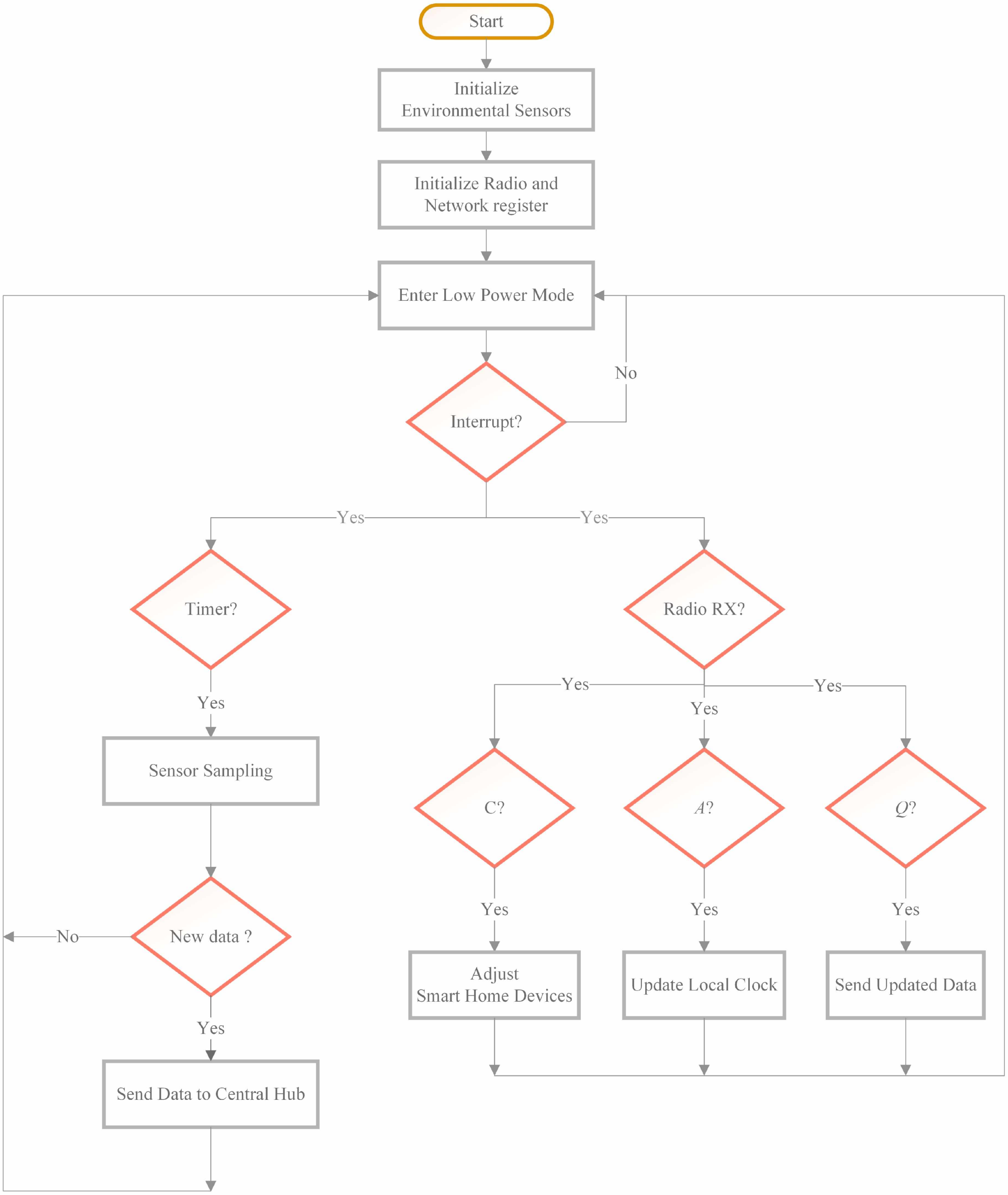


Figure 31: Smart home system software flow chart

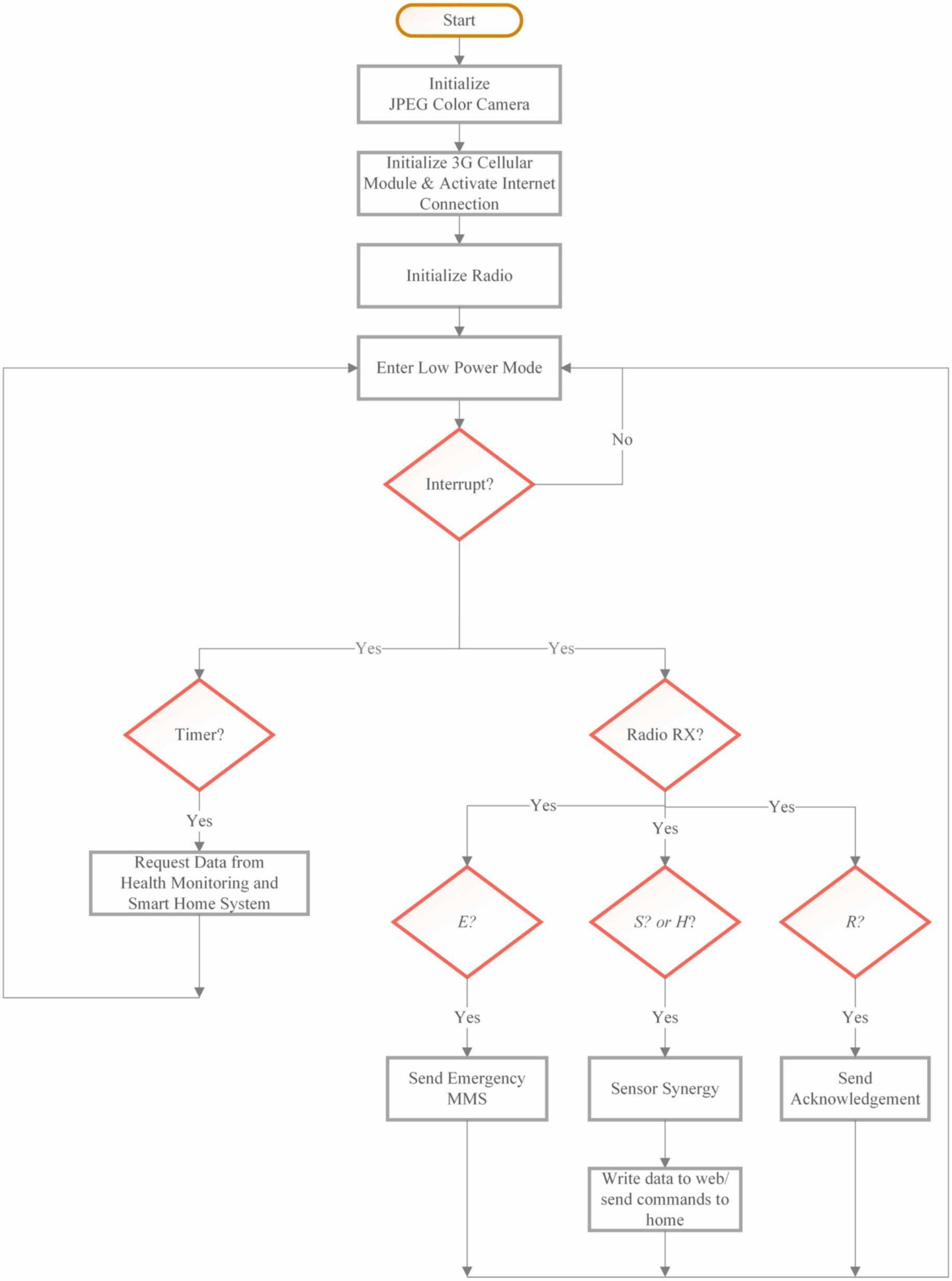


Figure 32: Central hub system software flow chart

Chapter 6 Data Processing and System Synergy

The previous chapter describes data collection using custom software design. This chapter now provides details on data processing techniques for extracting important features from the collected physiological data. Also, this chapter presents an idea of a synergistic system development for improving health care.

6.1 Physiological Parameters

Heart rate and body temperature are continuously measured from the user. The health monitoring system is accountable for continuously monitoring the physiological data from the user. This physiological data is collected once per second. Initially, data is collected from the user and locally stored for comparing relevant changes. Next, the health monitoring system compares it with previously collected data. If the vital signs differ significantly enough, the system observes if there are any external artifacts that are affecting the user's physiological condition.

The external artifacts such as environmental conditions and physical activity affect different users at different levels. Important features cannot be extracted simply by using static threshold limits for observing changes in physiological parameters. Hence, a system learning technique is implemented to initially learn user specific vital sign data and store it in flash memory for determining the dynamic thresholds and detecting changes in physiological conditions.

In addition, the vital signs might not respond to the external artifacts right away. There might be a time gap between these two actions. Henceforth, the health monitoring system is developed to be scalable for determining possible delayed changes in physiological conditions. The environmental and physical activity artifacts contribute to modulations of vital signs. Therefore, a smart home system is used for detecting changes in the user surrounding environment, and also different kinds of physical activities continuously monitored as described in the following sections.

6.2 Activity Data Processing

The activity sensors (accelerometers and gyroscope) are sampled at 64 Hz sampling frequency. These sensors are used to detect features like body posture, sitting posture, walking, stairs climbing, rope-jumping, and detection of falls. The waist-worn accelerometer raw data collected from the user while walking is shown in the Figure 33. Due to force exerted on the accelerometer, all three axes are actively responding to the dynamic impact. The activity detection algorithms use a derivation of the vector sum of all three axes.

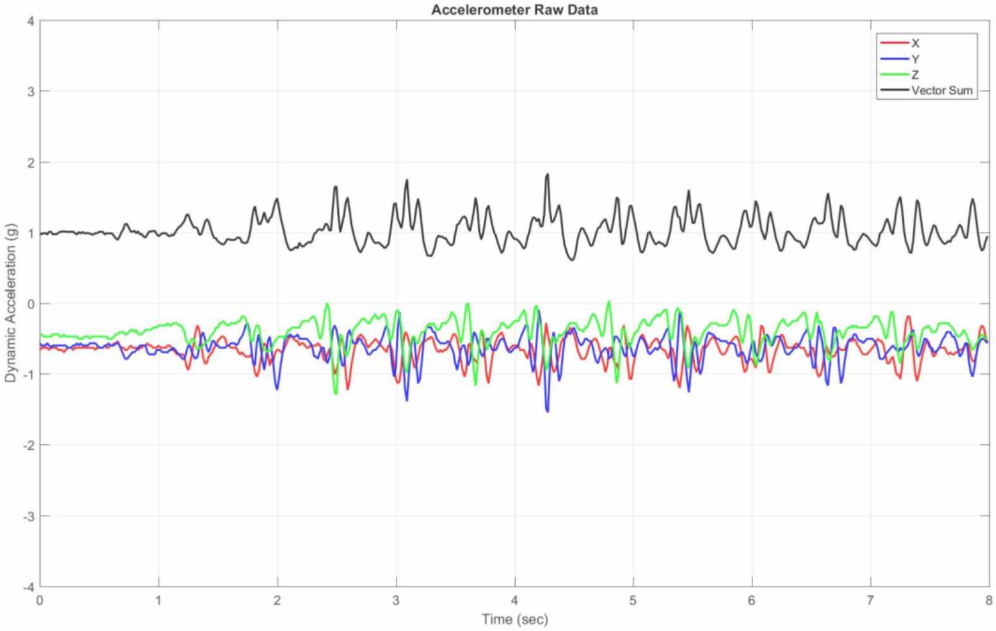


Figure 33: Wrist-worn accelerometer raw data while the user is walking

The raw data contains electrical noise and motional artifacts. Detecting activity status from this noisy data is difficult. In order to remove the artifacts, different filters such as averaging and low pass filters are used as shown in Figure 34. The low pass filter (with 2 Hz cutoff frequency) produced much smoother filtered data as shown in Figure 34. Hence, for further activity data analysis only low pass filtered data is used. Gyroscope data is also filtered using low pass filter to remove noise. Following sections describe methods used for detecting multiple physical activities.

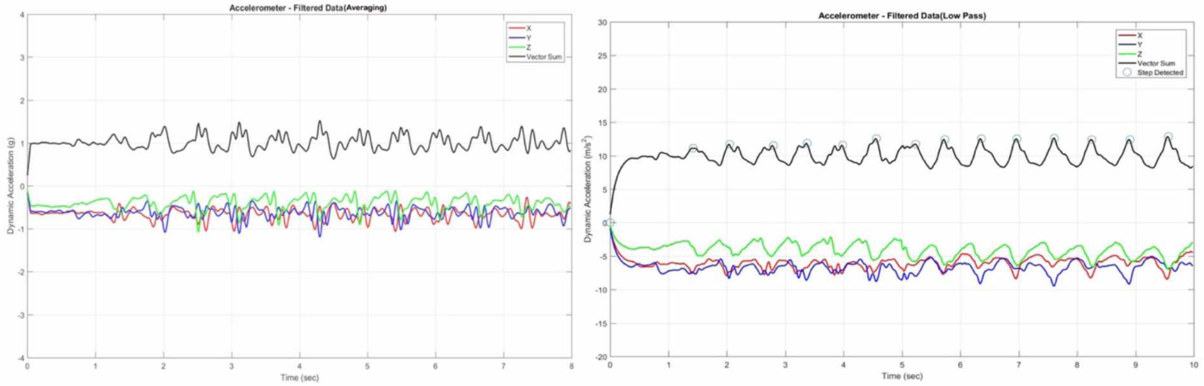


Figure 34: Difference between averaging and low pass filtered data

6.2.1 Body Posture

Determining the body posture of the user is an essential feature. By actively detecting the current body posture, the system can learn about activity and inactivity periods of the user. And, it can further help by sending activity reminders to the user for keeping him/her physically active. Furthermore, body posture is also useful to correlate vital sign changes with different body postures for detecting possible stress related situations. Using a waist-worn 3-axis accelerometer, the health monitoring system can detect relevant active axis that is related to the user position as shown in Figure 35. The activity cannot be determined just by comparing the sensor output at a particular instant; rather, it can be detected by comparing the average values in a sliding window of one second length. In this setup, the active Z-axis refers to laying down positions, the X-axis is associated with laying down laterally (left/right), and the Y-axis determines sitting/standing positions.

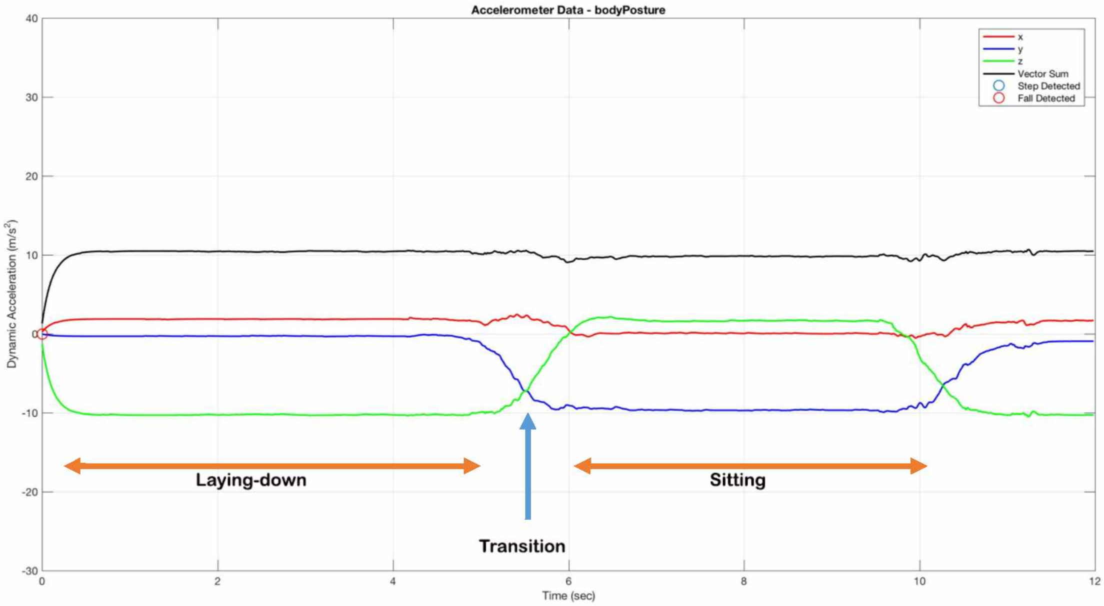


Figure 35: Waist-worn accelerometer output according to body posture

6.2.2 Crossing Legs

Patients who are being treated for high blood pressure are often advised to avoid crossing their legs while sitting. Researchers conducted several studies and concluded that crossing legs adds negative impact on health [93] because crossing legs while they are sitting enhances burden on the bottom leg's blood stream, which in turn rises the blood pressure. Hence, the health monitoring system uses sensor synergy strategies between accelerometer and gyroscope (attached at the shank) to detect crossing leg conditions. As shown in Figure 36, when the user is in sitting position and crosses their legs, the accelerometer detects impacts while the gyroscope determines the angular velocity of the knee. By using sensor synergy, the health monitoring system eludes false alarms and successfully detects crossing leg conditions and alerts the user to change their sitting posture.

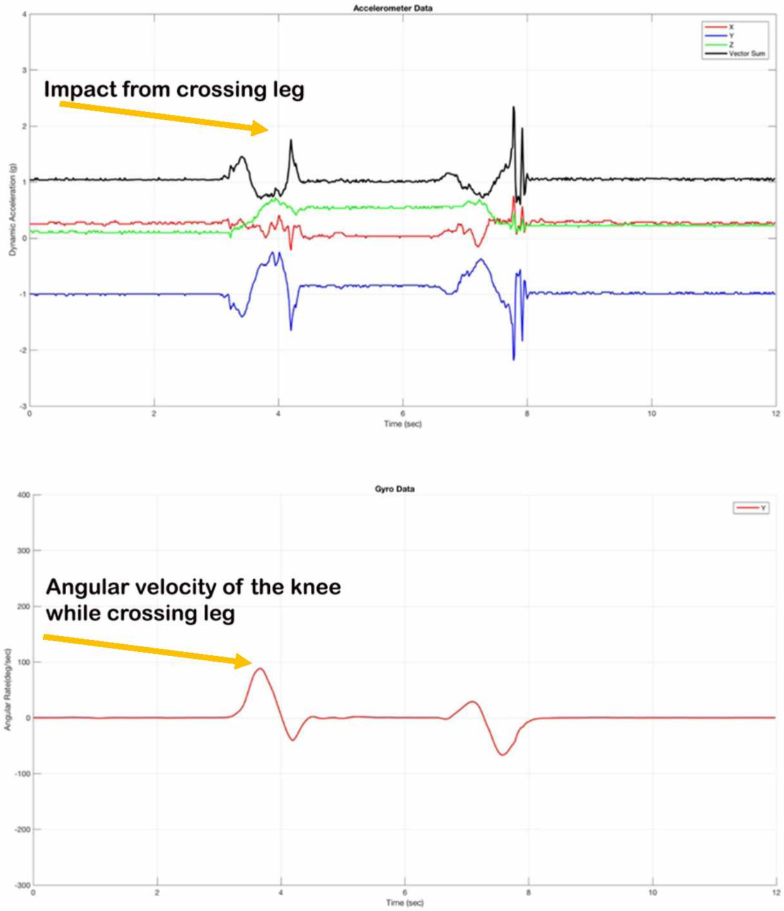


Figure 36: Shank attached accelerometer and gyroscope sensors output while crossing legs

6.2.3 Steps Detection

Walking and running are the easiest ways to exercise at home. A recent trend of 10,000 steps per day motivates people to stay physically active and healthy. The health monitoring system supports tracking footsteps by collecting data from the activity sensors. Previously, researchers used several methods for detecting the steps; however, a steps detection algorithm is developed to support a specific proposed sensor placement in this thesis. Figure 37 represents waist-worn accelerometer output during walking.

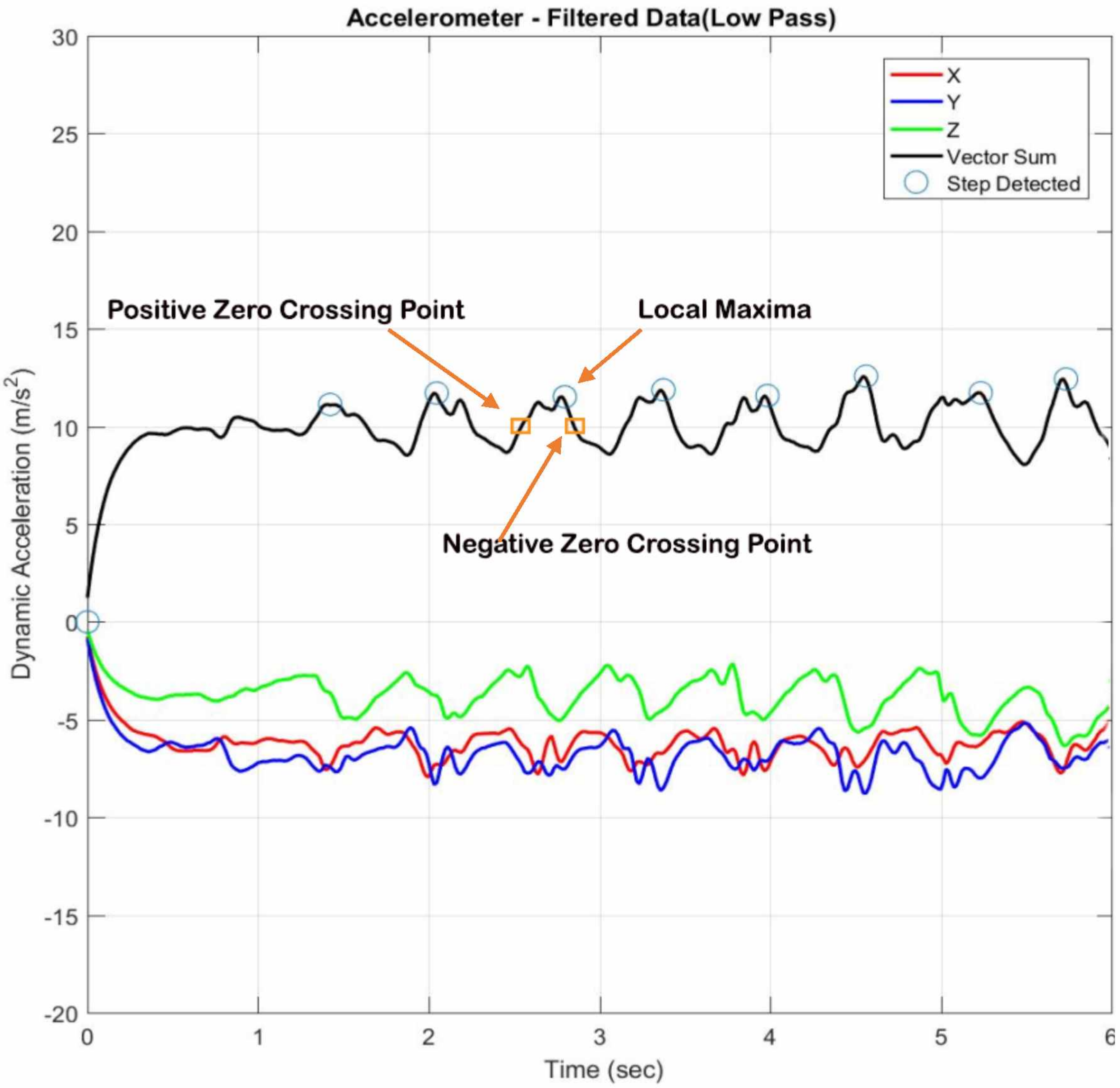


Figure 37: Waist-worn accelerometer output during walking

The first step is detected if the accelerometer's vector sum is above 11 m/s^2. After that, the system starts detecting the vector sum data between positive and negative crossing points (considering 10 m/s^2 as a zero crossing line). Also, the data is stored into a history buffer for finding the local maxima of a peak. Then, the local maxima are compared with a dynamic threshold to determine a step. If the local maximum value is above the threshold, then it's a valid step. Otherwise the step is not valid, and if a step is not detected for more than two seconds, the system automatically resets the threshold and starts looking for the first step again. Furthermore, the dynamic threshold is determined by averaging eight previous consecutive local maxima. Different users have dissimilar impacts while they are walking. By using a dynamic threshold, the system can automatically adjust its step threshold by using the amount of force being exerted on the sensor. By using the step detection method, the health monitoring system continuously monitors the user daily physical activity, and sends feedback to the user.

6.2.4 Stairs Climbing Detection

Walking on a level surface and climbing stairs produce a substantially different impact on vital signs. An accelerometer is unable to determine difference between inclined and uninclined walking. However, the gyroscope produces significantly different output while stair-climbing, as shown in the Figure 38. The system simply uses positive and negative zero crossing points, and relative difference between (positive and negative) local maxima for differentiating between normal steps and stairs climbing.

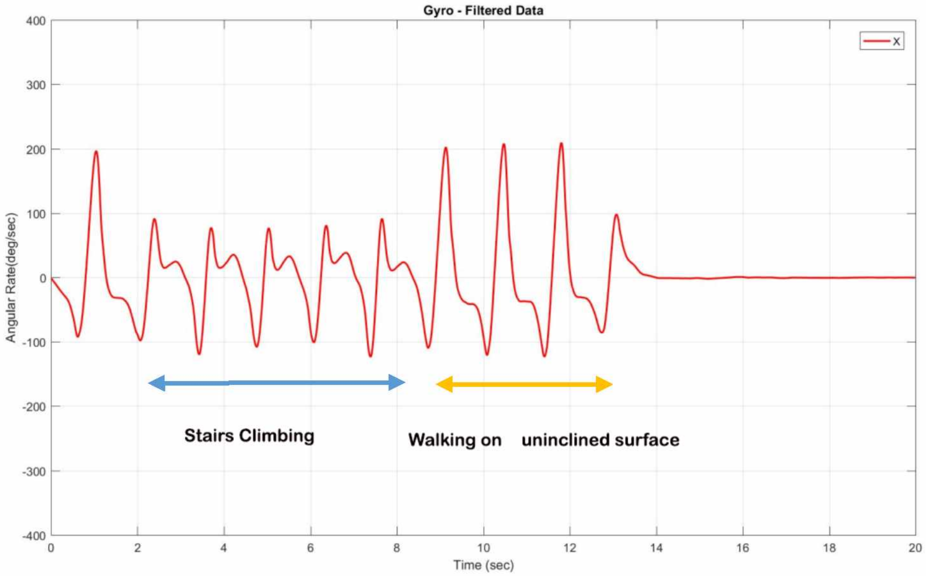


Figure 38: Shank attached gyroscope output while stairs climbing

6.2.5 Jump Rope Exercise

With support of an activity sensor, multiple physical exercise scenarios can be determined as described in previous sections. Rope jumping exercise is one of the exercise scenarios included in the system. The system uses a waist-worn accelerometer for detecting the jump rope exercise events. When the user is doing a jump rope exercise, comparatively heavy impact is applied on the accelerometer and also time spent in the air is much higher compared to normal walking. Hence, the system differentiates jumping and other activities by actively comparing these two scenarios as shown in the Figure 39. The system can be programed to determine even more exercises in the future.

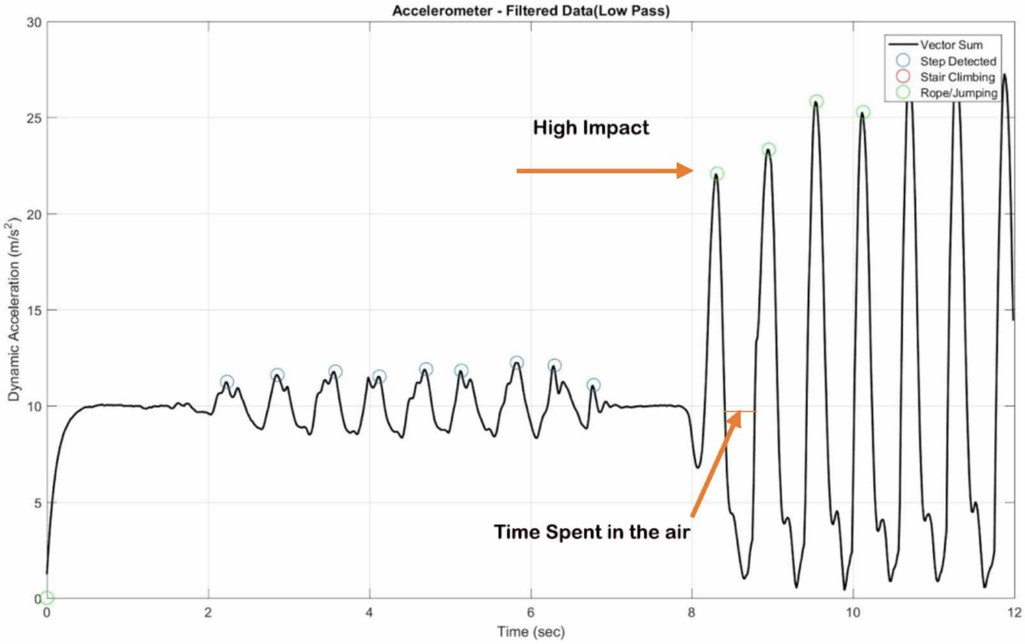


Figure 39: Waist worn accelerometer output difference between walking and rope jump

6.2.6 Detection of Falls

Injuries caused due to falls are most common in elder people and patients with disabilities. Hence, continuously monitoring user's physical status and actively detecting the falls is an advantage to the health monitoring system. Figure 40 shows steps involved in detecting a fall scenario. When a fall occurs, first, the sensors worn by a user experience a free falling motion before hitting the ground. Afterwards, the user hits the ground with a heavy impact as shown in Figure 40. Finally, if the user is seriously hurt, then their activity is minimal or non-existent.

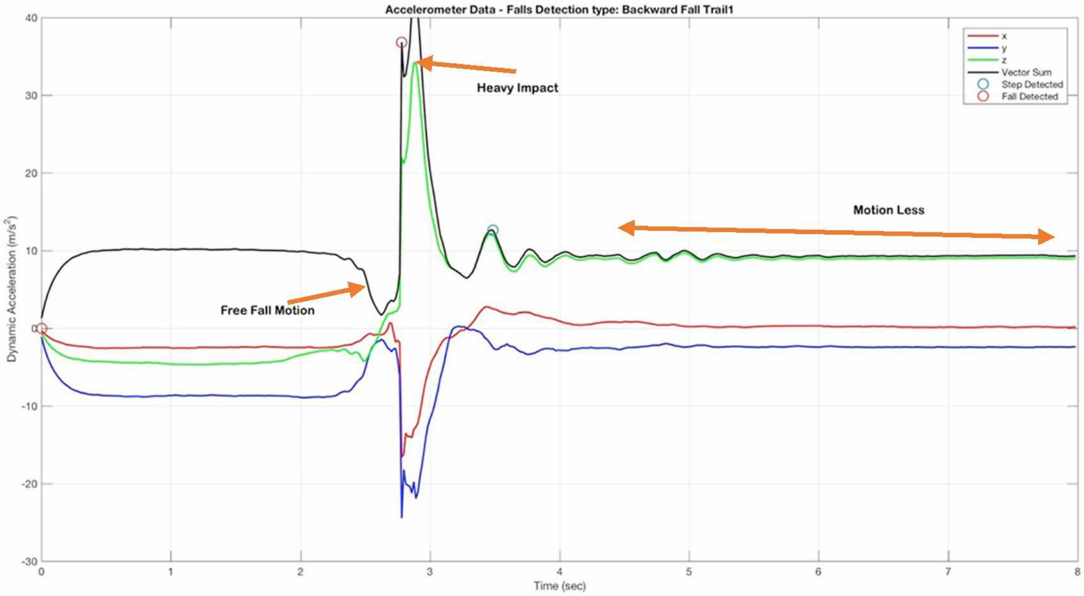


Figure 40: Waist-won accelerometer output during falls

The system uses a waist-worn accelerometer for the detection of falls. In a fall detection scenario, the health monitoring system detects the first stage by calculating the amount of time spent in the air (time for negative zero crossing). After detecting the time that is above the threshold, the system checks if there is any immediate heavy impact exerted on the sensor. If the second condition is true, the system determines the user's body posture, and checks if there is any activity for the next five seconds. If the user is motionless, then the system confirms a fall and sends an immediate alert to the central hub to call for help. The central hub responds by taking a picture from the camera and sends it as an MMS (shown in Figure 54).

6.3 System Synergy

Elders and patients with disabilities have difficulty controlling many home appliances in the same way healthy people can, so it is desirable to automatically adjust the environment based on user's physiological condition and physical environment status. By integrating the health monitoring system and the smart home system, the health care quality is likely to increase. The wearable health system is capable of detecting several physical activities. Also, it detects relative changes in physiological conditions such as heart rate and body temperature. Hence, through system synergy, the smart home system can be improved to advance healthcare by supporting some of the scenarios as described below:

1. The automated home heating appliances can be further implemented to automatically adjust user surrounding environmental conditions based on their activities and physiological conditions. For instance, if the user is actively exercising, the body temperature will likely increase. Hence, by decreasing the home heating levels the system can provide more comfortable environment for the user.
2. A lack of sleep contributes to many health issues. One of the ways to improve sleep efficiency is by changing light colors to create a more comforting sleeping environment [94]. Smart bulbs provide a remote access for adjusting intensity of light along with various changes in colors. By integrating with the health monitoring system, smart bulbs can provide a relaxing environment for sleeping, when the system detects that the user is in a sleeping body posture.

3. As mentioned previously in section 3.3.1, through system synergy the smart home systems can help reduce the damage caused by falls. When the health monitoring system detects a fall scenario, the smart home system can immediately send an alert along with a current picture of the user. In addition to sending an emergency message, the smart home can be further implemented to provide easy access to emergency services by automatically unlocking the doors using currently available smart lock systems.
4. If a person is experiencing mental stress, their heart rate is subjected to abnormal changes [13]. Soothing music has been shown to have relaxing effects on human beings. It slows down our heart rate and lowers blood pressure and thereby decreases the production of stress hormones [95]. When the health monitoring system detects an abnormal heart rate, through system synergy the smart audio/multimedia devices can be implemented to reduce stress levels by automatically playing relaxing music.
5. Most of the elder people and patients are often advised to take their medication regularly. Irregular medication intake can cause abnormalities in physiological conditions. The smart home systems can be implemented to track medication intake of the user by attaching RFID (radio frequency identification) tags or contact switches or motion sensors to a medicine cabinet. By accessing the medication intake data and the data relevant to changes in physiological conditions, distant healthcare professionals can further guide the patients for improving their health.

Chapter 7 Results

7.1 Results of The Wearable Health Monitoring System

7.1.1 Physical Activity Measurements

The wearable health monitoring system was tested by measuring different levels of physical activity, using data processing methods presented in Chapter 6. Initially, the waist-worn accelerometer was used for determining the steps count (refer to Section 6.2.3). The waist-worn accelerometer was only able to measure the force exerted on the body while walking in different phases. The amount of force applied while stair climbing was similar to the force applied while walking on level ground. Hence, the waist worn accelerometer was not able to differentiate between walking on level ground and climbing stairs, as shown in Figure 41.

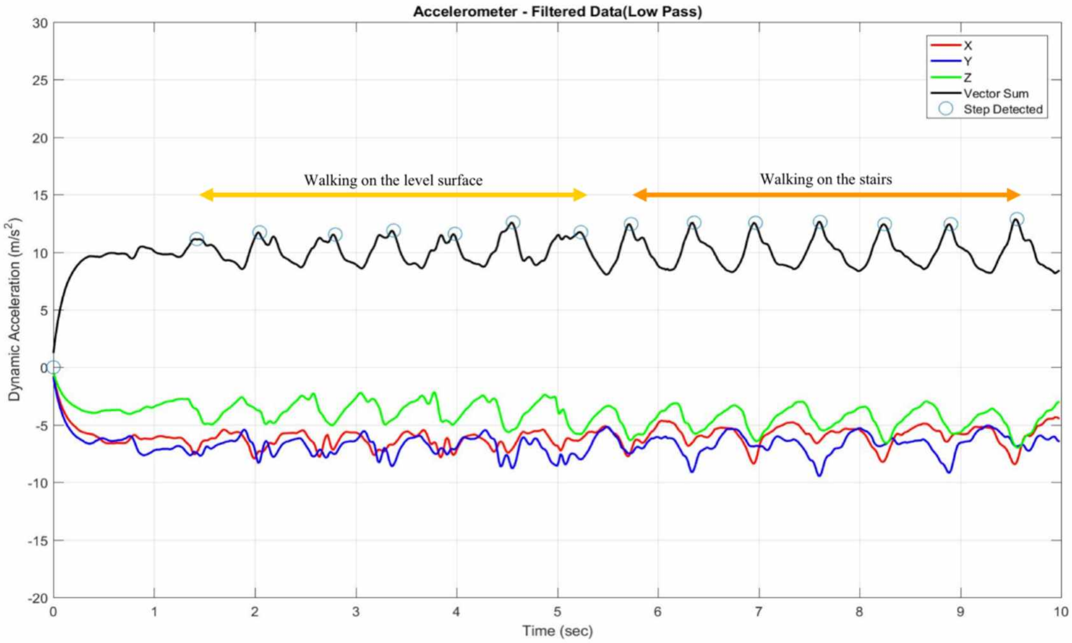


Figure 41: Waist-worn accelerometer output

To try to alleviate that problem, the gyroscope sensor was introduced into the health monitoring system. It was used to measure the angular velocity of the shank. The angular velocity is different for walking on the level surface and stairs climbing. Therefore, the output response from the gyroscope was used in differentiating amongst various styles of walking (stairs and steps). First, the gyroscope was placed on the right thigh, and data was collected to distinguish between steps and stairs climbing. Unfortunately, the results were almost similar for steps and stairs, as shown in Figure 42.

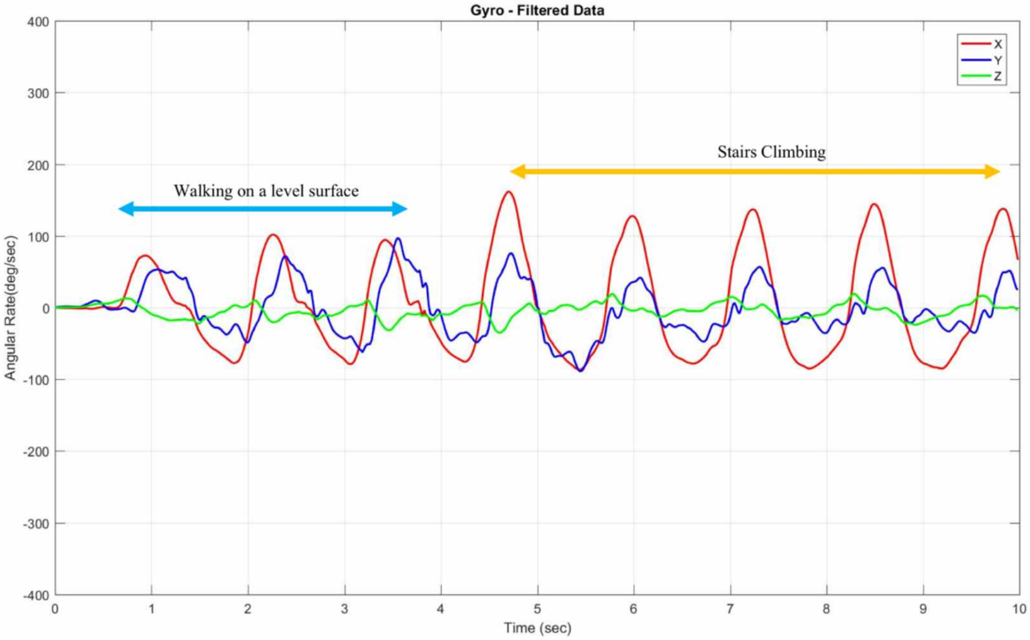


Figure 42: Thigh attached gyroscope output

In the next experiment, the gyroscope was placed at the shank (below the knee) to test sensor's accuracy to differentiate leg movements. Figure 43 shows the results collected from the gyroscope sensor attached to the shank. By using methods discussed in section 6.2.4, the system was able to determine stairs climbing scenarios. Furthermore, the gyroscope sensor reading was collected at different speeds as shown in Figure 44. The data demonstrated that, even for variable walking speeds, the relative difference between the positive and negative peaks of the sensor readings were consistently different for walking on the ground level and climbing stairs. This difference was used to determine that the user is climbing stairs.

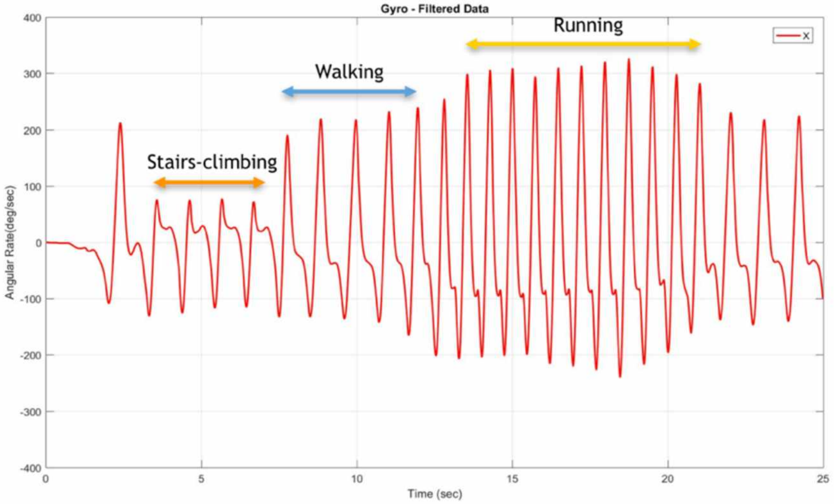


Figure 43: Shank attached gyroscope output

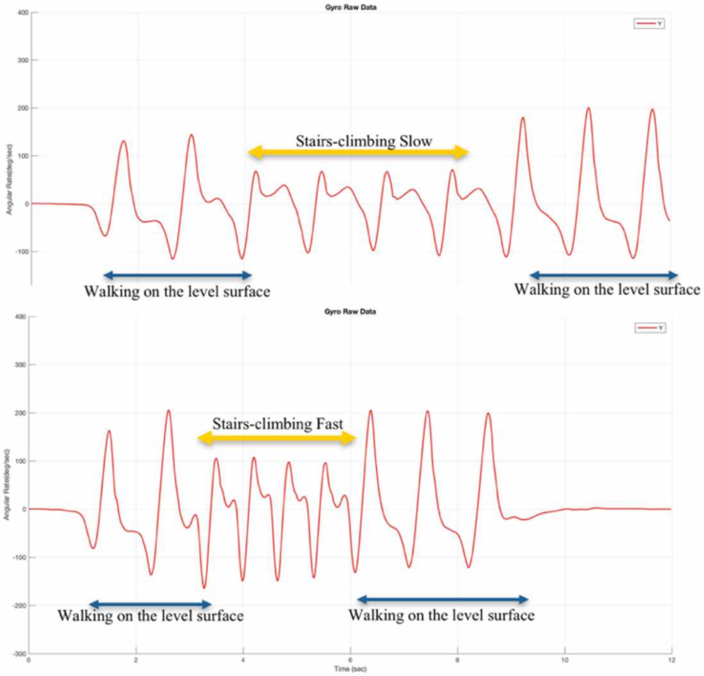


Figure 44: Shank attached gyroscope output

Using sensor synergy between the waist-worn accelerometer and shank-attached gyroscope, the health monitoring system was able to automatically distinguish between steps and stairs climbing, as shown in Figure 45. Furthermore, the system was tested on multiple users, to evaluate the system's adaptability and reliability in collecting the data, and its ability to accurately process the data to extract the required features. Data was collected from five users with ages ranging between 23 and 28. Every user walked 400 steps and climbed 50 or 70 stairs, while wearing the health monitoring prototype system, a Fitbit, and a smartphone, to compare the accuracy. Table 5 and Table 6 show the results obtained from multiple users. The preliminary results revealed that the health monitoring system was 99.9 percent accurate in determining the steps, whereas it achieved a 98.1 percent efficiency in detecting stairs climbing. The synergistic system outperformed the traditional step detecting devices (smartphone and Fitbit).

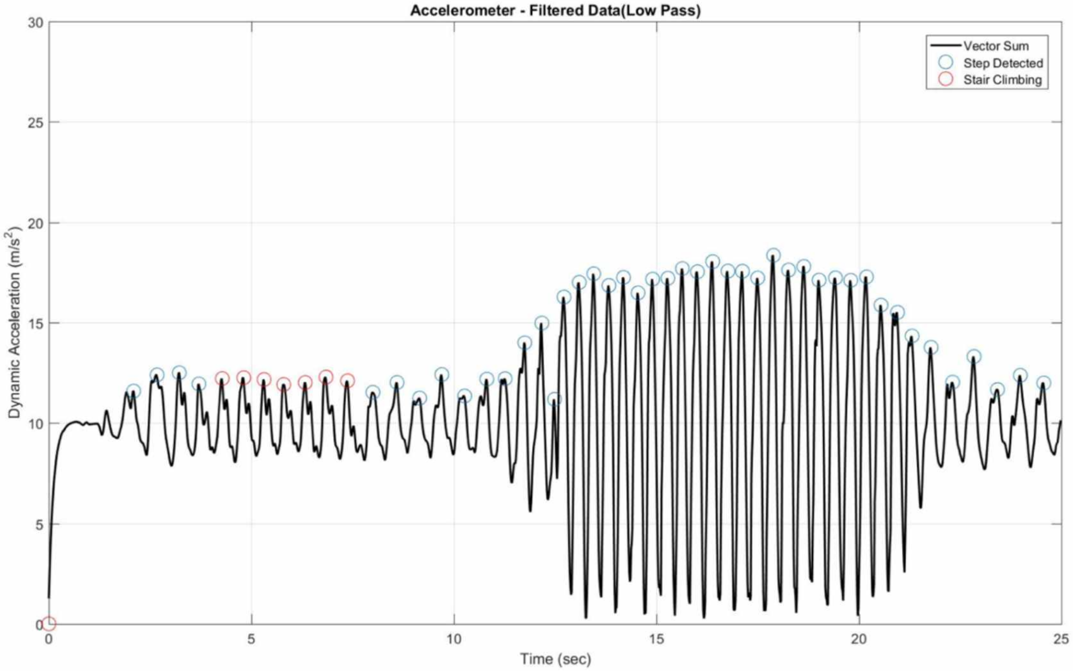


Figure 45: System's ability to differentiate between steps and stairs climbing

Table 5: Step count comparison

User	Actual Count	Wrist-worn Fitbit	Smartphone	Proposed System
A	400	372	382	398
B	400	378	400	401
C	400	400	354	400
D	400	386	384	400
E	400	398	400	400
	Efficiency:	96.7%	96%	99.9%

Table 6: Stairs climbing comparison

User	Actual Count	Wrist-worn Fitbit	Smartphone	Proposed System
		N/A: Not supported		
A	70	N/A	N/A	66
B	50	N/A	N/A	52
C	50	N/A	N/A	54
D	50	N/A	N/A	49
E	50	N/A	N/A	50
	Efficiency:			98.1%

Figure 46 shows different physical activities (as discussed in Chapter 6) such as steps, stairs climbing, and rope jumping, detected by the system. In the past, researchers conducted several experiments to determine the energy expenditure based on accelerometer step count. Some activity calorie determining studies are listed in [96]. By adopting an energy expenditure [97] equation as shown in equation (6) and (7), the current system can ascertain the amount of calories burned. This can help the user to maintain their daily physical activity levels. The adopted energy expenditure equation was formulated based on a given body mass index (BMI), stride length (SL), and steps count per minute. However, for this thesis, the structure of the equation is adjusted as represented by Equation (6), (7) and (8).

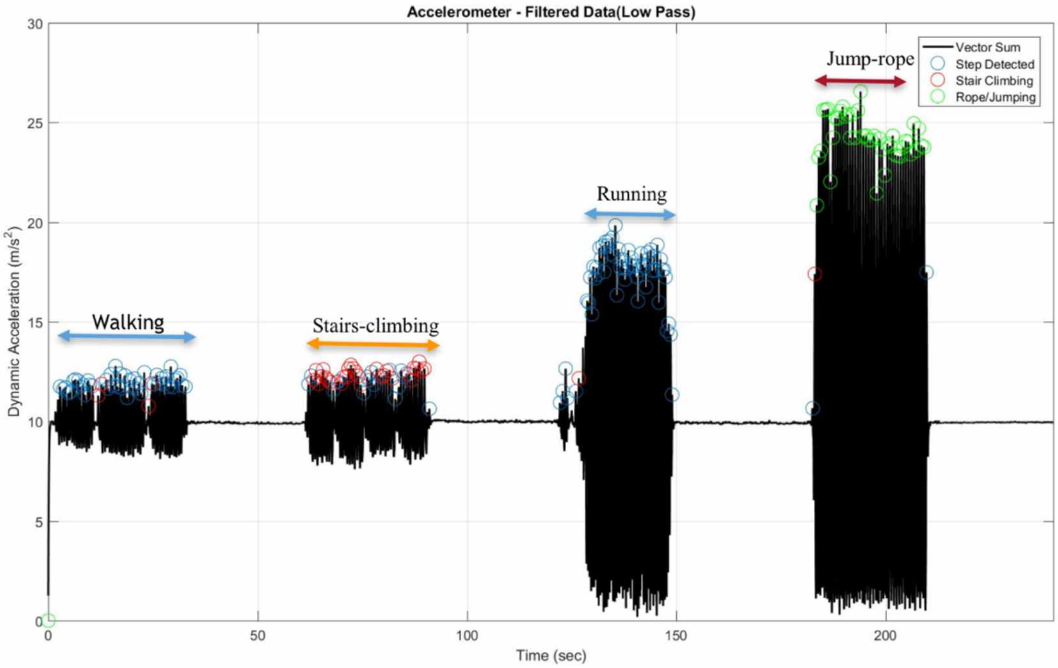


Figure 46: Sensor output from the wearable health monitoring system

$$Males: 1.637 + (0.116 * BMI) + SL * AF + (0.002 * \mathrm{BMI} * \mathrm{AF}) \tag{6}$$

$$Females: 0.542 + (0.116 * BMI) + SL * AF + (0.002 * BMI * AF) \tag{7}$$

$$AF = C_1 * SPM + C_2 * CPM + C_3 * JPM \tag{8}$$

Where,

AF = Frequency of activity

SPM = Steps per minute

CPM = Climbing stairs per minute

JPM = Jump-rope per minute

C_1, C_2, and C_3 = Constants

In Equation (8), the health monitoring system was able to determine activity variables such as (SPM, CPM, and JPM). Further studies are required to accurately determine the constants C_1, C_2, and C_3.

7.1.2 Fall Detection Measurements

Falls are detected using the accelerometer sensor data as discussed in section 6.2.6. Series of tests were conducted on multiple users to analyze the system's ability to determine falls. The accuracy was tested by evaluating the criteria for sensitivity (Equation (9)) [6] and specificity (Equation (10)) [6], where sensitivity is the ability to detect fall, while specificity refers to system's ability to only detect fall scenarios.

$$Sensitivity = \frac{TP}{TP + FN} \tag{9}$$

$$Specificity = \frac{TN}{TN + FP} \tag{10}$$

Where,

True Positive (TP): a fall occurs, the system senses it

False negative (FN): a fall occurs, but the device does not sense it

True negative (TN): a normal movement is performed, the device does not announce a fall

False Positive (FP): the device declares a fall, but it did not occur

Table 7: Fall detection comparison

Category	Trial Count	Detected by the System
Forward Fall	24	23
Backward Fall	24	24
Lateral Fall	30	30
	Sensitivity:	98.7%

Table 7 shows the data that was collected from 8 different users. The preliminary experiments were conducted in a safe environment to avoid any injuries during falls. All of the users were asked to conduct different fall scenarios such as forward fall, backward fall, and lateral fall (left or right). Each user repeated the given fall scenario for at least three times, and in the end, they were asked to conduct some neutral activities such as walking, sitting and standing, lying flat on the bed and rising, or picking up some object from the ground. One of the users performed yoga (sun salutation), which consisted of several random body movements as shown in Figure 47, but none of the random movements were detected as a fall. As shown in Table 7, the collected data shows system's sensitivity of 98.7 percent. Whereas, the system achieved a fall detection specificity of 100 percent with zero false positives.

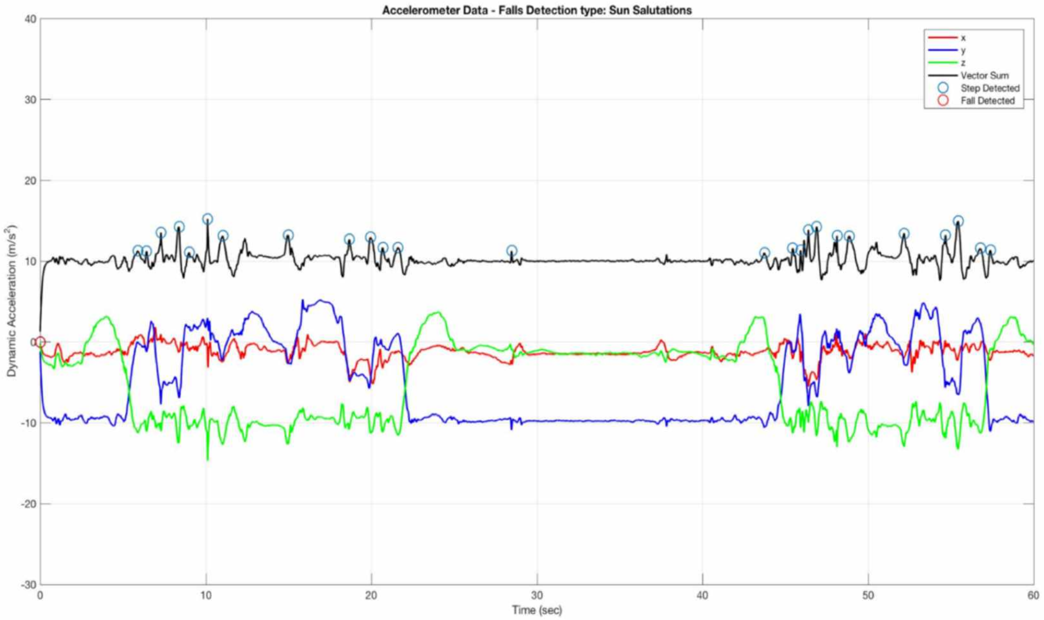


Figure 47: Waist-worn accelerometer output during sun salutations

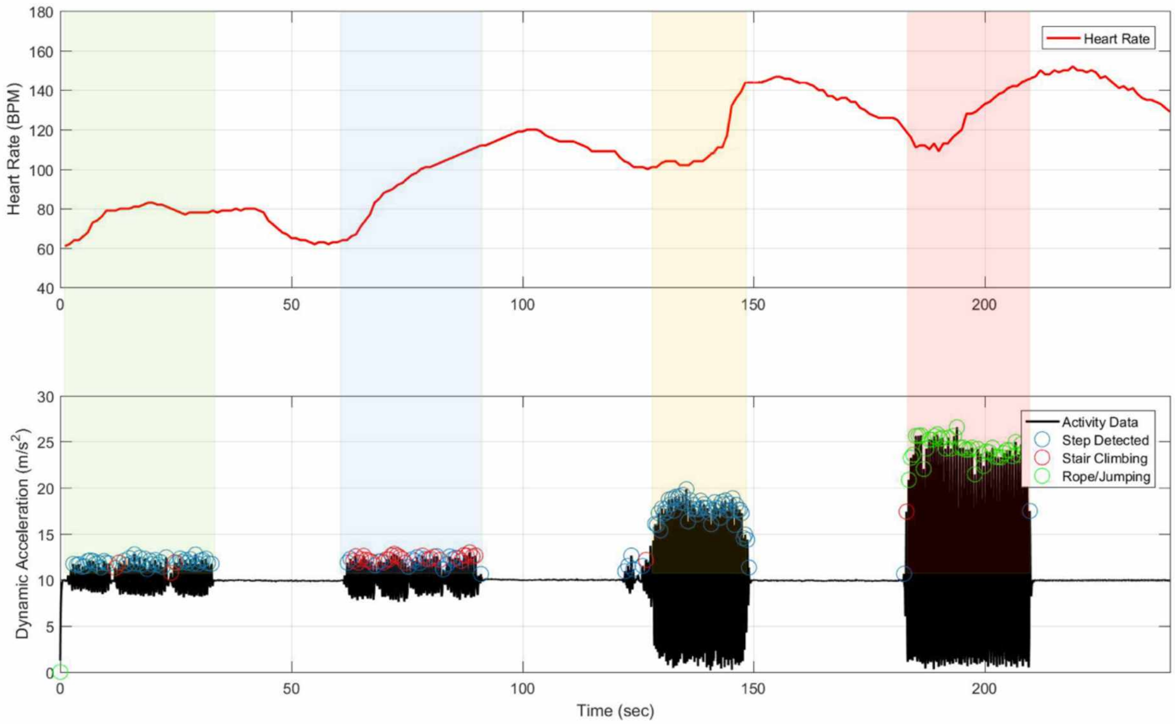


Figure 48: Changes in heart rate data with various physical activities

7.1.3 Physiological Sensor Data Collection

For observing the modulations in vital signs, the physiological parameters were compared with the physical activity levels. As shown in Figure 48, the heart rate was increased depending on the physical activity type. As observed from the figure, the heart rate variations started with a delay after the commencement of physical activity. Also, the heart rate took some random time to settle down.

Furthermore, the physiological data was collected for extended periods of time. As shown in Figure 49, the heart rate and body temperature were collected while a user was exercising on a treadmill. Each user was at rest for the first 2 minutes, for the next 2 minutes the user walked at 2 MPH speed. After that, jogging for another 2 minutes at 4 MPH speed. Next, the speed was further increased to 6 MPH for the next 2 minutes. After actively running (at 6 MPH), the speed was decreased in steps of 2 MPH at each 2-minute window.

Figure 49 shows the rise and fall of the heat rate with increase and decrease in the activity levels, respectively. Unfortunately, the temperature data was not reliable as the system was not reporting accurate body temperatures. In fact, the temperature sensor used in this prototype reports relative changes in the body environment temperature, and would need to be replaced by a medical grade body core temperature sensor. The preliminary results show the sensors outputs with different activity levels.

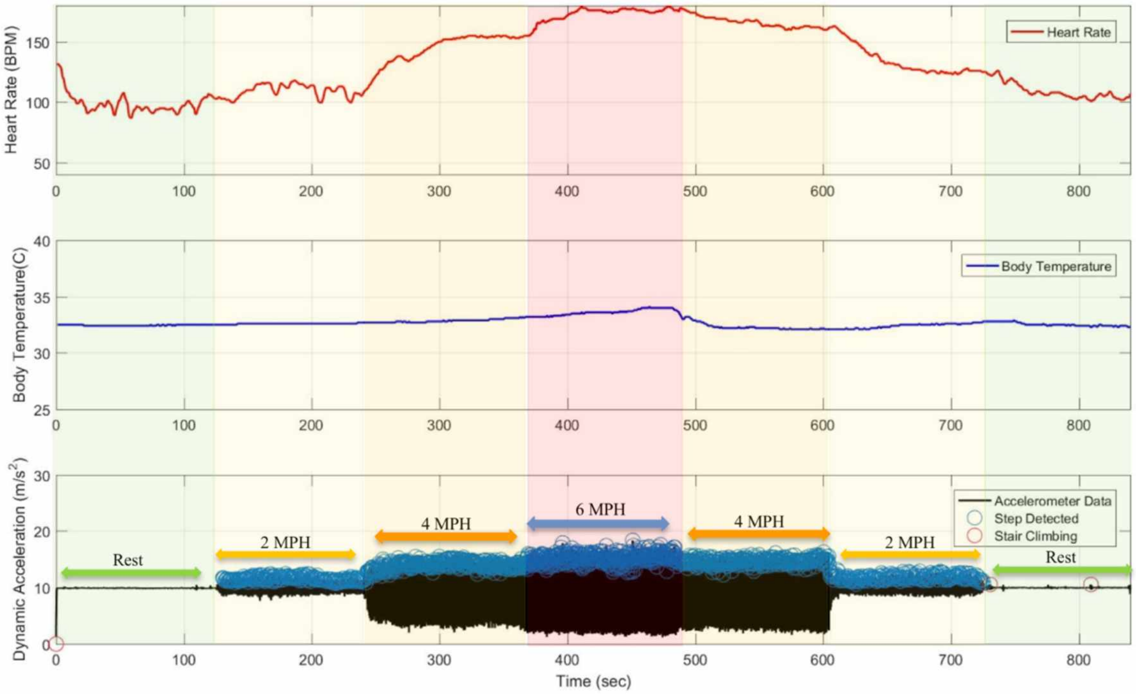


Figure 49: Vital sign modulations compared to level of activity

The changes in physiological conditions (heart rate) were tested on multiple users. Furthermore, the heart rate modulations were tested on people with various physical fitness levels. Hence, the users were selected based on their physical fitness. All the users were given the same instructions (same routine as represented in Figure 48) and the results were taken on the same treadmill with similar environmental conditions. Figure 50 presents the heart rate modulations for multiple users. It is observed that heart rate modulations are comparatively extreme for the users who are physically less active. Also, their heart rate settling time was moderately high when compared with the physically active user (an athlete).

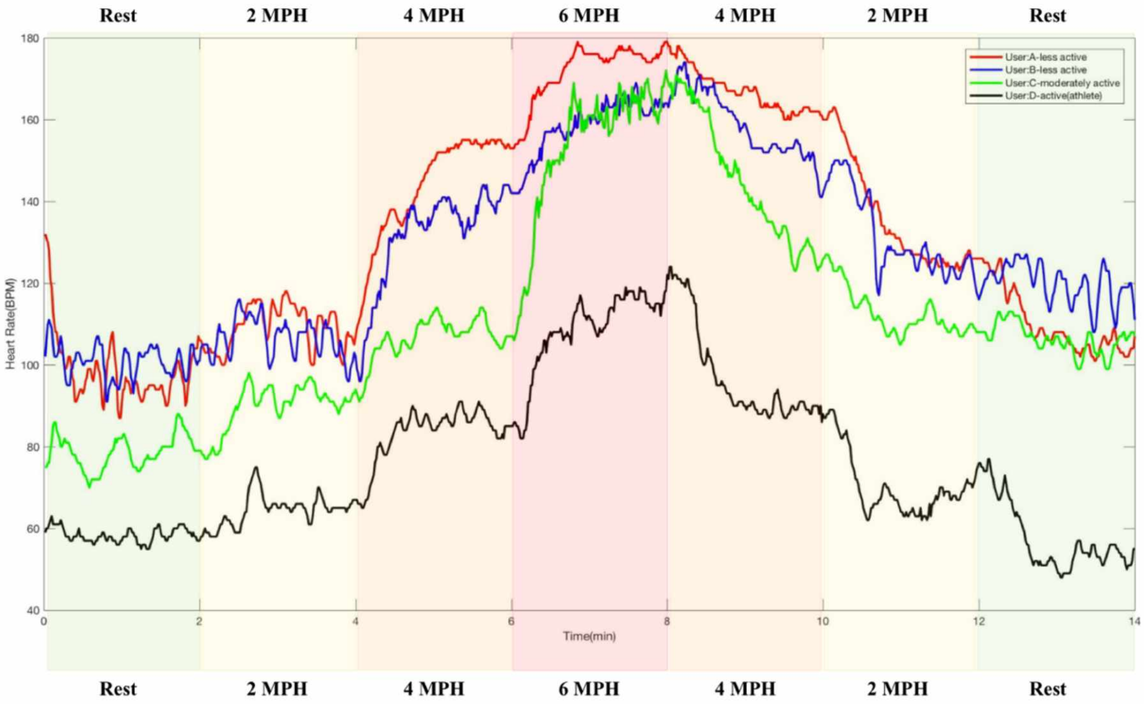


Figure 50: Comparison of heart rate variability for different users

From the results obtained in Figure 50, it is also observed that under similar physical activity levels different users might have different physiological modulations. The reasons affecting this variability are dependent on multiple factors such as age, gender, height, weight, and physical fitness. If the system is designed to alert the caregivers based on static threshold limits, this could result in the system detecting false positives or failing to detect real emergency situations. To reduce these false alarms, a system learning technique was added to the wearable health monitoring system. The idea of system learning technique is to reduce false alarms and increase efficiency. Initially, the system requires user specific training to adjust its vital sign threshold limits accordingly. After the training phase, the system automatically detects any abnormalities related to the vital signs and physical activities.

During the training period, the system's goal is to collect vital sign data while the user is performing predetermined physical activities, such as laying down, sitting, walking at different speeds, stairs climbing, and rope jumping, then storing the associated physiological data (minimum and maximum) in the flash memory. After that, the system actively compares the newly collected to these thresholds, too determine if the user's vital sign readings are within a safe range.

For this prototype system, in order to prove the system learning concept, the training phase was simplified to store maximum values of the vital signs while the user was at rest, and during physical activity. After storing these two parameters in flash memory, the system continues to detect any possible emergencies or abnormal conditions, such as mental stress, or extreme physical exercise scenarios that a patient was not allowed to perform. If the system detects any emergencies, it sends a message to the central hub (refer to section 3.3), which will send alerts to distant caregivers.

7.2 System Synergy Results

Possible system synergy between the wearable health monitoring system and the smart home system is discussed in Chapter 6.3, whereas Table 8 lists the discussed synergy scenarios. Also, some of the synergy scenarios were developed using the prototype systems. The health monitoring system was detecting the different body posture (refer to section 6.2.1), and the smart home was adjusted to alter the smart LED color according to the changes in user's body posture. As shown in Figure 51 and Figure 52, the smart home system automatically illuminated a green LED while the user was in sitting position, and while laying down the color was automatically changed to yellow. The smart home system receives commands from the health monitoring system (through a central hub; refer to section 5.5) about user's current posture and acts accordingly. For example, as shown in Figure 53, the smart home might illuminate a different color and display a message to instruct the user to changing their posture. In this example, the goal of the system was to help the user avoid crossing their legs while sitting.

Table 8: List of synergy scenarios for the proposed system

Wearable Health Monitoring System Output	**Corresponding Smart Home System Response**
User active, rise in body temperature	Automatically reduce home environmental heating
Sleeping body posture	Reduce light intensity using smart bulbs, and change colors allowing comfortable sleeping
Detected a fall scenario	Take a picture, send emergency alert, and unlock doors using smart locking system
Heart rate abnormal => Stress	Automatically play soothing music using smart audio devices
If monitoring Elder/Patient	Monitor diet, calorie consumption, and medication intake

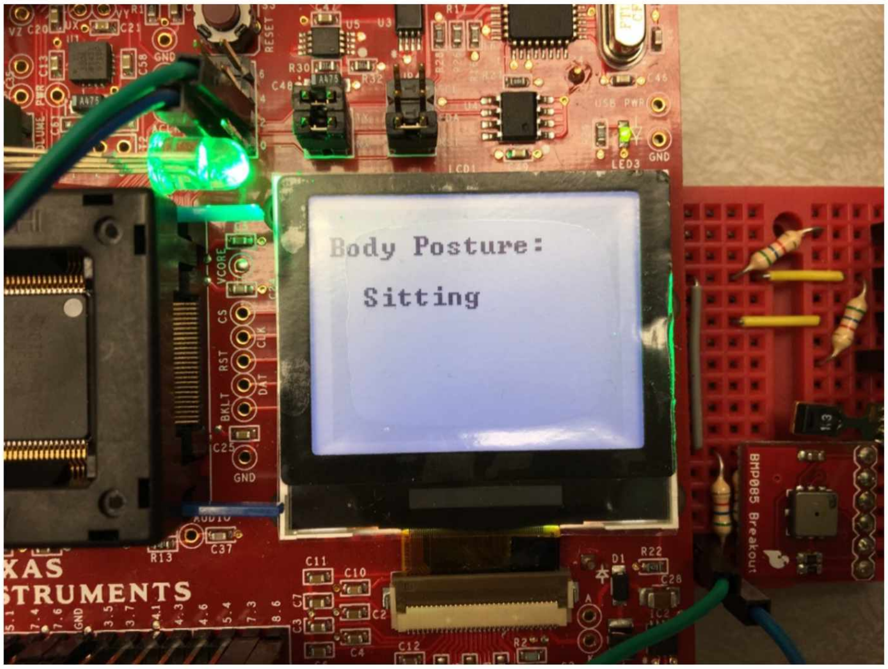


Figure 51: Smart response for body posture – sitting

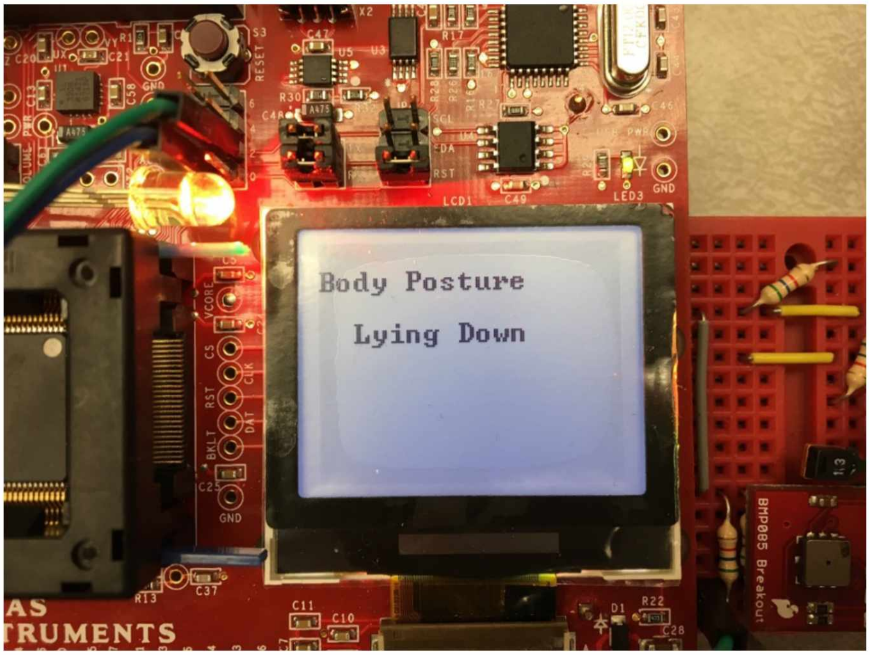


Figure 52: Smart response for body posture – lying down

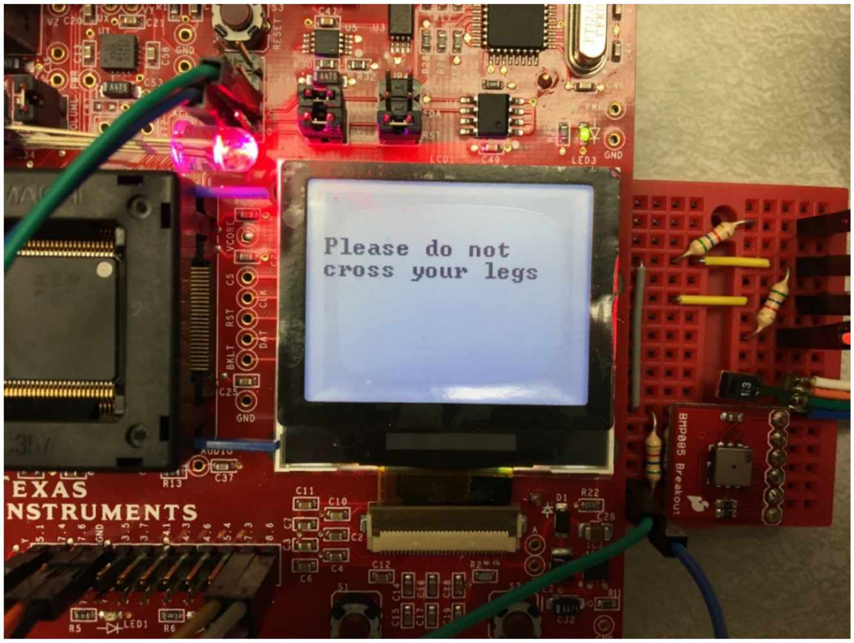
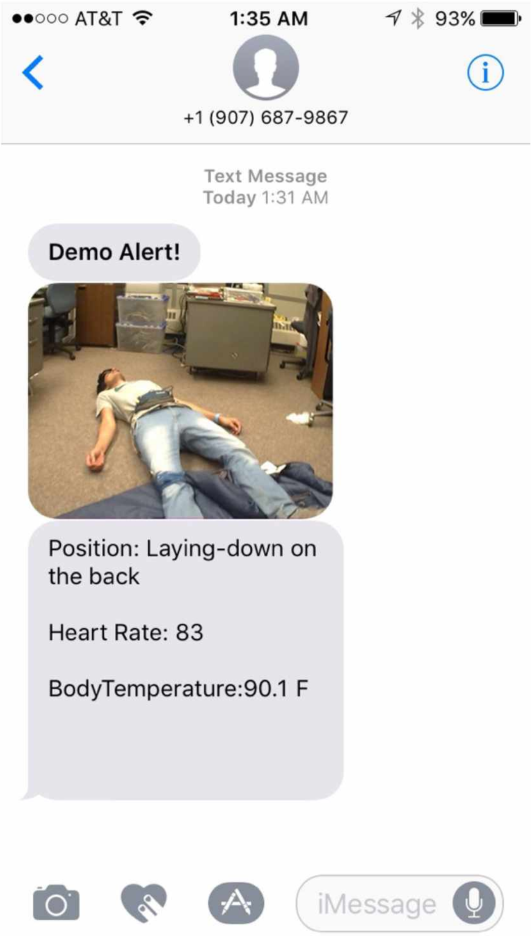


Figure 53: Smart response for body posture – crossing legs while sitting

On the other hand, if a fall scenario was detected by the wearable health monitoring system, it would send an emergency packet to the central hub to report a possible threat to the user (as described in section 6.2.6). In this scenario, the central hub responded by taking a picture using the JPEG color camera and forwarding an MMS through the 3G cellular module. The alert includes a current picture of the user, along with his current body posture and physiological conditions as shown in Figure 54. Further testing and implementation are required to fully integrate the proposed heterogeneous systems by exploiting all available system synergy techniques.



Text Message
Today 1:31 AM

Demo Alert!

Position: Laying-down on the back

Heart Rate: 83

BodyTemperature:90.1 F

Figure 54: Screenshot of the emergency (demo) alert sent from the central hub system

Chapter 8 Conclusion and Future Work

The health monitoring systems delivers low-cost alternatives to in-home monitoring and recovery-assist medical applications, while providing more personal health care services. A synergistic wearable health monitoring system is developed to continuously monitor physiological conditions and physical activity levels of the elderly/patients at home. The developed system uses sensor synergy and system learning techniques for physiological data collection and processing. Data collected from the system shows that the proposed method is accurate enough for a successful use in health care applications (as discussed in section 7.1). On the other hand, the smart home systems are becoming more and more prominent in delivering comfortable and secure living environments through advanced smart home appliances and controls. Hence, by integrating the health monitoring system with an intelligent home system, the home can be more user-friendly, which further comforts the users trying to improve their health condition.

Therefore, the health care system further benefits from the integration with the smart home system. Through synergistic approach enabled by that integration, the home environment can be controlled to be more user-friendly and to encourage a healthy lifestyle for the patient. Moreover, by exploiting synergy between various physiological sensors, the number of false alarms is reduced, and more useful data (regarding the user) is provided to the health care services.

However, even though the health monitoring system's primary intended goal was to actively monitor the elderly or patients who are going through rehabilitation, the system was so far primarily tested on users of ages between 23 and 28. In the future, the system should be tested on its intended end users (elderly). In addition, a number of additional biomedical sensors can be added to the current system, so that it can be used in different other medical applications. The system supports multiple communication interfaces such as I2C, SPI, UART, and analog, therefore covering practically all currently available sensors on the market. Also, the web page can be further developed to provide a two-way web communication channel between the healthcare system and a remote caregiver.

Furthermore, the power efficiency and performance of the health monitoring system can be further improved by using the techniques that are developed (as part of other projects) at UAF. Using dynamic voltage and frequency scaling methods [98], the system can be adjusted to deliver more performance when the user is in an emergency scenario, and more energy can be saved (to increase battery life) when the user is at rest. In addition, using the sliding window time synchronization techniques [99], the health monitoring system can maintain synchronization with the smart home network without losing any valuable information even if the user is moving around between different surrounding temperatures such as indoor and outdoor (especially in Alaska). Moreover, using a well defined MAC protocol that is specially designed to integrate with several home appliances [21], the wearable health monitoring system can more easily integrate with the smart home system for producing improved medical results.

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