A WEARABLE SENSOR JACKET AND ENABLING TECHNOLOGIES
FOR A TELEMEDICINE SYSTEM

by

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M.A.Sc., The University of British Columbia, 2013

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Mechanical Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

October 2014

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Abstract

Telemedicine will alleviate the pressure on healthcare systems by reducing avoidable hospital visits and providing a service that can directly address the specific needs of patients, notably of the elderly and the disabled. Unlike the current healthcare services, which primarily focus on treatment of illness in a centralized manner, a telemedicine system has the promise of distributing the medical consultation, which can provide rapid and convenient healthcare particularly for under-served rural communities. This thesis develops enabling technologies for a convenient and wireless telemedicine system. The system uses a multi-sensor jacket, which a patient wears for acquiring the vital information that a medical professional would need to make accurate diagnosis of common illness. In the system that is developed in the present thesis, the sensor jacket will automatically inflate in a conformable manner when the patient wears it. The sensors are properly located to acquire the vital data. The acquired signals are wirelessly transmitted to a local computer for processing, and transmitting to the medical professional through a public communication network. A wireless telemedicine system relies more on the bandwidth of the communication network than a wired system does. Hence, size reduction of the data stream is important. This thesis proposes a new method to reduce the size of an ECG signal, for example, by determining the key attributes of the signal. The key attributes are transmitted instead of the entire ECG waveform. Then the proposed method regenerates a representative ECG waveform at the doctor’s end using the transmitted attributes. Illustrative examples show that the method is quite accurate and effective in medical diagnosis. For better mobility and easier access of the communication network, the patient end application primarily runs on a mobile device such as an iPhone. The patient end application provides live video and audio interaction between the doctor and the patient. During an active video session, the system streams vital data to the doctor in real-time. Besides receiving, storing and displaying the vital data of the patient, the doctor end can use the video conference feature to discuss the medical condition with other medical professionals.
Preface

The contributions presented in Chapter 2 and Chapter 3 have been published in journals, as follows:


For these two papers, Dr. Clarence de Silva provided the concepts and the methodologies, and supervised and guided the overall project. I implemented the methodologies in the computer and in hardware, conducted testing, acquired data, and performed processing. Dr. Maoqing Li provided experimental facilities for system testing and some advice. Dr. Cheryl de Silva provided advice on representation and interpretation of the acquired signals, and performed diagnosis based on the transmitted results.
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Acknowledgements

It would not have been possible to perform the work presented in this thesis without the help and support of my research supervisor, Prof. Clarence de Silva. I would like to express my deepest gratitude to him for spending time and effort to guide me in both academic matters and in life.

I wish to thank the members of my Supervisory Committee, Prof. Farrokh Sassani of UBC Department of Mechanical Engineering and Dr. Cheryl de Silva of Staten Island University Hospital, NY.

I am grateful to the current and past members of the Industrial Automation Lab for creating a home away from home in the laboratory environment.

I would like to thank my parents, who have always encouraged and supported me in my endeavors, without whose sacrifices I would not be where I am.

Special thanks are owed to my beloved wife Xiaoyue. She was always there cheering me up and stood by me through good times and the bad.

This research project has been supported in part by the 985 Program of Xiamen University: Construction and Data analysis of Telemedicine System, and by research grants from the Natural Sciences and Engineering Research Council (NSERC) of Canada, the Canada Foundation for Innovation (CFI), the British Columbia Knowledge Development Fund (BCKDF), and the Canada Research Chair in Mechatronics and Industrial Automation, held by Prof. C.W. de Silva.
Chapter 1: Introduction

During the past decade the advances of sensor technologies, wireless and mobile networking, digital signal processing (DSP), and cloud computing have radically changed the prospects providing healthcare from distance through telemedicine. Unlike the current healthcare services, which primarily focus on treatment of illness in a centralized manner and are concentrated in urban areas, telemedicine will be able to provide healthcare in a distributed manner, conveniently and rapidly, without needing the patient to travel to central healthcare facilities. The tremendous development and wide use of wireless communication and information technologies enable the access to high quality medical services from distance, notably in rural areas. Telemedicine will alleviate the pressure on healthcare systems by reducing avoidable hospital visits and by providing a service that can directly address the specific needs of elderly and disabled patients.

This thesis develops enabling technologies for a convenient and wireless telemedicine system. The system uses a multi-sensor jacket, which a patient wears for acquiring the vital information that a medical professional would need to make accurate diagnosis of common illness. In the system that is developed in the present thesis, the sensor jacket will automatically inflate conformably when the patient wears it. The sensors are properly located to acquire the vital data. The acquired signals are wirelessly transmitted to a local computer for processing and transmitting to the medical professional through a public communication network. The patient end application provides live video and audio interaction between the doctor and the patient. In this manner, the doctor will be able to receive vital data on the patient that is necessary in order to make an accurate diagnosis and prescription [1].

1.1 Background

With improvements of healthcare in the past few decades, more people are able to receive high quality health services. The existing healthcare systems face tremendous challenges, however. Increase in population and the percentage of the senior citizens with considerable demands of healthcare is one challenge. More people choose to live in rural areas, which provide better employment and services. As shown in Figure 1.1, in China alone,
approximately 49% of the population lives in rural areas (in 2012). But only 13% of hospitals are located in the rural area [2]. In terms of the density of healthcare, this represents an even greater deficiency of healthcare, which is another challenge. In view of the poor transportation services and road infrastructure, travel to centralized healthcare facilities is also a significant challenge in rural areas.

![Image showing hospital and population distribution](image)

**Figure 1.1: Urban and rural Hospital distribution (left); Urban and rural Population distribution (Right).**

At present, almost 50% of individuals over the age of 65 suffer from at least one chronic condition in China [3]. Individuals living with chronic conditions such as heart disease, stroke, Chronic Obstructive Pulmonary Disease (COPD) and diabetes account for a disproportionate demand for healthcare facilities as they require frequent visits to a clinical center. Table 1 shown the comparison of people cared by hospital and the total population), This problem is further complicated by a projected shortage of health services. According to the Association of American Medical Colleges, there will be a shortage of 150,000 doctors in USA by the year 2025 [4]. Also, a significant disparity exists between the quality of healthcare available in rural and urban areas. As a result, patients from rural areas often have to travel long distances to reach clinical centers in cities to get proper care. There is an urgent need to develop new patient management approaches to ensure appropriate monitoring and treatment.
1.2 Technological Trends

Remote health diagnosis has been proposed as a potential solution to some of the healthcare challenges. With proper disease management and regular health monitoring, many patients with chronic conditions can avoid serious complications and live a long and active life. In recent large-scale studies [5, 6], remote health monitoring has been shown to be effective in helping patients better manage their chronic conditions, leading to significant reduction in re-hospitalizations and the overall cost of care. Remote health monitoring can also enable clinicians expand the range over which they can provide care by allowing them to monitor and treat patients who are located in remote areas.

For patients living with chronic conditions, regular remote assessment of their health parameters can lead to early diagnosis of detrimental trends and enable the clinicians to take preventative measures. Remote health monitoring can also play an important role in patient education, especially after discharge from an acute care setting, which has been shown to reduce the rates of re-hospitalization. Periodic monitoring of health can also provide feedback about the efficacy of treatment, which can be used by clinicians to deliver treatment interventions on an individual basis in an effective manner, making medical care to be more personalized [7].
1.3 Objective
The objective of the present thesis is to develop and evaluate some key enabling technologies for a telemedicine system. The developed system focuses on obtaining vital information from a patient from their local setting using wearable sensors jacket, and processing and transmitting key medical data to a medical professional at distance for effective diagnosis and prescription [1]. With the developed system, the patient is able to receive real-time healthcare without having to leave their living environment. The system has no key restrictions on the location of the patient. In particular, the patient will be able to receive healthcare from virtually anywhere as long as the sensor jacket and a public communication network are available. The wearable sensor jacket will collect the medical signals from the patient and send the processed vital information to the doctor at the hospital through a telemedicine server. Using the proposed system, a doctor is able to obtain medical data, while maintaining a video and audio link with the patient, to facilitate health monitoring and diagnosis.

1.4 Outline
This thesis is organized as follows:

Chapter 2, System Architecture, presents the system framework and architecture of the proposed telemedicine system. Also it provides examples of important aspects of signal processing related to the data monitored from a patient.

Chapter 3, Multi-sensor Jacket, presents the development of a wearable sensor jacket, which is easy to use and robust, for acquiring vital data from a patient.

Chapter 4, System Software and User Interface, presents mobile and personal computer (PC) applications for the telemedicine system that is developed in the present thesis. It facilitates live audio and video interactions between the patient and the doctor. During an active session, the wearable sensor jacket streams vital data that is acquired by it to the doctor, after processing.
Chapter 5, Conclusions, summarizes the key contributions of the thesis and proposes possible future work.
Chapter 2: System Architecture

This chapter presents the system framework and architecture of the proposed telemedicine system. Also it provides examples of important aspects of signal processing as related to the data monitored from a patient. ECG or EKG (electrocardiogram) signals and stethoscope signals are analyzed in particular.

2.1 Overall Telemedicine System

Using the telemedicine that is developed in the present thesis, a doctor is able to interact with a patient at distance, via live audio and video communication. Simultaneously, the sensor jacket that is worn by the patient will provide vital medical data of the patient. The data may be processed locally to extract key information that is needed by the doctor before transmitting the information to the doctor. In this manner, the doctor will be able to carry out medical diagnosis and make necessary prescription. If necessary, the doctor may consult with other professionals, on line, and may also use other available resources in arriving at the diagnosis and prescription. A schematic diagram of the proposed system is shown in Figure 2.1 [1].
Using integrated mechatronic methodologies [8], we will design and develop a wearable jacket with an embedded and distributed suite of sensors to monitor vital signs (e.g., temperature, heart rate, respiration rate, acoustic cues, blood pressure, electrocardiogram or ECG, blood oxygen level).

Before transmitting the vital signals from the patient to the doctor’s local interface, the embedded sensory hardware and the host computer at the patient’s local interface will process the data as appropriate. In particular, the processing will remove noise in the data through proper filtering, and also amplify it. In addition, high-level processing may be carried out for such needs as trend detection, compression, and extraction key information and attributes that may be needed by a doctor for effective diagnosis and prescription. The
processed information will be transmitted to the doctor in a medical facility at distance, in real time. At the doctor’s end, the transmitted information will be presented using a convenient graphical user interface (GUI) on a clinical computer. Through the GUI the doctor is able to conveniently communicate with the patient through a video-audio link. By using a high-definition video and audio capturing device, the doctor will be able to obtain from the patient additional information such as visual cues from throat, skin, and eyes; unnatural audible sounds; and verbal responses to questions from the doctor. Simultaneously, the doctor will examine the patient data (including information transmitted by the monitoring system), and will perform medical assessment, diagnosis, and prescription. The doctor may consult with other medical professionals in office or on line, and may also use other available resources in arriving at the diagnosis and prescription.

The proposed telemedicine system will incorporate a wearable outfit with embedded sensors. An overview of the system hardware is shown in Figure 2.2. A basic set of sensors that is incorporated in the sensor suite is indicated in the figure. Sensory data together with real-time visual and acoustic cues from the sensor suite will be filtered, amplified, further processed for artifact removal and parameter extraction, condensed, reformatted, and communicated to the doctor at distance, who will diagnose the patient. The advances in sensing, data processing, communication and multimedia are enabling factors in the development of the system.
2.2 Signal Processing

There are many types of vital medical signals, such as blood pressure, temperature, pulse, oxygen saturation, stethoscope signal, ECG or EKG (Electrocardiogram), lung sounds, heart sounds, CT (computed tomography), and MRI (Magnetic resonance imaging), which a doctor may require from a patient for accurate medical diagnosis. In this thesis we use ECG signals and breath sound signal as examples to show the performance of the proposed telemedicine system.

2.2.1 Electrocardiogram

Electrocardiogram (ECG or EKG) signals are an important segment of the patient information as monitored through the sensor jacket. An ECG signal contains both low-frequency and high-frequency noise and artifact components that enter due to disturbances (e.g., respiration, body and sensor movements) during recording. Much of the extraneous signal components should be removed prior to analog-to-digital conversion (ADC). General noise is removed using low-pass and high-pass (or band-pass) filtering. Narrow-band noise (due to ac power source, electromagnetic interferences from other equipment, etc.) is
removed by a notch filter. Common-mode signals (noise components that are common to both inputs of operational-amplifier—op-amp; say, due to improper grounding) is removed through a differential op-amp circuit. A typical ECG signal has a low voltage (e.g., 0.2 to 2 mV) and some amplification (say, at a gain of 7 V/V) has to be done before filtering. However, much of the signal amplification is done at the ADC stage. Details of these procedures are found in [9]. The basic circuit for hardware preprocessing of an ECG signal is indicated in Figure 2.3.

**Figure 2.3: Hardware preprocessing of an ECG signal.**

Consider a pre-processed ECG signal as shown in Figure 2.4. It consists of some key attributes, which are used by physicians in their diagnosis exercises. The attributes marked on the signal are the five waves and two somewhat flat segments: Small wave (P wave); flat region (PQ segment); QRS complex (valley Q wave, peak R wave, and valley S wave); extensive flat region (ST segment); and the T wave. Typically, the QRS complex is considered as a single attribute because the Q, R, and S waves occur very close together and may not be distinct in the signal [1, 10]. Different features of the waveform such as the duration, amplitude, and morphology of the QRS complex are useful in diagnosing cardiac arrhythmias, conduction abnormalities, ventricular hypertrophy, myocardial infarction, and other disease states.
Figure 2.4: A pre-processed ECG signal.

For a 40 s of record of ECG signal, at the sampling rate of 1 kHz with 12-bit data points, we get approximately 0.5 Mbits of data. For a typical rural area network condition with a transmission rate of 1Mbits/s, the time of data transmission would be about 0.5 seconds, which is negligible in the overall timeframe of diagnosis. The more crucial issue will be the information loss during transmission. For example, if the QRS complex is corrupted during transmission, the diagnosis will become erroneous.

Our approach is to determine the key attributes of the pre-processed ECG signal, locally at the patient end, transmit them to the doctor’s computer, and recreate a representative ECG signal there using a reasonably simple model. Specifically, the valleys and peaks of the pre-processed ECG signal are identified and the associated amplitudes and durations are computed. The processing time that is needed for this task is negligible. The computed attributes are transmitted repeatedly for several times to the doctor’s computer, the transmitted data are authenticated (from the repeated data), and the ECG signal is reconstructed, and displayed on the doctor’s screen. An ECG signal recreated in this manner at the doctor’s computer is shown in Figure 2.5. Attributes from the original signal shown in
Figure 2.4 were used for this purpose. A physician has confirmed that the information that is needed for a diagnosis is retained in the recreated signal [1, 10].

![ECG Signal Diagram](image.png)

**Figure 2.5: Recreated ECG signal using the transmitted attributes.**

ECG readings used by physicians include rhythm strips similar to the reconstructed signal shown in Figure 2.5. Typical 8 or 12 lead ECGs will generate individual rhythm strips from each lead, which when taken together will form an overall picture of the patient’s heart conduction pattern. For example, abnormalities in conduction patterns may indicate the onset of acute disease in myocardial infarction or give insight into chronic deterioration in elderly patients with heart failure. In the sensor jacket, 12 ECG leads are available. Information from each lead is processed, transmitted, and reconstructed on the doctor’s display screen at distance. This will accurately depict readings similar to ECGs taken within a hospital or clinical setting. In particular, examination of the variations in wave and valley formations on each individual rhythm strip, in comparison with those normally expected from a healthy subject, may indicate particular pathologies. In this manner, the ECG readings transmitted to the physician’s screen will facilitate proper diagnosis, following interpretation.
2.2.2 Spirometry

Digital stethoscope is an integral part of the sensor jacket that is being developed by us. A signal from the stethoscope may be used for a variety of clinical purposes. For example, it may be used in spirometry, to assess respiratory problems of a patient. To test this aspect of the sensor jacket, we placed a small microphone with a stethoscope-like diaphragm in the neck region of a subject and recorded the breathing (respiratory) sounds. The monitored signal was high-pass filtered to remove low-frequency. The resulting signal was passed through an anti-aliasing filter with cut-off frequency at 1 kHz, to remove high-frequency noise and also to compensate for aliasing due to subsequent data sampling. The filtered signal was transmitted to the patient-end host computer using a Bluetooth antenna. The received signal was sampled at 2 kHz for subsequent processing in the host computer. The frequency of the primary breathing sounds are known to be in the frequency range of 200 Hz to 800 Hz, and this information was used in the choice of the sampling rate and the cut-off of the low-pass filter. A frequency domain analysis was performed to obtain the spectrogram of the time-domain data [1, 10]. This process of signal processing is shown in Figure 2.6.

Figure 2.6: Processing of a stethoscope signal for spirometry.

Figure 2.7 shows the spectrogram for the cases of breathing and non-breathing of an individual. It is seen that the spectrum clearly shows the key frequency bands of the respiratory signal.
Figure 2.7: Frequency spectra of stethoscope data: Breath transmission absent (left); Breath transmission present (right).

Similar frequency spectra may be obtained when digital stethoscopes embedded in the sensor jacket are placed along the patient’s lung fields (chest cavity). If the breath sounds are not transmitted, or if the amplitude of the breath spectrum is diminished, particular disease processes may be present. Absent breath sounds as depicted in the left segment of Figure 2.7 may indicate various conditions including pneumonia, heart failure or pleural effusion. Auditory signals transmitted to the physician interface simultaneously with visual data will further aid in diagnosis, as the character of the breath sounds can be clearly identified by the physician. For example, typical abnormalities in the character of breath sounds include wheezes, rhonchi or rales, which can lead to a diagnosis of asthma, and Chronic Obstructive Pulmonary Disease (COPD) or pneumonia.

2.3 Software System Architecture
Our design contains five main modules as follows: (a) sensor interface, (b) signal processing, (c) local storage, (d) user interface, and (e) remote database access module, as presented in Figure 2.8. The sensor interface module handles all data transmission with the wearable sensor jacket. This module is the same for every application, utilizing the same set of sensors,
and consequently it is entirely repeatable.

Figure 2.8: Architecture of the personal application of the telemedicine system.

The signal-processing module performs specific signal processing tasks. For example, temperature represents human body temperature and stethoscope represent lung sound signal. They have the same basic filtering and integration tasks, which are embedded in the wearable sensor jacket. The acquired are processed in the signal-processing module since each application requires specific processing procedures.

The local storage module handles data archiving at the patient’s end. The local SQLite database [11] and CSV (Coma Separated Values) files are used to store these data. The user interface module collects user input from the patient, gives feedback to the patient and provides the video and audio interaction between the patient and the doctor.

The remote database module facilitates communication with the remote server. It provides data uploading to and fetching from the remote server. This module can usually be
reused in each application without any modification.

To ensure both data security and high availability of the remote health monitoring service, a well-maintained central portal server provides a secure and reliable central location for coordinating data collection and video communication services. The server of telemedicine software system contains four modules: web application programming interface (API), data storage, data processing and mining, and data access and visualization, as presented in Figure 2.9.

**Figure 2.9: Application architecture of the remote server.**

The web API accepts physiological data from the personal devices and stores it in the provided data storage. It also allows personal devices access to the data that is already stored in the database. Since the database contains private health information, the web API must require authentication before it allows personal devices to store or retrieve information from the database. Moreover, communication between personal devices and web API should be encrypted to provide secure data transfer.

Main purpose of the data storage module is to provide permanent data storage for physiological records. Typically, the data storage module is implemented as a traditional
relational database, since it provides flexibility of data models, allows easy access to a subset of data using standardized queries, and utilize proven, stable, and reliable database management system. Relational model of the database should be carefully tailored to provide flexible and efficient physiological data storage.

The data access and visualization module should allow authorized users easy access to recorded data. Since the database typically contains physiological data from multiple users, the module must restrict access of each user to a subset of data he/she is authorized to access. Moreover, the module may implement adequate visualization to facilitate and accelerate visual inspection of the records. Visualization can be achieved using charts, tables and/or similar data representation methods.
Chapter 3: Multi-sensor Jacket

This chapter describes the development of the multi-sensor jacket, which is a key component of the telemedicine system. The sensor suite is integral with the sensor jacket, which is worn by the monitored patient. The sensor jacket should be robust, easy to use and maintain, and conformable into the body shape of the patient so as to maintain adequate body contact. This is an engineering and technological challenge. Selection of sensors and associated hardware, optimal embedding of them in the jacket, and proper contact with the body of the wearer are particularly crucial for the function of the jacket [1]. An inflatable jacket, which is adapted from a commercially available jacket similar to a life vest, is used in the present development. Inflation of the jacket by means of a portable air compressor unit enables a snug fit. A graphic representation of the sensor jacket is shown in Figure 3.1.

Figure 3.1: The sensor jacket.
The jacket design and the integration of the embedded sensors and other hardware are done in an optimal manner by using the concepts of mechatronic design [8]. In particular, the approach of mechatronic design quotient (MDQ) is applied. It will incorporate such design attributes as component shapes and dimensions of the jacket, jacket material, sensors, signal conditioning and communication hardware, locations of the embedded devices, and the necessary auxiliary devices such as antenna, power sources, and air compressor. The design process has a hierarchical nature. Specifically, conceptual design and the topological design of the electro-mechanical configuration of the sensor jacket is carried out in the top layer. A lower layer represents the possible functional type choices for each component. For example, sensor types include motion sensors, force sensors, tactile sensors, temperature sensors, pressure sensors, energy sensors, and fluid flow sensors. Next, a detailed design of the sensor jacket is performed to achieve the performance specifications and requirements. Specific choices for a component type (e.g., piezoelectric accelerometers, optical oximeters), including their parameter values (e.g., size, specifications, power requirements), and determination of the sensor locations and configuration within the jacket to improve/optimize the process of data acquisition are done in a lower layer of detailed design [1]. Many of the sensors in the jacket are commercially available with integrated signal conditioning hardware. Hence, signal conditioning hardware is also included in this level.

3.1 Sensors
Selection of the sensors and associated hardware, particularly with respect to their type, size, and features to match the performance specifications of the system (as established during the design) is an important aspect of the present work. The following basic types of sensors are considered in this respect, giving particular attention to commercial availability: Medical CCD Camera, to acquire images of various regions of examination of the patient; 12-lead Digital ECG Unit, to obtain a full electrocardiogram of the patient; Digital Stethoscope, to acquire audio cues from the heart and lungs of the patient; Digital Blood Pressure Monitor, to acquire the blood pressure and the pulse rate of the patient; Digital Ear or Arm-pit Thermometer, to obtain the body temperature of the patient; and Pulse Oximeter, to measure the blood oxygen level of the patient. A pulse oximeter may be placed at a fingertip or earlobe. It has light-emitting diodes or LEDs (red and infrared) and a photo-detector on the
two sides of the body extremity. A record of the light intensity variation due to pulsatile arterial blood flow at the sensed location will provide an estimate of the arterial oxygen level and saturation (SpO2).

In telehealth applications, which involve long-term monitoring of body functionality, typical information that is regularly monitored on an on-going basis includes the following: Weight, body temperature, pulse rate, blood pressure, blood sugar, oral health, hearing, eyesight, lung function, and mobility. For our system, which specifically addresses telemedicine, involving suddenly manifested serious medical conditions, we use the sensors listed in Table 3.1.

**Table 3.1: Sensors integrated into the sensor jacket.**

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrocardiogram</td>
<td>Heart activity</td>
</tr>
<tr>
<td>Blood Pressure</td>
<td>Pressure exerted by circulating blood on the walls of blood vessels</td>
</tr>
<tr>
<td>Electromyogram</td>
<td>Measure of electrical activity produced by skeletal muscles</td>
</tr>
<tr>
<td>Temperature</td>
<td>Body temperature</td>
</tr>
<tr>
<td>Stethoscope</td>
<td>Measure of sounds and murmurs in lung</td>
</tr>
</tbody>
</table>

3.2 ECG
The electrocardiogram (ECG or EKG) is often used to monitor the electrical and muscular functions of the heart. The ECG Sensor has become a commonly used diagnostic sensory tool today. It can diagnose a variety of cardiac pathologies ranging from myocardial infarction to myocardial ischemia. It represents an invaluable testing device in modern medicine.

In our system, the ECG sensors are mounted on an inflated pressure vest at carefully selected key locations. This allows the ECG sensors to be placed on the body without
needing professional medical skills. The pressure vest is inflated by a 3V air pump controlled by the micro-controller unit (MCU) of the sensor jacket. The vest with the sensors is shown in Figure 3.2.

Figure 3.2: The vest with the sensors mounted on it.

The placement of the ECG leads on the sensor jacket corresponds to the “Electrocardiogram Augmented Limb Lead configuration [12].” As shown in Figure 3.3, this topology allows for moving the reference electrode from the left leg to the center front abdomen.
The design of the ECG amplifier circuit shown in Figure 3.4 is based on the reference design provided by Texas Instrument [13-15].

Figure 3.4: ECG amplifier circuit.

This circuit is comprised of four parts:
1. The Right Leg Drive Loop
2. The Instrumentation Amplifier
3. Filtering and Amplification Circuit
4. ADC Compliance Circuit.

3.3 Stethoscope (Lung Sound)

A lung sound signal may include many cycles of ventilation or breathing. A ventilation or breathing cycle is divided into three stages: inhale (Ti), exhale (Te), and transitional pause (T – Ti – Te). They are identified by ventilator variables; e.g., airway pressure cycles (positive-negative-neutral) in ventilated patients, or by smoothed breathing wave profiles in natural breathing. Apparently, the power during inhale is much larger than that in the pausing phase. Accordingly, for signal processing, lung sounds may be considered as consisting of three stochastic processes: inhale, exhale, and pause. Each process will have different properties and they are interlaced by switching from one process to another during a breath cycle, repeatedly from cycle to cycle [18]. Figure 3.5 shows a typical spectrum of lung sounds.

![Characteristics of a lung sound signal](image)

**Figure 3.5: Characteristics of a lung sound signal [16].**

The inhale and exhale waveforms contain rich information for diagnosis. This information is usually inspected by an experienced physician to detect abnormal sound patterns such as wheeze and crackles. To facilitate computerized sound analysis, it is necessary to identify certain variables that are relevant to medical diagnosis. These will include both time-domain and frequency-domain characteristics. For frequency domain
analysis, it is desirable that a stochastic process is stationary. While the overall breathing sounds are not stationary processes, signals that are confined in each stage are approximately stationary, or may be repeated to be so in the record that is analyzed [16]. Mathematically, if one extracts all exhale segments of a breathing sound and concatenate them into a single waveform, then this waveform is approximately stationary [17, 16]. For a stationary process, one can perform frequency-domain analysis using standard techniques of Fourier analysis and generate such representations as power spectral density [17]. The main component of a power spectrum of the lung sounds for both normal and abnormal persons are within 500 Hz, and components above 1 kHz are rarely seen. If a lung sound signal is sampled at the rate of 2 kHz at 12-bit resolution, then the data rate of lung sound is 24 kbps.

In our system, the stethoscope is held in the correct location of the inflated pressure vest. This allows the stethoscope sensor to be worn on the body without needing professional medical skills. The pressure vest is inflated by a 3V air pump controlled by the MCU of the sensor jacket. The stethoscope used in our system is shown in Figure 3.6.

![Figure 3.6: Digital stethoscope.](image-url)
The stethoscope placement for the system, shown in Figure 3.7, is followed according to the available guidelines on “How to Place Stethoscope in steps.” We use multiple stethoscopes to acquire sounds from different locations of the upper body.

![Figure 3.7: Locations of stethoscope placement.](image)

3.4 Temperature Sensing

Body temperature is a key piece of information that a doctor uses to detect and diagnose the medical condition of a patient. We use a digital thermometer to measure the temperature [20, 21] (see Figure 3.8). It can plug into the USB port to conveniently transfer digital data.
Measurement of body temperature is of great medical importance. The reason is that a number of diseases are accompanied by characteristic changes in the body temperature. Likewise, the course of certain diseases can be monitored by measuring the body temperature, and the efficiency of a treatment can be evaluated as well by the physician using periodic sensing of the body temperature. Table 3.2 presents a classification of body temperature corresponding to several medical conditions. In our system, the temperature sensor is mounted under the left arm (see Figure 3.9).

Table 3.2: Classification of body temperature corresponding to some medical conditions.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Temperature Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypothermia</td>
<td>&lt;35.0 °C (95.0 °F)</td>
</tr>
<tr>
<td>Normal</td>
<td>36.5–37.5 °C (97.7–99.5 °F)</td>
</tr>
<tr>
<td>Fever or Hyperthermia</td>
<td>&gt;37.5–38.3 °C (99.5–100.9 °F)</td>
</tr>
<tr>
<td>Hyperpyrexia</td>
<td>&gt;40.0–41.5 °C (104–106.7 °F)</td>
</tr>
</tbody>
</table>
3.5 Blood Pressure

Systolic and diastolic are the two numbers in a blood pressure reading that are used by a medical professional for detecting hypertension and other medical conditions. For instance, a typical reading might be 120/80. When the medical professional places the cuff of the sensor around the arm and inflates it, the blood flow is restricted due to the pressure exerted by the cuff. When the pressure in the cuff is released, the blood flow resumes normally and the flow can be detected through a stethoscope. The reading as the blood flow resumes (120) is the maximum output pressure of the heart (systolic reading). With time, the medical professional continues to release the pressure and monitors through the stethoscope until there is no detectable sound. The subsequent reading (80) indicates the pressure when the heart is relaxed (diastolic reading) [22].

Certain blood vessels might be constricted by certain hormones, such as adrenaline, which is released when a person is under stress. This will increase the blood pressure. It follows that a person’s blood pressure will go up when you are under constant stress. In this
situation, the heart has to function harder. Besides, deposits in the arteries and the loss of elasticity as the blood vessels age, will also increase the blood pressure. High blood pressure may cause malfunction and failure of the heart and the kidneys. Table 3.3 presents a Classification of blood pressure according to some medical conditions [23, 24].

Table 3.3: Classification of blood pressure according to medical conditions.

<table>
<thead>
<tr>
<th>Category</th>
<th>Systolic (mmHg)</th>
<th>Diastolic (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypertension</td>
<td>&lt; 90</td>
<td>&lt; 60</td>
</tr>
<tr>
<td>Desired</td>
<td>90–119</td>
<td>60–79</td>
</tr>
<tr>
<td>Prehypertension</td>
<td>120–139</td>
<td>80–89</td>
</tr>
<tr>
<td>Stage 1 Hypertension</td>
<td>140–159</td>
<td>90–99</td>
</tr>
<tr>
<td>Stage 2 Hypertension</td>
<td>160–179</td>
<td>100–109</td>
</tr>
<tr>
<td>Hypertensive Emergency</td>
<td>≥ 180</td>
<td>≥ 110</td>
</tr>
</tbody>
</table>

To measure the blood pressure, one only needs to wear the arm band on the left wrist or arm and keep steady, as shown in Figure 3.10.

![Figure 3.10: Wearing position of the blood pressure band.](image)

3.6 Muscle Sensor

Electromyography (EMG) is a technique for evaluating and recording the electrical activity produced by skeletal muscles. The muscle membrane potential ranges between less than
50 μV and up to 20 or 30 mV, depending on the muscle under observation. This potential signal may be measured using an EMG sensor with a typical sensing range up to 90 mV [25, 26]. The surface EMG and the intramuscular (needle and fine-wire) EMG are the two main EMG sensing techniques that are widely used in the medical field. In order to obtain intramuscular EMG, a needle electrode or a needle that contains two fine-wire electrodes need to be inserted through the skin into the muscle tissue. The electrical activity can be observed by a skilled professional while inserting the electrode. There are certain body locations that limit the performance of the EMG, when used by non-professionals [27-29]. In our system, we only employ surface EMG data. The sensor used in our system is shown in Figure 3.11.

![Figure 3.11: EMG sensor.](image)

Important information about the innervating nerve of the muscle is provided by the EMG sensor. When a normal muscle is at rest, normal electrical signals will reach the inserted EMG needle. If there is damage in the nerve and/or muscle, the resulting abnormal and spontaneous activity can be observed using the EMG sensor. Then, the patient is asked to contract the muscle softly. The shape, size, and frequency of the resulting electrical signals can be monitored by a medical professional to establish medical conditions. The EMG electrode is retracted a few millimeters and the activity is analyzed again until at least 10–20 motor units have been collected [26].
A local activity profile of the entire muscle can be tracked by an EMG electrode. In order to conduct a precise analysis, the electrode has to be placed at various locations because of the difference of the skeletal muscles in the inner structure. There are four disease categories that can be classified and diagnosed using an EMG sensor. They are neuropathies, neuromuscular junction diseases, and myopathies [30]. To perform a diagnosis using EMG data, we need to connect the two electrodes to the patient’s arm as shown in Figure 3.12.

Figure 3.12: EMG sensor placement.

3.7 Wireless Module
The telemetry system of the present sensor jacket uses two major components: a Micro control Unit (MCU) and a BLE 4.0 module. Both components are connected through a communication port and are powered by a dc voltage source. The MCU used in the present work is the megaAVR from Atmel. This microcontroller contains 32kB of flash program...
memory, 6 analog input channels with a 10-bit analog-digital converter (ADC). The MCU is used for data sampling and packing. And then sends the data package to the BLE communication module.

The Bluetooth module that is used in the present study is the NRF51 module. The NRF51 takes data from the Atmel microcontroller. The data received is then modulated and broadcast to a Bluetooth connected device through the antenna of the NRF51 module. The NRF51 Bluetooth module is shown in Figure 3.13.

![Bluetooth module](image)

**Figure 3.13: Bluetooth module.**

A schematic of the hardware in the present telemetry system is shown in Figure 3.17.
Figure 3.14: Schematic diagram of the telemetry system.
Chapter 4: System Software and User Interface

This chapter presents mobile and personal computer (PC) applications for the telemedicine system that is developed in the present thesis. It facilitates live audio and video interactions between the patient and the doctor. During an active session, the wearable sensor jacket streams vital data that is acquired by it to the doctor, after processing. The graphic user interface (GUI) at both patient end and doctor end is crucial in this regard. The chapter presents the relevant considerations of GUI.

4.1 Telemedicine Server

A portal server in a data center of a healthcare provider can only be used to access securely encrypted services, such as SSL VPN or SSH. Using the database, web server, video conference and live data streaming, the software client of both patient and doctor can perform background data communication and live interactive by using the secure communication channels.

On the central server, there are three network services. The first one is the web/database server. It not only stores data, but also provides access, view and management to the patient data. The second one is database. It contains long-term medical data of all patients. The last one is the live video streaming service, which is provided by a Openvcs open source server. Using the video server, a clinician is able to initiate a video conference session with the patient.

According to the requirement of a third daemon, the central server should be a live data forwarding daemon. By using this daemon, a decimated version of a patient's live medical data can be directly forwarded to the clinician's web GUI. This allows real time monitoring of live data streams alongside live video by the clinician.

Apart from storing physiological records and recording their context, our database is designed to manage and guide a variety experiments in a research environment. With a
specified protocol, experiments can be conducted by authorized investigators according to a list of sessions, with multiple participants and generating physiological, activity, and multimedia records.

Figure 4.1 shows the tables in the category of Session Data in the database. The core of the database can be represented in these three tables, which contain actual physiological records and references to their context. The table session can add a new row for every recorded session. In this session table, there are not only references to the subject of recording and the personal device used for data uploading, but also the experiment to which it belongs, and the protocol used during recording, if applicable. In addition, it contains the information of start and end times of the recording.

Figure 4.1: Tables of session data in database.

In the records table, there may contain multiple instances for each session signal. The actual physiological data with the precise time of the recording for the particular data set are stored in the records table. In this approach, not only the information about ambient conditions (e.g., only part of the data were recorded) can be preserved, but easy data synchronization across multiple time zones can be provided as well.

To collect and access all the data that may be needed by a hospital, we have designed an iOS App. This will help the hospital get every important information in a paperless manner, as shown in Figure 4.2. It has three tabs. From left to right, the first tab is for the
personal information of the patients. The second tab is for insurance information. The third tab is for the signature of the patient.

![Patient data form](image)

**Figure 4.2 The patient data form.**

The Web Portal provides easy access to biometric data and the visualization of these data. It requires a web browser to access a session that is recorded in the Database of our server. Each authenticated user is allowed to access only the subset of data, which he/she is authorized to access. Typical screen view of the Web Portal application is shown in Figure 4.3.
Figure 4.3: Screen view of the Server Web Portal.

4.2 Patient End

An iOS device is used as the patient’s end (Remote End). iOS is an operating system developed and maintained by Apple.

The App developed in the present work is based on the Bluetooth communication open source application. In the original Bluetooth communication, the user can send short messages to another paired device. One example of the use of the Bluetooth communication was to send some text to an iOS device over the Bluetooth Protocol. If the user sends “Hello” to the paired iOS device, the device would respond back to the sender with the same message but at a randomizes delay.

As sensor data is gathered, the data synchronizing daemon runs in the background to automatically link to the central server and send it the collected biometric signal. A video conferencing feature provides live video interaction between patient and doctor. Through an lively video conference, the wearable sensor jacket also streams biometric signals through the telemedicine server. Figure 4.4 shows the GUI while acquiring and streaming when the ECG data.
Since the body sensor network is intended for operation without supervision by professional staff for extended periods of time, the robustness of the system is quite important. This means that the system needs to be able to recover from errors and avoid data losses. In the present work, we have applied several methods to improve the robustness of the patient’s end and prevent signal attenuation. First, the microcontroller of the sensor jacket cyclically stores checkpoint at a specific sector of the solid-state drive. When a sensor happenstances any error that crashes the system, the node can be rebooted by a computer operating properly timer. Immediately the node rebooted, the system stacks the most recent stored checkpoint from the Solid-state drive and continues data collection without overwriting previously collected data.

The goal of the iOS app is to provide the user with a display for the ECG signals while making video conference with doctor. Through the Bluetooth protocol, the mobile phone can receives data from our wearable sensor jacket. This application has 5 primary functions as shown in Figure 4.5.
The five primary functions of the application are:

1. Live Chat without vital data streaming
2. Live Chat with vital data streaming
3. History Record
4. Doctor Information

4.3 Doctor End

Besides collecting, storing and securely providing medical data of the patient, the system developed in the present thesis also supports real-time video conference between the doctor and the patient. By the video chat feature, the doctor can remotely access medical data sessions. The doctor can access the patient data and speak to patient using the video conferencing service, if needed. Figure 4.6 shows the GUI for the doctor to access medical data and video conferencing with the remote (patient) end in real-time.
Figure 4.6: GUI at the doctor’s PC.

The goal of the software platform developed in the present work is to continuously sensing clinically relevant information from the sensor jacket worn by a patient. The limitation of bandwidth, communication environment and power consumption make it not possible to perform all task in real-time. Furthermore, the necessary bandwidth may not be available to stream all medical data to a server. Thus several compromises have to be made between information delay and information quality. For example, an important medical event may require extensive computations that are not possible in real time. In this case, it is possible to process some of the data and buffer the rest for later processing. During dormant periods (e.g., when a subject is still), it may be adequate to report only a subset of the features.
Chapter 5: Conclusion

This concluding chapter summarizes the key contributions of the thesis and proposes possible future work.

5.1 Summary and Contributions
This thesis proposed a wireless telemedicine that uses a public communication network. A prototype of the real time telemedicine system was developed and presented in the thesis. Using the developed system, patients are able to consult with medical professionals at distance, in real time, without having to leave their home location, and receive healthcare quickly and conveniently. The developed system has no significant restrictions on the patient’s location. A patient in an underprivileged community or in transit may receive the healthcare services as long as the sensor jacket is available and the location is covered by a public communication network. The wearable sensor jacket, which has been developed in the present work, has multiple embedded sensors that are properly located and is inflatable to conform to the shape of the patient’s body. It collects vital medical signals from the patient, processes them, and sends the necessary information to the doctor at a hospital through the telemedicine server. Using the developed system, a doctor is able to obtain medical data from a patient, and simultaneously interact with the patient through a live video and audio link.

This thesis considered both hardware and software requirements to support the telemedicine system. The technologies developed in the present work are not only important for remote monitoring and medical diagnosis of patients, but also in establishing a test bed of services to support further research in the area of telemedicine.

The main contributions of this thesis are as follows:

- The development of a general framework for a telemedicine system
- The design and development of a multi-sensor jacket for health monitoring of a patient from distance
- The development of signal processing methodologies for representation and communication of some vital medical signals such as ECG
• The development of a mobile application for collecting vital data and carryout live video and audio communication between a doctor and a patient
• The development of software for the GUIs, particularly for the PC at the doctor’s end to display vital data of the patient effectively, and to carry out video conferencing with the patient and other medical professionals without geographic restrictions.

5.2 Possible Future Work
Possible future work will consist of completion of the entire system of telemedicine. This may require development and integration of more functions to the software and improvement of the coverage medical conditions by incorporating additional sensors and related hardware.

Improvement of the security of the telemedicine server is important. Any action using the Web API requires authentication, particularly for data uploading and data retrieval.

Data communication issues need further investigation. Testing the latency of the system command, data transmission and video conferencing will require particular attention.

Test the accuracy and reliability of the system is an important consideration, which will involve conducting realistic clinical trials with the assistance of a medical professional.
References


[28] Texas Court of Appeals, Third District, at Austin, Cause No. 03-10-673-CV. April 2012.