I, Piyali Das, hereby submit this original work as part of the requirements for the degree of Master of Science in Computer Science.

It is entitled:
Smart Shoe for Remote Monitoring of Parkinson’s Patients

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Committee member: Chia Han, Ph.D.
Smart Shoe for Remote Monitoring of Parkinson’s Patients

A thesis submitted to the
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ABSTRACT

This thesis describes development of a sensor based ubiquitous-monitoring system that aids to Parkinson's Disease (PD) patients. The system, hidden inside a shoe sole, monitors PD patients gait impairments, detects Freezing of Gait (FoG), turns on its laser beam for visual cuing upon detection of FoG automatically and continues until freezing ceases. Monitoring makes use of wireless technology such as WiFi module, whereby the data from wearable sensors are recorded and sent to a remote server. We store this data to make a gait repository. Thus, this work contributes to make a repository which may be used for analyzing gait-data of the patients in future. We also developed a user interface for graphically representing the stored data based on user’s choice of input. A user can fetch data and graphically observe variation of data over a period of days, weeks and months. The work herein shows that wearable sensors combined with an embedded system make real time decision of initiating cue and provide reliable detection of FoG and send the information that can be used for further clinical inferences. Real patients’ gait data will make the repository a useful resource of gait data set for future development of smart gait recognition techniques based on artificial machine learning. Moreover, PD patients who are residing at remote places, can only come to a doctor once in a month for check-up and can be monitored by their doctor at any-time. The doctor can easily log-in to the server and can access his patient’s gait data whenever needed. The reason to combine a hidden gait monitoring system, FoG detection system and visual cuing system together is to provide an end-to-end hassle-free
solution for PD patient care. Furthermore, online monitoring is considered and implemented in order to provide a data driven approach towards gait data repository.

Keywords: Embedded System, Freezing of gait, Gait repository, Online monitoring, Parkinson’s disease (PD); Remote Monitoring, WAMP Server, wearable sensor system.
This work is dedicated to my parents
Mr. Pulin B. Das and Mrs. Juthika Das
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## Abbreviations

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<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>AP</td>
<td>Access Point</td>
</tr>
<tr>
<td>APDA</td>
<td>American Parkinson Disease Association</td>
</tr>
<tr>
<td>DHCP</td>
<td>Dynamic Host Configuration Protocol</td>
</tr>
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<td>EMG</td>
<td>Electromyography</td>
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<tr>
<td>FoG</td>
<td>Freezing of Gait</td>
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<tr>
<td>FSR</td>
<td>Force Sensing Resistors</td>
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<tr>
<td>H&amp;Y scale</td>
<td>The Hoehn and Yahr Scale</td>
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<tr>
<td>IT</td>
<td>Information Technology</td>
</tr>
<tr>
<td>LoS</td>
<td>Line of Sight</td>
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<tr>
<td>MAS</td>
<td>Movement Analysis System</td>
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<tr>
<td>PD</td>
<td>Parkinson's Disease</td>
</tr>
<tr>
<td>PHS</td>
<td>Personal Health System</td>
</tr>
<tr>
<td>PTF</td>
<td>Polymer Thick Film</td>
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<tr>
<td>QoL</td>
<td>Quality of Life</td>
</tr>
<tr>
<td>RSSI</td>
<td>Received Signal Strength Indicator</td>
</tr>
<tr>
<td>SVM</td>
<td>Support Vector Machine</td>
</tr>
<tr>
<td>UI</td>
<td>User Interface</td>
</tr>
<tr>
<td>UPDRS</td>
<td>Unified Parkinson’s Disease Rating Scale</td>
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<tr>
<td>WAMP</td>
<td>Apache, MySQL and PHP for Windows</td>
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<tr>
<td>WBAN</td>
<td>Wireless Body Area Network</td>
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<tr>
<td>WBASN</td>
<td>Wireless Body Area Sensor Network</td>
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1. INTRODUCTION

1.1 PARKINSON’S DISEASE: AN OVERVIEW

Parkinson’s disease (PD) was initially known as “paralysis agitans” better known as shaking palsy to most people. In 1817, a British surgeon James Parkinson described the disease “paralysis agitans” and documented his finding in an essay “An Essay on the Shaking Palsy” where he described six cases of paralysis agitans. The term "Parkinson's disease" was coined several years later by Jean-Martin Charcot, a French neurologist.

Figure 1.1 Essay of James Parkinson's on shaking palsy.
PD is a progressive neurodegenerative disorder that affects motor and non-motor functions of human body. More than 1 million people in the US are affected by this disease according to American Parkinson Disease Association (APDA) [1]. Parkinson’s disease foundation, Inc. has reported that every year around 60,000 Americans are diagnosed with Parkinson's disease. Despite advances in the understanding of PD pathophysiology, appropriate characterization of the motor status and, particularly gait, remains a major unmet need in the management of PD. Personalized monitoring of motor status between in-clinic evaluations is expected to facilitate tailoring of therapy and improvement of health-related outcomes. Gait impairment, including shuffling, festination (progressive reduction in stride length with inefficient increase in cadence), and freezing of gait (FoG); paroxysmal inability to lift the feet off the ground) are important variables in the assessment of the risk for falls and other ambulation-related injuries. Out of these FoG has always been the major area of interest as it results in the analysis of several key factors in PD patients. FoG is used as a principal component for analyzing spatial and temporal information [2], gait related cerebral alterations [3], study of brain tissue loss [4] and lots more.
1.2 CLINICAL ASSESSMENT OF PARKINSON’S DISEASE

PD is a slow progressing disease which does not have any recovery treatment. Treatment to PD only relies on different symptoms study and assessment from the patient’s response which are mainly based on the observations and judgements by clinicians. Research studies of PD require a means of rating the severity of disease by measurement of motor manifestations, assessment of ability to perform daily functional activities, and symptomatic response to medication. The most commonly used rating scale for the clinical study of PD is the Unified Parkinson’s Disease Rating Scale (UPDRS) [5]. It is comprised of the following sections.

Part 1: Assessment of behavior, mental state and mood,

Part 2: Assessment of daily activities of life,

Part 3: Therapist monitored motor evaluation,

Part 4: Severity analysis of PD using Hoehn and Yahr scale [6], and

Part 5: Schwab and England scale system of daily activities.

Apart from this the The Hoehn and Yahr (H&Y) [6] scale and the Schwab and England rating of activities of daily living are used for clinical assessment. H&Y scale is used for severity analysis of PD and report the advancement in patient’s condition. Different stages based on this scale are:

Stage 1: One side of the body shows symptoms; no or little functional disability,

Stage 2: Both side of the body shows symptoms; no balance disability,

Stage 3: Mild to moderate disability and balance impairment; physically independent,

Stage 4: Unassisted movement but severe disability, and

Stage 5: Confined to bed or wheelchair; no movement without assistance.
Though these rating scale and metrics are widely used, these techniques are not efficient and accurate enough. Most of the observations are based on the patients visit to the clinic, or based on his memory about the occurrence of any shaking or freezing event. This data is highly unreliable as the patient tend to behave very differently in a home environment as compared to the supervised and monitored clinical visit. These conclusions are mainly drawn from the statements and feedbacks of the patient which is not itself very reliable and lacks firm proof.

1.3 ROLE OF TECHNOLOGY IN HEALTH MONITORING

When a patient is aware of the fact that he / she is being monitored by someone, which mostly happens in a supervised visit in physician’s clinic, his motor-neural behavior may differ and his / her symptom does not seem to show properly, leading to an improper prediction. As a clinical visit is only a glimpse of the patient’s severity of the disease, only symptoms are assessed and not his / her actual condition of motor and non-motor aberrations are taken into account.

Hence, the need of a home monitoring system is highly felt which would correctly observe the day to day activities and behavior of the patient and would be easier for the doctor to monitor online or even offline. This has raised the idea of Personal Health System (PHS). Remote monitoring of the patient becomes utmost important in this regard. Information Technology (IT) plays a key significance in this regard. Advancement in technology has allowed us to create devices with the ability to collect, transmit and store human behavior in the form of data. These body parameters could send signals with the help of different body sensors. With advent of technology, creation of high end devices and monitoring systems, it is able to automatically
gather data necessary to outline and conclude about the health state of each individual. Information processing and communication are centrally involved in health care activities such as: patient data collection; information sharing with patients; communication among health care professionals; decision making in diagnostics and therapeutics; interpretation of laboratory results; collection of clinical research data, are among the few.

Moreover a wearable system capable of collecting a patient’s gait movement data for a considerable period of time, say over weeks or month, is needed. This system could actually record the fluctuations and monitor the patient’s different body parameters across a wide range of time. Hence the doctors get to study a complete scenario of a patient’s well-being even when he is at home without anyone’s deliberate presence. It also helps providing some sort of rescue mechanism or rather ways of giving non-pharmaceutical assistance and even call for emergency in case a patient falls or meets with an accident. Particularly for PD patients, there are couple of existing systems that are used for monitoring. Some are used only, for indoor monitoring, some only sense when a person has stopped or has fallen in the ground while walking and inform emergency or rescue team about that incident. Some also provide certain kind of visual or auditory cue to help the patient recover from the FoG to some extent. We propose a platform where technology has lot to contribute continuously to the betterment of the PD and monitoring the patients.
1.4 CURRENT TECHNOLOGIES IN MONITORING OF THE PD PATIENT

In last couple of years, there has been a number of attempts to address the issues of Parkinson’s patient well-being and better management and monitoring of their daily activities. Many literatures report a wide spectrum of applications based on different techniques that measure or monitor PD out of which sensor system is proven to be most useful. Only a few movement analysis systems (MAS) have been reported for the ambulatory measurement of different disorders in PD. Also several data mining techniques, Support Vector Machine (SVM), machine learning algorithms, Pattern Recognition techniques on received signals have also been studied to conclude about the severity of the disease. Since most PD patients need a palliative treatment, any kind of external support system that eases their lives is on high demand. The MAS system for PD patient allows doctors to personalize and customize treatment to the specific needs of the patients.

**Wearable sensor system**

Most of the commonly known systems that are currently available are based on wearable sensors like motion sensors, accelerometers, gyroscope, and pressure and force sensors. Patel et al. [8] proposed a monitoring system for PD patients using accelerometer sensors and predicted the UPDRS score. In another work, Caldara et al. [9] used five sensors across body to quantify Gait quality, gait direction, Bradykinesia, tremor, etc. and thereby transmit the data using Bluetooth technology. Mariani et al. [10] developed a wearable on-shoe strap enabled with accelerometers
and gyroscope to measure the motor symptoms during gait analysis along with an assessment of turning, swing width and other relative parameters of PD patients to conclude about a subject.

**Electromyography**

Electromyography (EMG) is yet another technique to detect and classify PD. EMG is known to be a technique that detects and evaluates electrical signals from muscles activities by attaching electrodes to the surface of the selected skeletal muscles. It detects and monitors the health of muscle and predicts any kind of medical abnormalities, aberration in normal muscular behavior or mechanics of human movement. Kugler *et al.* [11] proposed the use of surface electrodes and accelerometers to extract feature and analyze severity based on the results of SVM. But with EMG method, gait movement could be barely studied in PD. Across decades many work has been reported that shows EMG has been helpful in different analysis of gait in PD though not much successful in studying mobility conditions or patterns of motion (Albani, Sandrini *et al.* 2003 [12]; H. Mitoma, R. Hayashi *et al.* 2000 [30]).

**Different Monitoring systems**

Received Signal Strength Indicator (RSSI) has been proven as an important tool in designing monitoring system for PD patients. Measuring the proximity of a person in terms of the central sensing system or the presence of any object across a predefined periphery, is an important feature of RSSI that is being used. Jamthe *et al.* [13] proposed a home monitoring system using
Received Signal Strength Indicator (RSSI) from sensor motes placed on walls and floors of a room and the Base station located in the center of the room. They were able to detect whether a person is static or in motion with variation in RSSI value. Salarian et al. [14] proposed a method to improve the accuracy of monitoring posture transitions. They verified the accuracy of the system by a comparative study of UPDRS score of PD patients with video recording. A real time remote monitoring system has been proposed for PD patients by Chen et al. [15]. They aimed at remote tuning of post operation Deep brain stimulators though a client-server architecture. This model encompasses around Bluetooth communication protocol using a software framework. A different aspect of monitoring PD patients is through Electromyography (EMG). Use of two channel EMG system has been developed by Wright et al. [16]. They proved that Fast Fourier Transform (FFT) of EMG signal received from a typical PD patients and a healthy person differs significantly in the frequency domain. Hence, severity of the disease could be predicted from the variation of the EMG signals. Smartphone based monitoring system has been proposed by Mengalingam et al. [17] for elders and patients.

**Non-pharmaceutical assistance to FOG**

Several results and survey shows the use of non-clinical methods to provide aid to FoG. Different types of external cue stimulate the motor impulses in the patients, thereby helping them to overcome the freezing state. Stepping over any visual cue, ticking sound of auditory cue, walking sticks etc. is proven to be extremely beneficial in this case. Sarma et al. [18] proved the effect of visual cue on the behavior of PD patients. They used several different techniques like behavioral
tasks, subject analysis and microelectrode readings to draw conclusions. Chang et al. [19] developed an active robotic walker named Cairow, for PD patients which targets to reduce the FoG and falling problems. The system is basically a walker which can help in automatic location finding, subject discovery and new path determination. Bachlin et al. [20] proposed a Fast Fourier Transform based FoG detection algorithm using several accelerometer across the legs and a central coordinator at the back that uses Bluetooth for transmitting data to a central hub. It also provides auditory cue for FoG assistance to certain extent. Another visual and auditory cue providing system is proposed by Yan et al. [21] that also addresses regulation of stride length. A multi cue unit was developed by Yan et al. [22] which can be placed anywhere in the body and can provide conditional cue on FoG occurrence. Along with this, Rempark [31] is also known to be a portable system for monitoring PD patients. It has sensing and transmission wearable unit to be worn in the waist area. This device senses the patients freezing events and provides auditory cue to help recovering from that FoG state. The Rempark system has a central server for data storing, processing and analyzing patient information to determine the status of patient’s health situation. But, this device is still a visible unit which the patient has to carry with himself/herself at all times and is not hidden in that regard. A patient is aware of the fact that he is being monitored constantly. Also, it is medically proven that visual cue aids in recovery from freezing state more efficiently than auditory cue. Hence, this system also has certain flaws that need to be taken care of.
1.5 OBJECTIVES

The primary objective of this thesis is:

- To design and create a compact non-invasive monitoring system for ambulatory movement analysis of PD patients to detect Freezing of Gait (FoG) throughout the day and overall assessment of the patient’s condition.

Additional goals of this thesis are:

- To use pressure sensors to identify change in gait pattern in PD patient including tremor, bradykinesia, gait impairments and cease of movement,
- To make the entire system hidden and wearable. We wanted the system to be light weight and easily wearable and carried on by the PD patient and still monitor their daily activities,
- To create an assessment and monitoring system which will enable movement analysis system,
- Automatic detection of FoG in real-time with minimal delay (negligible) for higher accuracy,
- To automatically turn on visual cue upon detection of FoG, and keep the cue on until freezing ceases,
- To wirelessly transmit the gait data accumulated from the sensor system in real time to remote server for online and offline monitoring and
- To store the data in a repository and display real-time data in graphical and chart format for better understanding. We also provide retrieval of the previous stored data based on
date and time stamp and display graphically to depict the complete health scenario of a PD patient.

1.6 THESIS OUTLINE

In this section, we present the organization of this thesis work. In Chapter 2, we discuss about the different concepts that is widely used in this research area and acts as a foundation to the thesis. In section 2.1, we briefly present an overview of Freezing of Gait (FoG) as this is one of the major concepts for this thesis. In section 2.2, we review the concept of RSSI and its implications in our WBAN system. Its pros and cons in the application of a monitoring device has also been considered. In Section 2.3, a brief introduction to wearable system and WBAN is presented. It also covers the use of a sensor network to form a non-invasive monitoring platform. Section 2.4 provides the motivation for working on this thesis. This includes current challenges and demerits of the prevalent monitoring systems and what factors need to be added hence forth. Chapter 3 is an overview of our proposed system. It considers the idea behind our work, the novelty of our system, the key features it possesses, and the materials and components that is used. In Section 3.1, we present the concept or the idea behind the innovation of this system. Section 3.2 talks about the salient features of our proposed system. Section 3.3 describes the hardware components that are mainly used in this project. In Section 3.4, we discuss about the working principle of this system. It describes the sensing and monitoring scheme that our system has employed. In Section 3.5, we present the online data collection system. Section 3.6 presents our
results and detailed discussion about the results. In section 3.7, the online tools and the software is presented for analysis purpose. Section 3.8 discusses about the possible application of our system in different other areas. Lastly, in Chapter 4, we draw conclusions and indicate some follow up future work for some challenging scenarios and possible extension of this thesis.
2. FOUNDATION

2.1 FREEZING OF GAIT (FoG)

Freezing of gait (FOG) is a short duration, unique, involuntary inability to initiate step or take very small step and continue movement with utmost difficulty as experienced by around half the population of patients with advanced Parkinson’s disease. This is as mentioned by Macht et al. [35] and J.G. Nutt et al. [41]. The major difficulty in walking is observed during initiating a movement or during making a turn while walking. Normally, FOG lasts a couple of seconds, but episodes can occasionally exceed 30 seconds. N. Giladi and A. Nieuwboer [37] define it as “an episodic inability (lasting seconds) to generate effective stepping in the absence of any known cause other than parkinsonism or high level gait disorders.” FOG usually depends on the walking situation.

A. Amini Maghsoud Bigy et al. [36] used Kinect sensors to recognize the postures and FoG of Parkinson’s Disease patients. They recognized different freezing episodes based on standing posture, tremors or falling incidents. FoG is normally encountered at turns, start of walking, upon reaching the destination and in open spaces as mentioned by Schaafsma et al. [38]. It is also observed that patients tend to get affected more with FoG while approaching narrow spaces, such as corridors or doors. FoG instances have also been witnessed when people are in crowded places. While a patient is at home, freezing episodes tend to happen at the same location every day as reported and observed.
FOG is actually known to be an episodic phenomenon. Hence monitoring the different episodes of FoG across a day or week is utmost necessary to make any conclusion about a patient’s health. Unlike continuous gait disorder, where the slow progression of gait disturbance allows patients to adapt slowly to the alterations in their walking, with episodic gait disorders it is very hard to make those adjustments. FOG is pretty much unpredictable, which influences the Quality of Life (QoL) of the patient in two ways. Falls in the elder age are a great cause of hip fractures, resulting in high mortality in PD patients or admission in the healthcare providing institutions and clinics. Secondly, it provides an obstacle to the normal way of living. A person faces huge amount of difficulty in walking or moving from one place to another alone. He mostly avoids walking or even performing daily activities becomes challenging.

Freezing of Gait is identified as having four main symptoms. They are listed as below:

**Tremor**

It is the involuntary shaking of hands, fingers, legs and sometimes parts of faces as well. It might range from mild shaking in hands while holding any object or while trying to do any action involving muscles. It is also observed that the patients are shaking their different body parts even at rest. This is one of the primary symptoms of PD. A person could also shake his legs vigorously even when he is standing and not intending to walk.
Rigidity

Another important symptom that is observed is that portion of the limbs and muscles of a person seems to be rigid. This is mostly reported by the person as a feeling that in occasions of bending the hands or legs or even fingers, it seems like the muscles and bones have become stiff and rigid.

Bradykinesia

It is another symptom due to dysfunctionality of the nervous system. In this stage a person is not being able to initiate his movement and start the onset of walking. It also seems difficult for them to make decisions about walking through narrow spaces, enter through a door. Even normal activities and tasks seems difficult to be executed by the patients. During this phase the shaking is also increased to a certain extent.

Postural Imbalance

This is the most difficult stage and symptom of a PD patient. Due to the dysfunctionality of the central nervous system a person tend to loose balance while walking, sitting, standing or performing any activity. This often results in falling of the patient and major fractures in different joints.
2.2 RECEIVED SIGNAL STRENGTH INDICATOR (RSSI)

RSSI is a Radio-Frequency (RF) that stands for Received Signal Strength Indicator. It represents the power level that an RF device is receiving from the radio infrastructure at a given location and time. Like a nearby Access Point (AP) gets detected from a wireless IEEE 802.11 devices based on the signal strength that the device receives. RSSI is the measure of the signal strength, though it is invisible to a user of a receiving device. Because signal strength can vary greatly and impact functionality in wireless networking, often make the measure available to users. Usually, higher is the RSSI, better is the quality and speed of the communication through the radio segment. Many work has been reported to use RSSI as a signal strength indicator while working on the PD patient monitoring application. RSSI does decrease with distance and also indirectly measures the distance between the transmitter and receiver.

S. Chakraborty et al. [32] and S. Chakraborty et al. [33] in their work observed the drop in the RSSI value with any moving object obstructing the Line of Sight (LoS) between the sensors and the base station (BS). This variation in the RSSI value is used to detect any PD patient’s stability or fall condition. This method is useful to a certain extent, especially for location determination of a person. Though it is not evident whether the subject who is detected to be standing in the LoS of the BS and the motes are the actual patient or any other person present at home. Also by this mechanism it hinders the mobility of a person from one place to another. The patient is always aware of the fact that he / she is being monitored. Also he needs to get the sensor motes affixed to his body at several places to accurately determine his motion pattern. Though in most of the cases, it is not possible to determine any idea about the freezing of gait episodes or a
patient’s health conditions. It is also not possible to make any idea about the past occurrences of FoG and to study the symptoms of the disease.

2.3 WEARABLE SYSTEM

Wearable systems are the leading innovations and pioneering moves in recent technological market. While the available technologies are worn close to the body, or for some cases inside the body it becomes wearable technology to carry with you. Health care gadgets are the major example of wearable technology. Apart from that consumer electronics (wearable glass or watch), military wearable gadgets, etc. are few other examples of wearable technologies. Our system is more a health monitoring system. In this section, consider about few features of wearable technology and emphasize salient features of our system.

Features of a wearable system:

- Easy to wear and operate,
- Low power device,
- Manageable shape, light weight and easy to carry,
- Application specific computing ability,
- Wireless networking with other smart gadgets, and
- Personalized settings to get best service from the system.

These features are the basic requirements of a wearable system. A health care system must take care of capturing, processing and sending the important parameters with reasonably low latency
and high reliability. Thus, designing a wearable health care system is a bit more challenging than designing a wearable entertainment gadget. Previously work has been done to determine many neurodegenerative diseases using wearable devices [34]. Our developed device is an exclusive PD patient FoG monitoring and cuing system. Below are the salient features of this smart shoe as a wearable system.

- Easy to wear and carry,
- Microcontroller based programming dedicated for FoG detection,
- Automatic activation of visual cuing system upon detection of FoG,
- Wireless or LAN based connectivity for gait data transmission,
- As it is a shoe and FoG can only happen while a PD patient may try to walk hence it doesn’t need to be worn all the time, and
- Finally the smart shoe pair is designed with very minimal electronics and sensor device.

Thus, our approach in devising a wearable smart shoe is a novel one to cater the PD patient care and monitoring.

### 2.4 MOTIVATION

Different monitoring system aims at analyzing or recording several parameters like the number of Freezing instances, type of freezing instances like short FoG or long FoG, Bradykinesia, fall determination, Emergency notification to rescue system, etc. In 2013, similar work supported by the NSF has been developed using a sensor network [23] was reported. The system was based
on placing sensors at two levels of the room, human mid-height level and sleeping level. The basic idea is to determine whether a person is standing or sleeping and quick change in the position indicates fall of a person by using the RSSI value. It calls for emergency services when a patient falls. But this system fails to provide an independent and personalized monitoring system for the PD patients. Another recent NSF supported work [24] manages security of healthcare devices at home and remote clinics, without adding burden on the homeowner or clinical staff and verification is done using medical directives issued to remote devices. From an engineer's perspective, we did an extended literature survey on PD patient's well-being, monitoring, aiding and found few areas to work on. We worked together with specialized doctors to understand the need of a patient and came up with an engineering solution to alleviate this. A 'hidden' monitoring and automated cuing system is one of the major needs.

Moreover, a wearable system capable of collecting a patient's gait movement data for a considerable period of time, say over weeks or months, is needed. If that system can detect any freezing on real-time basis and immediately can provide the patient a visual cue, will immensely be helpful to both the patient care takers and the patient himself. There is hardly any available system which provides cueing assistance to patients while their freezing state is persistent. Hence, a method of assisting PD patients with visual cue at the time of their FoG and turning off the cue on successful recovery from freezing is highly desirable.
3. HIDDEN CUEING AND MONITORING SYSTEM

3.1 IDEA/SYSTEM CONCEPT

We have discussed earlier about the different monitoring system that have been used for Parkinson’s Disease and also identified the kind of system desirable to overcome serious challenges in the monitoring system. We came up with the idea of transforming a shoe into an independent data collection platform. Whenever a patient walks, he puts on a shoe for sure and from that time onwards, the system starts monitoring his gait. The shoe is equipped to sense the change in movement of a patient, record that information and send it to a server for further analysis. So, this shoe has to be intelligent enough to perform these tasks and make necessary decisions. We also enabled the shoe with a visual cueing system that can stimulate a patient to step on the particular light beam on the floor. This visual cueing helps a PD patient to get over the freezing of motion. All the parameters in this system can be easily customizable to suite individual needs. All these together gave rise to an intelligent hidden monitoring system which acts like someone’s personal assistance and activity recorder.

We also took care of the fact that the data generated from this system is to be used by the doctors, clinicians and caregivers who would like to monitor the health status of a patient. For this, we designed a Web Application with a simple to use user interface. A huge volume of sensor data can sometimes make no sense to a layman and hence we thought of making the data viewing and data retrieval process very much simple to be used by anyone without any engineering knowledge. This application can be used to monitor health of the patient based on
the date and time, over a period, or live. The stored data from the shoe system can be interpreted by the physicians in a more user friendly manner. The statistics presented by the graph with a visual representation is more helpful rather than looking at the individual data. It is also easier to summarize the finding of the patient’s health with this tool. This helps the doctors, caregivers or physicians in making decision on data and to graphically view a large dataset.

![Figure 3.1 Block diagram of the sensing and monitoring system](image-url)
3.2 SALIENT FEATURES OF THE SYSTEM

We are proposing a system that has different features, making it a unique and different from rest of the monitoring system that is currently available. This entire monitoring system comprises mainly of two major parts:

a) The Shoe based sensing and cueing system, and

b) Software based online data storing, monitoring and retrieval tool.

The features of the Shoe based sensing system are:

- The system is a light weight wearable device,
- The system is a non-invasive and hidden inside shoe,
- It is an intelligent stand-alone device with the capability of detecting FoG,
- It can wirelessly transmit sensed information to a Web Server,
- The system is a real-time system and transmits data to the server with negligible delay,
- It projects laser beam automatically on the floor as soon as freezing is detected, and
- The LED based visual cue for recovery from FoG is kept ON till normal motion is resumed back
The main features for the software system of this monitoring project are:

- It stores the data in a MySQL database,
- The data is retrieved with the help of WAMP server,
- It displays the live data in the form of graphs for better understanding of a patient’s current health scenario,
- Graphical display of stored data based on date and time filtering for better analysis of patient’s progress and daily status, and
- A simple User Interface (UI) for date time filtering as well as graph display ideal for naïve users.

3.3 WEARABLE HARDWARE COMPONENTS

The prototype of the shoe has been made up using Force Sensing Resistor (FSR) 402 single zone force sensors, Arduino UNO with ATmega 328 microcontroller and Arduino WiFi shield to transmit the data wirelessly to a central server. The FSR 402 [29] sensors are absolutely lightweight and flexible with very high sensitivity and a quick response time less than 3 μs. A picture of FSR sensor used in the system is shown in figure 3.2. It has a 14.7 mm diameter active area for sensing and 56 mm in length. There are 4 connection options available. The sensors have a force sensing range of approximately 20 Newton. FSRs are devices comprising of two wires. They are
made of Polymer thick film (PTF) sensors and the resistance varies inversely with increase in force applied to the surface of the sensor.

![Force Sensing Resistor (FSR) 402](image)

Figure 3.2 Force Sensing Resistor (FSR) 402

The Arduino UNO with ATmega 328 microcontroller is of 2.7x2.1 sq. inch and typically requires a power supply of 5 V with 40 mA current supply [28]. An Arduino UNO microcontroller is shown in figure 3.3. Arduino is enabled to program easily with its software backbone compatible with Proto- C language. It has a Flash Memory of 32 KB. This little memory present is actually used by the microcontroller for making instant decisions like switching on the LED, data transmission to a central hub via ETHERNET, WiFi, Bluetooth or similar data transfer technologies as well as other small task. Arduino is not capable of data storing mechanism hence we need some way to store the data. Here in this project we have used WiFi to transmit the data from the pressure sensors in the shoe sole to a central data repository. The central server acts as a Gait data repository.
which is accessed for data analysis and patient’s health monitoring. We have also tried our system to transmit data using ETHERNET mechanism as well.

![Arduino Uno with ATmega 328 microcontroller](image)

**Figure 2.3 Arduino Uno with ATmega 328 microcontroller**

Arduino UNO compatible WiFi component as shown in Figure 3.4 is used for transmitting the pressure sensor data generated from the shoe sole to the central server. For this Adafruit CC3000 WiFi breakout is used which is connected via wires to the Arduino UNO. It has an onboard 3.3V regulator that can handle the 350mA peak current. It is equipped with onboard ceramic antenna so it is easily compatible and configurable for WiFi connectivity. The Adafruit CC3000 WiFi breakout component is of dimensions 26.22mm / 1.03" x 40.45mm / 1.59" x 2.95mm / 0.11" and is extremely light weight of about 3.4 grams. It supports 802.11b/g, open/WEP/WPA/WPA2 security modes to connect to any WiFi router. It also supports communication over both TCP and UDP. A laser LED is used in the front of the shoe that projects on recognition of freezing.
The Arduino Ethernet Shield allows the Arduino UNO to connect to the internet as in figure Figure 3.5.a. The shield mounts on top of the Arduino microcontroller and connects to all the necessary pins of the Arduino for connections as shown in figure 3.5.b. This works similar to the WiFi with the only difference being data transmitted via standard RJ-45 connection. The Ethernet Shield W5100 is actually based on the Wiznet W5100 ethernet chip. It supports both TCP and UDP. It also has provision of adding SD card for temporary data storage. It follows IEEE 802.3af standards.
Figure 3.5 a. Ethernet Shield W5100 for Arduino UNO

Figure 3.5 b. Ethernet Shield mounted on top of Arduino UNO
3.4 SENSING AND MONITORING

Arduino sampling

We have been interested only in taking into account the change in the pressure value instead of the absolute pressure value. This is because we want to detect the FoG based on the pressure sensor variation that is being recorded. We are not quantifying the pressure value. Though any individual with wide range of body weight exerts different amount of pressure yet the Arduino scales the pressure measurements onto a scale of 0 to 1023 where 0 denotes absence of pressure and 1023 denotes maximum pressure. These quantized values were used to derive significant pressure differences. This feature of Arduino helps it to be scalable enough to be used by any individual irrespective of body weight.

Threshold determination

We used samples from our stored gait data repository for analyzing gait behavior of several patient. From these derived values we plotted a histogram to study the frequency and range of the pressure values that is prevalent in these data. From these statistics a good choice of threshold for sensor value has been determined. The x-axis shows the sample of pressure segments (each segment is 50 units) starting from 650 up to 1023. The y-axis shows the number of occurrences in each pressure segment. Figure 3.6 shows the histogram that confirms a good choice of threshold value being 950 considering the FoG instances from several datasets. This is because all the previous occurrences of the FoG instances before 950 are considerably less than...
the frequency of 950 pressure values. Hence, it can be concluded that the information contained in the data after 950 is more useful for FoG determination. Hence we are interested in records after 950 to make decision of a person’s freezing and thereby fire the visual cue for assistance.

![Figure 3.6 Histogram of FoG Sample Distribution](image)

**Figure 3.6 Histogram of FoG Sample Distribution**

**Sensing system**

We have used four sensors hidden inside the shoe sole. The locations of the sensors are chosen based on the theories of R. W. Soames, 1985 [26]. The paper talks about the pressure distribution of a human's foot while wearing a shoe and making surface contact with the shoe at certain points. The magnitude of the pressure varies across the surface of the foot. They identified 15 specific foot points and plotted pressure distribution to analyze those pressure zones. They found
out the peak magnitude of pressure at those points. Especially in heel, metatarsal heads and mid foot.

Scott et al. [39] mentioned that heavier people tend to put more pressure in the lateral side of foot, hence we chose of placing 1 sensor in the lateral area. Our choice was based on selecting the points where the magnitude of pressure exerted was maximum. From the analysis of R. W. Soames [26], we concluded to use the major peak pressure points which were 3 along with one lateral point to cover the entire foot pressure measurement. Hence together we used 4 pressure measuring point and placed 4 pressure sensors at those points. Different survey and literatures have proven this theory (I. A. Kapandji, 1974 [25]; O. Mazumder, et al. 2012 [27]). We have used the first sensor to record the thumb pressure, second one just below the thumb area, third sensor in the lateral foot region and fourth one in the heel. We have named the sensors S0, S1, S2 and S3 and mapped it to the different foot pressure point locations.

![Figure 3.7 Pressure points for sensor placement in shoe sole](image)
The schematic diagram of the strategic positions of the sensors under foot is shown in Figure 3.7. Though the pressures in these points vary drastically in different patients, but, in general, these regions cumulatively gather the information of pressure variation. The recorded pressure sensor information is used to detect FoG. We have been interested only in taking into account the change in the pressure value instead of the absolute pressure value. Arduino scales the pressure measurements onto a scale of 0 to 1023 where 0 denotes absence of pressure and 1023 denotes maximum pressure. These quantized values were used to derive significant pressure differences. The pressure variations from different sensors cumulatively allow to determine whether freezing has occurred or not. Exceeding the threshold pressure value for a certain period of time enables the embedded system to make a decision whether freezing has occurred or not and thereby decision of firing LED is made. This threshold value is determined from the histogram of several FoG samples collected.

The cut off time for the determination of freezing is actually dependent upon a patient’s behavior. As discussed earlier, there several kinds of FoG episodes ranging from few seconds to longer than that. Patients tend to have wide range of behaviors while their freezing episodes. Some tend to freeze for multiple short durations say for 1 to 2 seconds and some tend to freeze for a few more seconds like 5-10 seconds. In our experiments and system we have used the time frame of 5 seconds to make the decision of freezing. The time frame of 5 seconds was chosen to be as an optimum value as a medium FoG instance duration.

In the best possible scenario, based on a particular patient and his freezing behavior, the system needs to be adjusted and modified so that the best result is obtained. Also the choice of threshold could also be tweaked and customized based on the patient’s characteristics. Hence the system
is capable of personalization to an extent. This always results in getting a personalized monitoring system according to someone’s need similar to a Personal Digital Assistant (PDA) like mobile phone, laptop, smartphone or digital watch.

Figure 3.8 Flow chart of the working principle of proposed system

Figure 3.9 shows the circuit connection for Arduino UNO microcontroller to sense pressure data and based on the findings switches on the LED light. As discussed earlier, the FSR sensor is activated with 5V power, so we connected one leg of the FSR to the 5V pin of Arduino and one leg to the analog input A0 of the Arduino. This reading from analog A0 pin is fed to the embedded
system to make decision about the occurrence of FoG. All the other sensors are also connected in the similar fashion. The sensor legs are activated with 5 volt of power supply and their output is accumulated to be fed in the microcontroller and thereby recorded in. The value of the individual sensor reading is noted and accumulated value from all the sensors are also studied.

Figure 3.9 Circuit diagram for Arduino sensing pressure and firing LED
3.5 ONLINE DATA COLLECTION

The pressure sensor data generated from the Arduino is used to transmit over the internet to store in the database and get processed by the central server. We used CC300 WiFi breakout for this purpose. Figure 3.10 actually shows the circuit diagram and connections to use the CC300 WiFi module with Arduino. The diagram depicts the connections made to use Arduino record the sensed pressure data and simultaneously send it to a central storage over the internet with the help of the WiFi module. The pressure sensing mechanism has already been explained in the figure 3.9 where a sensor is activated with 5 volt power and its output is recorded by the microcontroller analog input. All the four sensors are connected together in the same fashion. The value of the individual sensor reading is again noted for this case and the accumulated value from all the sensors are also studied to have a better understanding of the behavior of the sensors at different points.

To facilitate the data upload via CC300 WiFi, we need to provide the login credentials of the router to authenticate the WiFi module to connect to the internet, followed by the IP address of the server where Arduino wants to establish the connection and send the sensed data. CC300 WiFi module is only enabled to authenticate open/ WEP/ WPA/ WPA2 security modes.
Figure 3.10 Circuit diagram for Arduino sensing pressures and uploading via WiFi module
The data generated from pressure sensor needs to be sent to the processed by the server end and get stored in a Database. For this we have used the WAMP application. The WAMP application package provides developers the flexibility to host a server and deploy web applications. It comprises of four key elements: an operating system (OS), a database (DB), Web server and Web scripting language. WAMP is the acronym for Windows/ Apache/ MySQL/ PHP where Windows is the OS, MySQL is the DB, Apache is the Web Server and PHP is the scripting language used for Web Development.
Figure 3.12 shows the User Interface where the data logged in by Arduino is stored. The data is recorded along with the original timestamp which thereby helps in future analysis. This data is
accessible with the IP address of the server. It gives the caregivers and health care providers to monitor patient’s data on real time basis or even later.

Figure 3.13 shows the similar server data log with four sensors sending data simultaneously and then getting stored in the server. This figure displays the UI where multiple sensor data has been taken as input and stored.

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Figure 3.13. UI displaying the multiple sensor values stored in server
3.6 RESULTS AND OBSERVATIONS

Experiments have been performed with our system and a complete end to end monitoring was also done. With the data being stored continuously, we created a gait data repository with data from different subject for varied interval of time. Primarily to test whether the data received at the server end is actually the data generated by the Arduino UNO microcontroller or not, we took a note of the sensed data from the serial monitor of the Arduino UNO. Figure 3.14 shows a part of the readings from serial monitor of Arduino microcontroller. These data was continuously verified to be exact and accurate based on the subject’s movements. Whenever the subject stopped applying pressure it went to 0 and when there was movement the variation in the pressure was noted.

In the Figure 3.15 the serial monitor output simultaneously from four sensor readings is shown. It is noticed that Sensor 3 (sensor placed right below the toe) contributes to much larger pressure variation when we plotted the graph separately. This is because the pressure exerted in Sensor 3 is always low as compared to other pressure point areas. This can also be studied from the pressure variation graph provided by R. W. Soames [26].
Figure 3.14 Arduino serial Monitor output for sensing pressure sensor data
As we started getting data from the Arduino, we tried plotting that into a graph to understand the variation of the data values. Figure 3.16 shows pressure variations that differentiate a normal pause or halt in walk and freezing. We could also make analysis of steps in the motion recordings of the subject. In the graph, the first FoG duration is 16 secs and the second FoG duration is 12 secs. From the graph shown in Figure 3.16, it seems that the rapid pressure variations in the data values is due to the freezing. During this time a patient tries to continue his motion but is not being able to complete the gait properly and a rapid shaking and trembling is noticeable. This results in a quick change of a pressure value giving the thick lines in the shown graph. Whenever
a person takes a natural and intentional pause from walking then we get a constant sampled value of 1023 for that pause period. During this time, the peak of the graph is much smooth and continuous. Apart from this the crest and troughs in the graphs is generated because of the pressure exerted during walking and having normal footsteps.

Figure 3.16 Pressure sensor data plotted against time (10 samples per second) showing FoG, deliberate pause and movement pattern

Figure 3.17 shows the graphs plotted from the pressure data received from individual four sensors simultaneously at every instance. The other three sensor data except the one below the toe, when plotted gives almost the similar variation pattern. This is because the pressure exerted at all other points are almost similar. That is why even with slight changes at any instant of time, the pressure distribution is pretty much the same.
Figure 3.17. Gait data collected simultaneously and plotted for four sensors

Figure 3.18. Resultant gait data from four sensors
Figure 3.19 Gait cycle quantified from pressure sensor data

GAIT QUANTIFICATION

We have used pressure sensors in shoe sole to determine the force exerted by a patient’s feet which gives us an estimation of changes in footsteps, stride length, gait cycle and walking pattern. These parameters collectively give us an idea of variations during the FOG event and thereby provide a quantifiable platform to measure the gait impairment among the patients. In the Monash University research repository a work was reported by Gowanda [45] mentions that on an average of a person takes 1.283s and 1.208s for the right limb and left limb respectively to complete one gait cycle walking at 3 km per hour. By Gait cycle we mean the time elapsed between one of the foot making contact with the ground for two successions. The gait cycle starts when one foot makes contact with the ground and ends when that same foot contacts the ground.
again [46]. In other simulated walking conditions, which were intended to portray abnormal gait situations, subjects took longer time to complete one gait cycle. The slower the walking speed, the longer was the gait cycle. In figure 3.20 we showed part of the graph to depict a complete gait cycle and this is reported from our results obtained from the shoe sensing system using a simulated patient subject.

From the statistics, gait data results and gait analysis shown by Gowanda it is evident that in the 30 stride results that they used for experiment and analysis were of about 6 to 8 strides. Stride length is the distance between two steps. The average time for stride is 1.28 s. Another work of Chakraborty et al. [33] showed alternate way of quantifying gait data with simulated patient scenario. In ref. [48] quantitative features from sensors were used to develop models that output 0-4 scores to predict UPDRS score.

In the following graph presented in figure 3.20 we have shown that how the 4 sensor data quantify gait and are correlated with the movement of the subject. In the circular chart given below, the center represents absolute zero pressure on the sensor i.e the subject is in normal motion. The periphery, on the other hand says that subject is exerting high pressure on all of the 4 sensors i.e., the subject is standing. Thus the circular graph quantifies the subject motion on a scale of 0 to 4 where 0 represents normal movement and 4 represent zero movement of gait. However, the intermediate regions represents uneven distribution of pressure among the sensors. The variation of pressure is mostly seen in the two sensors. These two sensors are the major contributor in decision making and concluding about FoG.
Figure 3.20 Quantification of gait with respect to the number of sensors used

WiFi DATA ACQUISITION

Similar experiments have been done to see whether the WiFi module is able to properly connect to the internet or not. For this we tested the serial monitor output from the Arduino connected with the WiFi module. Figure 3.21 shows the screenshot of the serial monitor output. The system also prints the IP that the router has dynamically assigned to it following the Dynamic Host Configuration Protocol (DHCP) standards. Additionally, other connection details like the subnet mask, the gateway information and Domain server IP is also obtained. After every data received from the pressure sensor it checks for the connectivity of the WiFi to make sure that the data is successfully transmitted to the server end. It is also checked whether the data shown at the serial
monitor is actually sent to the server side or not, by verifying the server entry and checking the intermediate database where these records have been stored.

Figure 3.21 Arduino serial Monitor output for sensing pressure sensor data and sending to the server via WiFi

There is a certain amount of delay that is observed in the readings of the server. The delay between two readings is the sum of the “interval” value (10,000 = 10 seconds) and the sum of all the time it took to read the sensors and send the data to the server which is approximately 13 seconds. Moreover using 4 sensor data individually and sending them over to server incurs a considerable amount of delay hampering the real-time performance of the monitoring system.

A reading from a sensor takes approximately 750 milliseconds in 12 bit (default) mode.

This delay is calculated as a summation of the interval time between each reading and the sum of all the time it took to read the four sensors and send the data to the server.
Which is: \[500 \text{ ms} + 4 \times (750 \text{ ms}) = 3000 \text{ millisecond of delay in every reading.}\]

This definitely makes the system slower than what is desired. This is also due to the fact that sensing four sensors happens simultaneously but sending it over to the internet consumes only one channel. This leads to ‘time-slicing’ mechanism of the channel while transmitting data.

### 3.7 DATA RETREIVAL AND ANALYSIS TOOLS

We have designed a user interface where this stored data can be interpreted by the physicians in a more user friendly manner. The application converts the data into graphs which makes more sense in analyzing and interpreting the data. The Graphical User Interface (GUI) is simple to operate by any naïve users. The interface has option to display data based on user’s choice. As shown in Figures 3.22 and 3.23 the user can select a particular date range as his choice of selection. The GUI provides the choice of filtering data based on one to many days, weeks or even month.

The UI is also enabled with a check box. This checkbox is used to activate live data display. On clicking this checkbox the current that is captured by Arduino and stored in the database, gets called to the frontend UI and is then displayed in the form of graph. In figure 3.24 the “Live Data” checkbox could be seen at the bottom towards the center and it continuously displays data at current timestamp. Based on user’s input, stored gait repository is searched for the gait data and is displayed in the form of graph. Instead of looking at the individual data, the statistics presented
by the graph with a visual representation is more helpful. This helps the doctors and physicians in making decision on data and to graphically view a large dataset.

Figure 3.22 UI for graphical display of data and Date picker functionality
Figure 3.23 UI for graphical display of data and Date picker functionality

Figure 3.24 UI for graphical display of data and Live data display functionality
When the live data checkbox is ticked or in other words the live data is activated, the User Interface of the system starts picking up the current data and plots the graph based on the pressure sensor data it receives in the current time instance. With this feature it is very helpful to see the pressure pattern while a patient is walking from doctor’s clinic remotely. At any instance of time the graph will keep on getting generated to provide the live view of the patient’s gait pattern. This system is very handy and useful for a layman to understand the overall scenario of the subject’s health.

3.8 APPLICATION IN OTHER AREAS

Our proposed system for monitoring, online data collection, offline data retrieval for analysis of patient’s health can also be used in several other areas. This system can be customized in several ways to alleviate different persisting problems.

- Our monitoring system can be applied to construct an in-home surveillance system for the patients suffering from the impending problem of several other neurodegenerative diseases, such as the Progressive Supranuclear Palsy which include the inability to walk, falling spells, and stiffness.

- WBASN technology is used to integrate different physiological data from sensing and monitoring devices and constantly check the firefighter’s health in training or in action. Several studies suggest that firefighters are under high risks of cardiac attacks due to heat stress and quick high physiological exertion. Thus, it is very important to track the location
of firefighters in a real fire scenario, so as to alert the crew chief during medical emergency of these first responders.

- It can be used to monitor the postural balance and stability of athletes in real time and provide valuable feedback to the coaches and trainers so as to minimize the injury to athletes and maximize their playing potential. Also, this since this system is enabled to log the sensed data, thus providing the analyst and the coach ability to monitor past performances of athletes and thus help in determining the level of injury that an athlete is currently suffering or has suffered and a progress report can be generated based on that.

- Accelerometer and Gyroscope can be jointly used along with this system to determine mobility of a person suffering from Paraplegic diseases.

- This system can be a solution to uninterrupted monitoring for emergency services that require prolonged and constant attention.
4. CONCLUSIONS AND FUTURE WORK

4.1 CONCLUSIONS

In the concluding chapter the major aspects of PD patient care can be highlighted and the ways such a system is developed and is capable of serving them. Firstly, the patients need an external cue to come back from FoG. Various medical methods suggested both visual cue and auditory cues. Visual cues may be an illuminated spot in front of the patient’s foot or a LASER mark or line. Auditory cue is a kind of rhythmic beat which helps the patient to resume back his or her normal gait rhythm. In most of the marketed system, the cuing systems are static in nature. That means they are always turned on even when the patient is maintaining the normal gait pattern. Our system turns on the visual cue only when a FoG is detected. In the prototype developed, we used an LED to light up while the FoG is detected. In future, a better quality LASER LED may be used for better illumination on the floor.

The other monitoring systems are, mostly visible to the patient. Sometimes the knowledge of being monitored leads to abrupt gait behaviors. But we approach towards a hidden monitoring system capable of acquiring gait data and sending it wirelessly to a remote server. Hidden system will not influence on the patients psychology hence we can expect to capture more intrinsic gait pattern.

Remote monitoring and gait data repository is a novel idea to facilitate both the doctors and the researchers who are working with the gait impairments. While doctors will be able to have 24X7
access to the gait data of his patients, the gait data repository will serve as a data bank for the researchers who are working with advanced gait feature recognition and extraction. Thus our system serves some of the very important aspect of PD palliative care giving processes and future research activities.

4.2 FUTURE WORK

The work herein presented is a smart PD patient monitoring system that leverages wearable sensor technology, WiFi connectivity and a client-server application to collect and analyze gait movement data. Our endeavor results in a smart shoe that demonstrates the capability of analyzing wearable sensor data, detecting FoG and providing visual cue automatically. The embedded system we could prototyped and reported here is built with a general purpose microcontroller, Arduino Uno. We had to use different shields for WiFi and Ethernet. Hence in future we can try to produce application specific integrated circuit that may reduce the bulkiness of the circuit further. Moreover the sensors are used can be upgraded with superior quality of sensors those are able to differentiate minor change in pressure. Now the system could be considered for further upgrading by adding artificial intelligence into it. We can implement learning mechanism for personalized FoG detection with minimal latency in providing visual cue. The system can be even tested with large number of PD patients and the huge gait movement data thus generated could be gathered in an online repository as a large variety of database for further gait data analysis and pattern mining. Gait data mining and finding different gait data classes may be a future approach towards data driven PD gait impairment research.
BIBLIOGRAPHY


