

# Ubiquitous Personal Assistive System for Neuropathy

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## ABSTRACT

The improvement in processor performance through continuous breakthroughs in transistor technology has resulted in the proliferation of lightweight embedded systems. Advances in wireless technology and embedded systems have enabled remote healthcare and telemedicine. Continuous and real-time monitoring can discretely analyze how a patient's lifestyle affects his/her physiological conditions and if additional symptoms occur under various stimuli.

Diabetes is one of most difficult challenges facing the health-care industry today. One of the primary afflictions of diabetic patients is peripheral neuropathy (loss of sensation in the foot). As a direct result of this condition, the likelihood of ulcer increases which in many cases leads to to amputation. We have developed a wireless electronic orthotics composed of lightweight embedded systems and non-invasive sensors which can be used by diabetic patients suffering from peripheral neuropathy. Our proposed system monitors feet motion and pressure distribution beneath the feet in real-time and classifies the state of the patient. The proposed system detects the conditions that could potentially cause a foot ulcer. This system enables a continuous feedback mechanism for instance in case of an undesired behavior or condition a preemptive message wirelessly to the patient's cell phone/PDA/PC and over the WEB to the patient's caregiver. This system can potentially reduce the amputation rates resulting from neuropathy by a huge factor.

## Categories and Subject Descriptors

C.3 [Special-Purpose and Application-Based Systems]: Real-time and embedded systems; J.3 [Computer Applications]: Life and Medical Sciences Medical information systems

## General Terms

Design, Architecture

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## Keywords

Ubiquitous Systems, Neuropathy, Classification, Body Area Network

## 1. INTRODUCTION

Recent advances in electronics industry and wireless communication have enabled many new interesting domains of applications. Embedded processors and systems are becoming widely used in people's everyday life, in such areas as mobile communication, automotive industries and medical applications. Demands for a higher level of health service and the need to achieve quality health care at lower costs and lower overhead has increased significantly throughout the years. The large health care market, along with research opportunities, are strong motivations for researchers in electrical engineering and computer science to develop technologies that can be adopted in medical fields. Telehealth refers to the application of telecommunications and information technologies to the delivery of health care and health related services and information beyond physical borders [13].

A variety of applications lie under the Telehealth category. Initially, Telehealth mainly referred to remote consultation of physicians located in different geographical locations for diagnosis and treatment advices. Later on, with advances made in robotics and high-speed communication, telesurgery applications emerged where a surgeon performs surgery on a patient when he/she is not physically in the same location. Nowadays, all aspects of health care ranging from physiological signal monitoring, diagnosis, rehabilitation and treatment to surgical procedures utilize advance technologies and are referred to Telehealth. Telehealth systems are not only used to make health care applications available in remote areas, such as homes, schools, nursing homes, and military camps but also in ubiquitous infrastructures that can improve the quality of overall health care. Studies have been made to explore communication challenges in telesurgery [4] or communication requirements [14] for a reliable framework. Furthermore, researchers have studied wireless sensor networks as a means of health care [12] and robotics challenges for patient monitoring [6].

Diabetes is one of most difficult challenges facing the health-care industry today. According to the CDC, last year there were 21 million people with diabetes in the United States. The diabetic population in the United States is projected to increase to 27 million by 2010. Insurance companies, Medicare and the health care system currently expend \$132

billion per year on treatments for diabetes. One of the primary afflictions of diabetic patients is peripheral neuropathy (loss of sensation in the foot). With peripheral neuropathy, diabetic patients often develop pressure wounds (foot ulcers) on the soles of their feet. Last year, with the current treatments for preventing foot ulcers, 90,000 amputations were performed on diabetic patients in the United States. The treatment of these complications cost \$9B. We have developed a prototype electronic orthotic insert for diabetic shoes. The system will be identical in form and function to the custom-made diabetic orthotic inserts that are prescribed and used today - with the addition of an embedded wireless sensor mesh and an electronic processing and communication system. Our proposed system detects the conditions that would cause a foot ulcer to form and then sends a preemptive message wirelessly to the patient's cell phone and over the WEB to the patient's caregiver.



**Figure 1: A foot after amputation as a result of neuropathy**

Today the best method available to prevent diabetic foot ulcers is doctor prescribed shoes and accommodative orthotic inserts to support and reduce excessive abnormal pressure. Unfortunately, today's solution is passive and does not provide any indication or warning if there are conditions in the shoe that are approaching the creation of a pressure sore. Diabetic foot ulcers often appear in spite of today's recommended treatments and in fact are sometimes caused by the prescribed orthotic inserts themselves.

## 2. ARCHITECTURE

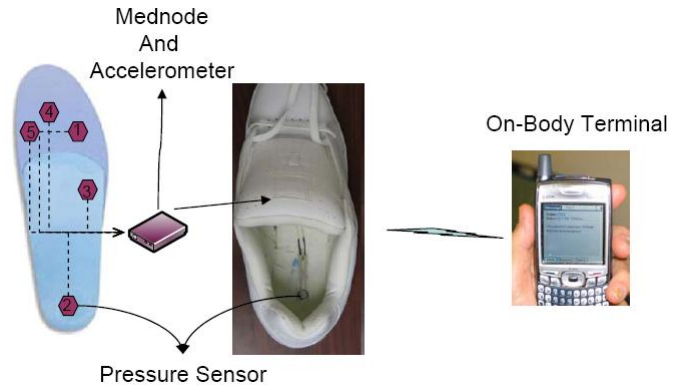
The Electronic Orthotics Shoe system is implemented with standard, ubiquitous, lightweight wireless embedded systems to ensure the largest impact and potential for adoption. The following sections describe the hardware and software architecture of the Electronic Orthotics Shoe system.

### 2.1 Hardware Architecture

The high-level system architecture of Electronic Orthotics is illustrated in Figure 2. The main components of our system include:

- Sensors for monitoring pressure distribution, motion and gait analysis
- MedNode: Embedded components for data acquisition, signal conditioning and wireless communication
- On-Body Terminal which is personal portable device for data storage, classification and representation as well as providing feedback

- Central server (medical enterprise) which stores patients' history and information for further analysis



**Figure 2: General architecture of our system, starting from the sensors to personal server (on-body terminal)**

In the rest of this section, we describe each component in more details:

#### 2.1.1 non-invasive sensors

We incorporate two different set of sensors. (i) Pressure sensor sheet: This is an array of flexible pressure sensors [2] that is placed inside the orthotic and covers the bottom of the foot. Through this sheet of sensors, pressure and weight exerted on different sections of the foot can be sensed and quantified. Pressure sensors are ideal for measuring forces without disturbing the dynamics of a test. They can be used to measure both static and dynamic forces. They are thin enough to enable non-intrusive measurement. (ii) 3-Axis accelerometer: This sensor [1] is used to measure acceleration in 3 perpendicular axis. The acceleration information is used for motion classification and gait analysis. Motion classification and gait analysis will enable detection walking behavior which may cause ulcer. More details will be provided in future sections.

#### 2.1.2 MedNode

Mednodes are the basic building block of our telehealth devices which are composed of a low-power wireless transducer, signal conditioning board and a battery. There is a small light-weight transducer embedded in the orthotic which is connected to the pressure sensors and reads the data from them. This transducer can be reconfigured to sample the data at various rates and with different precisions. The collected data is wirelessly transmitted to the on-body terminal and/or base station. The MedNode [11][10] can interface with various types of sensors, such as pressure, accelerometer, galvanic skin response, flex, piezo-electric film and temperature sensors. These sensors can provide continual physiological measurements as well as environmental measurements, even when people are operating in hazardous environments.

#### 2.1.3 On-Body terminals

The on-body terminal is a light-weight monitoring device used for visualization, monitoring and local data processing on gathered information from sensors. Off-the-shelf devices, such as cell phones or PDAs can be configured as the on-body terminal through software. One of the main functionalities of the on-body terminal is information processing, transmission from/to base station and to/from other terminals.

#### 2.1.4 Central Server

The final layer of the system (which in fact is independent of the application) provides connectivity from the on-body terminal to the medical enterprise. The central server is responsible for storing patients' information and maintaining a reliable history of behavior.

## 2.2 Software Architecture

The software architecture in our system consists of two main components. First component is the embedded software, which is running on the processing unit embedded inside the shoe. The second part is the software, which is getting executed on a personal device such as cell phone or PDA. The software running on the embedded processor is responsible for data acquisition, some preliminary data and signal processing, and transferring collected data to the personal device. Software running on personal device is responsible for more computational and storage intensive tasks such as data filtering and signal processing in addition to the user interface, which can display the collected data from different sensors and also the pressure's severity under the patient's feet in real time.

#### 2.2.1 Embedded Software

In order to collect data from pressure sensors and accelerometers embedded inside the shoe, and perform some local data processing, we used TinyOS operating system [8]. TinyOS is an open-source operating system, developed at UC Berkeley, which has component based architecture. TinyOS has been designed to facilitate rapid application development for wireless embedded sensor networks. We developed the software using nesC, which is an extension to C that let the developers to express the model of the execution for TinyOS applications [7].

The program in each timer interrupts reads data from processing units' ADC channels that have pressure sensors and accelerometers attached to them and perform some local data processing. It later sends the sensed and pre-processed data to the personal device, either using Zigbee or Bluetooth. The components of our software are developed on top of deluge [9]. Deluge is a reliable dissemination protocol, which lets the user to reprogram the sensor nodes in the network. The software developed on deluge is reconfigurable even after deployment. This gives users the power of software reconfiguration on the processing node in the shoe to meet the application's specific requirement. Such a reconfiguration can be, changing the sampling frequency, changing the data transport medium from Zigbee to Bluetooth. For example if the user/application decide to reduce the accuracy to achieve availability, it can reconfigure the software to sample and stream data less frequently to save battery power.

#### 2.2.2 Personal Device

Sensor data collected from data acquisition units in the shoe can be streamed to variety of devices, as long as they are Bluetooth enabled or have Zigbee interface. For experimental purpose we interface the shoe with both a PDA and PC. The software running on personal device has the following 4 layers of architecture. These 4 layers are network interface, processing, presentation and notification. In Network layer, streamed data received from the shoe is buffered, arranged to make sure that they are in order and batched before sending to processing layer. Processing layer is responsible to log streamed data, perform signal processing, and provide an API to use each of its components. Processing unit can implement different techniques such as filtering, feature selection and classification to convert raw data to a meaningful chain of information, which can be interpreted and reason based on its variations. Logging module is storing received data from each sensor through network layer. The logged data can be used for variety of purposes such as displaying the activity on UI and monitoring patterns in long period of time.

User can interact with processing and network layer through provided API. Presentation layer displays the data reading from each pressure sensor and accelerometer in real time. It also has the capability of playing the logged data for desired period of time. Through presentation, graphical user interface, real time normalized data stream from each pressure sensor and accelerometer is displayed in separate charts, one for pressure and one for accelerometer. GUI also can display log replay in addition to an interactive image of human feet, where the location of each sensor on the bottom of the feet is marked and corresponding regions color is changed according to the severity of pressure (from pink as no pressure to red as too much pressure). The notification layer is connected to processing layer and it acts when an event is triggered by processing unit, which is an indication of emergency, abnormal situation, or some event which needs attention. Notification component is responsible to propagate the detected situation to the user via user interface and other mediums, such as SMS, email, phone calls etc.

The software architecture diagram is presented in Figure 3 and the graphical user interface is illustrated in Figure 4.

## 2.3 Networking Options

In addition to the embedded Zigbee transceiver module in the Mednode (which is based on the Mica2 technology), a Bluetooth transceiver module is interfaced to the mote. Comparing to Bluetooth, Zigbee has lower energy consumption and better time considerations i.e. network join time [3], which makes it the first choice for energy restricted embedded systems.

However, although Bluetooth communication has higher power consumption and cost [3], many embedded monitoring devices [5] take advantage of it, due to its availability and wide use in laptops, smartphones and PDAs. Since normal smartphones and PDA are used as Medshoe's monitoring interface to the patient and clinicians, using Bluetooth reduces the additional cost and burden of interfacing Zigbee transceiver modules to these devices.

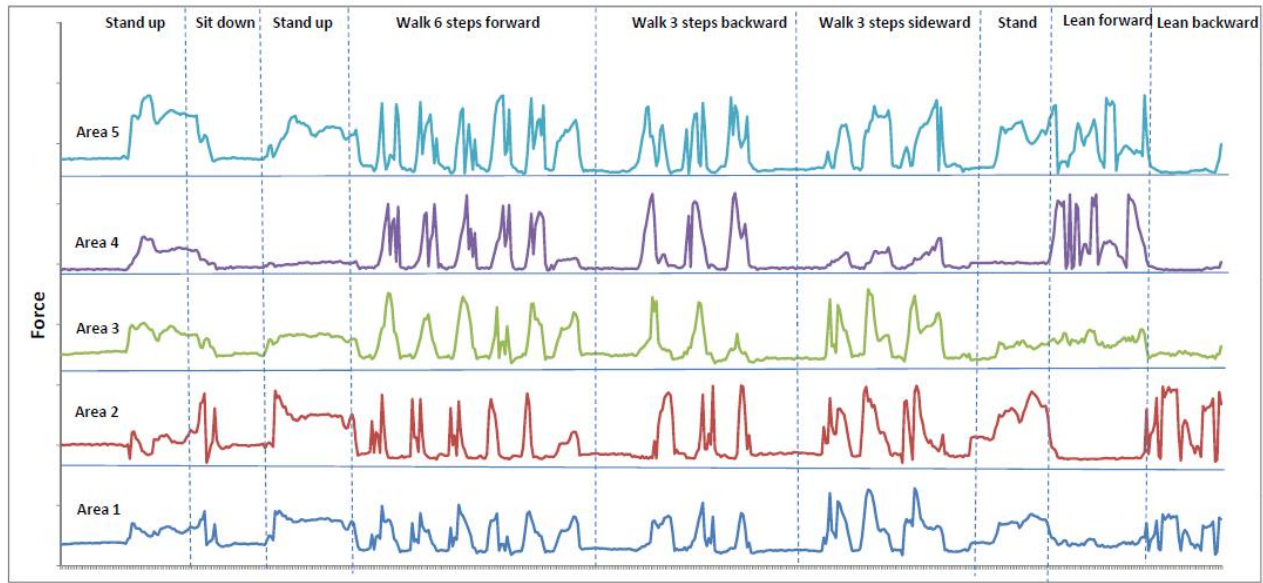


Figure 5: Data from the pressure sensors embedded in the Electronic Orthotics Shoe system for the five different regions in Figure 2. The experiment duration was 30 seconds and the pressure values have been normalized to the maximum force.

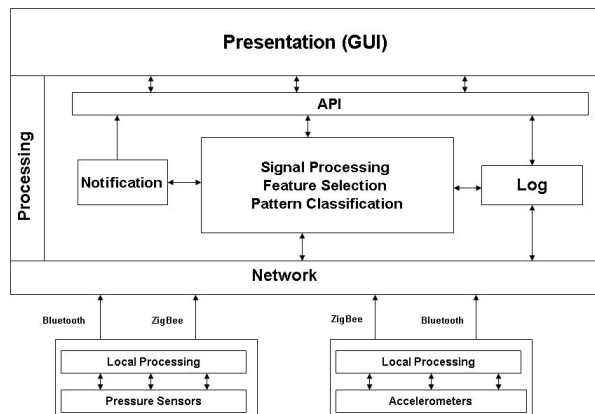


Figure 3: Software architecture for the Electronics Orthotics Shoe System

### 3. SYSTEM FUNCTIONALITIES FOR ULCER PREVENTION AND FOOT CARE

Meticulous attention to foot care and proper management of minor foot injuries are key traditional methods to preventing ulcer formation. Daily foot inspection by the patient (or a caretaker if the patient lacks sufficient visual acuity or mobility to perform the examination) is the cornerstone of proper foot care.

Our proposed system can improve the prevention significantly through maintaining certain specifications and func-

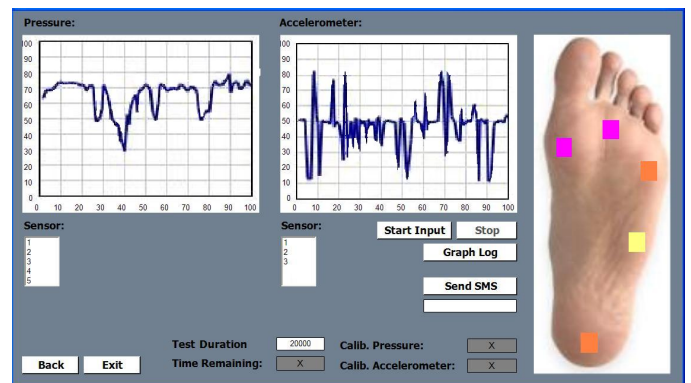


Figure 4: A snap shot of the GUI. Left window represents the data from a pressure sensor and the right window illustrated the data from one axis of the accelerometer.

tionalties as a result of real-time pressure and motion monitoring. The system will be able to perform the following actions according to the real-time needs:

- Alert the patient and/or caregiver that conditions leading to skin compromise or a foot ulcer may be forming. The warning can be a text messages or any other convenient method which will be determined during the proposed research.
- Real-time feedback about the amount of time she/he can safely stand/walk on the foot, or rest their feet on the ground while sitting.
- Real-time feedback on the amount of time she/he can

safely wear their shoes.

- Provide information about activities and/or exercises that the patient can perform without increasing the risks.
- Provide physiological data to physicians and clinical databases.
- Can be dynamically and automatically reconfigured and customized for different patients in different environmental situations.

One of the main challenges in the proposed system is interpretation of data and pattern classification procedures. Data from pressure sensors and accelerometer are used to classify how the person wearing the shoe is moving and to analyze his/her activities.

#### 4. EXPERIMENTAL RESULTS

We have been running different experiment with the Electronic Orthotic Shoe. The information from the sensors is analyzed on the our Matlab classification software on the server. Figure 6 shows a snapshot of the information along with graphical representation of the regions on the foot which are experiencing severe pressure. An instance of the experimental results is illustrated in Figure 5. The duration of this experiment was 30 seconds and the pressure values of 5 regions in Figure 2 have been normalized to the maximum force in that region and plotted (the results are for the left shoe). Throughout the experiments, the subject performed seven different behaviors: Standing up, from a chair, sitting down on floor, slowly standing up, walking forward, backward and sideward, standing still, leaning forward and finally leaning backward.

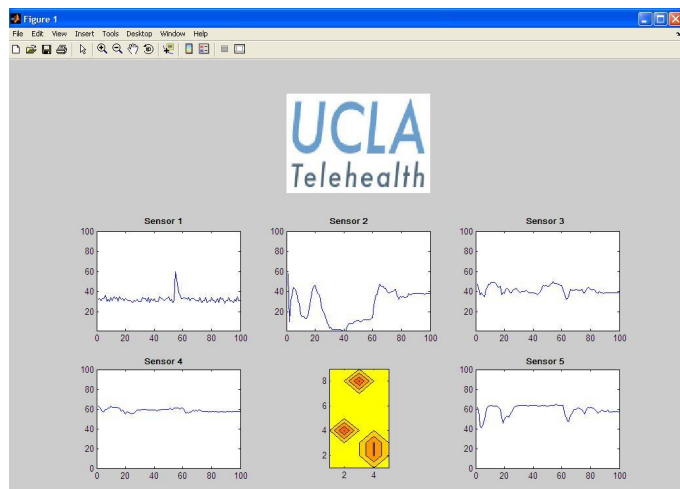


Figure 6: The Matlab-based classification software run on the server

The overall purpose of this experiment is to illustrate how we can reliably monitor realtime motion and pressure distribution and based on the state of the person, the pressure values and the duration of the pressure, conclude events the can result in foot ulcer. We store similar graphs for the 3-axis accelerometer as well. A snapshot the y-axis of the accelerometer is shown in Figure 4

#### 5. CONCLUSION AND FUTURE WORKS

In this paper, we presented the Electronic Orthotic Shoe system as a means of ulcer prevention for patients suffering from neuropathy. This system is designed and developed using lightweight wireless embedded systems and non-invasive sensors. Furthermore, we illustrated some experimental results showing how we can extract the pressure pattern below the foot and how we can use this information for classification and gait analysis. This system enables real-time monitoring and provides feedback to the patient/caregiver.

There are potentially many essential objectives that we will pursue in future. First, we are developing multiple systems for conduct a clinical study and quantify the effectiveness of our system. Although, we can classify and detect various phenomea on this system, lightweight classification and calibration algorithms are among interesting problem which we are exploring. Furthermore, there are two major technical problems that we are currently investigating which are the reliability of the system/service and its security.

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