A wireless sensor insole for collecting gait data

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A Wireless Sensor Insole for Collecting Gait Data

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Abstract. This paper presents the status of EU project WIISEL - Wireless Insole for Independent and Safe Elderly Living, with focus on protocol for inertial sensors calibration and wireless communication design. Communication between the sensors embedded into insole (pressure and inertial) and the Smartphone (collection of signals) is done via ½ wavelength dipole antenna and utilizing Bluetooth Low Energy.

Keywords. Fall, wearable insole, embedded sensors, pressure sensor, inertial sensors, Bluetooth low energy

Introduction

Falls are a major health problem for elderly people causing both immediate effects like fractures and head injuries as well as longer term problems such as disability, fear of falling and loss of independence. Early detection of individuals at risk of falling is thus of importance for health providers since therapy preventing falls should ideally be introduced before any accidents can impair a person’s independence, self-confidence and quality of life. The European project WIISEL (Wireless Insole for Independent and Safe Elderly Living) is aimed at creating a flexible research tool for collecting and analyzing gait data from users in their everyday lives.

A wearable gait observation system is being developed in the form of autonomous insoles that can collect sensor data throughout the day. Each insole comprises 14 pressure sensors for studying posture and inertial sensors for measuring the trajectories of the feet (3-axis accelerometers and gyroscopes). Both pressure and inertial sensors are off the shelf components that are integrated in flexible insoles for a faster system development. A commercially available Smartphone is used to wirelessly collect data

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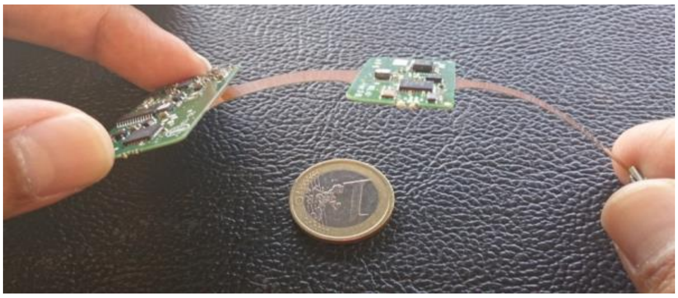

Figure 1. The embedded flex-rigid electronics system.

in real time from the insoles and transfers it to a backend computer server via mobile internet connection. Transfer of sensor data from the insoles to the Smartphone is implemented using the Bluetooth Low Energy wireless standard.

The risk of falling will be assessed using pattern recognition based on multiple gait parameters. The WIISEL system will allow researchers to quantify activity and assess the quality of gait under real life conditions. It will enable clinicians to evaluate and monitor fall risk in elderly patients, in the home and community environment, mostly reflecting everyday life behavior.

1. Integrated Insole System

The WIISEL insole is designed to contain a complex system of sensor electronics embedded in a wearable insole. The electronics have to be highly protected from moisture and from mechanical damage while the insole also has to provide comfort to the user. To ensure flexibility of the insole, electronic components are mounted on a flex-rigid printed circuit board, Figure 1, and a less than 1mm thick semi flexible battery (…) is used to power the system.

For protection and comfort, the electronics system is entirely encapsulated in materials typically used for custom made insoles. Since the entire system is encapsulated, the battery is charged using the inductive Qi standard that is getting popular for wireless charging of mobile phones and other consumer product.

1.1. Pressure Sensors

A matrix of sensors is placed in the insole to capture gait parameters related to foot pressure distribution, Fig. 2. Each sensor plate is a commercially available pressure sensitive resistor. The 14 individual sensors are connected between a voltage supply level and an analog multiplexer that can be controlled to connect one sensor at a time to the input of a transimpedance type amplifier. The output voltage from the amplifier is read using an analogue to digital converter on a microcontroller that can scan the pressure distribution up to 50 times per second. The conductivity of each resistive pressure sensor is generally linearly proportional to the pressure applied to it while the constant of proportionality varies a lot between individual sensors. The standard deviation is of order 10%. Hence all pressure sensors need individual calibration in a compression test machine in order for the insole to accurately measure the posture of a user.

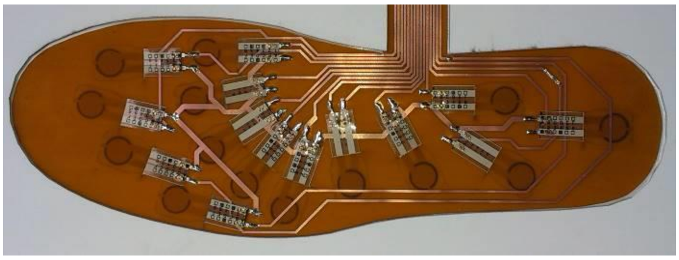

Figure 2. Encapsulated pressure sensor layer.

1.2. Inertial Sensors

Inertial sensors can be used for observing a multitude of different gait parameters. Temporal parameters such as step time, stance time and swing time can be recorded using accelerometers that are relatively cheap and consume little power. To extract spatial parameters like step-length and foot-clearance over the ground one must on the other hand combine data from accelerometers with data from gyroscopes that are used to keep track of the orientation of the accelerometers relative to the ground. Gyroscopes generally consume several milliwatts of power compared to a few tens of microwatts for an accelerometer and are also more expensive.

Each WIISEL insole includes a motion tracking inertial sensor that combines a 3-axis accelerometer with a 3-axis gyroscope in one integrated circuit. The sensor has a SPI communications interface that allows a microcontroller to collect inertial data directly in digital form and it has relatively low power consumption compared to other gyroscopic systems on the market.

All inertial sensors have static offsets as well as variations in sensitivity to acceleration and rotation that to some extent are compensated for by the circuit manufacturer. It is however recommended to calibrate them again after mounting them on a circuit board since thermal stresses during soldering can introduce differences to the factory calibration. It is convenient to use a linear model for the measurement errors of inertial sensors so the calibrated accelerations, a_{xyz}, and rotations, r_{xyz}, are calculated using linear expressions of the raw sensor data outputs acc_{xyz} and rot_{xyz}.

$$a_x=k_x*(acc_x-b_x);\quad a_y=k_y*(acc_y-b_y);\quad a_z=k_z*(acc_z-b_z) \tag{1}$$

$$r_x=l_x*(rot_x-d_x);\quad r_y=l_y*(rot_y-d_y);\quad r_z=l_z*(rot_z-d_z) \tag{2}$$

The calibration procedure is aimed to obtain as good estimates as possible of the zero acceleration and rotation biases b_{xyz} and d_{xyz} as well as optimal estimates of the sensitivity scale factors k_{xyz} and l_{xyz}.

To calibrate an accelerometer one can utilize the fact that the vector sum of the 3-axis post calibration acceleration values should add up to the earth gravitational field $g=9.82m/s^2$ when the accelerometer is kept at rest:

$$(k_x*(acc_x-b_x))^2 + (k_y*(acc_y-b_y))^2 + (k_z*(acc_z-b_z))^2 = g^2 \tag{3}$$

All real measurements will contain random noise so the calibration parameters k_{xyz} and b_{xyz} can't be chosen to give a perfect match to g^2 for a series of more than six measurements. Instead the individual deviation from g^2 for each measurement in a large set is represented by err_i in (4) below. The six calibration parameters can then solved for so they minimize the sum of errors squared for a large set of measurements as described by (5).

$$err_i = (k_x*(acc_x - b_x))^2 + (k_y*(acc_y - b_y))^2 + (k_z*(acc_z - b_z))^2 - g^2 \tag{4}$$

$$\sum err_i^2 \tag{5}$$

To reduce the influence of random noise on the calibration procedure, several hundred measurement samples should be used for one calibration. Furthermore, to achieve stable estimates of the calibration parameters one should use measurement data from the accelerometers positioned in 6 orthogonal orientations relative to the earth gravitational field. When calibrating an insole it should subsequently be positioned with the flat side up and down then turned on its side up and down and then put upright standing on the toes and heel. It is not crucial that the 6 different positions are exactly orthogonal since the axes of the accelerometer are not calibrated individually but it is the vector magnitude that is compared to 1*g*. A few degrees of deviation from perfect 90^o angles are tolerable. Measurements made when changing the position must however not be included in the analysis since they will also contain acceleration from movement which means that the expected vector magnitude is not exactly 1*g*.

A gyroscope can be calibrated in a similar way using a rotation table that can be set to rotate at a predefined number of degrees per second. The angular velocity of the table, *R*, would take the place of *g* in the equations above and the sum of squares of the post calibration 3-axis vector components from the gyroscope should add up to R^2.

1.3. Wireless Communications

The WIISEL system is designed to continuously monitor the gait of a user wearing the sensor insoles throughout the day. A commercially available smartphone is used to collect the data wirelessly in real time from the insoles and to transfers it to a backend computer server via mobile internet connection. Transfer of data from the insoles to the smartphone is most conveniently implemented using a wireless standard already found on available smartphones.

Most modern smartphones have Bluetooth for enabling short range exchange of data with external devices. The classic Bluetooth protocol is not however optimized for power conservation. Thus unsuitable for the WIISEL system since the batteries used in the insoles must be thin and flexible and therefore have limited capacity to store energy. The Bluetooth Core Specification v4.0 adopted in 2010 introduced the so called Bluetooth Low Energy (BLE) standard that is optimized for devices with limited power supplies. The maximum effective application data throughput of BLE is far less than that for classic Bluetooth but it is sufficient for the WIISEL system.

For central processing and wireless communications, each WIISEL insole includes a combined microcontroller and BLE transceiver chip. The fact that the system will be integrated in insoles complicates the design of Bluetooth antenna since both feet and ground can effectively shield the radio signals. Several antenna types were tested for the WIISEL system including chip antennas and antennas printed directly on PCB. In the end, best performance was achieved by connecting the differential RF transceiver port of the microcontroller chip directly to a very simple ½ wavelength dipole antenna made of two 30mm long isolated wires, Figure 3. This type of antenna has the

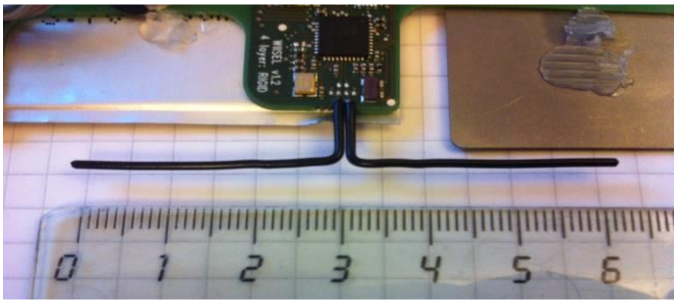

Figure 3. Bluetooth ½ wavelength dipole antenna.

advantage that it can be embedded near the outer edge of the insole. The dipole antenna is not omnidirectional but radiates most strongly in directions orthogonal to the axis of the metal wires. Relatively strong radio signals will thus penetrate in directions out from the side of the shoe.

The embedded microcontroller implements a Generic Attribute Profile (GATT) server interface that makes it possible for the smartphone to control each insole via Bluetooth Low Energy. The smartphone can for example read and write to all control registers on the inertial sensor, read the battery level on the insole, set up sampling conditions like the sampling rate and order the insole to start or stop sampling. The GATT server interface is also used for streaming sensor data to the smartphone. Continuous transfer of sensor data is implemented by streaming so called notification packets with 20 bytes maximum application data payload at rates up to 100 packets per second from each insole.

The maximum sampling frequency used for both pressure and inertial sensors is 50Hz. Pressure data is collected with 10 bit resolution from 14 individual sensors while the accelerometer and the gyroscope generates 3-axis data vectors where each element has 16 bit resolution. A 32 bit millisecond precision timestamp is furthermore saved for each data sample. Hence the total data throughput is 13.4kBit/s when the system is collecting data from all sensors at 50Hz frequency. In practice it has not been possible to increase the sampling frequency further since the evaluated smartphones have not been able to handle receiving data simultaneously from two insoles at higher rates over extended periods.

Before collecting sensor data from the two insoles it is highly desirable to synchronize the local clocks that run independently on them generating the sample timestamps. It is however not a trivial operation since there is an irregular latency between issuing a write command in the smartphones application code and a corresponding BLE data packet being sent over the air. The BLE communications protocol lets the master (smartphone) exchange data packets with the slaves (insoles) at periodic events separated by a predefined connection interval that is 7.5ms or higher. A write operation from master to slave consists of the master sending a write data packet to the slave and subsequently receiving a write data acknowledgement packet back from the slave after one or more connection intervals. The exact points in time of the connection events are however not available for application programs on the smartphone. The time between issuing a write command on application level to receiving the acknowledgement message back to application level can on the other hand be measured with nanosecond precision. To achieve slave clock synchronization of about milliseconds accuracy it is hence possible for the master to repeatedly send clock update commands to the slave until the time from write to acknowledgement is close to the predefined connection interval. This infers that the write command was issued just before the connection event it was transferred on which means that an up to date clock value will have been written to the slave. Compensating for radio reception to application level latency on the slave insole side is trivial since the time to next connection event is available for the application programmer. A small latency due to over the air transfer time also exists but it is equivalent for both insoles so it has little significance for synchronization.

1.4. Power System

An off the shelf, rechargeable single-cell Lithium Polymer battery is used to supply power to the WIISEL insole system. The battery is less than 1mm thick and the area is small enough to allow it to be encapsulated inside an insole. The battery is flexible to some degree but to reduce wear due to flexing, the battery is placed in the heel area of the insole. The energy storage capacity of the battery is enough to power the WIISEL system in full sampling mode for about 20 hours.

To ensure protection from moisture and mechanical damage, all electronic components including the battery are encapsulated within the insole. Hence the battery must be charged wirelessly and preferably using chargers that are readily available on the market. For this reason the insoles were designed to comply with the Qi standard for wirelessly charging electronic products [?], developed by the Wireless Power Consortium. A Qi charging pad transfers energy inductively to a coil embedded in the insole which is coupled to an integrated receiver that stores the energy in the battery. Since users of the WIISEL system are intended to charge the two insoles overnight it will be most convenient to use a dual charging pad that can charge both insoles simultaneously (e.g. Energyzer Inductive Charger Qi).

Figure 4. Smartphone displaying data from WIISEL insole.

1.5. Power System

A smartphone application is developed to function as a control interface for the WIISEL system and to collect and store sensor data from two insoles in real time. Since the WIISEL system is intended to be used independently by the elderly, user friendliness of the smartphone application is very important. The user will be able to connect wirelessly to his insoles by pushing a single button on the application main screen after he puts on his shoes in the morning and the smartphone will subsequently store all data collected during the day on the smartphones internal flash memory. At the end of the day the user will take of his shoes and charge the insoles on a charging pad. At the same time he will connect the smartphone to its charger and while it is being charged it will transfer the sensor data collected during the day to a backend server using mobile internet connection (WiFi or 3G).

The application is developed for the Android operating system since it is the most common OS and it is also open-sourced which gives the developer a lot of freedom in customizing the application to run continuously throughout the day. Platform support for the Bluetooth Low Energy standard was introduced in Android version 4.3 (API Level 18) released in 2013. Hence the WIISEL system requires a smartphone running Android 4.3 or higher that have hardware supporting BLE.

1.6. Data Analysis Platform

Data storage and data analysis will take place at a backend computer server and a web application will enable authorized researchers and clinicians to access the results. It is the server's job to collect the data from all mobile devices associated with it and to perform analysis on the data.

Raw data from the insoles inertial and pressure sensors are first processed on the computer server to extract gait parameters such as stride time, step length, foot clearance and postural sway (displacement of the user's center of pressure). Spatial parameters such as step length and foot clearance are obtained by integrating data from the inertial sensors.

Pattern recognition algorithms will be used to establish a measure of fall risk for a user by evaluating the different gait parameters from the data. Once patterns have been established within the server, they will be presented in the form of a fall risk measure in the web application. This will be a customizable interface, where clinicians involved in the person's case can go into various levels of detail. A traffic light system indicating imminent risks will make up the front page of the fall risk interface. Furthermore, the user's personal details will be available on the web application including their medical and fall history.

The pattern recognition system will use datasets from known fallers and known non-fallers. In a learning phase, the system analyses several gait parameters within these datasets and thereby finds patterns, markers and thresholds that differentiate these two groups. In the working phase with new users, fall risk and the level of the fall risk index are extracted on the basis of the patterns that have been found. The system is constantly learning with new data coming in. The recognized patterns from old user data will be compared by the algorithm against the actual gait tendencies of a user indicate a fall risk for the specific user and monitor this risk over time.

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