Development of a mist computing device for a smart insole aiming on human gait analysis

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***Abstract* — Plantar foot measurement systems are used to monitor human gait, which is proven to be a useful tool for many diseases diagnosis and treatment monitoring, such as Parkinson's and Alzheimer's. In recent years, many Research and Development teams have been designing and developing instrumented shoes for gait-related data acquisition and wireless transmission using various sensor and electronics technologies, often featuring low power consumption. Working in that direction, the Smart Insole project aims at the development of an integrated system that can act as a gait monitoring and analysis tool for aiding gait-affecting diseases diagnosis, treatment monitoring and personal safety among others. The current work focuses on the main characteristics and initial test results of the developed in-sole device. This device consists of sensors, a powerful microcontroller and dedicated embedded software for high sampling rate and Bluetooth Low Energy communication and has been developed so that it can be integrated in the shoe.**

Keywords—Smart Insole, Gait Monitoring, Health, Safety, Gait-Affecting Disease

I. INTRODUCTION

Walking is a typically smooth movement. In normal conditions the pattern of human gait should be stable and symmetrical. However, various pathological health conditions and especially neurological diseases, such as Parkinson's [1] and/or Alzheimer's [2], can cause disturbance in the normal gait pattern, abnormal or uncoordinated gait, leading to what the health experts describe as "ataxic gait" [3]. Gait Analysis is an established field of research with many medical applications in the field of medicine and rehabilitation. From a clinical point of view, changes in gait reveal important information about the health, the development state of specific diseases and the life quality of a person [4]. In addition, balance and gait disorders are among the most common causes of falls of older adults [5]. The accurate knowledge of a person's walking and its monitoring and evaluation over time, allows the diagnosis of diseases and their complications and helps to determine optimal treatment [6].

A number of different devices have been developed and used in order to monitor gait patterns, including camera-based systems [7], pressure platforms [8] and wearable devices [9][10]. The wearable devices present a number of advantages over the others, such as the ability to easily and remotely collect gait data for long periods of time while the patients follow their everyday activities, without the need to visit and stay in expensive healthcare facilities [11]. With the increase in electronics scale integration, these devices become gradually smaller and unobtrusive as far as gait is concerned [9]. Their most important feature is the fact that they can provide objective evaluation of the various parameters of walking, with measurements that often are as accurate as these of devices that can be found in laboratory environments on one hand and a large volume of data spanning a wide range of gait characteristics on the other [11]. With the continuous development of microcontrollers, these devices continuously obtain better processing capabilities, gradually developing into mist computing or mist-assisting apparatuses [12]. An extensive review of contemporary in-sole based systems is presented in [9].

The goal of the Smart Insole project is the development of an integrated platform for gait data collection, storing and processing, that can be used as a diagnostic and monitoring tool for medical personnel dealing with patients suffering from Parkinson's or Alzheimer's disease. At the very edge of the system, there is a smart, wearable, battery operated, shoe-incorporable device that is able to collect information on feet pressure and orientation, movement patterns and walking morphology, with wireless communication and mist computing capabilities. A mobile device application allows any smart mobile device to become a gateway that can temporarily store and visualize gait data collected by the device located in the shoe and transfer them to a remote server for permanent storing, analysis and visualization in a way that is useful for medical experts. The present work focuses on the device located in the shoe that collects gait-related sensor data and its communication with the gateway application. The main advantage of this sub-system is its ability to collect data from 25 sensors at a high sampling rate of 100 samples per second that can monitor all types of gait from shuffling to running, while its Bluetooth Low Energy (BLE) communication with the gateway application provides intermittent communication that saves energy and ensures continuous operation of up to 3 hours.

II. SYSTEM ARCHITECTURE

The architecture of the Smart Insole system is presented in Fig. 1 below:

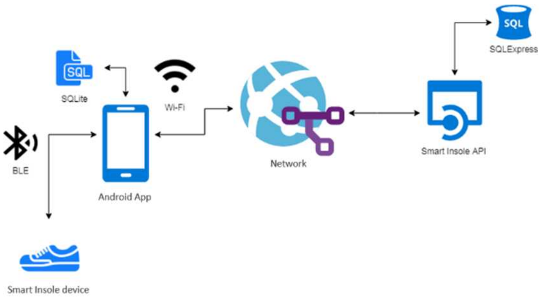

Fig. 1. Overview of the Smart Insole communication system architecture

The above system includes the following subsystems:

Smart Insole device. This device is integrated into the footwear in order to monitor the gait. It consists of several pressure sensors and an inertial measurement unit to monitor the movement and orientation of the person wearing the device. This system includes a microcontroller, which collects data from the sensors and allows wireless communication of the system with a mobile device via BLE.

Smart Insole Mobile application. In the Smart Insole system, a mobile device acts as a gateway to collect data from Smart Insole devices via BLE and send them to a remote server for storage and processing. The application provides the ability to store walking-related data from Smart Insole devices in a local SQLite database. It also provides the ability to display walking data stored both on the server and locally.

Smart Insole API. The Smart Insole Application Programming Interface (API) running on a remote server communicates with the mobile device in order to exchange data. Walking data collected from Smart Insole devices are stored in a database server for further processing and presentation.

A. Hardware

The Smart Insole device consists of the following components:

Central Processing Unit (CPU): The built-in unit selected for the implementation of the prototype includes a microprocessor, with two independently controlled cores. It includes a set of commands for digital signal processing and supports wireless communication and specifically BLE, which is crucial for this project.

Inertial Measurement Unit (IMU): The main purpose of an IMU in a gait-monitoring system is the acquisition of movement and orientation-related data. The chosen unit incorporates a three-axis accelerometer, a three-axis gyroscope and a three-axis magnetometer and communicates with the CPU via an I^2C bus. It is suitable for integration in wearable electronic IoT systems, both due to its small size and its low power consumption.

Sole: During the course of the project, a flexible sole that incorporates 16 piezoresistive sensors was developed for foot pressure monitoring, which is crucial for gait analysis.

Battery: The battery ensures the autonomous operation of the Smart Insole device for a specific time. The battery selected was lithium-ion type (Li-Ion) with small size and weight.

Gateway/Mobile Device: A mobile device plays the role of the gateway for receiving data from the Smart Insole device and transmitting them to the server. This way, the Smart Insole device can communicate via BLE, saving energy and extending the device's autonomy when compared to other communication protocols like Wi-Fi.

Due to the technological innovation and complexity of the proposed project, the Spiral Model has been chosen as the most appropriate methodology for its implementation. This methodology was selected because it is based on the idea of iterative development, which allows incremental releases and constant evaluation of the system under development until the final release of the product [13].

All the individual units presented above were integrated in a single layout, constituting the first complete prototype of the Smart Insole device, which is presented in Fig. 2 (left). This first prototype also allowed a number of external devices to be connected to it for development, testing and failsafe reasons. After testing the first prototype of the system, the research and development team moved on with its redesign in order to make it significantly smaller, while maintaining its full functionality. The end result is presented in Fig. 2 (right). Its size was reduced from 33.9 x 53.8 mm to 29.9 x 35.1 mm.

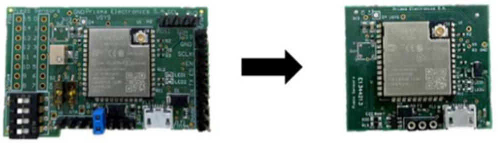

Fig. 2. First (left) & second (right) version of the Smart Insole device

B. Embedded Software

Dedicated embedded software that runs on the developed hardware implements the various system functionalities, namely:

Initialization of the Smart Insole device and its communication with the mobile application. During the Smart Insole device startup, the device itself and its peripherals are initialized and the data acquisition parameters are set. The BLE communication between the Smart Insole device and the mobile device is also initiated and the Smart Insole device receives its initial timestamp.

Sensor data acquisition. The CPU of the embedded system receives data from 25 different sensors: 16 piezoelectric sensors of the developed sole and nine (9) from the sensors of the IMU. The 16 analog signals produced by the pressure sensors are converted to digital via the ADC of the CPU, while the IMU data are obtained via I^2C. The acquired data and a timestamp produced based on the initial timestamp that the Smart Insole device received from the mobile device form JSON packets that are subsequently sent to the mobile device via BLE. The data acquisition process is repeated continuously until the mobile device is disconnected from the Smart Insole device. The sampling rate achieved is 100 samples per second, which, according to the requirements, is adequate for gait monitoring, even when the end user is walking at a fast pace [14].

Communication between the Smart Insole system and the mobile device is based on the BLE protocol. This protocol was chosen over the classic Bluetooth or Wi-Fi communication protocols as it achieves lower energy consumption and for this reason it is used in communications with low data rates such as health and fitness monitoring devices [15]. Communication via BLE is based on a Server – Client logic, with the Smart Insole device being the Server and the mobile device playing the role of the Client. After the establishment of their connection, JSON packets containing timestamped data from the Smart Insole device are sent to the client. The client unpacks each JSON file and stores the data contained in it temporarily in an SQLite database installed in the mobile device before sending them to a remote server for permanent storage and processing. Fig. 3 presents the data flow within the Smart Insole device and between the Smart Insole device and the Smart Insole mobile Application in block form.

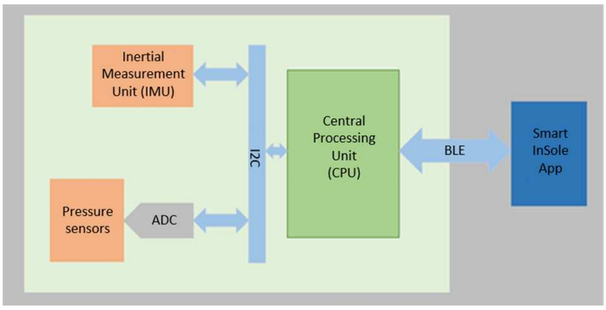

Fig. 3. Data transmission architecture

III. DEVICE TESTING

In order to confirm the proper operation of the completed prototype of the Smart Insole device, some tests were carried out, which are divided into six categories:

1) *Continuity and power supply tests* that ensured that there are no unwanted short circuits between points that should not be electrically connected and that all peripheral devices on the Smart Insole device were supplied by the proper voltage.
2) *Sensors tests*, in order to verify and evaluate the operation of each unit separately, namely the sole with the built-in pressure sensors and the inertial measurement unit.
3) *Communication and data transmission tests*, which aim at verifying both the correct communication between the Smart Insole device and the mobile device and the integrity of the data sent by the Smart Insole device and stored locally on the mobile device.
4) *Battery autonomy tests*, which aim to inspect the connection and sampling when the device is powered by a battery, as well as to check the operating time of the device while using the battery.
5) *Range tests*, in order to check the operation of the device when the distance between the mobile device and the Smart Insole unit changes.
6) *Tests of the overall data acquisition system*.

Initially, all tests were carried out at laboratory level. In order to test each type of sensor, dedicated embedded software was developed and loaded on the Smart Insole device, while the sensors values were monitored and verified through the device's serial port and a serial monitor. All sensors are working as expected and the system is capable of data sampling and transmission. Regarding the battery autonomy tests, two rechargeable lithium-ion batteries with a capacity of 450 mAh and 500 mAh were used. The test showed that the system can be fully functional when powered by batteries for at least 3 hours. In order to test the communication range between the Smart Insole device and the mobile device, experiments were carried out in which the distance between the devices was progressively changed. The experiments showed that in an open space without obstacles the devices remain connected while being up to 8 meters away from each other. In contrast to the above, when the experiments were conducted in an enclosed space with obstacles between the devices, the devices remained connected within a distance of up to 6.5 meters. As observed, the existence or absence of obstacles is a factor that highly affects the communication range of the devices.

After the basic functionality tests were completed, the Smart Insole unit was tested in real conditions. More specifically, the developed sensor-bearing soles were placed inside a shoe and the Smart Insole devices were placed on the outside of the shoe, as shown in Fig. 4. In order to test the overall system, the user wore the devices during walking and falling. Each experiment was conducted five times, according to standard laboratory testing practice. As mentioned before, the data collected and sent to the mobile device by the Smart Insole system is saved in an SQLite database. Android Studio was used in order to export the database and DB Browser for SQLite was used to convert the SQLite tables to csv. Matlab was used in order to depict the collected data in curve form.

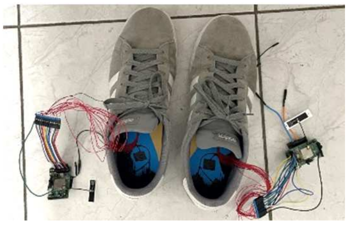

Fig. 4. Smart Insole system inside a pair of shoes

The experiments of the overall system showed that the devices work properly according to their requirements. From the data received it is able to recognize different gait phases and patterns. Fig. 5 shows how the piezoresistive sensors react when walking. The vertical axis corresponds to the values of the ADC as read by the Smart Insole device, while the horizontal axis depicts the samples cardinal number. The pressure sensors' values present a periodical behavior that corresponds to gait cycles. The figure shows that there are moments in which some sensors output a small constant value, which corresponds to a state where the user does not apply pressure on the sensor and moments when their values are significantly bigger. Depending on each sensor's sensitivity, some of their voltage values get saturated. This means that the voltage they produce is more than 3.3 Volts, which is the maximum voltage that the integrated ADC of the CPU can measure. The sensitivity of the sensors can be changed through a digital potentiometer.

During the tests the position and facing direction of the device was also altered. Fig. 6 shows the accelerometer values for the devices placed in both the right and left shoe while walking. The vertical axis of the diagram corresponds to acceleration values in m/s^2, as read by the IMU and sent by the Smart Insole device, while the horizontal axis corresponds to the cardinal sample number. The periodic patterns in the recorded acceleration observed in Fig. 6 correspond to the different gait cycle phases.

When falling, the response of the piezoresistive sensors is almost the same with the one when walking. However, the behavior of the accelerometers is different. More specifically, the values of the accelerometer before falling are different to the ones after falling, as denoted in Fig. 67 by numbers (1) and (2), respectively, while the intense disturbance in the acceleration corresponds to the fall itself. The reason for that is that the human body after falling cannot get back up immediately, but it rather stays in a motionless position for a short period of time. This fact can be used as a criterion to detect fall, which is crucial, especially in cases of gait-affecting diseases, such as Parkinson's or Alzheimer's.

In general, of all the experiments conducted, the integrity and quality of the data acquired by each Smart Insole device were also verified. Regarding the integrity of the data, it was verified that the acquired data did not change during packing and transmission to the mobile device or during unpacking and local storing in the SQLite database. In addition, no data packets were lost during the transmission. In terms of data quality, measurements taken by the devices in the different experiments were compared. It was observed that the values of the two devices diverge slightly, which confirms the validity and reliability of the data acquisition device.

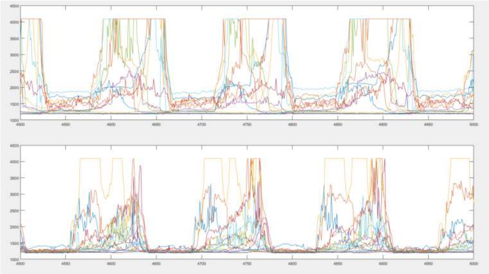

Fig. 5. Right (up) & left (down) sole pressure response when walking

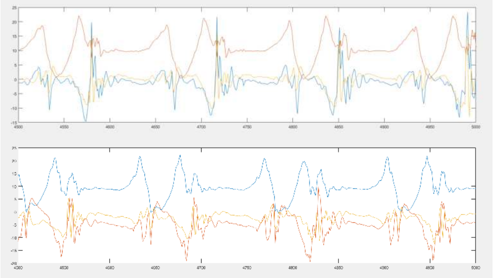

Fig. 6. Values of the accelerometer of right (up) & left (down) device when walking

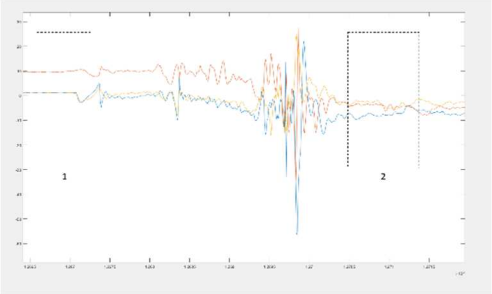

Fig. 7. Values of the accelerometer of a device when falling

IV. Conclusion

Wearable devices integrated in the shoe can significantly help medical experts monitor gait cycles and patterns, practically employing these systems as tools for diagnosis and treatment monitoring. In the present work, the design, development and testing of a wearable device that enables gait monitoring was presented. The device consists of a microcontroller that collects pressure data from a sole with built-in pressure sensors and an IMU. It is also able to transfer data to a remote server via a gateway application running on a mobile device via BLE in packets of optimal size for full bandwidth exploitation, giving it mist computing characteristics. The tests carried out in order to verify the overall device functionality and collected data quality, verified the device's ability to acquire sensor data at a high sample rate that can be used for accurate gait pattern reproduction and detection.

This device, which is part of an integrated system for monitoring and analyzing gait patterns of people with Parkinson's or Alzheimer's disease, can also be used in order to acquire gait data for many different use cases ranging from other neurological diseases diagnosis and treatment monitoring, provided that the disease itself or the treatment affect gait, to safety condition monitoring and workplace safety risk mitigation. The next steps regarding further development of the device include its redesign in order to achieve a higher TRL (Technology Readiness Level), with the ultimate goal towards this direction being its classification as a medical device. Use of flexible electronics and wireless charging are some of the features that, once incorporated in it, will enhance the overall user experience, while updates in the embedded software that could support the execution of algorithms for data filtering on the edge, could enhance the device's mist computing capabilities and further make it stand out among similar developed systems.

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