Venato Smart Shoe

Medical Engineering, Project Course
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Abstract

In the area of digital health, there is a huge demand of collecting data about an individual's gait deviations, such as in pathological subjects like parkinsonians, hemiplegics or choreiforms as well as in elderly people. Gait analysis using an instrumented treadmill, which is the commonly used method produces a noisy signal due to the friction in a belt [1]. Considering this, a smart shoe could be a solution for a more reliable gait analysis. Equipped with force sensitive resistors and IMUs, it can be used to keep track of the foot pressure distribution and several gait parameters.

Introduction

Smart wearable technologies, with potential to gather information through sensors [2], has shown to have the possibility to improve one's life either in a reactive way or a preventive way [3]. There is a huge demand of collecting data about an individual's gait deviations, for instance in pathological subjects like parkinsonians, hemiplegics or choreiforms as well as in elderly people to check their posture or joint health. Furthermore, the extraction of pressure and gait parameters can be exploited by fitness users who want to track their training sessions through steps count and visualize their progress on mobile devices.

The concept of a smart shoe for reliable gait analysis has already been implemented with several different methods, one approach is through data gathering from pressure sensors, accelerometers and gyroscopes [4].

As such, the purpose of this project is to create a instrumented sole with force sensitive resistors and IMUs which can be used to keep track of the foot pressure distribution and several gait parameters in order to identify and assess gait deviations.

Design

The Smart Shoe is a wearable and low-cost monitoring system that enables gait analysis, transmission and logging of the acquired data to a MATLAB application. It comprises of an instrumented insole inside the patient's shoe and a shoe attachment containing the circuit board positioned on the ankle. The insole and shoe module contains:

- a generic shoe insole compatible with any shoe;
- five Force Sensitive Resistors (FSR05BE-ND) that measure continuous pressure;
- two 9-axis IMU (LSM9DS1) containing a 3D magnetometer, a 3D accelerometer and a 3D gyroscope with I2C and SPI for the analysis of the kinematic motion of the foot;
- an Arduino NANO 33 BLE with the nRF52840 microcontroller and a Bluetooth Low Energy connection;

A block diagram of the system architecture is shown in figure 1.

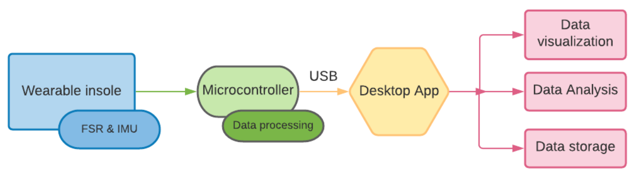

Figure 1: System architecture and data processes

Hardware implementation: The force sensors have a change in resistance based on the applied force. The hardware implementation to measure this consists of an opamp circuit in an inverted configuration to measure the current and voltage output through the resistor. The output of the opamps are then connected to the ADC pins, and both of the IMUs over the I2C bus. A circuit board was milled to contain the analog circuit, shown in figure. Later changes in PCB design placed a bigger emphasis on modularity, included wider traces and adjusted resistor values (figure 4). Future expansions ought to reduce the size of circuit even further with surface mounted components and the use of individual units like BLE module and microcontrollers, rather than the Arduino NANO 33 BLE.

FSR calibration: To get desired output, the FSRs need to be calibrated using weights. By adjusting the feedback resistor in the opamp we can manipulate the gain and by adjusting voltage to the +ve terminal of the opamp, we can create an offset to ensure the output voltage is within the range of the ADC. Figure 9 shows the FSR response for different resistors. The response time and repeatability of the FSR was measured (figure 10) and was found to be 70ms and 6% respectively.

Software implementation: The embedded software is developed using ARM mBed. At first, the data supposed to be filtered and aggregated in a packet, sent over BLE to a computer. However, due to limitations on MATLAB and BLE in terms of packet size, reading speed and packet loss, the data is instead send through USB and saved as Text files. A third-party app "PuTTY" was used to log incoming data and MATLAB scripts to post process foot pressure distribution and gait parameters.

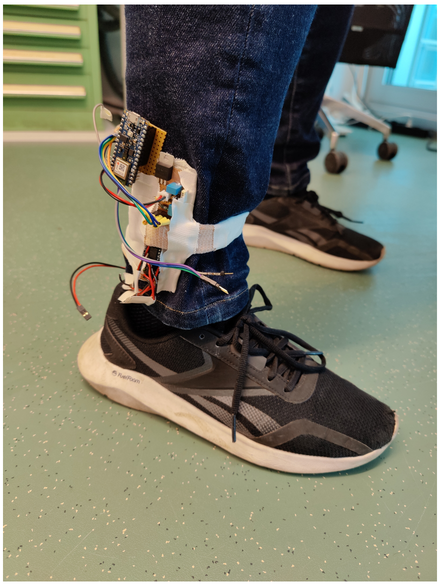

Figure 2: Final prototype

Evaluation

IMU data processing: Firstly, we compensate the sensor inaccuracies such as zero level offset, scaling, and misalignment in three axes of the accelerometer and gyroscope contained in the two IMUs. Stančin e Tomažič refinement [5] is implemented for this purpose. The calibration model used is the following:

$$q = C_s(q_s - q_s)$$

where:

- q is the column vector of the physical quantities to be measured (real values).
- C_s is the 3x3 calibration matrix
- q_s is the column vector of the values measured by the 3D sensor along its 3 sensitivity axes (uncalibrated values).
- q_o is the offset vector.

Results from the calibration of the IMUs are shown in figures 5 and 6.

Once the IMU has been calibrated, initial and final foot contacts (ICs and FCs) are estimated using Trojanello method [6]. Time intervals of trusted swing (T_{SW}) and trusted stance (T_{ST}) are determined and the remaining time intervals are used for searching the ICs and FCs merging information given by gyroscope and accelerometer signals.

After identifying ICs and FCs, temporal parameters including Stride Time, Swing Time, and Stance Time are computed per gait cycle. Furthermore, spatial parameters are estimated using a method named Trusted Events and Acceleration Direct and Reverse Integration along the direction of Progression ($TEADRIP$) [7]. The main steps are the following:

- Identification of the instants of integration;
- Removal of gravity from the acceleration;
- Estimation of the boundary conditions of velocity using the inverse pendulum model;
- Removal of the mean value acceleration;
- Reorientation of accelerations along the direction of progression (DoP);
- Direct and reverse integration for speed estimation;
- Simple integration for displacement estimation;
- Estimation of stride length and stride velocity.

In figures 7, 8, the outcomes from the IMU processing are shown. Due to estimation inaccuracies of ICs and FCs, the results are not constant during the gait and outliers appear in the plots. Nevertheless, it is useful to know the average values of the computed parameters since a significant deviation from standard averages can be synonymous with gait pathologies. For this reason, a clinical report with all the patient's average parameters is automatically created after the processing.

Pressure data processing The force sensor produces a response curve resulting in a drop in resistance proportional to the force applied. The sensor has an accuracy of about 95% and an added drift of <2% under continuous use, and so cannot be relied upon for absolutely measurements. However, the relative forces give us the weight distribution between heel and foot as well as the transverse distribution. Studies have shown that aging related anatomical effects on the foot can be diagnosed using the pressure distribution during the various gait phases [8]. The forces sensors also help in segmenting the gait into the different phases. The differences in amplitude of force graphs are used to detect femoral anteversion, internal tibial torsion, and matetarsus adductus (in-toe and out-toe).

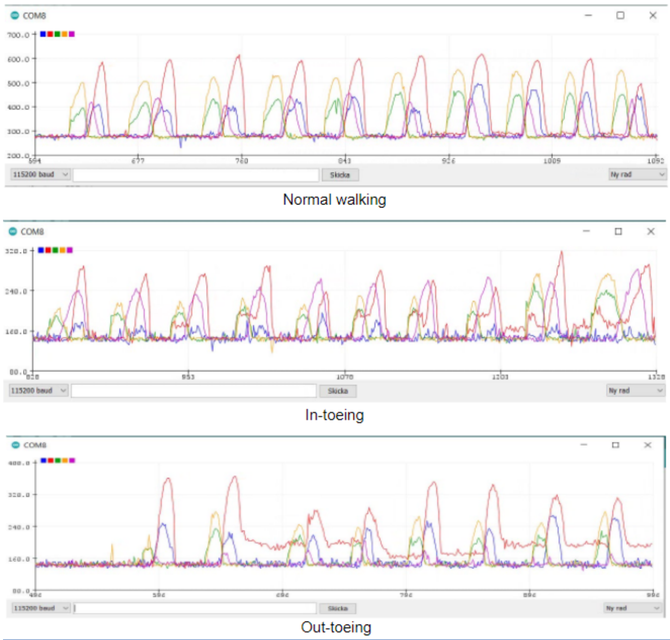

Figure 3: Force sensor readings for straight footed walking, in-toeing and out-toeing

Conclusion

In conclusion, we outline the considerations for the design and fabrication of a smart shoe sole to analyse gait parameters for monitoring, diagnosis and rehabilitation. The sole offers low cost and portable alternative to traditional methods while circumventing some of their drawbacks. Beyond m-health, this device have shown to sucessfully record and with post-processing of acquired data; provide solid ground for fitness tracking, gait correction and monitoring. However, due to technical and software limitations, some of the features originally planned were not fully incorporated, such as the use of BLE to transfer data and real-time processing in MATLAB for both FSR values and IMUs readings. The calculations, files and additional materials can be accessed via GitHub [9].

References

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[9] *Github - Venato smartshoe*. 2022. URL: `https://github.com/rohitrathnam/venato-smartshoe`.

Appendix

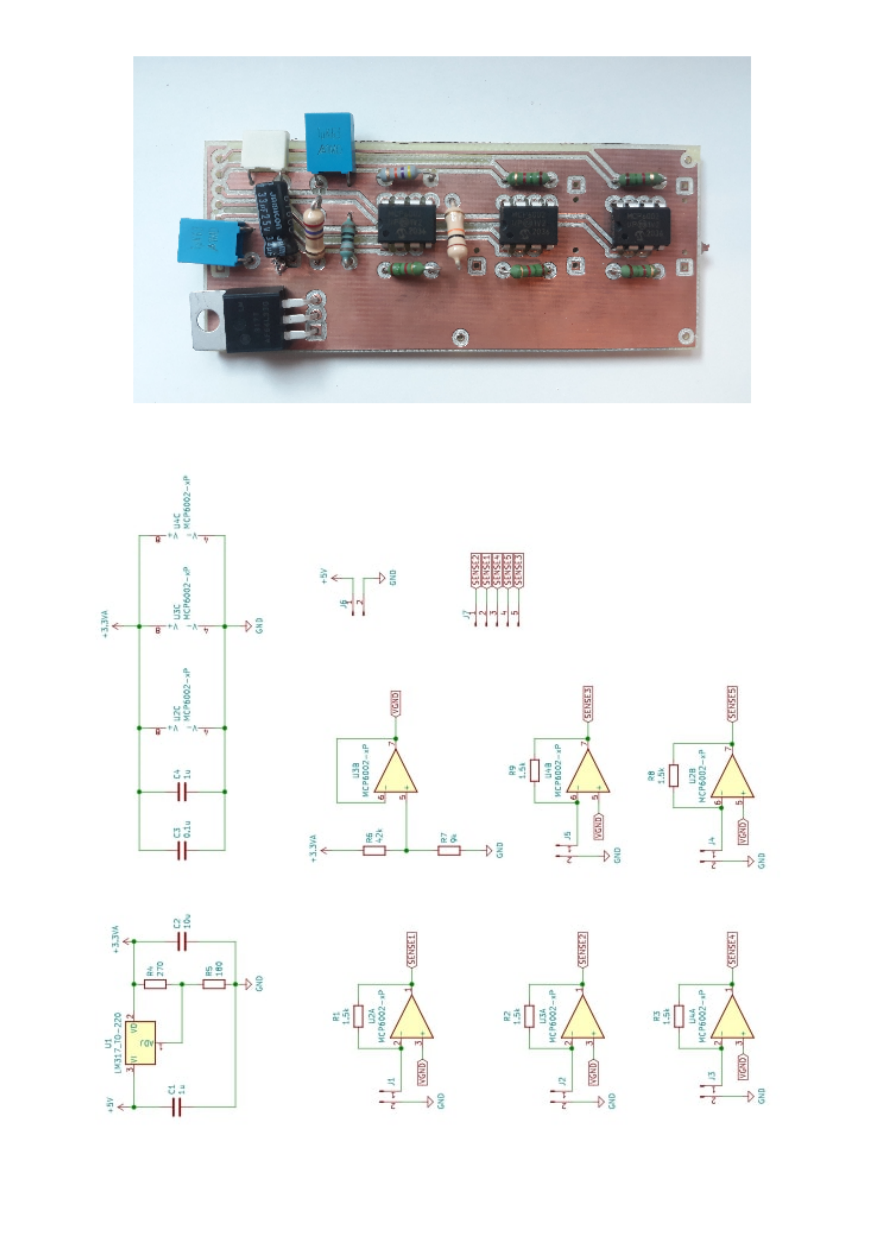

Figure 4: Schematic and circuit board

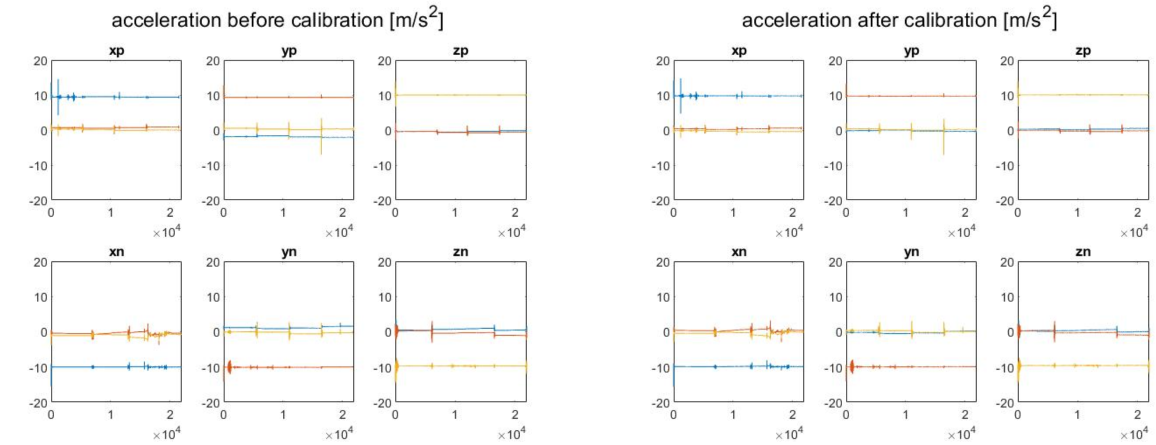

Figure 5: Acceleration along the three axes for different orientations of the IMU before and after the calibration

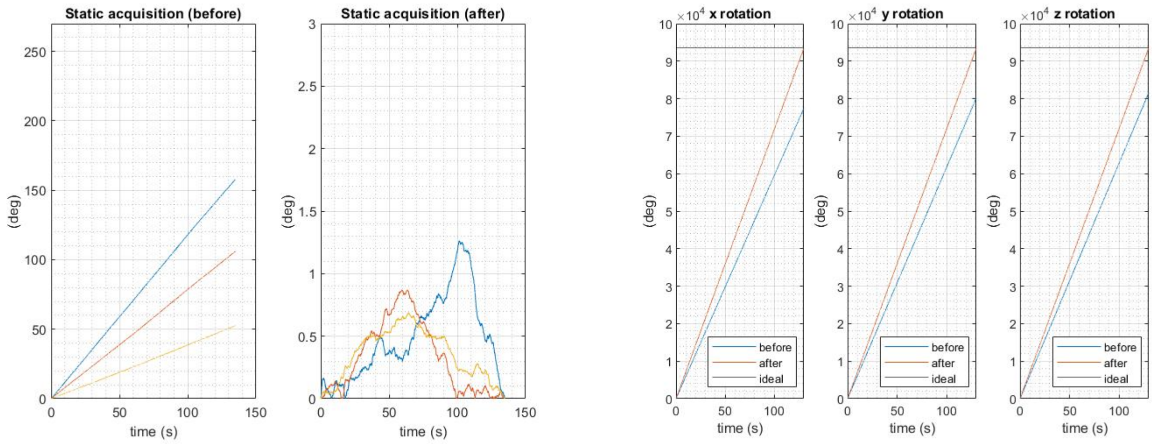

Figure 6: Rotation angle computed through integration along the three axes for static and dynamic acquisitions before and after the calibration

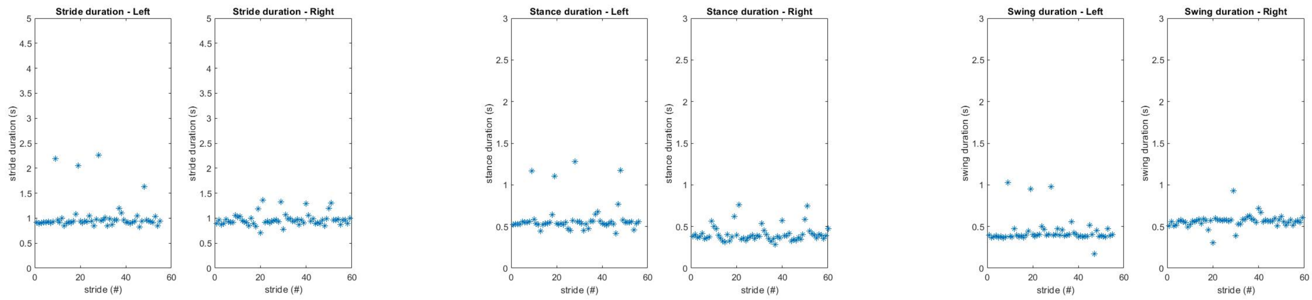

Figure 7: Temporal parameters estimated

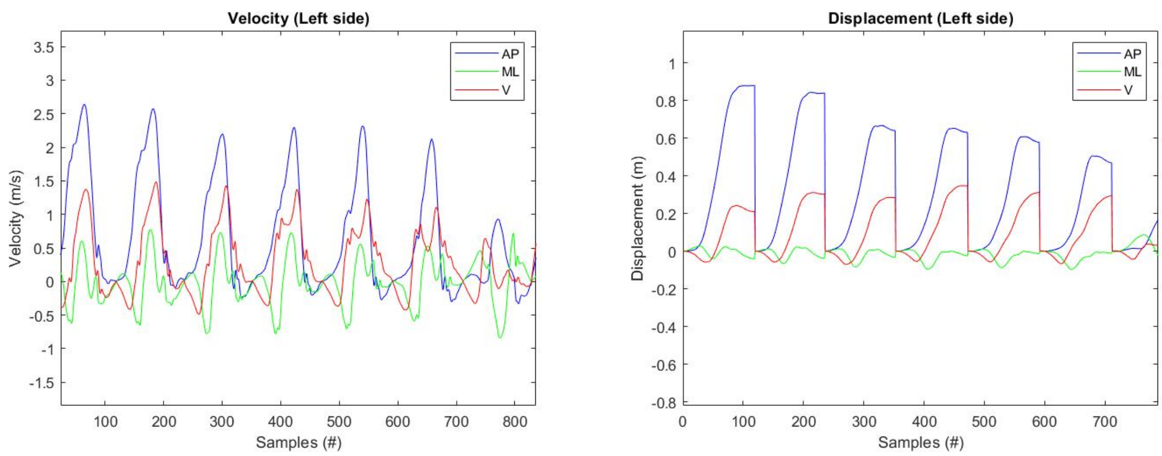

Figure 8: Outcomes of TEADRIP method

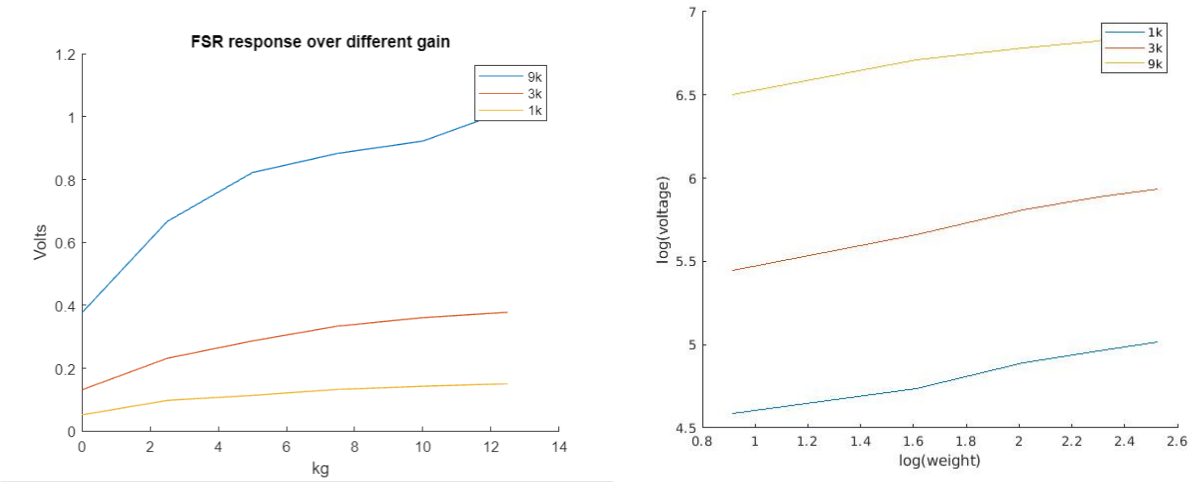

Figure 9: FSR response with different gain values

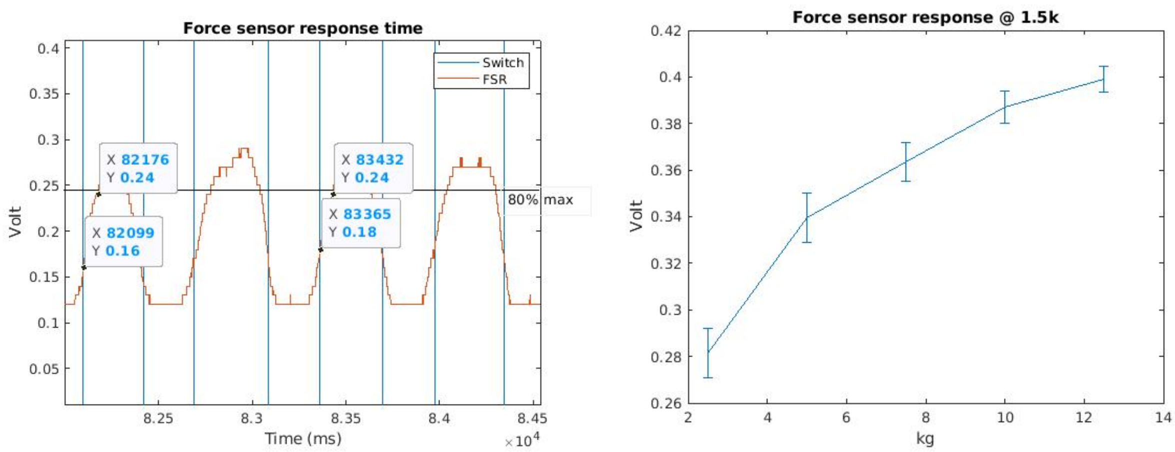

Figure 10: FSR response time and repeatabillity