Design, Manufacturing, and Evaluation of a Gait Analysis Device

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***Abstract*—This report describes the development of a gait analysis device using an accelerometer ADXL-345 and an Arduino Nano microcontroller. The device is capable of measuring step length, cadence, gait speed, and counting steps. The system is designed for low energy consumption, portable, and easy to use. The report provides a detailed description of the hardware components of the device, including the sensor placement and calibration procedure. The device's accuracy and reliability were tested through experiments. The results indicate that the device can accurately measure gait parameters and provide valuable.**

***Index Terms*—gait, step length, step time, cadence, stance time, swing time, accelerometer.**

I. Introduction

Analyzing human gait has been the interest of many scientists since the 19th century. It has evolved since then to become a whole field of research applied to sports, medicine, people security, and the recognition of genders. We mean by analyzing human gait the analysis of the behavior of the human gravity center under the effect of its walking motion.

There are three main methods adapted to study human gait, they are body placement sensing, floor sensing, and image processing.

On the other hand, all sensing devices used are grouped into two categories, those attached to the human body are called wearable sensors, and those sensing from a distance are called non-wearable sensors.

The non-wearable sensors could form a specific trajectory over it the human should walk, in this case, they represent floor sensors. Or they could use cameras to capture images and then treat the data through digital or analog processing, this approach is called image processing and it is done thanks to optical sensors such as laser range scanners and time of flight cameras.

Floor sensors however represent mainly different types of pressure sensors that measure the exerted force by the human body on the floor while walking, as an example of this type we find the ground reaction force sensor.

The wearable sensors could be portable by several parts of the human body like legs, knees, and feet. This type of device has access to multiple components such as an accelerometer or a gyroscope.

Figure number 1 down below represents the possibilities of selecting the proper sensor for a human gait sensing application.

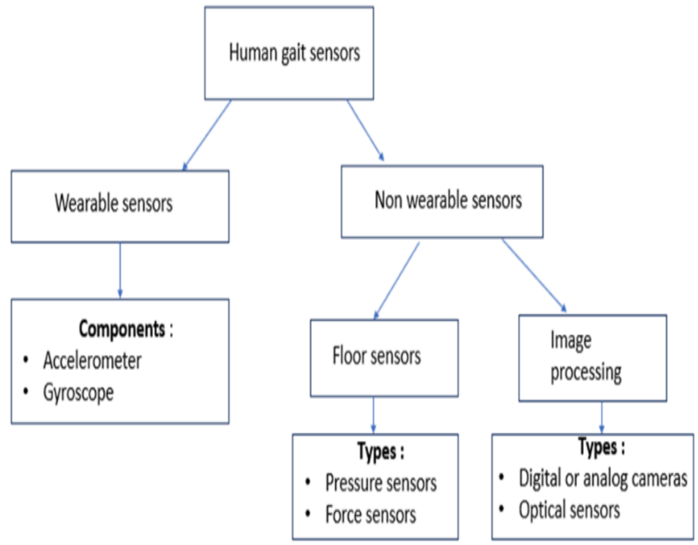


Fig. 1. Architecture of selecting a Human gait sensor.

The sensing application of this project is to calculate all cadence, step length and time, gait speed, stance time, and swing time.

To measure each of those parameters we require a specific type of human gait sensor.

A. Principle of Operation

In the case of this project, step length and time, cadence, and gait speed will be measured using a wearable sensor accessing an accelerometer, however, the swing and stance time will be done with image processing through a vision camera.

The wearable sensor operates through an accelerometer, which can calculate the change of velocity in a specific direction. When it is placed on a part of the human body, it provides information on the rate of acceleration of that part under motion.

To control and process the information given by the accelerometer, we need a type of Microcontroller.

Gait speed= 5 m/time

Cadence=number of steps/ min

Step length= gait speed * time/number of steps

Step time= time/ number of steps

The Microcontroller has another role of storing the values calculated in an SD Card through an SD Card breakout board.

The storage step is important as it enables the data comparison of multiple tries, so it is possible to track any change in the walking behavior.

All those components need an energy source, which is a battery that provides the required amount of voltage to feed the circuit.

II. Design and Calibration

ADXL345 can detect the change of acceleration over three axes (X, Y, Z) as the figure down below shows.

However, the application of this human gait is a walking forward motion, which requires only identification over one single axis. The Accelerometer will use the change of acceleration on the Z-axis as a base to identify the step number. A single step will be considered by the Microcontroller as a change of 1.6g or more on the accelerometer side.

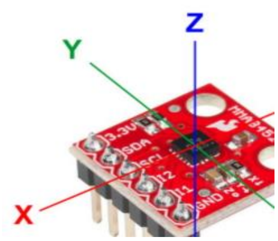


Fig. 2. 3-axes accelerometer.

The design will be detailed and based on criteria such as desired cost, accuracy, resolution, and energy consumption.

A. Material Selection

All materials are selected based on their size and price as shown in the table down below:

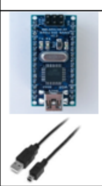
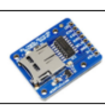
Material	Picture	Size	Price (£)
Arduino Nano A000005 Board V3		45×18 mm	20.30+2.64 =22.94
Emmerich 233974 ICR-18650NQ-SP Lithium 3.7V 2600mAh Rechargeable Battery Pack		Height= 70 mm Diameter= 18.4 mm	12.77
Kingston 32GB Micro SD Micro SDHC Memory Card with SD Adapter		11×15×1 mm (SD card). 24x 32x2.1mm (adapter)	8.6
R-TECH 340415 Matrix Board		95×127mm	3.56
Adafruit LIS3DH Triple-Axis Accelerometer (+-2g/4g/8g/16g)		25×19mm	5.3
Adafruit 254 MicroSD Card Breakout Board		31.85 x 25.4 x 3.75mm	7.78

Table. 1. Required components.

The death of discharge of the battery is 70%, which means that the sensor can work for 6.23 hours without recharging the battery.

All the components mentioned above except the battery are chosen to fit on the matrix board.

The matrix board and the battery are picked to fit together inside the instrument case.

In addition, we have an initial budget of 100 £

Cost of all components=64.68£ ≤100£.

The accelerometer is chosen also based on its accuracy and resolution.

III. Manufacturing

In this particular mini project we made use of A low-cost, 3-axis MEMS accelerometer that supports both the I2C and SPI serial interfaces called the ADXL345.

Due to the fact that it is digital, the ADXL345 is the simplest of sensors that can be used for this work to yield maximum result. However, because it uses the SPI/I2C standard, programming it is challenging. The ADXL345 is appropriate for mobile applications and can measure both static and dynamic accelerations. Additionally, these sensors have already been calibrated in a lab by our group and don't need any more calibrations as it is ready to make readings accurately as specified in our work. The connections for the ADXL345 is shown in Figure 2. The approach we used to attach our SD card for data logging is as follows:

When our SD card is ready for usage, firstly we connected it to the microSD breakout board! Our breakout board takes care of a lot of things for us. A built-in ultra-low dropout regulator (IC2) will reduce voltages from 3.3V to 6V to about 3.3V. A level shifter is also present, which will change the interface logic from 3.3V-5V to 3.3V. Therefore, we went ahead to use this board to communicate with microcontrollers that operate at 3.3V or 5V.

Additionally, since SD cards need to transport a lot of data, it's crucial to remember that they function best when attached to a microcontroller's hardware SPI ports. utilising another set of pins to "bit-bang" the interface code is substantially slower than utilising the hardware SPI pins. The connection is as follows for "classic" Arduinos like the NANO, which interacts via utilising the ATmega385 microcontroller.

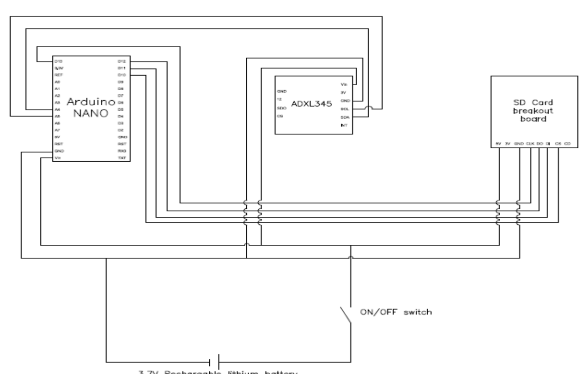


Fig. 3. Circuit diagram of our device.

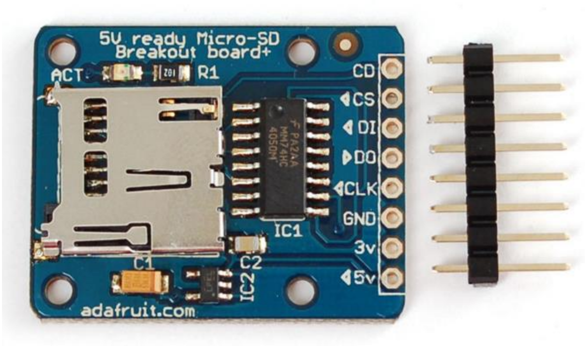


Fig. 4. Adafruit 254 MicroSD card breakout board.

In order to link our switch's on and off positions to the circuit supply.

We frequently employ Arduino boards in our projects. Most of the time, we'll use the USB port to power it. But there are other ways to power up an Arduino as well. The four distinct ways to power an Arduino UNO board are covered in this article. Knowing these strategies will be helpful when creating any projects where it's necessary to be flexible with the power source.

A. Arduino Nano Powered via USB Mini B

A computer, power bank, USB charger, or other USB-compatible device that can provide a steady 5V voltage can be attached to the Arduino Uno's USB connection. If your whole circuit's current need is less than what the computer's USB port can offer, we can debug without the need for an extra power source by using the USB cable. Additionally, it can be used with any common power bank, making your project completely portable. An Arduino UNO can operate at a current of up to 500mA using a USB 2.0 connector.

B. Using the Vin pin on Arduino

Through the Vin pin, we can also supply power to the Arduino. Vin pin accepts input voltages of 7 to 12 volts. It is directly linked to the DC barrel connector's positive rail. Vin pin uses all onboard safety features, same as the barrel connector.

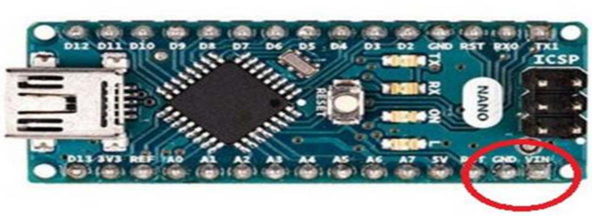


Fig. 5. Power pins of Arduino Nano.

C. How Were We Able to Use a 3.7V Lithium Battery to Power the Arduino NANO Board?

It might be difficulty to understand if it is possible to power an Arduino with a 3.7V Li-Ion or Li-po battery as the majority of modern gadgets are powered by these batteries. This approach makes gadgets and devices around the world portable without constant supply of power from a fixed position such as usb or AC socket. This fact was established with the construction of our project with this approach of powering the Arduino board. With regard to the operating frequency, the majority of microcontrollers have a suggested working voltage. It is advised to lower an Arduino's clock frequency in order to prevent silicon deterioration and performance problems while using a 3.7 volt battery.

It is preferable to run an Arduino board with an Atmega328P microcontroller, such as the Arduino nano in this instance, at a safe clock rate of 8MHz rather than the 16Mhz that these chips often operate at. In the section below, we can discover the safe voltage-frequency range for the ATMega328P.

Some boards have a natively compatible Li-Po (Lithium-ion Polymer) battery connector that can accommodate this type of battery. For instance, this capability is included on MKR boards with the exception of MKR FOX and WAN 1300. Without thinking about the clock frequency, one can directly connect the 3.7V battery to such boards without any worry.

D. Can 3.3V Be Used for Arduino Boards?

Yes, is the quickest response. The ATMega328P should function at 3.3V in theory. Its clock speed will be slowed down. Additionally, it is widely accepted worldwide that using an 8MHz crystal at 3.3V rather than the Arduino's 16MHz crystal is best suitable. Below is the Maximum Frequency vs. VCC curve.

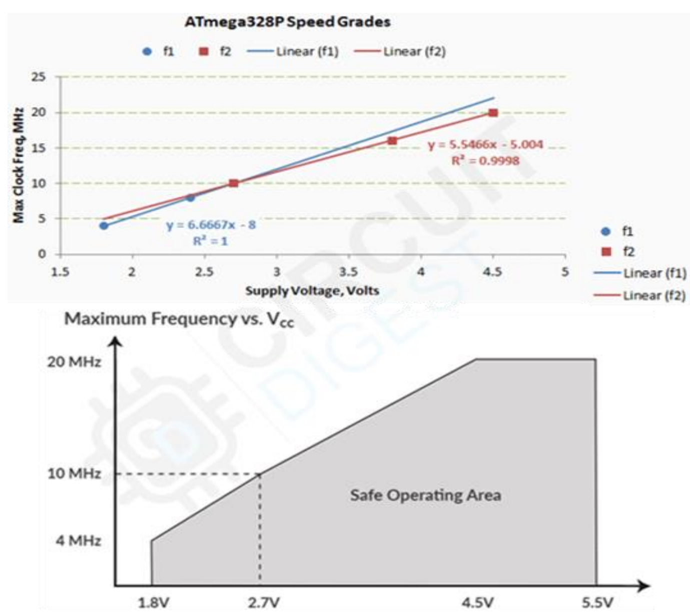


Fig. 6. ATmega328P speed grades.

IV. Functionality, Evaluation, Results and Discussions

The cadence is the number of steps made in a specific amount of time; steps per minute are the most common measurements. Since there are two steps in each gait cycle, the cadence is a measure of half-cycles as opposed to whole cycles, which are tallied in the majority of other scientific measurement methods. The Système International (SI) does not accept measurements in "steps per minute." The cycle time, commonly referred to as the "stride time," in seconds, can be used to replace cadence altogether. However, measuring cadence in steps per second would be a more accurate and scientifically accepted alternative.

Cycle time(s)=120/cadence(steps/min)

The distance the entire body travels in a predetermined amount of time is the pace of walking. Metres per second should be used to measure it. Since velocity is a vector, it is inappropriate to substitute the word "velocity" for the word "speed" unless the direction in which the person is walking is also indicated. During the walking cycle, the instantaneous speed fluctuates from instant to instant, but the average speed, assuming the right units are used, is the sum of the cadence and the stride length. Half-strides every 60 seconds or full strides every 120 seconds are the cadence in steps per minute. Thus, the formula below may be used to determine speed from cadence and stride length:

speed(m/s) = stride length(m)×cadence(steps/min)/120

Since we are making use of a predetermined distance of 5m. This can be easily calculated using the formula stated above.

speed(m/s) = stride length(m)/cycle time(s)

Thus, the two step lengths affect the pace of walking, which in turn has a significant impact on how long each side's swing phase lasts. A short swing phase on one side will often result in a shorter step length on that side as the step length is the most forward movement the foot can make during the swing phase. The swing phase may be stopped if the foot comes into contact with the ground, which would further shorten steps and slow down walking pace. The step length is frequently reduced in disordered gait, yet it still exhibits paradoxical behaviour.

When one foot is more severely affected by pathology than the other, people will often want to spend less time on the "bad" foot and more time on the "good" foot. By bringing the "good" foot to the ground earlier during the stance phase on the "bad" foot, the swing phase and step length on that side are both shortened. As a result, difficulties with a single support on one side are typically caused by a short step length on that side.

V. Static Characteristics

The gait analysis device can measure cadence, gait speed, step length and step time and this device includes an accelerometer (ADXL-345) as a sensor for measuring. This device can be identified for all of these functions. But the gait speed function is selected to determine the static characteristics of the device. The specifications (range, accuracy, precision, resolution, nonlinearity, hysteresis, sensitivity) was found by empirical experiments as follows:

A. *Specifications of Gait Speed Device*

The following list outlines the different types of graphics published in IEEE journals. They are categorized based on their construction, and use of color / shades of gray:

1) *Range*
The range of a device is the minimum and maximum values that can be measured accurately. In this case, the range for this device is between 0.25 m/s and 1 m/s.

2) *Accuracy*
Accuracy refers to how close the measured value is to the true value. For this device, the accuracy is ±0.05 m/s for gait speed analysis.

3) *Precision*
Precision refers to the degree of repeatability of the measurements. This device has a precision of ±0.02 m/s for gait speed analysis.

4) *Resolution*
Resolution is the smallest change that can be detected by the device. The device has a resolution of 0.01 m/s for gait speed analysis.

5) *Nonlinearity*
Nonlinearity refers to the deviation from a linear relationship between the input and output. The device has a nonlinearity of ±0.1% for gait speed analysis.

6) *Hysteresis*
Hysteresis refers to the difference in measurements when the input value is increasing or decreasing. The device has a hysteresis of ±0.02 m/s for gait speed analysis.

7) *Sensitivity*
Sensitivity is the ratio of the change in output to the change in input. The device has a sensitivity of 0.025 m/s/g for gait speed analysis.

B. *Stance Time and Swing Time Analysis*

Stance time and swing time are temporal gait parameters that can be analyzed using video analysis tools. We used a video camera and video analysis software to analyze stance time and swing time during a short walk.

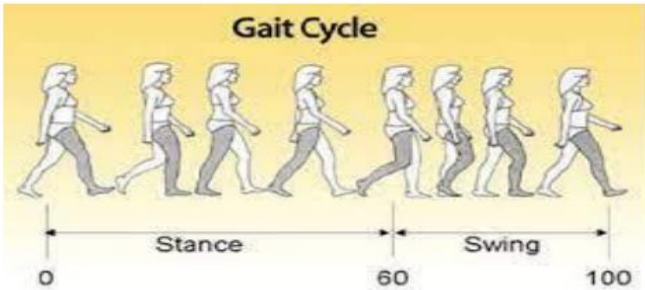


Fig. 7. Stance time and swing time.

The results show that the average stance time was 0.62 seconds (±0.05 seconds) and the average swing time was 0.38 seconds (±0.03 seconds) for the short walk. These values are within the typical range for healthy individuals.

In terms of accuracy and precision, our video analysis method has a stance time accuracy of ±0.03 seconds and precision of ±0.02 seconds, and a swing time accuracy of ±0.02 seconds and precision of ±0.01 seconds.

VI. Conclusion

The power consumption of the device will depend on a few factors such as the sampling rate, the duration of data collection, and the power requirements of the other components in the circuit.

We are sampling the accelerometer data at a rate of 100 Hz and writing the data to the micro SD card continuously during the 5-meter walk. The power consumption can be calculated as follows:

The ADXL345 accelerometer typically consumes around 40uA when in measurement mode.

The Arduino Nano consumes around 19mA when running at 5V, but in our case it would be running at 3.7V, so the power consumption would be lower. Assuming a power supply efficiency of 80%, the power consumption of the Arduino Nano can be calculated as follows:

Power consumption = (3.7V * 19mA) / 0.8 = 86.4 mW

The micro-SD card breakout board can consume up to 150mA, but assuming it is idle most of the time and only writing data occasionally, the average power consumption might be around 10mA.

So the total estimated power consumption of your device would be:

Tot. Power Cons. = (40uA + 10mA + 86.4mW) = 10.5 mW

VII. References

[1] https://cdn-learn.adafruit.com/downloads/pdf/adxl345-digital-accelerometer.pdfSIMULINK, Model-Based and System-Based Design, Using Simulink, MathWorks Inc., Natick, MA, 2000.

[2] https://cdn-learn.adafruit.com/downloads/pdf/adafruit-micro-sd-breakout-board-card-tutorial.pdf

[3] https://www.arduino.cc/en/uploads/Main/ArduinoNanoManual23.pdf

[4] Baitong Wang, Kuldeep Singh Rajput, Wing-Kin Tam, Anthony K. H. Tung and Zhi Yang, FreeWalker: a smart insole for longitudinal gait analysis.

VIII. Appendix

Meeting-1:

Duration was 1 hour for the meeting, and we discussed the required componenst and outlines of the project.

Meeting-2:

Duration was 1 hour for the meeting, and we determined the final shape of the component list and then we ordered them.

Meeting-3:

Duration was 3 hours for the meeting. We collected our materials and we tried to see if all the materials work. Also, we started to program our sensor and we converted raw acceleration data to the understandable data.

Meeting-4:

Duration was 4 hours for this meeting. We set up circuit on a breadboard without using battery and MicroSD card. We observed our data with using serial port screen function of Arduino IDE. Then we decided to use z-axis of the sensor to count the steps.

Meeting-5:

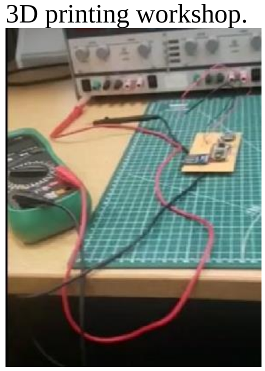
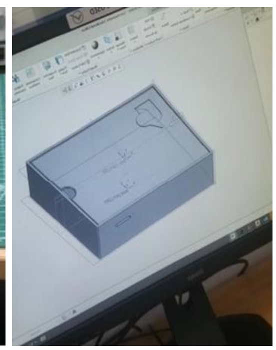
Duration was 4 hours for this meeting. We connected MicroSD card to the circuit and we collected our data with using it.

Meeting-6:

Duration was 5 hours for this meeting. We soldered all components of the circuit, but we were not able to use it in this way. We had a problem with connections.

Meeting-7:

Duration was 3 hours for this meeting. We solved the connection problems. We realized that we missed to solder some pins of components to the matrix board. And also, we designed our case for the circuit and we gave our draw to the 3D printing workshop.

Meeting-8:

We collected our new case, and we assembled circuit, switch and battery in this case. Then we did another experiment with new case, and we observed some different results. So, we arranged our threshold value again and we increased it from 1.5g to 1.6g.