# ASSESSMENT OF DISTANCE MEASUREMENT USING A 3-AXIS DIGITAL ACCELEROMETER

Guillermo Puchalt Casáns
Miguel Alcañiz Fillol, Rafael Masot
*Master's Degree in Sensors for Industrial Applications*
*School of Design Engineering*

# Contents

# Abstract

This project consisted on evaluating the capability of a triaxial accelerometer as a straight forward distance measuring pedometer as the current existing ones rely on a user calculated mean stride for multiplication with the step count. A device was developed for the purpose using the ADXL345 triaxial accelerometer and the PIC18LF14K22 microcontroller in combination with MATLAB for data filtering and processing. Three approaches were taken in consideration when calculating the distance walked by the subject through double integration of the acceleration (integrating all the data ($R^2$=0,9710), integrating the data in batches ($R^2$=0,8513), integrating the steps ($R^2$=0,9835) and integrating the steps (only XZ axes) ($R^2$=0,9791)) and results were contrasted against a mechanical pedometer ($R^2$=0,9947), a smartphone app pedometer ($R^2$=0,0266) and the real distance walked. **From this project it was known that using an accelerometer and any of the three approaches a distance of at least five meters could be measured with a coefficient of variation of 4,2278%, although the first approach proved to be very reliable for distances of twenty meters ($C_v$=2,5622%).**

Keywords: accelerometer, distance, pedometer, double integration

# 1. State of the Art

A pedometer is a device used to measure daily activity in the form of a step count. Nowadays pedometers offer other functions, like calorie counter, time exercising, mean speed and above all, distance traveled. But there is a catch to this function, and is that it does not measure the truly distance traveled, but it counts the number of steps the user has done and multiplies it by a mean value of the user's stride. This method is not reliable for knowing the true distance the user has traveled because the stride's length can vary for various reasons:

a) If the user walks at a slow speed, or has a considerably body mass, the steps will not be counted, consequently, less distance [1].

b) If the user performs longer, or shorter, strides for any particular reason[1], the total distance traveled will be different than the real one is.

c) Any movement done by the body besides walking could increase the step count, therefore, greater distance will be displayed.

d) If the user has a peculiar gait, the step count will not be consistent, hence the distance traveled will be different than the real one.

But besides those general problems, there are also some special problems depending on the type of technology used by the pedometer. On the market there are three types of technology regarding pedometers [2]:

1) Based on a mechanical system (*Figure 1, pg 4*)

   This type of technology is the cheapest of all three but comes with its own drawbacks. It is composed of a pendulum that moves vertically up and down when a step is done, and such movement activates a switch, increasing the step count. Because of this type of behavior, the pedometer brings some problems, besides those already mentioned:

   a) It must be perpendicular to one of the legs, otherwise it will not count the steps accordingly. This happens because the pendulum moves due to hip movement as a consequence of setting the foot down. If the pedometer is not in line with the movement propagation up the leg, the pendulum will not work.

   b) Every step has to be uniform as any abnormal movement of the legs will not move appropriately the pendulum and miscount the step, or count more than once.

   c) The return spring that stabilizes the pendulum can wear off over time and make the pedometer more sensitive to slightly active movements. Although this is one of the reasons usually found, according to [3], after intensive use the pedometer will have an error less than 5% in relation with the amount of steps counted.

[1] Like walking up, or down, a hill or stairs

d) Because the pendulum relies on the vertical propagation of the step movement, if the user is walking up, or down, a hill the pendulum will not move appropriately either.

2) Based on an acceleration sensor

This type of technology is the most reliable on the market as it detects the acceleration caused by the movement propagation of the step. Because of its multiple axes, positioning of the pedometer in the body is not as crucial as the previous type of technology. Yet, it still has its problems, like those described in general terms beforehand.

Although the device developed also relies on an accelerometer it differs from the pedometers using this type of technology that it provides the distance measurement directly rather than being calculated from the amount of steps.

3) Based on a GPS receiver

This type of technology is the most expensive of all, but can give really good results. Of course, it will work only if the user is physically moving in space and it receives a strong GPS signal. Therefore, when walking on a treadmill, or being indoors, or being in a location with no GPS signal reception, the pedometer will not measure the distance traveled accurately.

**The objective of this project is to create a low-cost pedometer that measures the distance traveled, indoors or outdoors, with the aid of acceleration measurements, without knowing the amount of steps or the mean stride length or relying on other types of position data[2].** This way, the true distance traveled will be measured accordingly and independently of the speed of the user, its stride variation, its gait, where it goes and what it does.

Of course, walking in a treadmill will not be possible either as the device will physically be in the same region of space rather than moving forward.

[2] Based on [16], gyroscope data can be left aside because during gait the rotational components can be redefined as a function of translational components of acceleration (if it was necessary to now the rotational components) because such components are large enough to be detected. If, like in aerospace navigation, the rotational components were small then they could not be a function of translational components as they will be too small to be detected.

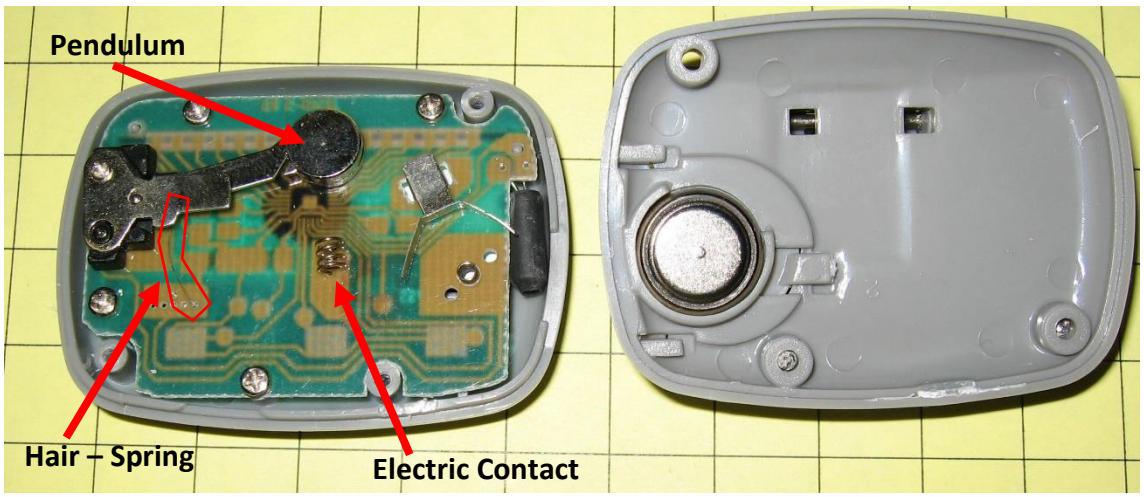



*Figure 1: Insides of a pedometer with a mechanical system*

# 2. Materials and Methods

## 2.1. Design of the pedometer

### 2.1.1. Aspects to be considered

From the read literature, two key features of the device's characteristics were established. These features were:

- Sampling frequency of 100 Hz or higher

  Despite that the data will be filtered through a low pass filter at approximately 20 Hz, sampling was carried at 100 Hz. In most of the literature the sampling frequency was between 60 Hz and 500 Hz, being 100 Hz the most used sampling frequency.

- Acceleration range of ±2g

  Based on the conclusions from [4], the acceleration sensor should have a range of ±6g. Reviewing the article in depth it was found that when walking the acceleration amplitudes at the pelvis were of [-0.3 0.8]g in the vertical axis and ±0.2g in the horizontal axis while walking. Based on this data, a range of ±2g was selected as the sensor used does not allow for anything smaller.

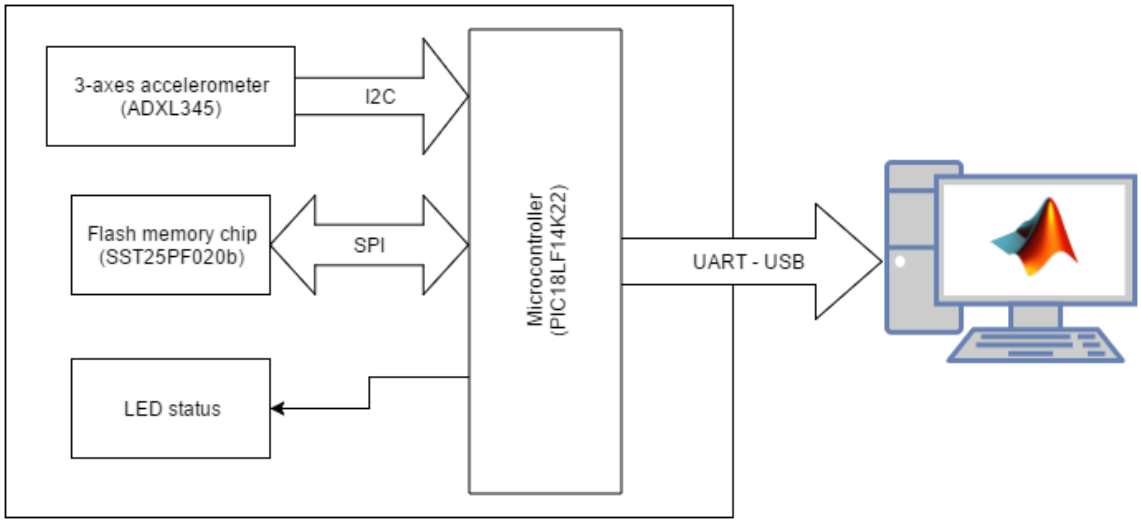
Each data package that represented one sample of the acceleration profile had the following structure of 8 bytes:

1) Start byte
2) 6 bytes of data (in pairs of 2 bytes per axis as the data is of 10 bits of length)
3) Checksum

At lab the available wireless circuits were not sufficient for transmitting in real time the amount of data produced every second and store it in file at the computer[3]. To solve this issue, instead of transmitting the data wirelessly, it was stored in a memory chip and later downloaded to the computer with the help of an UART – USB converter cable.

[3] Although the wireless circuit used was capable of a baud rate of 9600 bps (the circuit generated 6400 bits per second), experimentation showed that the computer was not capable of receiving such amount of data.

### 2.1.2. Block Diagram of Device




### 2.1.3. Design of hardware

The device circuit was developed using Proteus 8 Design Suite software, transferred to a two side PCB (Figure 2, pg 7) through photoengraving, and applied chemical etching. Consideration was taken for the battery pack placement and fixing[4], as well as the sensor fixing to the PCB[5]. The latter is a crucial aspect of the device because if the sensor was badly fixed to the circuit board, it will resonate while the subject walks and it will record its own acceleration oscillations[6].

Due to the communication problem discussed earlier[7] a memory chip had to be chosen for data collection. By recommendation of the directors, it was used a SPI flash memory chip, but several requirements had to be fulfilled:

A) Memory capacity

The amount of memory required for the gathering of data was calculated based on a 5-minute time span of data gathering and the amount of data generated per second in bits:

(3 axes x 2 byte/axis + start byte + checksum byte) x 100 samples/s = *800 bytes/s*

800 bytes/s x 5 min x 60 s/min = *240 kB*
240 kB x 8 bits/byte = ***1.92 Mb***

**So the memory's capacity had to be equal or greater than 1.92 Mb.**

[4] The battery pack was placed in the bottom layer and caution was taken that all of the electronic components were placed facing up in the top layer so that they do not overlap.
[5] The holes used for fixing had to be placed somewhere where they had minimal impact to the paths. This could not be done for the battery fixing holes as it was fixed in the middle as described earlier.
[6] *Mechanical Considerations for mounting, pg 28* [5]
[7] *Aspects to be considered (pg 4)*

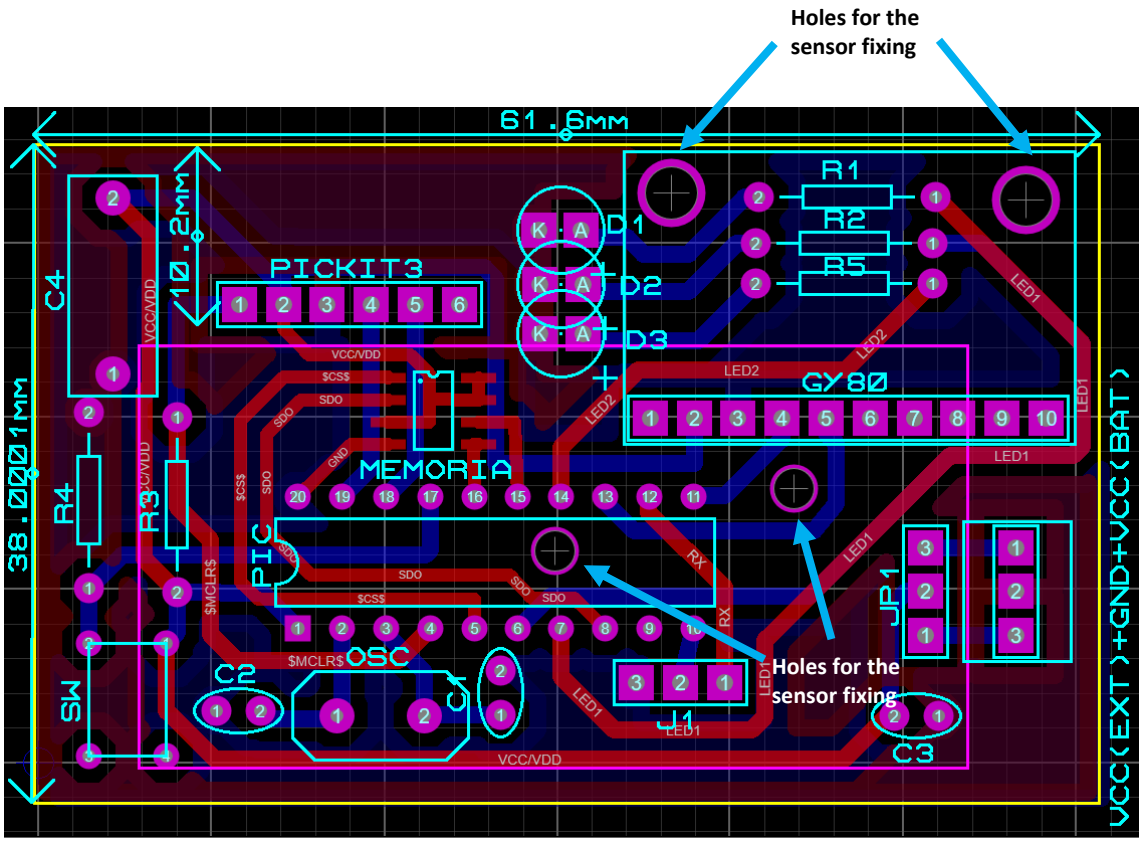



*Figure 2: PCB representation with all the components and board dimensions*

B) Sequential writing function[8]

This function is crucial for the device's operation as it allows for faster writing procedures of data in the memory chip in comparison with singly byte writing procedures.

C) Erase all memory command

Of the memory chips searched, some didn't have this command available. Instead, the memory chip had to be erased with multiple executions of the erase command[9]. For simplification of the firmware design it was preferably that the memory chip had this function available.

D) Availability in Proteus 8 Design Suite

Although it is not an essential feature to be fulfilled, it will simplify much the debugging process of the firmware design using Proteus 8 Design Suite. Additionally, if the memory chip is already in the program's library it will also have its packaging.

E) Had to be available at Farnell Components preferably

This feature was more of a recommendation from the directors as they were already about to make a purchase of materials for the department from this provider.

Using the electronic components search engine Octopart[10] and looking over the datasheets of the obtained results, the 2Mb flash memory chip **SST25PF020B** (Figure 4, pg 9) was the best candidate. It met all of the requirements except for one: It was not available in the Proteus 8 Design suite program.

This inconvenience for the hardware design was solved by using a random chip that shared the same package (SOIC-8) and reassigning the pinout numbers in the same way that the original memory chip has. In the case of the firmware design process, the problem was solved by substituting the flash memory chip for an SRAM memory chip (23A256) that was available in the Proteus 8 libraries.

The behavior between both memory chips is similar regarding for the reading and writing data sequences. The only important difference between both of them came on the way they handled the sequential writing instruction sequences. While the SRAM memory only required at the beginning of the sequence the sequential write command, the Flash memory required at the beginning the sequential write command and the 3-byte address, and for every two desired bytes to be written, the sequential write command had to be sent beforehand again.

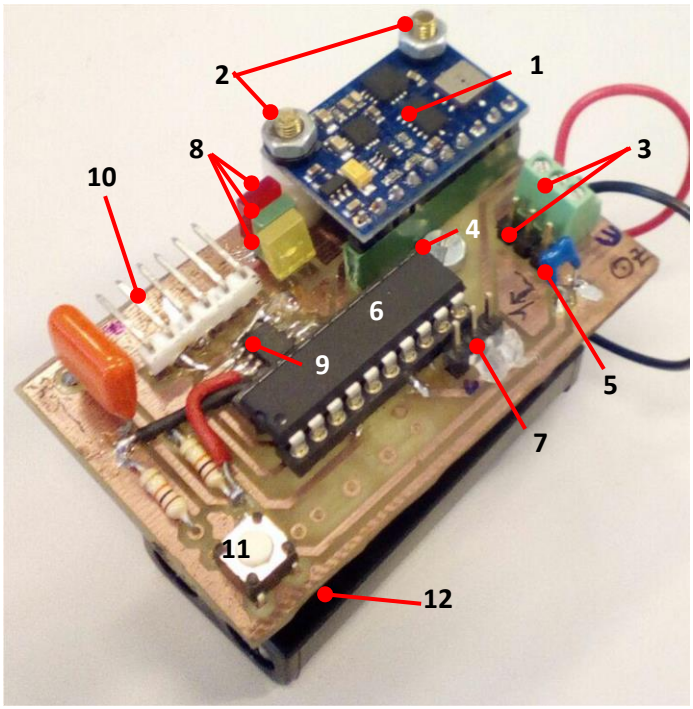
One final aspect to comment about the flash memory chip is that during testing it was found out that a decoupling capacitor of 0.1 µF was required for filtering noise from its power supply pin (Vdd) for proper operation or it wouldn't work at all.

The accelerometer used in the device was the **ADXL345**, which is a widely used MEMS accelerometer. It is integrated in a PCB (Figure 5, pg 10) alongside with a compass, a gyroscope, a barometer and a thermometer. The most frequent use of this type of sensors is for inertial

[8] This function allows writing several bytes continuously without having to write every time the address to store each byte.

[9] Depending on the memory chip, it could be erased by sector of memory of different sizes but nor the entire memory available.

[10] https://octopart.com




| Nº | Board Component |
|---|---|
| 1 | Accelerometer |
| 2 | Mechanical fixing of multi-sensor board to PCB |
| 3 | Power supply and selection jumper |
| 4 | Mechanical fixing of battery pack |
| 5 | Decoupling capacitor |
| 6 | Microcontroller |
| 7 | UART communication port |
| 8 | Status LEDs |
| 9 | Memory chip |
| 10 | Firmware download port |
| 11 | Mode selection push button |
| 12 | Battery pack (2xAA) |

*Figure 3: Final product of device with component indication*

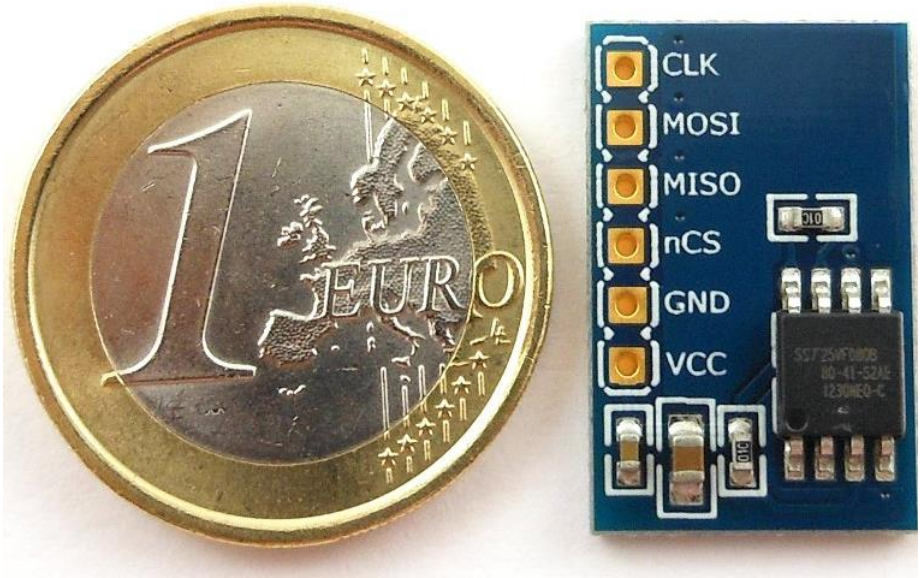



*Figure 4: Breakoutboard with a similar memory chip used (the difference relies on the operational temperature range).*

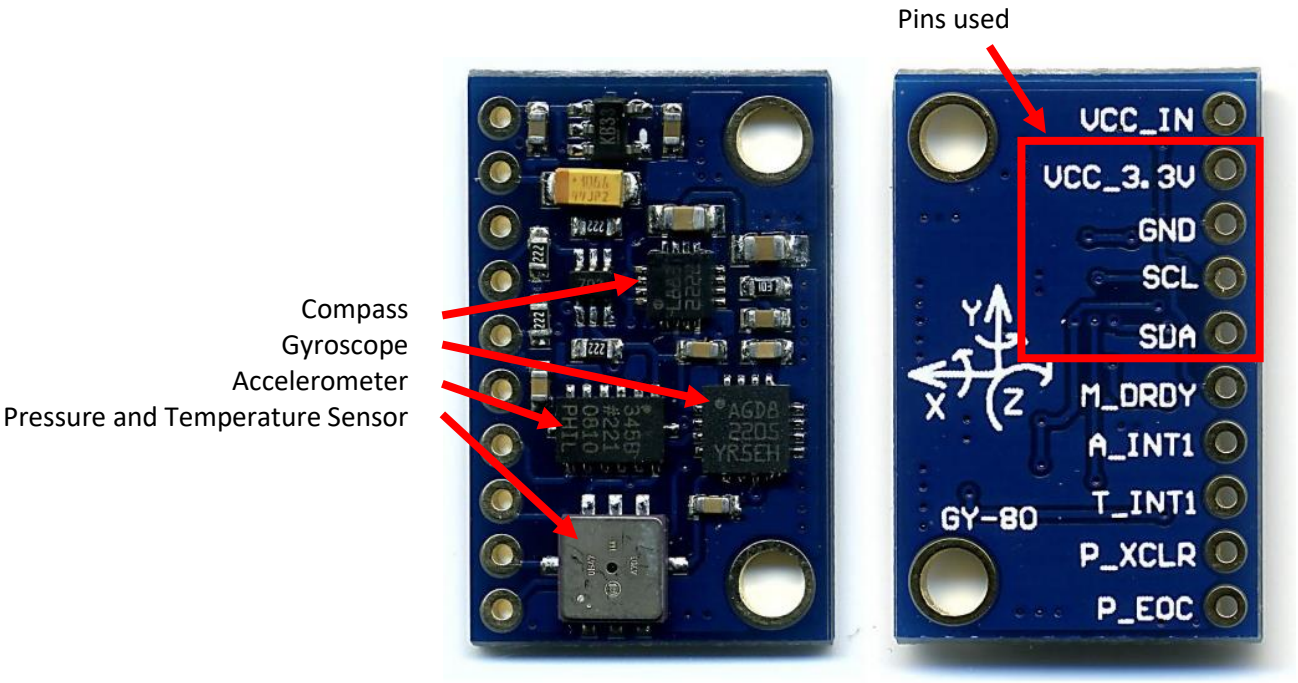



*Figure 5: GY-80 PCB sensor platform used*

measuring equipment for airplane navigation, medical equipment, gaming and pointing devices, industrial instrumentation and hard disk drive protection [5].

This accelerometer presented the same problem as the flash memory chip with Proteus 8 Design Suite. It was substituted for debugging purposes by the $I^2C$ controlled ADC converter (MCP3424). Three signals were attached to simulate acceleration measurements. Little difference was found between both of them besides the commands used for communication. Meanwhile, its package footprint did not present a challenge as it was already integrated in a PCB and had a 0.1" SIL pinout for interfacing with the device.

The microcontroller used in this project was the **PIC18LF14K22** 8-bit microcontroller which is ideal for this master's degree final project, due to its capacity, cost and flexibility. Additionally, it was used in different subjects of the Master, so the available tools to work with it were already available. It was operated with a clock frequency of 16 MHz[11].

During design it was evaluated if the device will be powered by a 3xAA (4,5V) or 2xAA (3V) battery pack. The difference between using each one of them relied on whether using a 3,3V low-dropout linear voltage regulator or not. Because all of the components used could work at 3V or lower it was decided that with a 2xAA battery pack will be sufficient for the power needs of the device. Just in case, it was added the possibility of allowing the device being powered by an external power source so that the batteries were not consumed while debugging.

Furthermore, during the hardware designing stage, it was considered that it was needed three LEDs for debugging purposes that will act as indicators of mode in which the device is working (Figure 3, pg 9).

### 2.1.4. Design of firmware

For the design of the microcontroller firmware, it was used MPLAB X IDE and C programming language, aided with the Proteus 8 Design Suite software for basic debugging (Figure 6, pg 12) . As mentioned previously, some hardware components were not available in Proteus 8 Design Suite and were substituted by components that had certain resemblance with the originals[12]. Of course, once the final hardware was created, the debugged firmware had to be changed to adapt to such hardware and debug again although much less thoroughly.

Besides the debugging adaptation problem, there was a communication problem. As mentioned previously, it was used SPI and $I^2C$ communication simultaneously because the acceleration sensor cannot communicate through SPI[13]. So, in order to overcome this problem, an improvised software based SPI communication system was developed using four GPIO pins as the clock, input, output and $\overline{\mathrm{CE}}$ pins. The SPI communication sequence worked as follows:

1) $\overline{\mathrm{CE}}$ pin set to zero
2) SCL pin set to cero
3) MOSI pin set to the result of applying an AND mask with the number 0x80 and shifting to the left seven times

[11] It was the fastest clock speed that the internal oscillator of the microcontroller could achieve. This was the amount of time of capturing the acceleration data and storing it in the memory chip was reduced to the minimum amount of time.
[12] Design of hardware, pg 5
[13] Technically speaking, it can communicate through SPI, but the PCB sensor board had the connections made for $I^2C$ communication and they couldn't be modified.

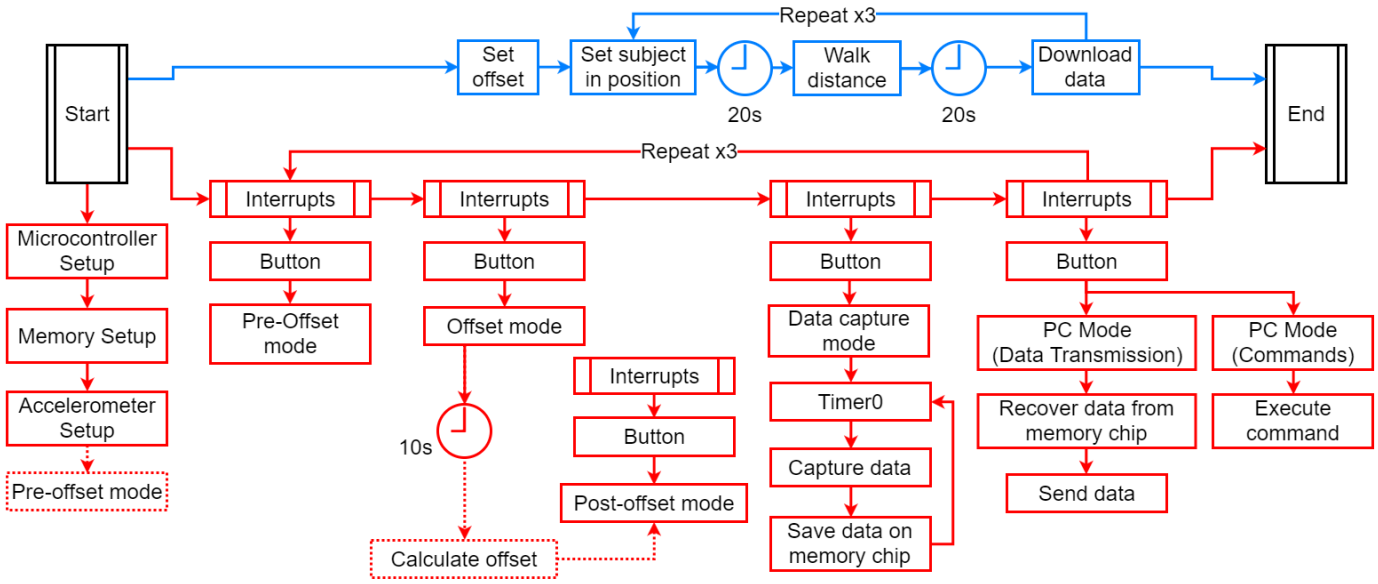



*Figure 6: Diagram of how the device is used during the data capture procedure described in pg 25, Protocol Followed (in red at firmware level and in blue at procedure level)*

4) Input data variable is rewritten with the original variable shifted to the right once.

5) SCL pin is set to one

6) Output data variable is set to be the result of adding the logical value of the MISO pin and the result of shifting once the output data variable

7) Repeat steps 1-5 another seven times

8) If the RW variable is one (indicating that the function was called for a reading purpose), return the output data variable.

9) $\overline{\text{CE}}$ pin is set to one

$I^2C$ communication was performed using the PIC18F14K22 MSSP peripheral and the $I^2C$ library available.

A function was implemented that combined the software based SPI communication and the $I^2C$ communication systems[14]. That way, the firmware was simplified as it was required many times to use one of the communication systems.

When the device is powered up, all the required peripherals[15] of the microcontroller are configured, as well as the memory chip[16] and the sensor[17], and the microcontroller is set for the one of its operational modes.

There are 5 different operational modes that run their functions once the external interrupt is activated by the device's button. In order to avoid multiple external interrupts because of the bouncing of the signal of the button, Timer3 was used as a debouncing mechanism. By using the timer, two conditions (timer and external interrupt activation) had to be achieved in order to change mode with the button.

These modes are:

a) Standby prior offset calculation (Green LED off, Red LED on, Orange LED on)

This mode is responsible for erasing the memory chip completely so that the new data does not get mixed with old data. When the device powers up, it starts on this mode but doesn't execute its functions as the interrupt handler hasn't been called.

b) Offset calculation (Green LED off, Red LED off, Orange LED blinking)

This mode is responsible of calculating the offset of each axis. Once the offset is calculated, this mode will not allow any recalculation of the offset until the device µC is powered down[18].

[14] pg 13 for further details

[15] Timer0, Timer1, Timer3, USART, MSSP (for $I^2C$ communication for the acceleration sensor), Internal oscillator, Interrupts configuration and GPIO configuration for the software based SPI system, LEDs, and button.

[16] Disabling overwrite protection

[17] Full resolution mode, right data justification, ±2g range (register 0x31 pg 26 [5]), Stream FIFO mode (register 0x32 pg 27 [5]) and setting the output data rate at 200 Hz (register 0x2C pg 25 [5])

[18] A reset command will also work

There is a 10 second delay (with Timer1) prior to executing this function. That way, if the user doesn't want to execute an offset calculation process it can press again the button before the time is up.

Once the delay has elapsed, the device turns on the sensor, resets the offset variables inside the microcontroller, and captures ***n*** samples[19] of data at a rate of 100 Hz[20]. Once the samples were collected, a mean value was calculated for each axis, divided by the sensitivity of the sensor and multiplied by -1[20]. Because the Z axis is in an upright position, the offset calculated will have registered the value of gravity as well. This value was subtracted from the mean value calculated, assuming perfect sensitivity. As mentioned in the sensor's datasheet, sensitivity can vary for different reasons and by so, the Z axis offset result can be different than what should actually be. Based on the example given in the sensor's datasheet this aspect can be discarded as the error due to sensitivity differences is minimal.

c) Standby for capture of data (Green LED off, Red LED on, Orange LED off)

This mode holds the device on standby previous to the capture mode while the device is set in its final position on the subject. This mode is crucial as offset calculation is done on a flat surface rather than on the subject.

d) Capture of data (Green LED blinking, Red LED off, Orange LED blinking)

In this mode, the device captures the data relative to the acceleration profile that the acceleration sensor detects. Before capturing data, the memory chip is prepared for the sequential writing processes and the sensor is turned on. Once the preparations are completed, Timer0 is enabled and the capturing process begins. For every time the Timer0 interrupt activates, the interrupt handler does the following:

1) Reload of Timer0 registers based on the selected sampling frequency. Turn the orange LED on and toggle the green LED.
2) Assign the starting value to the checksum byte of the data package.
3) Read the data from the registers that correspond to the axis of interest with the help of the communication function. Because the function returns the value as a 16-bit integer, the number has to be fragmented in 2 8-bit integers. Each individual number is set in its corresponding position in the data package[21].
4) Add to the checksum byte of the data package the two new bytes.
5) Repeats steps 2-4 for the two other axes.
6) Add one to the data package counter variable.
7) Send the data package to the memory chip.
8) Turn off the orange LED.

[19] The amount of samples to be taken is specified by the constant *samples*
[20] Following the recommendations given by the sensor's datasheet ( [5] pg 30)
[21] The data package sent to the memory chip has 8 bytes has this structure: Start byte – X axis 2nd byte – X axis 1st byte – Y axis 2nd byte – Y axis 1st byte – Z axis 2nd byte – Z axis 1st byte – Checksum

The LED control is important during the capture mode as indicates that the capture process is happening (green LED) and allows to measure with an oscilloscope the duration of the capturing process (orange LED). This is proven useful when debugging the firmware in order to evaluate if the firmware fulfills the timing requirements of the sampling frequencies[22].

e) Computer communication (Green LED on, Read LED on, Orange LED blinking)[23]

In this mode the device is under the control of the computer interface. It is used mainly for transferring the acceleration data to the computer, but it is also used for debugging purposes (selecting a different sampling frequency, controlling the memory chip or the sensor, microcontroller reset, etc). Additionally, this mode disables any chance of writing in the memory chip by accident as well as turn off the sensor.

Data packages sent and received from the computer interface vary in length. In the case of data packages received from the PC, this were always 5 bytes long[24] whereas the data packages received from the device varied from 3 to 10 bytes, depending on the data transmitted.

Last but not least, the entire process of capturing and storing data in the memory chip had to be fast enough in order to accomplish the desired sampling frequencies. To achieve this goal, two sections of the firmware went through trial and error experimentation to test the time it took to capture and store data. This amount of time was measured by using the oscilloscope and testing when the orange led turned on and off. Such sections were:

A) The Timer0 interrupt handler

The interrupt handler had to be as simple as possible. One feature that is seen in the code is that the checksum function is not used although it existed. From experimentation it was observed that calculating the checksum manually made the handler faster.

Additionally, the sequential write process was helpful with this task, as it only required 3-byte packages consisting of the sequential-write command and two of the 8 bytes of each data package. The initialization of such process was carried when the capture mode was selected.

B) The communication function

The communication function proved to be a challenge among all the programming as it was called up to 15 times per data capture (3 times for reading data of each axis, and 4 times for every data package sent to the memory chip). It had to be fast enough so that the sampling frequency timing requirements could be achieved.

[22] See pg 5 for further explanation.
[23] See *Annex 2: Commands used between Microcontroller – PC* for details on the commands used
[24] The structure of the data package was: Start Byte – Command Byte – Data component nº1 – Data component nº2 - Checksum

On the first versions of the firmware, the way to differentiate between SPI and $I^2C$ communication was with the who variable and detecting it if was positive (representing the $I^2C$ addresses) or negative (SPI communication). From experimentation it was observed that if instead of detecting a negative value, it was detected a positive value (one higher than the highest $I^2C$ address value), the communication function worked much faster. Also, the reset of the output variable of the $I^2C$ communication part was done only when such communication was required, hence saving more time.

One aspect of the $I^2C$ communication that affected the design of the function was that two bytes could be read from the sensor. So rather than setting the output of the function as an unsigned char, it was set as an integer, so that two bytes of data could be passed out and later the firmware process the data and separates the number in two independent bytes.

### 2.1.5. Design of software

The computer interface that will access and control the device was implemented with GUIDE in MATLAB R2012b. It was designed for basic communication with the device as well as for data retrieval. Data processing is done through separate scripts as described in the next chapter.

The interface has four buttons at the left side that take care of data recovery, manual memory erase and sending specific commands. Such commands can be chosen from the drop down list of pre-established commands but can only be sent if the manual control mode is enabled in the interface. There are two text boxes for establishing addresses and data to be sent through the $I^2C$/SPI buses. These text boxes are enabled only when the selected command requires of such information.

There is another dropdown list for selecting the PC communication port that is connected to the device[25].

Communication from the device to the computer had certain complications as the received data packages were sometimes incomplete. A command[26] was programmed in the firmware so that in case of such problem it will ask the microcontroller to transmit again the last data package sent.

All of the received data packages that were related to the device operation contained the relevant information between the start byte and the checksum and are displayed directly in the interface. Meanwhile, the data packages that carry the measured acceleration have a different structure[27]. This way it is checked if data had been lost during the transfer.

Because the acceleration data is a 10-bit long number per axis, each piece of data has 6 bytes/sample[28], and when received at the computer they are converted into three digital

[25] In case the computer has multiple available communication ports.
[26] *Annex 2: Commands used between Microcontroller – PC*, command 19.
[27] Start byte – 2nd byte of data package number – 1st byte of data package number – Data bytes – Checksum
[28] Where each two bytes represent an acceleration value in one axis.

numbers with the help of function. This function combines each pair of bytes into one number and because the numbers are in two's complement, they are converted to regular numbers first. Once all three numbers are converted from their bytes, they are written into a text file and saved at the established destination[29]. The number was not converted into international units in the data retrieval process because the sensitivity value could be changed between experiments. They were converted at the processing scripts.

## 2.2. Design of the processing algorithms

Development of the different processing algorithms was done using MATLAB software once the data was captured. All of the scripts written had a basic structure:[30]

1) All of the repetitions of the acceleration data set files are read and converted into international units ($m/s^2$).
2) Each repetition has its own structured variable associated, where any processing of the repetition is stored. Because the sensor recorded the moments in which the device's button is pressed, the scripts cuts away the first 5 seconds of data and the last 15[31].
3) Absolute acceleration values are calculated in case of being needed, as well the gravity value measured, the time vector, the frequency vector and its name[32].
4) Double filtering processing of each repetition of the data set.
5) Data processing.
6) At the end of the script, a table is created showing calculated distance walked, standard deviation, 1$^{st}$ harmonic, number of steps and time taken to walk the distance[33].

Consideration was taken on if data of all three axes had to be used or not. Based on [6], the reference plane parallel to the ground will be recording the foot down and heel up event acceleration responses. Such data doesn't represent at all the inertial movement of the body and excluding it could make the data processing much easier.

But because the reference planes are tilted, the acceleration component due to body movement is distributed along all the axes and hence elimination of one of them will omit part of valuable data. Still, an attempt was carried in one of the algorithms to process the data by removing the data of the axis that represented the most of such unwanted acceleration data, whereas in the other algorithms the absolute magnitude of acceleration was used.

Within each algorithm there is a pseudo-algorithm responsible for counting steps. This pseudo-algorithm is independent of the data processing algorithms but it does use both filtering

[29] In this Project, the files were named following a specific structure: Distance walked – Repetition number – Location in the body – if it had offset
[30] Following more or less the guidelines established at [14]
[31] Further explained on *2.3.2 Protocol Followed pg 18*
[32] Except for the frequency vector, each aspect of each repetition of the acceleration data set is slightly different to the others. That is why the time vectors and gravity values were calculated for each repetition.
[33] All other numerical values of interest were displayed through the command window in MATLAB.

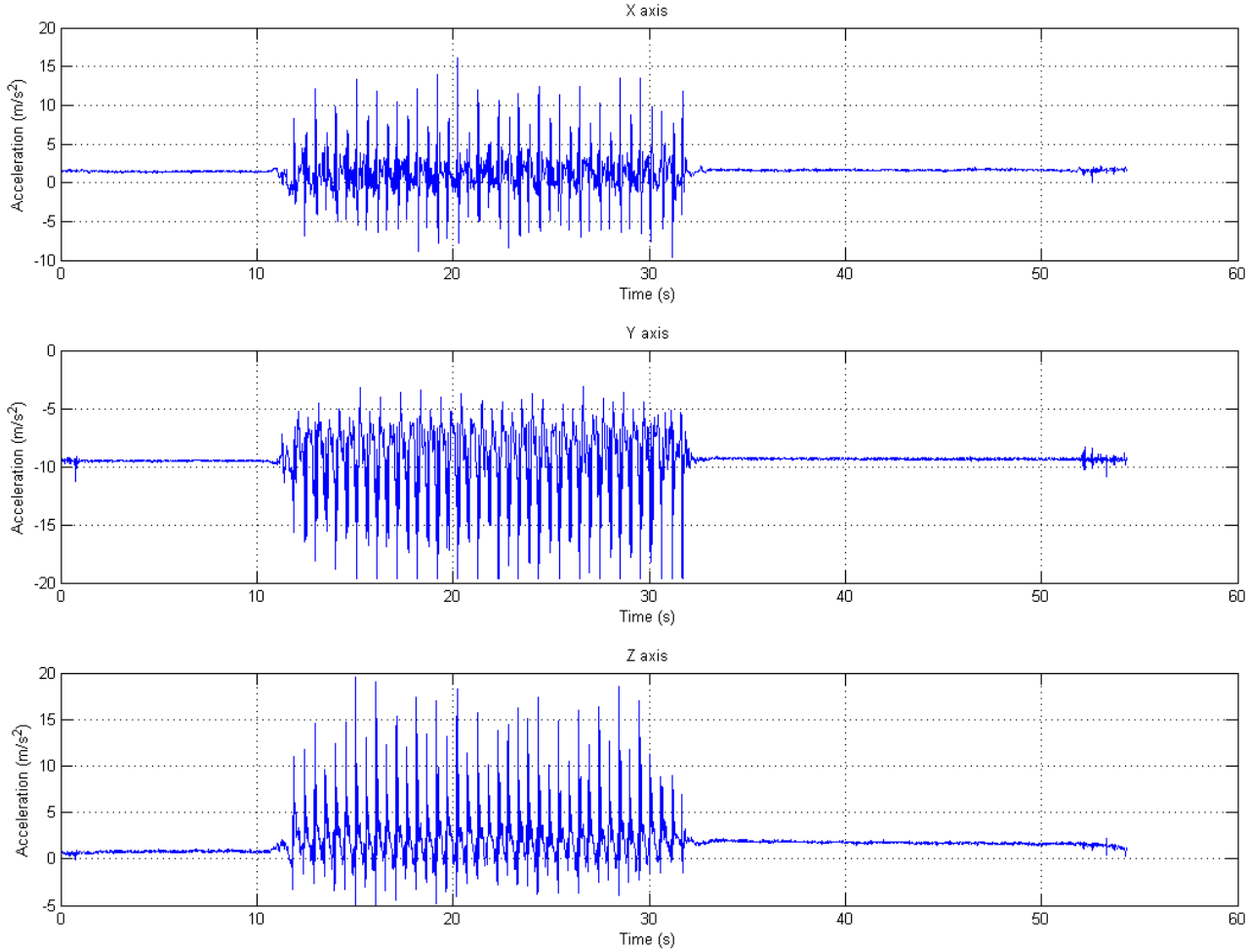



*Figure 7: First data set for 30m distance*

stages. It was used for comparison of the data from the device with the data obtained from the other pedometers[34].

### 2.2.1. Aspects to be considered

Although most of the development were based on the different approaches, the filtering portion of the algorithms was based partially on the literature used. For instance, on most of the literature, part of the filtering process consisted on applying a low pass filter with a cut-off frequency below the 20 Hz mark so that unwanted noise got eliminated.

In some cases [7], it was recommended to apply a high pass filter at very low frequencies (<2 Hz) so that the gravity component of the data could be attenuated as much as possible. Although this turned up to be true, it did produce an unwanted response on the data in the form of ringing. This is believed to happen because any offset in the data due to the gravity component was interpreted as a step function and filtering of such signal caused such response. The way this problem was solved was subtracting this offset due to the gravity component, rather than filtering it out[35]. Of course, such component was calculated from the data itself as the acceleration sensor can't make an exact measure of gravity and subtracting its theoretical value will still bring the same problem again.

This bandpass filtering is considered the first stage of filtering process of every data set. The second stage of filtering consists of a low-pass filter with a cut-off frequency at the first harmonic[36] of the acceleration data. This harmonic is believed to correspond to the subject's speed in terms of steps/s so any data at higher frequencies is just a harmonic multiple or acceleration due to other forces. But from trial and error it was observed that a cut-off frequency at the first harmonic was too strong, so the cut-off frequency was changed to the second harmonic of the data set.

The frequency value of the second harmonic was not obtained through FFT analysis as it had been done with the first harmonic, but rather calculated as a multiple of the first harmonic. This was done as so because the harmonic detection procedure based itself on search for peaks of power in the FFT analysis results and it was not always found the second harmonic as the true second harmonic. What happened was that in some occasions the true second harmonic peak had less power in comparison with other harmonic power peaks.

Testing also showed that using higher harmonics only added noise to the data set and increased variance in the final results.

### 2.2.2. Integrate all the data approach

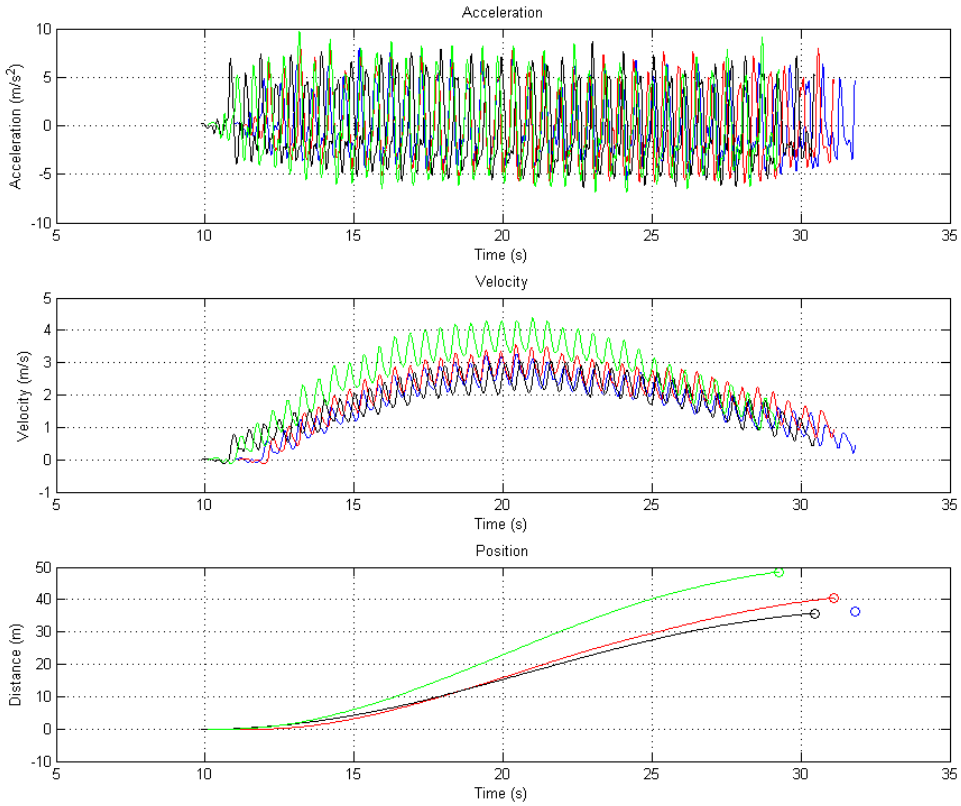
This approach is the simplest of all the ones tried. Basically it integrates all of the acceleration data after applying both filtering stages to obtain the speed of the subject, and it is integrated again to obtain the distance traveled. See Graph 1 (pg 20) for an example.

.

[34] *Other pedometers used for comparison (pg 18)*

[35] A similar method was used on [12], as one of the algorithms studied in such work was similar to the basic ideas (filtering, absolute magnitude of acceleration and gravity subtraction) used in the tested algorithms of this project

[36] Found through FFT analysis of each data set.




*Graph 1: Graphical representation of results for 30m, integrating all the data*

### 2.2.3. Integrate the data in batches approach

In this approach, the valid acceleration data set was first filtered and then cut in portions of approximately five seconds in length. Each data portion was subsequently integrated twice. When integrating speed, it was taken into consideration the final value of the previous data portion integration as the initial value for the next data portion integration. The same was done when integrating the speed results into distance. See Graph 2 (pg 22) for an example.

### 2.2.4. Integrate the data in steps approach

This approach is similar to the previous one but rather than slicing in sections of time, each portion is limited by each step the subject performs. This way each step is considered as independent from the rest. According to [6], a step consists on 4 different stages, which consists of:

1) Stance (heel and toe on the ground)
2) Push-off (heel off the ground, toe on the ground)
3) Swing (heel and toe off the ground)
4) Foot down (heel on the ground, toe off the ground)

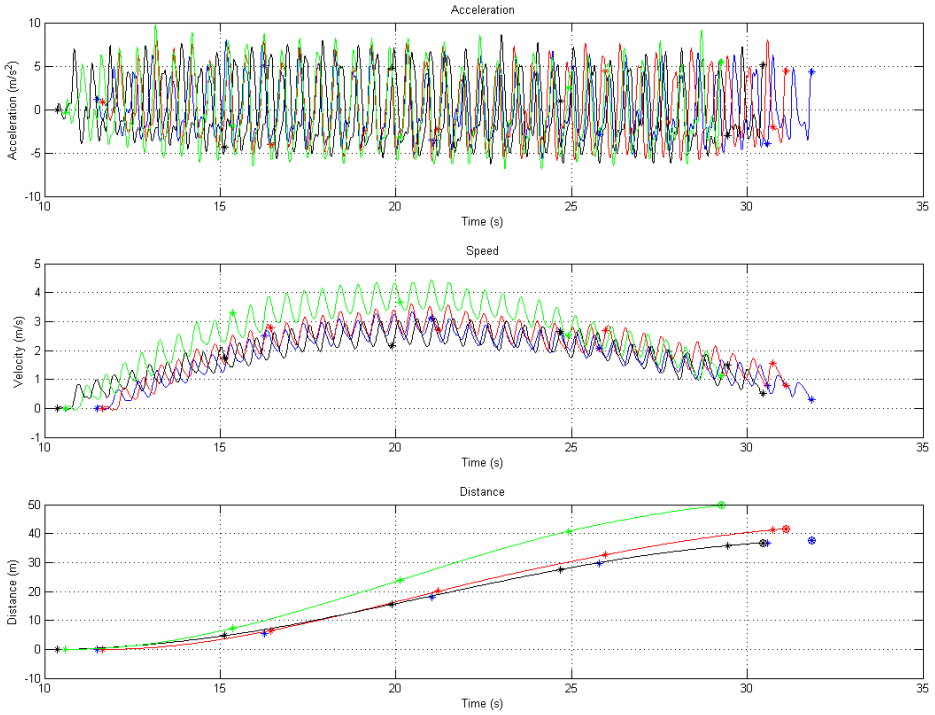
Based on [6], the acceleration spikes represent the fourth stage of each step as the heel touches the ground. Because the device is located at the lower back, each spike represented the heel strike of each foot rather than from one foot, as reflected in Figure 9. These spikes were used as markers that delimited each step of interest[37][38].

Now that each step has its beginning and end point, they are considered as independent entities and processed each one of them in the same way as done in the previous approaches[39][40].

There is a difference in the integration stage between this approach and the previous regarding the initial values for the integration of speed. In the previous approach, each time the data portion was integrated from speed values to distance, the final speed value of the previous data portion was considered as the initial value for the next portion. In this approach such consideration was not taken and each step was treated as if done separately from the previous one.

Additionally, this algorithm had two different cases in which their difference relied on using either the acceleration data of the XYZ axes or the acceleration data of the XZ axes. This way, the acceleration data that represents the most part of the foot down stage is eliminated and it was tested if such elimination provided any improvements over the results.

[37] The first step performed only has one marker (the final heel spike) so it was assumed that the first step lasted approximately five seconds.
[38] See Graph 3, pg 21 for an example of how the acceleration data was treated.
[39] The FFT analysis was done over the entire data set as each independent step did not have enough information to figure out the harmonics of the data.
[40] See Graph 4: Graphical representation of the acceleration data, the velocity and distance walked for every step taken into consideration in the first data set of the 30m session., pg 21, for an example of how the acceleration data got converted in one of the data sets.




*Graph 2: Graphical representation of results for 30m, integrating the data in batches (each batch is delimited by stars*

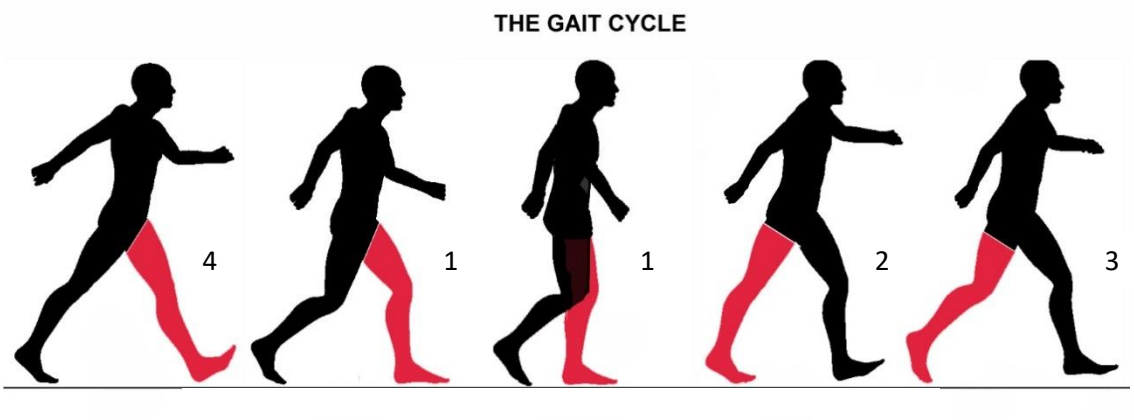



*Figure 8: Graphical representation of the gait cycle (1: Stance, 2: Push-off, 3:Swing, 4:Foot down)*

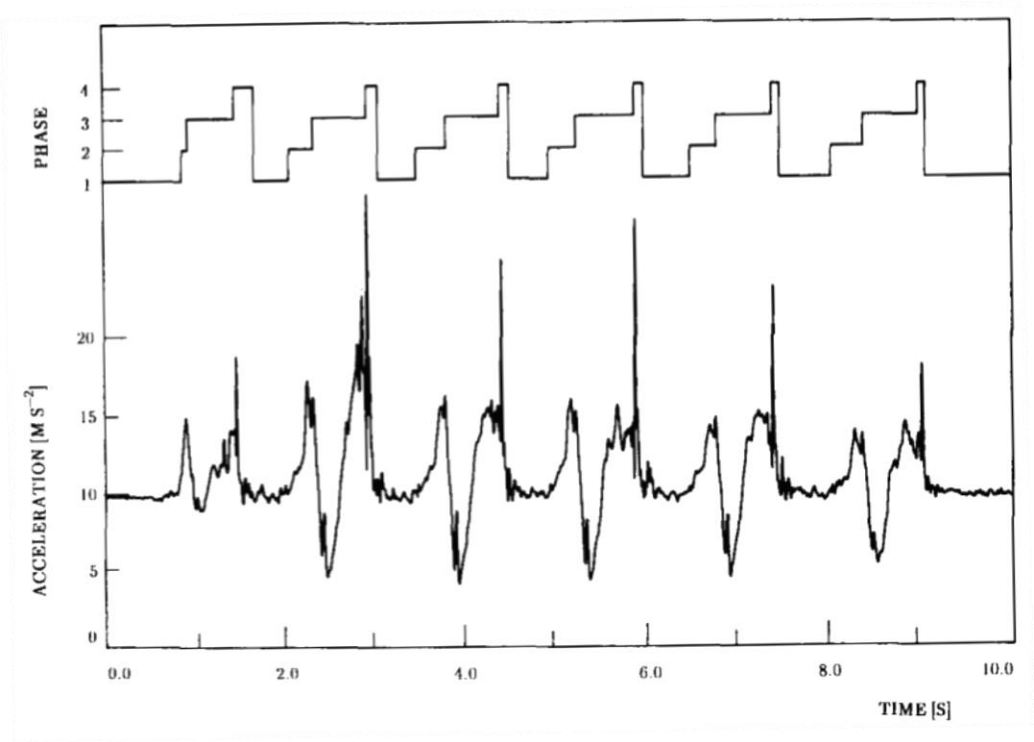
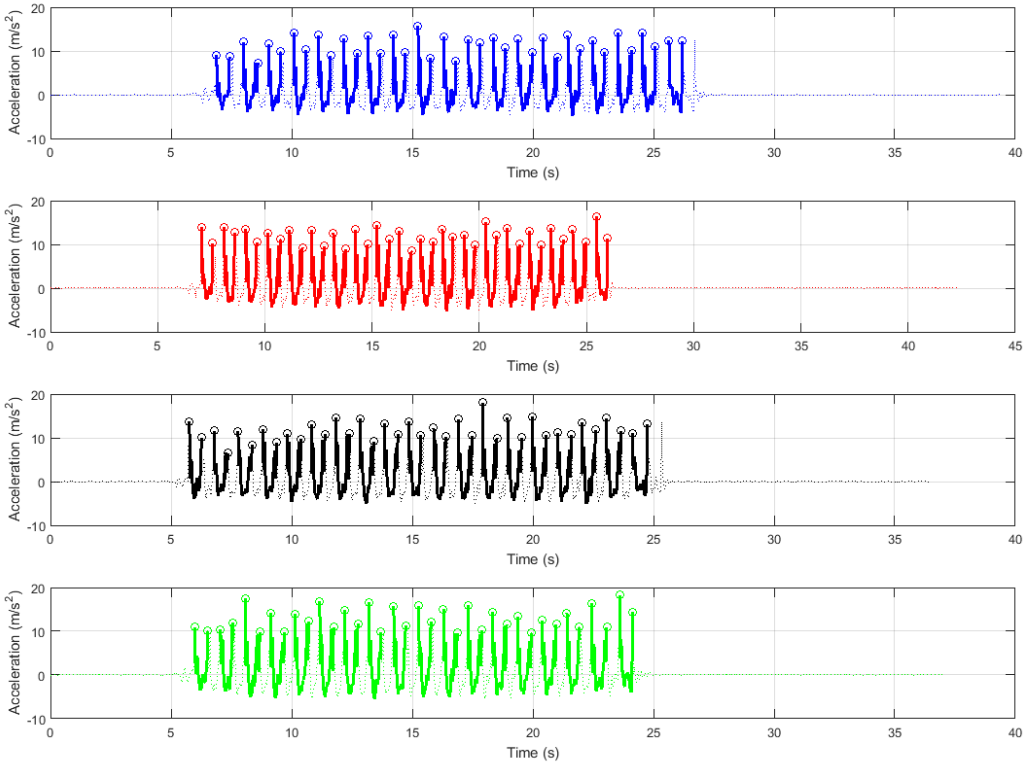
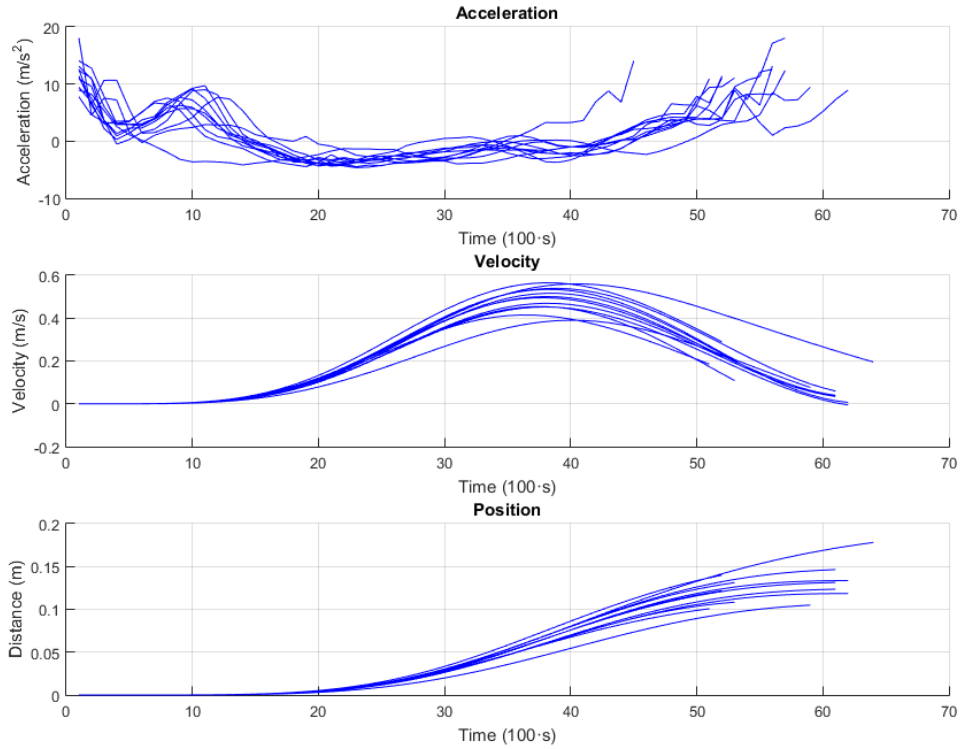



*Figure 9: Graphical representation of the acceleration modulus and the 4 stages of a step (Extracted from [6])*




*Graph 3: Graphical representation of the acceleration data used as representation of the different steps performed by one of the legs (solid line), overlaid over the absolute acceleration measured (dotted line) in the 30m session.*




*Graph 4: Graphical representation of the acceleration data, the velocity and distance walked for every step taken into consideration in the first data set of the 30m session.*

## 2.3. Design of the experimental setup

In order to evaluate the effectivity of the device and the algorithms, data had to be acquired of a subject walking in a straight line as steadily as possible. Making turns around a corner or walking up/down the stairs was not considered in this project as it will have added additional acceleration data to the Y-axis and the Z-axis respectively. Certain aspects had to be taken in consideration.

### 2.3.1. Other pedometers used for comparison

Effectivity of the device was compared against two other pedometers such as a pendulum based pedometer (Zippy8[41]) and a cellphone app (Noom Walk). According to [2], there are two more types of pedometers (using a GPS system and using an accelerometer), but both of them are quite expensive and weren't used in the experiences carried. Data of steps counted by both systems was recorded and in the case of the pendulum based pedometer, the distance traveled indicates in its screen too.

### 2.3.2. Protocol Followed

In order to evaluate the effectivity of the designed pedometer, a subject walked several measured distances and repeated each walking session four times. On one hand, the subject carried the designed pedometer on the lower part of its back, more specifically at the height of the sacrum (Figure 12, pg 29), as such location is closest to the center of gravity of the human body[42]. An alternative position could be in the ankle and hence the device could measure also distances at low speeds [8]. But from evaluation of [8] where it was placed a similar device on the waist and in the ankle is concluded that it will register greater variances of acceleration values and it is more prone to measure activities that are not related to walking[43].

Before being used, its offset was calibrated placing our device such as in the figure. Once the offset adjustment was set, the device was ready to be used for measuring walked distances. From experience gathered on processing data, and as mentioned in [6], the last step performed is usually weaker than the rest. This last weak step could not be detected with the different algorithms, so the subject had to do the final step with the same force as with the other steps in order to avoid such problem.

On the other hand, the pendulum pedometer was clipped to the belt of the subject at its right side. Such pedometer required certain calibration, based on the subject physiology like his weight and the mean distance of a single step. The mean distance of a single step was calculated by making the subject walk 10 steps, measure the walked distance and calculate the mean distance of a single step[44].

[41] Figure 10, pg 24
[42] See Figure 13, pg 26, for a picture of the device placement in the subject and Figure 12, pg 26, for a representation of the axes orientation of the accelerometer.
[43] For example, heel tapping or leg swinging
[44] 0,7793 meters


*Figure 10: Pendulum based pedometer used for comparison against the device and the cellphone app*

Finally, the app-based pedometer didn't required calibration at all, so the subject placed the cellphone into his right pocket on his pants.

For every set of data collected, before and after each walk, a pause of 10-20 seconds was performed for two special reasons:

1) The pause at the beginning (10 seconds) allows the accelerometer to stabilize once the device has been activated on capture of data mode and hence allow easy removal of any unwanted data recording the movement of the body when starting the device. Additionally, this data was used to assure that offset had been calibrated correctly and that the value of sensitivity was the right one by calculating the magnitude of gravity in such moment, from the acceleration values of the three axes.

2) The pause at the end of the walked distance (20 seconds) follows the same idea of easy removal of unwanted data when changing from capture of data mode to computer communication mode. Additionally, when processing the data, it was observed that there was a certain delay (Figure 11, pg 28) on the stabilization of the signal, so this additional time helped for this stabilization[45].

Distances were measured using a tape ruler and covering a distance up to 30 meters, creating marks every 5 meters. The subject started at distance 0m and walked until the mark corresponding the desired distance to be calculated. The procedure used for every distance walked was the following:

1) Subject is set at the zero distance mark, the pendulums' previous pedometer distance measure is set to zero and note was taken of the number of steps counted by the app.
2) Subject sets the device in recording mode and waits 10 seconds before starting walking.
3) Subject walks the desired distance to be measured, with a steady pace.
4) Once the distance desired is reached, subject must immediately stop and wait 20 seconds before stopping the device from recording data.
5) When the waiting period has elapsed, the device is stopped from capture of data mode and note must be taken from the steps counted by the pendulum based and the app based pedometers, as well as the distance traveled displayed by the pendulum based pedometer.
6) Download the acceleration data gathered by the device into the computer and give the file the appropriate name.
7) Repeat steps 1 through 5 three more times for the same desired distance.

[45] There could be two possible causes for this delay

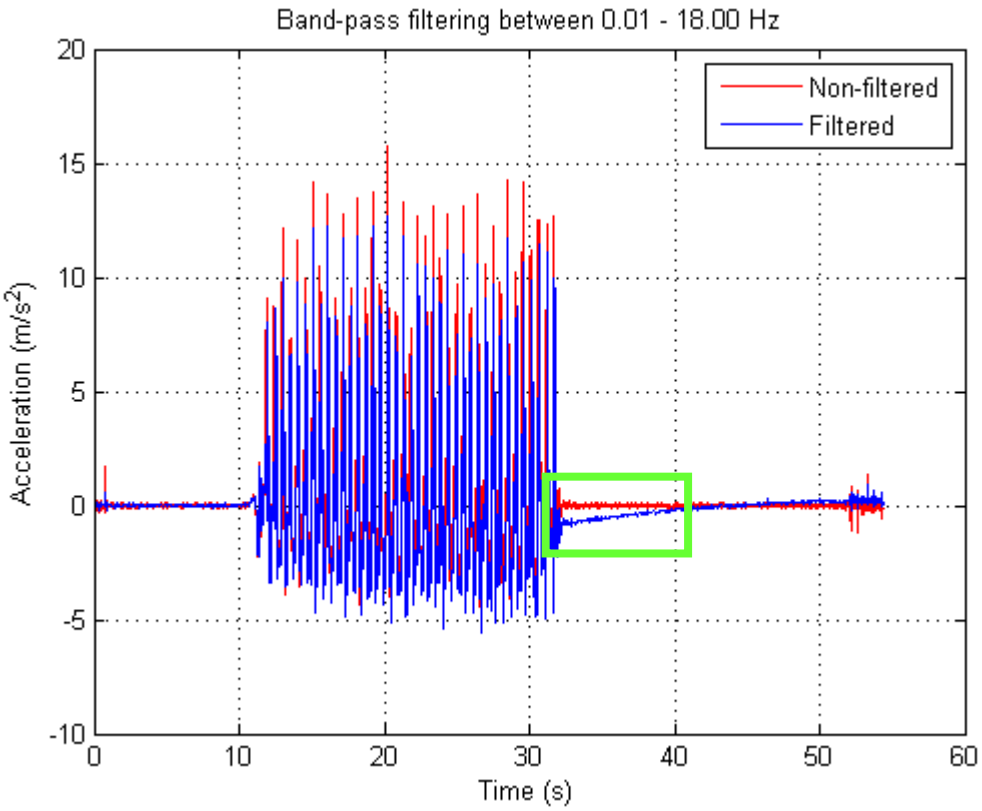



*Figure 11: Absolute acceleration data after first filtering stage of the first data set of 30m. The delay is highlighted in the green box.*

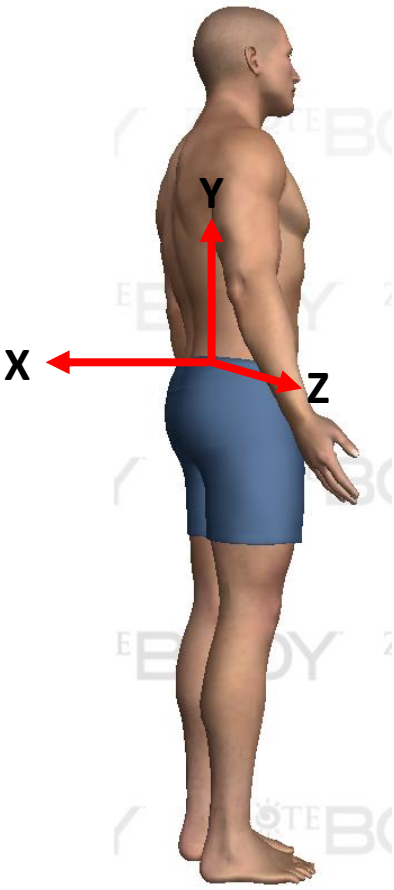



*Figure 12: Representation of the axes of reference of the acceleration in the body*

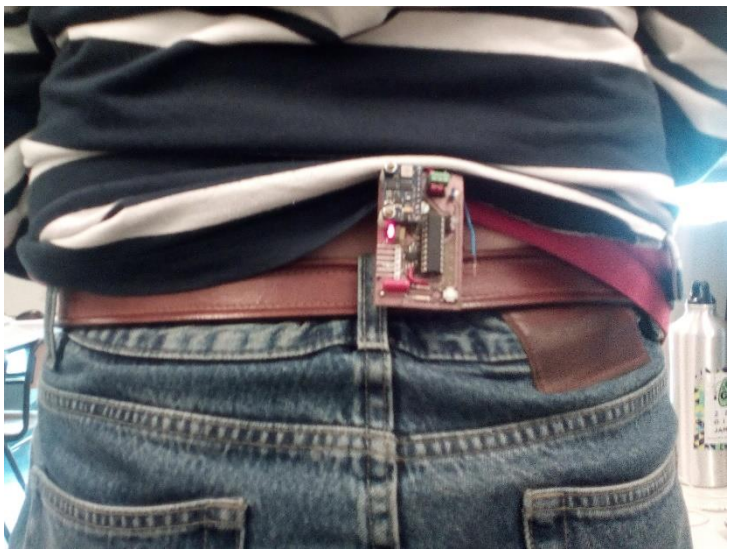


*Figure 13: Picture of device placement on subject*

# 3. Results and Discussion

## 3.1. Aspects to be considered

The results gathered from processing the acceleration data for each distance walked was studied applying simple linear regression to every set of results and using the coefficient of determination as a measure of the algorithms reliability. Additionally, for every simple linear regression, the fitted line will be represented and interpreted as a calibration curve between the data processed with a specific algorithm and the real distance walked.

Every algorithm has been compared with the data obtained from the pendulum based pedometer as it has proven to be quite reliable when measuring the distance traveled ($R^2$=0.9947). This observation should be handled with care because of the limitation of the pedometer in measuring distances in miles rather than on meters. As seen in Table 2: Statistical data relative to the distance data gathered from the cellphone app and the pedometer, the statistical data relative to distance measured by the pedometer is null and this happened because the pedometers' sensitivity was not high enough.

The cellphone app data has not been used for comparison as the data gathered was not consistent during the experimental procedure. As seen in Graph 5Graph 5: Comparison between simple linear regression of step data gathered by device, pedometer and cellphone app and Table 1: Statistical data gathered from the cellphone app, pedometer, counted steps and pseudo algorithm used for counting steps with the device, the data gathered from the cellphone app in relation with the amount of steps performed was barely consistent ($R^2$=0,0266).

In Table 1: Statistical data gathered from the cellphone app, pedometer, counted steps and pseudo algorithm used for counting steps with the device, mean values for data points, standard deviation and minimum and maximum values obtained from every algorithm. Same statistical data is present in Table 1: Statistical data gathered from the cellphone app, pedometer, counted steps and pseudo algorithm used for counting steps with the device for the cellphone app and the pedometer.

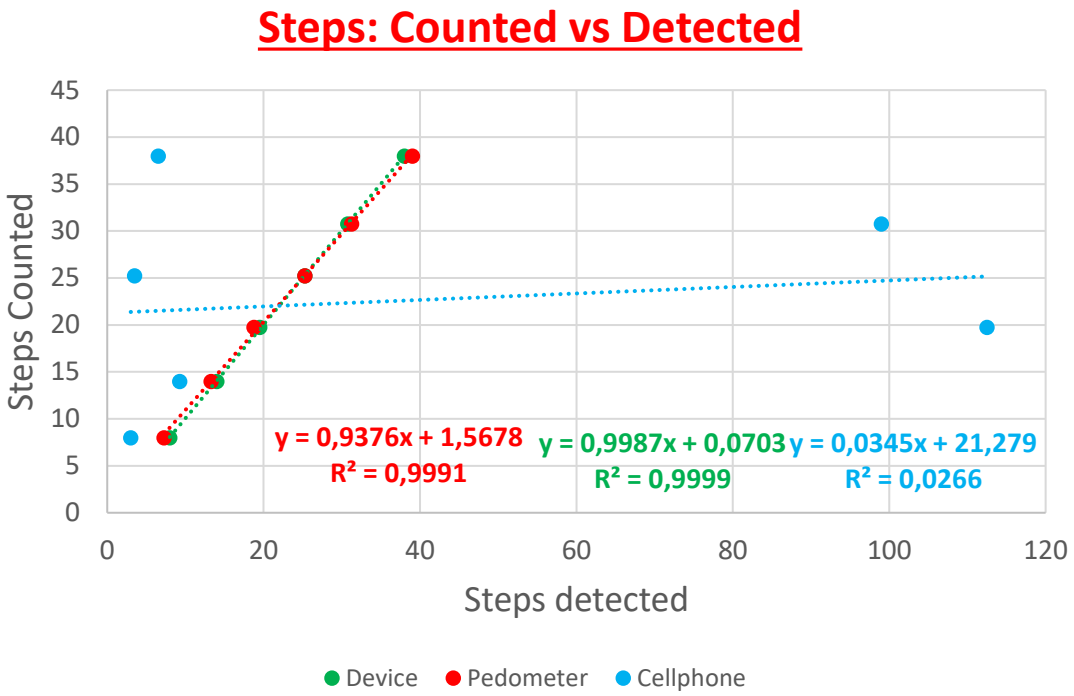
Excluding the third algorithm, it is generally observed that the velocity profile has a sinusoidal behavior. According to [9], this is normal due to forward and backward movement of the body during conversion of kinetic energy (moving forward) to potential energy (raising the leg for the next step) and vice versa.

## 3.2. Observations of integrating all the data ($R^2$=0,9710)

Using this algorithm, the calculated distances followed certain lineal tendency except for the data point corresponding to 30m walked, as seen in Graph 6: Comparison between pedometer and device (using the algorithm of integrating all the data) vs the ideal situation. It is observed that until 25m walked there is a relationship between true distance walked and distance measured of 0.5. It has been tried to correct the 30m data point by modifying the filtering procedure but results were worst.

There could be several reasons why this algorithm has problems with the 30m data point, which include:

a) It could be that due to integration error, this algorithm might not measure further than 30m of walking.
b) Maybe beyond 30m of walking the algorithm still has a linear relationship between distance measured and true distance walked but with a different calibration curve.




*Graph 5: Comparison between simple linear regression of step data gathered by device, pedometer and cellphone app*

| | Steps | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Cellphone | | | | | Pedometer | | | | |
| True Distance (m) | Mean Distance (m) | Standard Deviation (m) | Coefficient of variation (%) | Mininum Distance (m) | Maximum Distance (m) | Mean Distance (m) | Standard Deviation (m) | Coefficient of variation (%) | Mininum Distance (m) | Maximum Distance (m) |
| 30 | 6,5000 | 2,3805 | 36,6227 | 5,0000 | 10,0000 | 39,0000 | 1,4142 | 3,6262 | 37,0000 | 40,0000 |
| 25 | 99,0000 | 184,7052 | 186,5709 | 4,0000 | 376,0000 | 31,2500 | 1,2583 | 4,0266 | 30,0000 | 33,0000 |
| 20 | 3,5000 | 2,5166 | 71,9032 | 0,0000 | 6,0000 | 25,2500 | 0,5000 | 1,9802 | 25,0000 | 26,0000 |
| 15 | 112,5000 | 216,3647 | 192,3241 | 0,0000 | 437,0000 | 18,7500 | 0,9574 | 5,1063 | 18,0000 | 20,0000 |
| 10 | 9,2500 | 7,3655 | 79,6266 | 0,0000 | 18,0000 | 13,2500 | 0,5000 | 3,7736 | 13,0000 | 14,0000 |
| 5 | 3,0000 | 3,8297 | 127,6569 | 0,0000 | 8,0000 | 7,2500 | 0,5000 | 6,8966 | 7,0000 | 8,0000 |

| | Algorithms | | | | | Counted | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| True Distance (m) | Mean Distance (m) | Standard Deviation (m) | Coefficient of variation (%) | Mininum Distance (m) | Maximum Distance (m) | Mean Distance (m) | Standard Deviation (m) | Coefficient of variation (%) | Mininum Distance (m) | Maximum Distance (m) |
| 30 | 38,0000 | 1,4142 | 3,7216 | 36,0000 | 39,0000 | 38,0000 | 1,4142 | 3,7216 | 36,0000 | 39,0000 |
| 25 | 30,7500 | 0,5000 | 1,6260 | 30,0000 | 31,0000 | 30,7500 | 0,5000 | 1,6260 | 30,0000 | 31,0000 |
| 20 | 25,2500 | 0,5000 | 1,9802 | 25,0000 | 26,0000 | 25,2500 | 0,5000 | 1,9802 | 25,0000 | 26,0000 |
| 15 | 19,5000 | 0,5774 | 2,9608 | 19,0000 | 20,0000 | 19,7500 | 0,5000 | 2,5316 | 19,0000 | 20,0000 |
| 10 | 14,0000 | 0,0000 | 0,0000 | 14,0000 | 14,0000 | 14,0000 | 0,0000 | 0,0000 | 14,0000 | 14,0000 |
| 5 | 8,0000 | 0,0000 | 0,0000 | 8,0000 | 8,0000 | 8,0000 | 0,0000 | 0,0000 | 8,0000 | 8,0000 |

*Table 1: Statistical data gathered from the cellphone app, pedometer, counted steps and pseudo algorithm used for counting steps with the device*

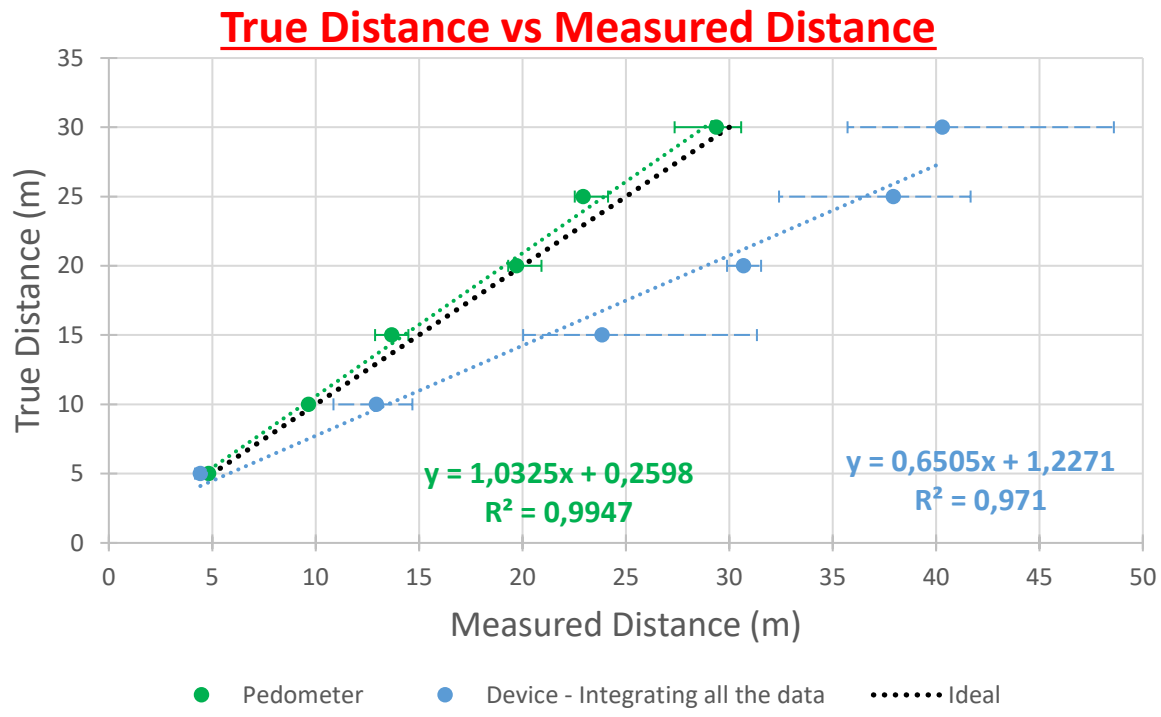
| | Data from other devices | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Cellphone | | | | | Pedometer | | | | |
| True Distance (m) | Mean Distance (m) | Standard Deviation (m) | Coefficient of variation (%) | Mininum Distance (m) | Maximum Distance (m) | Mean Distance (m) | Standard Deviation (m) | Coefficient of variation (%) | Mininum Distance (m) | Maximum Distance (m) |
| 30 | 6,5000 | 2,3805 | 36,6227 | 5,0000 | 10,0000 | 29,3705 | 1,5408 | 5,2462 | 27,3589 | 30,5775 |
| 25 | 99,0000 | 184,7052 | 186,5709 | 4,0000 | 376,0000 | 22,9332 | 0,8047 | 3,5088 | 22,5308 | 24,1402 |
| 20 | 3,5000 | 2,5166 | 71,9032 | 0,0000 | 6,0000 | 19,7145 | 0,8047 | 4,0816 | 19,3121 | 20,9215 |
| 15 | 112,5000 | 216,3647 | 192,3241 | 0,0000 | 437,0000 | 13,6794 | 0,9292 | 6,7924 | 12,8748 | 14,4841 |
| 10 | 9,2500 | 7,3655 | 79,6266 | 0,0000 | 18,0000 | 9,6561 | 0,0000 | 0,0000 | 9,6561 | 9,6561 |
| 5 | 3,0000 | 3,8297 | 127,6569 | 0,0000 | 8,0000 | 4,8280 | 0,0000 | 0,0000 | 4,8280 | 4,8280 |

*Table 4: Statistical data relative to the distance data gathered from the cellphone app and the pedometer*

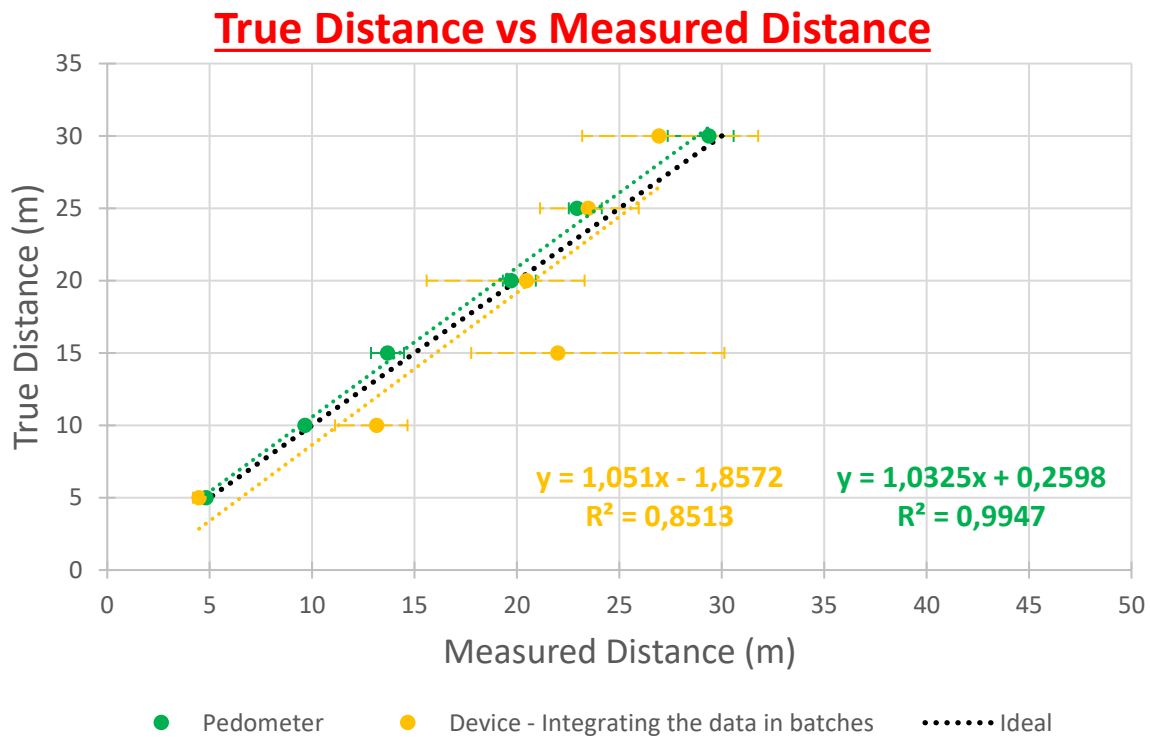
| | All the data aproach | | | | | Data in batches | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| True Distance (m) | Mean Distance (m) | Standard Deviation (m) | Coefficient of variation (%) | Mininum Distance (m) | Maximum Distance (m) | Mean Distance (m) | Standard Deviation (m) | Coefficient of variation (%) | Mininum Distance (m) | Maximum Distance (m) |
| 30 | 40,2951 | 5,9229 | 14,6987 | 35,7213 | 48,5986 | 26,9292 | 3,6522 | 13,5624 | 23,1838 | 31,7735 |
| 25 | 37,9262 | 4,3336 | 11,4265 | 32,4085 | 41,6714 | 23,4878 | 2,0022 | 8,5246 | 21,1265 | 25,9435 |
| 20 | 30,6803 | 0,7861 | 2,5622 | 29,8952 | 31,5400 | 20,4674 | 3,4355 | 16,7854 | 15,5904 | 23,3015 |
| 15 | 23,8373 | 5,1239 | 21,4955 | 20,0339 | 31,3394 | 21,9909 | 5,5401 | 25,1927 | 17,7690 | 30,1261 |
| 10 | 12,9265 | 1,6825 | 13,0158 | 10,8623 | 14,6789 | 13,1467 | 1,6220 | 12,3378 | 11,1208 | 14,6570 |
| 5 | 4,4238 | 0,1870 | 4,2278 | 4,1678 | 4,6024 | 4,4806 | 0,2018 | 4,5048 | 4,1836 | 4,6348 |

| | Step Approach | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | XYZ Axes | | | | | XZ Axes | | | | |
| True Distance (m) | Mean Distance (m) | Standard Deviation (m) | Coefficient of variation (%) | Mininum Distance (m) | Maximum Distance (m) | Mean Distance (m) | Standard Deviation (m) | Coefficient of variation (%) | Mininum Distance (m) | Maximum Distance (m) |
| 30 | 2,4915 | 0,3522 | 14,1360 | 2,0648 | 2,9274 | 4,4727 | 0,5921 | 13,2377 | 3,5863 | 4,8035 |
| 25 | 1,8927 | 0,1850 | 9,7764 | 1,6425 | 2,0568 | 3,5356 | 0,2183 | 6,1733 | 3,2656 | 3,7442 |
| 20 | 1,5360 | 0,0906 | 5,9017 | 1,4094 | 1,6192 | 2,5893 | 0,2599 | 10,0378 | 2,3542 | 2,9586 |
| 15 | 1,2614 | 0,1368 | 10,8449 | 1,0879 | 1,4128 | 1,8633 | 0,2799 | 15,0213 | 1,5136 | 2,1299 |
| 10 | 0,9101 | 0,0442 | 4,8534 | 0,8477 | 0,9418 | 1,4938 | 0,1061 | 7,1060 | 1,3418 | 1,5764 |
| 5 | 0,5833 | 0,0602 | 10,3253 | 0,5476 | 0,6734 | 0,8194 | 0,0940 | 11,4768 | 0,6835 | 0,8968 |

*Table 4: Statistical data gathered from data processing through the different algorithms of distance calculation*




*Graph 6: Comparison between pedometer and device (using the algorithm of integrating all the data) vs the ideal situation*




*Graph 7: Comparison between pedometer and device (using the algorithm of integrating the data in batches) vs the ideal situation*

c) It could be that the data gathered had some inconsistences as it is observed great variations (σ=5,9229 m) of distances calculated.

Furthermore, it is observed that the 20m data point has the smallest coefficient of variation (2,5622 %) of all the data points of all the algorithms.

## 3.3. Observations of integrating the data in batches ($R^2$=0,8513)

This algorithm proved to be much better than the previous one as it has a closer 1:1 relationship between true distance walked and distance measured. It is also very similar to the pedometer simple linear regression, but as observed in Graph 7 the data point corresponding to 15m is off the calibration curve with the widest variation of data (σ=5,5401 m).

There could be several reason why this algorithm has problems with the 15m data point, which include:

a) As mentioned previously it could be that maybe beyond 15m of distance the relationship between measured and true distance is still linear but with another calibration curve. This possibility is a long shot as the 20m data point is placed over the right of the 15m data point before it starts to show again a linear regression. This will mean that there is no way to measure distances between 15m and 20m.
b) It could be that the data gathered was not consistent between the various data sets, hence producing such wide variation and moving the data point to the left.
c) It could be that due to integration error, this algorithm is not suited for measuring distances further than 15m of walking.

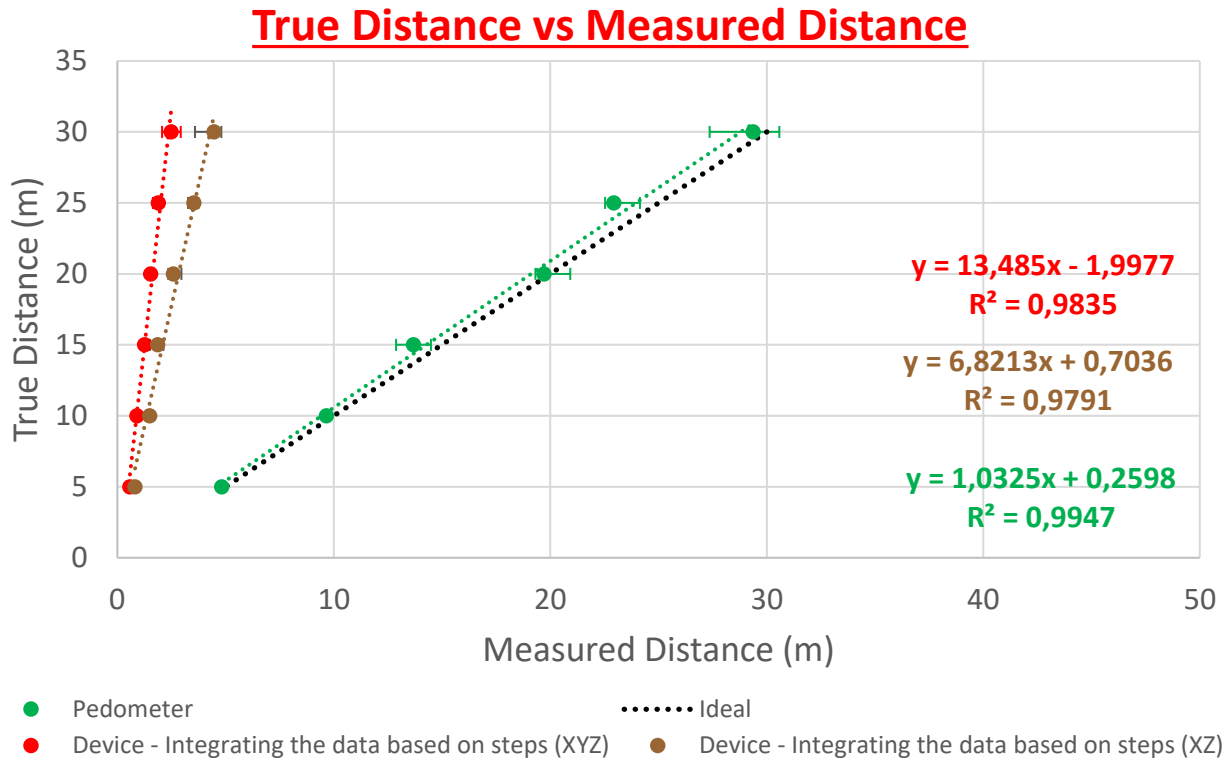
## 3.4. Observations of integrating the data based on the steps ($R^2$=0,9835 (XYZ) and $R^2$=0,9791 (XZ))

This algorithm showed very different results when compared with the results obtained through the other two algorithms and the pedometer. As seen in Graph 8, the calibration curves show the highest coefficients of determination ($R^2$=0,9835 when using the XYZ data and $R^2$=0.9791 when using the XZ data) obtained from all three algorithms but the calibration curves have steep slopes.

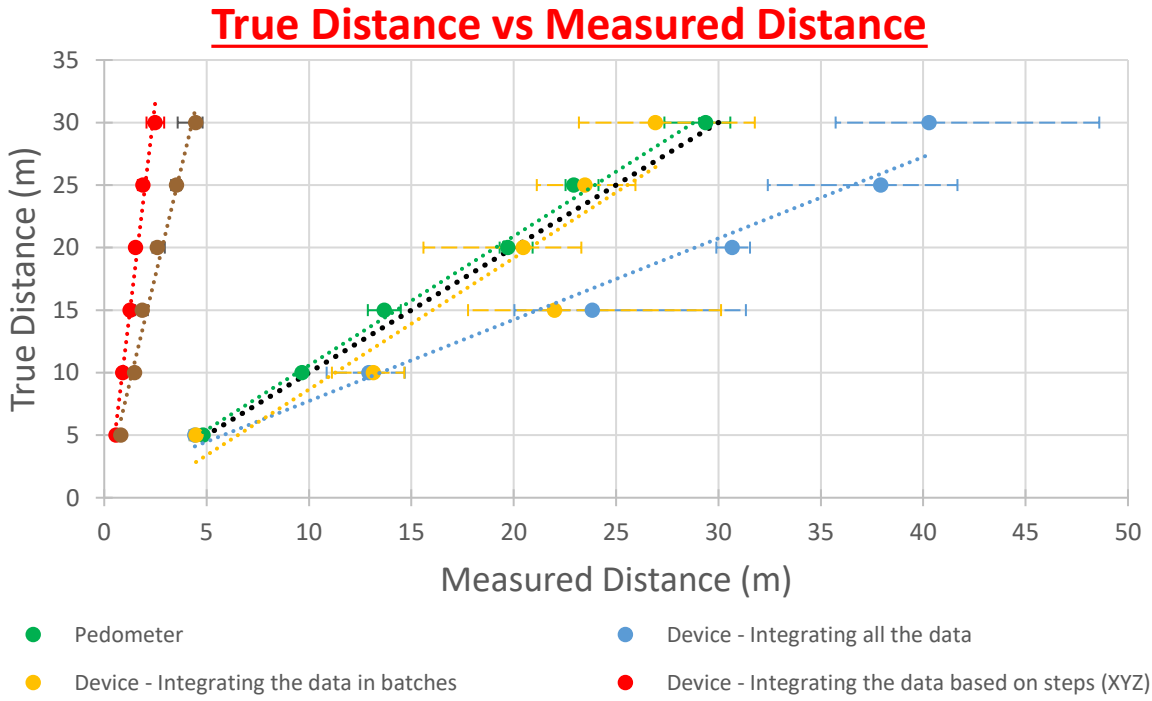
On one hand, it is observed that not taking into consideration the acceleration data from the Y axis causes a slight reduction in data quality[46], hence is less trustworthy when compared with the case in which the Y axis data was taken in consideration.

On the other hand, a possible explanation for such high relationships could be because of the way the steps are considered in the algorithm. As mentioned earlier[47], each step is treated independently from the others and they are integrated considering that the step starts with null velocity. This could have led to not take into account the overall gained velocity of the subject, which could represent the missing distance.

[46] The coefficient of determination is slightly lower and the coefficients of variation in 4 out of 6 data points increase.
[47] *2.2.4 Integrate the data in steps approach (pg 18)*




*Graph 8: Comparison between pedometer and device (using the algorithm of integrating that data by steps) vs the ideal situation*




*Graph 9: Comparison between pedometer data and device data processed with the different algorithms*

## 3.5. Comparison

One first aspect to compare is the capacity of counting steps between the device and the pedometer (Graph 5Graph 5: Comparison between simple linear regression of step data gathered by device, pedometer and cellphone app). Both systems show a perfect correlation between the amount of steps detected ($R^2$=0.9999 for the device and $R^2$=0.991 for the pedometer).

The device will have had a perfect coefficient of determination if it had not been for one of the data sets[48] in which the last step was done softer than expected and the pseudo-algorithm could not detect it.

One second aspect to compare is between the devices' data processed by the first and second algorithm and the pedometers' data is that the 5m data points are the more exact than any other data points, as seen in Graph 9[49]. These similarities could be happening because the 5m data sets where the shortest ones to be recorded, hence the different processing algorithms cannot reflect appreciable differences.

This reasoning could also be applied to the 10m and 15m data points of the first two algorithms as they barely reflect a difference between them despite been processed by different algorithms. Such kind of differentiation is appreciated starting at the 20m data point.

Surprisingly enough, these similarities between the first two algorithms are shared even with the standard deviations and maximum and minimum values for the 5m, 10m and 15m data points.

One last aspect to compare is about the third algorithm and its two variations (XYZ and XZ). On one side, in Graph 8 is seen that excluding the data of the Y-axis ended in a relationship between true and measured distances closer to the ideal situation. On the other side, the third algorithm has the highest coefficient of correlation of all three algorithms (the XYZ variation highest than the XZ variation).

[48] 3rd repetition of the 20m data set

[49] Although the 5m data point of the third algorithm is different from the 5m data point of the other two algorithms, it is very similar between the two variations of such algorithm.

# 4. Conclusions and Improvements

**Based on the work done it can be concluded that the device can measure distances of at least five meters with a deviation of 4,2278 % if the first algorithm is used.** The second algorithm could also be considered as reliable for the purpose but has a slightly higher coefficient of variation (4,5048 %). It could be extended to the 10m and 15m mark but their respective coefficients of variation are higher than 5%, no matter the algorithm used. Another alternative could be using the first algorithm for combinations of distances of 20m and 5m as for distances of 20m there is the smallest variation in the measured distances ($C_v$=2,5622 %).

The cellphone app data probably gave the random results because of misuse of the app.

It has to be stated that the third algorithm is not viable, despite its high coefficients of correlation ($R^2$=0,9835 (XYZ variation) and $R^2$=0,9791 (XZ variation)), because it has coefficients of variation higher than 5% in the data point of interest (5m and 20m).Moreover, it has proven that the device is a very reliable system to count steps ($R^2$=0,9999) with very little variation[50]. Although counting steps was not the objective of this project, it does shed light on the possibility of using the step counting features with the inertial measurements. Acceleration data can be collected and processed with the algorithm once the amount of steps corresponding to 5m is reached and add the distance calculated to the previous distance measured.

Even though the device showed positive results, improvements can be done for verifying the conclusions and check on the discrepancies of the observations done over the results obtained from the different algorithms, for example, only one subject was used for the data collection. An increase in number of subjects over a variety of conditions[51] will produce enough data about different types of gait and test if the conclusions are true.

Additionally, other improvements could be done to verify the conclusions presented. For instance, the procedure could be changed in a way that the subject has a pause every 5m. That way, the data is integrated in sequences of 5m rather than altogether. Furthermore, a pedometer with a higher sensitivity will produce better results for small distances, hence having a better comparison at statistical level.

Other improvements could be done to check the third algorithm more thoroughly. As mentioned previously, one cause that the third algorithm produced results that are far away from the ideal ones could be because the overall gained velocity is not taken into consideration. One way to prove if this is true is to collect data again but making a pause for every step made, hence avoiding that the subject gains a stable speed.

Finally, on the observations it is mentioned multiple times that the algorithms may not be able to measure beyond certain distances. A way to check if this is happening or is just integration error is to gather data of a higher variety of distances and more repetitions of each data set[52].

[50] The coefficients of variation for the steps counted with the device were normally the same as those calculated for the steps that were counted manually.
[51] Weight, height and age
[52] That way any data set in which the subjects gait has a certain peculiarity gets shadowed by the other data sets.

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# Annex 1: PIC Firmware implemented

```
/* La trama a mandar via UART es (8 bytes + 2 de trama [hiciste el cÃ¡lculo y salen 31250 tramas]):
 inicio-nº trama_H-nº trama_L-aX_H-aX_L-aY_H-aY_L-aZ_H-aZ_L-chekcsum

 La trama a GUARDAR en memoria es (8 bytes):
 inicio-aX_H-aX_L-aY_H-aY_L-aZ_H-aZ_L-chekcsum
 */
//A 16 MHz para que el tiempo de capturar dato y guardar sea el minimo posible
/* El tiempo minimo de espera entre byte y byte es de 10 us, asi que hay que comprobar el registro de
 * estado  para saber cuando poder volver a escribir*/
//24-2-2016, tiempo de captura y guardado de señal=1.9 ms

#include <p18f14k22.h>
#include <stdlib.h>
#include <stdio.h>
#include <i2c.h>
#include <math.h>

//Valores del resgistro del timer0 (de ms, para 16MHz y preescalar de 64)
#define registroH25 0xFF    //2.5 ms
#define registroL25 0x64    //2.5 ms
#define registroH5  0xFE
#define registroL5  0xC7
#define registroH10 0xFD
#define registroL10 0x8F
#define registroH100 0xE7
#define registroL100 0x96
#define registroH1000 0x0B
#define registroL1000 0xDC

//Estructuras de inicio de paquete
#define inicio 0x30 //48 en decimal (caracter cero)
//#define final 0x31 //49 en decimal (caracter 1)

//Configuraciones comodas I2C
#define sensor 0xA6 //Direccion sensor
#define START SSPCON2bits.SEN
#define STOP SSPCON2bits.PEN
#define RESTART SSPCON2bits.RSEN
#define ACK SSPCON2bits.ACKSTAT
#define NAK SSPCON2bits.ACKEN

//Limite de cantidad de bytes posibles para guardar (que son 4096 tramas de 8 bytes)
#define limite 0x7A12

//Configuracion para el ajuste de offset
//Ciclos de espera de 0.1 segundos del Timer1 para decidir si se quiere hacer un reajuste de offset
#define transicion 100
#define muestras 200 //No puede ser mayor de 255 (si no nunca dejará de tomar valores)
#define offsetH 0x3C
#define offsetL  0xB0
#define sensibilidad 4

//Declaracion de los pines del modulo software SPI (EN FUNCIÃ“N DE LA MEMORIA)
#define CE LATCbits.LATC5
#define CEConfig TRISCbits.TRISC5
```

```
#define MOSI PORTCbits.RC0
#define MOSIConfig TRISCbits.TRISC0
#define SCL PORTCbits.RC1
#define SCLConfig TRISCbits.TRISC1
#define MISO PORTCbits.RC6 //Esto es una entrada
#define MISOConfig TRISCbits.TRISC6

//Declaracion de los pines UART (para cuando se salte de un micro a otro)
#define pinTX TRISBbits.TRISB7
#define pinRX TRISBbits.TRISB5

//Declaracion de los pines de los LED
#define ROJO LATCbits.LATC3
#define ROJOConfig TRISCbits.TRISC3
#define VERDE LATCbits.LATC4
#define VERDEConfig TRISCbits.TRISC4
#define AMARILLO LATCbits.LATC2
#define AMARILLOConfig TRISCbits.TRISC2

void RT_Int_Alta (void);                // Declaracion de la rutina de tratamiento de las interr. de alta
prioridad
unsigned char checksum(unsigned char x[], char n);    //Funcion de calculo de checksum
int com(char quien, char RW,char dato); //Funcion de comunicaciones SPI e I2C

// Bits de configuracion (para el P18F14K22)
#pragma config FOSC = IRC           //Oscilador interno
#pragma config PWRTEN=OFF       //Power-up Timer Enable bit
#pragma config BOREN=SBORDIS   //Brown-out Reset Enable bits
#pragma config BORV=19              //Brown out reset voltage bits
#pragma config WDTEN= OFF       //Se desactiva el WatchDog
#pragma config MCLRE=ON          //MCLR Pin Enable bit
#pragma config STVREN=ON         //Stack Full/Underflow Reset Enable bit
#pragma config LVP=OFF             //Single-Supply ICSP Enable bit

//Parametros para hacer funcionar el sensor
//Secuencia de arranque (direccionens primera fila, datos segunda)
unsigned char datS[2][3]={{0x31,0x38,0x2C},{0x08,0x80,0x0B}};
//Secuencia de arranque (direccionens primera fila, datos segunda)
//unsigned char datS[2][3]={{0x31,0x38,0x2C},{0x00,0x80,0x0D}};
unsigned char toma[3]={0x32,0x34,0x36};
//Parametros memoria
unsigned char iniM[4]={0x50,0x01,0x00,0x00};//Instrucciones y datos de configuracion de arranque
//unsigned char
dM[2][6]={{0xAD,0x00,0x00,0x00,0x00,0x00},{0x03,0x00,0x00,0x00,0x00,0x00}};//dM[0][x]
//es para escribir y dM[1][x] para leer
//Declaracion de variables
unsigned char checksumM=0,checksumRX=0;//Para comprobar los checksum
unsigned char envioM[8]={inicio,0,0,0,0,0,0,0};//Trama a memoria
unsigned char envioT[10]={inicio,0,0,1,2,3,4,5,6,7};//Trama a mandar por UART
unsigned char BufferR[5];//Trama a recibir por UART
unsigned char rec[8];
unsigned int contadorP=0,contadorT=0,capturado;
unsigned char k,i,iM=0,estado=0;
unsigned char longitud=10;
unsigned char bloqueo=0,rT=2;
```

```
unsigned char
registroT[2][5]={{registroH1000,registroH100,registroH10,registroH5,registroH25},{registroL1000,registr
oL100,registroL10,registroL5,registroL25}};//Registros H y L del Timer0
/*Esto permite saltarse la recalibración del sensor una vez se ha hecho una primera calibración (se
pone a cero el offset quitando la alimentacion y a cero esta variable con un reset)*/
unsigned char calibrado=0;
//Para el numero de trama
unsigned int trama=0; //Solo hacen falta dos bytes para las tramas que se envien a ordenador
//Para el calculo de offset
unsigned char situacion=0,espera=0;
//int offset[3]={0,0,0}; //Esto ha de ser char a secas para tener el signo
float offset[3]={0,0,0};
int capturado2=0;

// Vectorizacion interrupciones de alta prioridad
#pragma code Vec_Int_Alta = 0x08// Vectorizaci?n de las interrupciones de alta prioridad
void Cod_Int_Alta (void)
{
        _asm goto RT_Int_Alta _endasm
}
#pragma code

#pragma interrupt RT_Int_Alta

void RT_Int_Alta (void)     // Rutina de tratamiento de las interrupciones de alta prioridad
{
    //La transmision de los datos
    if(PIR1bits.TXIF&&PIE1bits.TXIE) // Se comprueba si la interrupci?n es por transmisi?n
    {
      PIR1bits.TXIF=0;//Se borra el flag de la interrupcion
      if(iM==longitud)//Cantidad de bytes
      {
        iM=0;
        if(bloqueo)
        {
          bloqueo=0;
          trama=0;
          CE=1;
          //Por el comando 19
          PIE1bits.TMR1IE=0;
          VERDE=1;
        }
        PIE1bits.TXIE=0;
        return;
      }
     if(iM<longitud)
      {
        TXREG=envioT[iM];//Envio del siguiente dato
        iM++;
        AMARILLO=!AMARILLO;
      }
    }
    else if(PIR1bits.RCIF)
    {
      PIR1bits.RCIF=0;//Se limpia el flag de la interrupcion
      BufferR[iM]=RCREG;
      //Aunque se reciban comandos, hasta que no se acabe la transmision no se puede recibir nada
```

```
168             if(BufferR[0]==48)
169             {
170                iM++;
171             }
172             if(iM==5)
173             {
174                iM=0;
175                checksumRX=checksum(&BufferR,4);
176                if(BufferR[4]==checksumRX)
177                {
178                   if(estado==4)
179                   {
180                      AMARILLO=!AMARILLO;
181                      //Si se ha llegado hasta aqui, se ha recibido correctamente una instruccion desde el PC
182                      switch(BufferR[1])
183                      {
184                         case 0:
185                            //Leer un byte del sensor por I2C y devolver por UART
186                            Nop();
187                         case 1:
188                            //Leer dos bytes del sensor por I2C y devolver por UART
189                            capturado=com(BufferR[2],BufferR[1]+1,BufferR[3]);
190                            envioT[1]=capturado/256;
191                            envioT[1+BufferR[1]]=capturado%256;
192                            envioT[2+BufferR[1]]=checksum(&envioT,2+BufferR[1]);
193                            longitud=3+BufferR[1];
194                            PIE1bits.TXIE=1;
195                            break;
196                         case 2:
197                            //Leer dos bytes de la memoria por SPI y devolver por UART
198                            envioT[2]=com(58,1,0);
199                         case 3:
200                            //Leer un byte de la memoria por SPI y devolver por UART
201                            envioT[1]=com(58,1,0);
202                            envioT[2+3-BufferR[1]]=checksum(&envioT,2+3-BufferR[1]);
203                            longitud=3+3-BufferR[1];
204                            PIE1bits.TXIE=1;
205                            break;
206                         case 4:
207                            //Inicio/Fin de secuencia SPI
208                            CE=BufferR[2];
209                            break;
210                         case 5:
211                            //Escribir un byte BufferR[3] en la memoria por SPI
212                            com(58,0,BufferR[2]);
213                            break;
214                         case 6:
215                            //Seria para borrar memoria
216                            CE=0;
217                            com(58,0,0x06);//Se manda un write enable
218                            CE=1;
219                            CE=0;
220                            com(58,0,0x60);//Se manda la instruccion de borrado de chip
221                            CE=1;
222                            VERDE=!VERDE;
223                            CE=0;
224                            com(58,0,0x05);//Se manda instruccion de leida continuada del registro de estado
```

```
                    do{
                      capturado=com(58,1,0);
                      /*Hasta que el bit BUSY no pase a 0, no se sale de ahi (que sería cuando la
                       * memoria se hubiera borrado del todo)*/
                    }while(capturado&0x0001);
                    CE=1;
                    trama=0;
                    //Esto se hace para asegurar visualmente que se ha borrado la memoria
                    VERDE=!VERDE;
                    break;
                  case 7:
                    //Seria para recoger los datos desde PC (nada desde boton)
                    CE=0;//Se selecciona la memoria para configurarla y no se suelta
                    com(58,0,0x03);//Instruccion de lectura
                    for(k=0;k<5;k++,com(58,0,0));//Primera direccion y primer byte vacio
                    //for(i=0;i<6;,com(58,0,dM[1][i]));
                    longitud=10;
                    trama=0;
                    bloqueo=0;
                    break;
                    //La interrupcion de transmision se activa en el 17
                  case 8:
                    //Esto es para asegurarse que las comunicaciones funcionan
                    Nop();
                    break;
                  case 10:
                    //Lectura del JEDEC (BF 25 8C)
                    CE=0;
                    com(58,0,0x9F);
                    envioT[1]=com(58,1,0);
                    envioT[2]=com(58,1,0);
                    envioT[3]=com(58,1,0);
                    CE=1;
                    envioT[4]=checksum(&envioT,4);
                    longitud=5;
                    PIE1bits.TXIE=1;
                    break;
                  case 11:
                    //Lectura del ID (8C BF)
                    CE=0;
                    com(58,0,0x90);
                    com(58,0,0x00);
                    com(58,0,0x00);
                    com(58,0,0x01);
                    envioT[1]=com(58,1,0);
                    envioT[2]=com(58,1,0);
                    CE=1;
                    envioT[3]=checksum(&envioT,3);
                    longitud=4;
                    PIE1bits.TXIE=1;
                    break;
                  case 12:
                    //Esto es para probar una escritura y lectura controlada (3 secuencias)
                    //Primero hay que desbloquear la memoria
                    CE=0;
                    com(58,0,0x50);//Se habilita la escritura en registro
                    CE=1;
```

```
CE=0;
com(58,0,0x01);
com(58,0,0x00);//Se desbloquea la memoria
CE=1;
//Se habilita la escritura
CE=0;
com(58,0,0x06);
CE=1;
/*Ahora se empieza con una primera secuencia que establece escritura continuada*/
CE=0;
com(58,0,0xAD);
/*Con este for se establece la direccion 0x00 0x00 0x00 y los bytes 0x00 0x00
 porque hay que mandar la trama en parejas de dos bytes (afortunadamente son 8)
 y mandar una trama partida es mÃ¡s complicado para las siguientes tramas*/
for(i=0;i<5;i++)
{
   //Esta es la direccion de inicio donde se hara la escritura y los dos bytes vacios
   com(58,0,0x00);
}
CE=1;
//Tramas a mandar (3 con bytes numericos mas la primera de antes vacia)
for(k=0,contadorP=0;k<5;k++,contadorP++)
{
   for(i=0;i<3;i++)
   {
      capturado=0xABCD;
      envioM[2*i+1]=capturado/256;
      envioM[2*i+2]=capturado%256;
   }
   envioM[7]=checksum(&envioM,7);
   for(i=0;i<4;i++)
   {
      CE=0;
      com(58,0,0xAD);
      com(58,0,envioM[2*i]);
      com(58,0,envioM[2*i+1]);
      CE=1;
   }
}
/*Ahora ya se ha acabado de escribir y hay que mandar la instruccion de
 * deshabilitacion de escritua*/
CE=0;
com(58,0,0x04);
CE=1;
//Ahora hay que proceder a la lectura.
longitud=10;
//Primero hay que indicar que se va a leer y desde la direccion 0x00 0x00 0x00
CE=0;
com(58,0,0x03);//Instruccion de lectura
//Direccion desde donde empezar la lectura continuada
com(58,0,0x00);
com(58,0,0x00);
com(58,0,0x00);
/*Hay que leer los dos primeros bytes, porque estos estan vacios y romperían la
 estructura de las tramas leidas*/
com(58,0,0);
com(58,0,0);
```

```
339                 bloqueo=0;
340                 //La interrupcion por transmision se activa en el 17
341                 break;
342               case 13:
343                 //Escribir un byte por I2C
344                 com(BufferR[2],0,BufferR[3]);
345                 break;
346               case 14:
347                 //Deshabilitar/Habilitar boton
348                 ANSELbits.ANS2=!ANSELbits.ANS2;
349                 break;
350               case 16:
351                 //Con esta intruccion se cambia de tiempo de muestro por software
352                 rT=BufferR[2];
353                 break;
354               case 17:
355                 //Instruccion de recepcion por parte de MATLAB de mandar la siguiente trama
356                 if(trama<contadorT||trama<contadorP)
357                 {
358                   //Se recoge la secuencia de 8 bytes
359                   for(k=0;k<8;k++)
360                   {
361                     rec[k]=com(58,1,0);
362                   }
363                   checksumM=checksum(&rec,7);
364                   for(k=0;k<6;k++)
365                   {
366                     if(rec[7]==checksumM)
367                     {
368                       //Si los datos recuperados son buenos, se ponen en la trama
369                       envioT[3+k]=rec[1+k];
370                     }
371                     else
372                     {
373                       //Si los datos recuperados NO son buenos, se ponen ceros
374                       envioT[3+k]=4;
375                     }
376                   }
377                   //Se establece el numero trama
378                   envioT[1]=trama/256;
379                   envioT[2]=trama%256;
380                   trama++;
381                   //El checksum
382                   envioT[9]=checksum(&envioT,9);
383                 }
384                 else
385                 {
386                   //Se envia una trama corta indicando que se han acabado los datos a enviar
387                   envioT[1]=18;
388                   for(i=2;i<9;envioT[i]=0,i++);
389                   /*for(i=0;i<3;i++)
390                   {
391                     envioT[2*(i+1)]=((int)(offset[i]))%256;
392                     envioT[2*(i+1)+1]=((int)(offset[i]))/256;
393                   }*/
394                   /*for(i=0;i<3;i++)
395                   {
```

```
                        envioT[i+1]=(char)offset[i];
                      }*/
                      envioT[9]=checksum(&envioT,9);
                      longitud=10;
                      bloqueo=1;
                    }
                    PIE1bits.TXIE=1;
                    break;
                  case 19:
                    //Se remanda la ultima trama (como no se ha modificado nada, se manda lo mismo)
                    PIE1bits.TXIE=1;
                    break;
                  case 20:
                    //Para saber la cantidad de paquetes guardados en memoria
                    envioT[1]=20;
                    envioT[2]=contadorT/256;
                    envioT[3]=contadorT%256;
                    for(i=0;i<3;envioT[4+i]=offset[i],i++);
                    envioT[7]=checksum(&envioT,7);
                    longitud=8;
                    PIE1bits.TXIE=1;
                    break;
                }
              }
              //Para pasar de un estado a otro desde  PC, activando la interrupcion manualmente
              if(BufferR[1]==15)
              {
                estado=BufferR[2];//Estado previo al que se quiere pasar
                INTCON3bits.INT2IF=1;//Se activa el flag de la interrupcion manualmente
              }
              if(BufferR[1]==9)
              {
                Reset();//Para forzar un reset del PIC
              }
            }
          }
        }
        //Se comprueba si la interrupcion es por desbordamiento del temp. 0
        else if (INTCONbits.TMR0IF&&INTCONbits.TMR0IE)
        {
          AMARILLO=1;//Para medir con el osciloscopio cuanto tarda todo esto
          VERDE=!VERDE;//Se alterna el estado del LED verde
          INTCONbits.TMR0IF=0;        // Se pone a 0 el flag de desbordamiento del temp. 0
          TMR0H=registroT[0][rT];     // Se carga el valor de TMR0H y TMR0L para uno de los intervalos
          TMR0L=registroT[1][rT];
          //Esto es lo más rápido posible
          for(k=0,envioM[7]=inicio;k<3;k++)
          {
            capturado=com(toma[k],2,0);//Se obtiene el dato del eje correspondiente
            //capturado=0x4F23; //79 y 35 en decimal, es decir, es lo que tendra que aparecer en los datos
            envioM[2*k+1]=capturado/256;
            envioM[2*k+2]=capturado%256;
            envioM[7]=envioM[7]+envioM[2*k+1]+envioM[2*k+2];
          }
          contadorT++;
          //Forma de crear las direcciones mas rapida (comprobado con la calculadora)
          for(k=0;k<8;k=k+2)
```

```
453             {
454                CE=0;
455                com(58,0,0xAD);
456                com(58,0,envioM[k]);
457                com(58,0,envioM[k+1]);
458                CE=1;
459             }
460             /*Esto es para controlar que no se sobreescribe sobre los primeros datos. En el chip final hay
461              * una función que evita tener que usar esto*/
462             if(contadorT>=limite)
463             {
464                INTCONbits.TMR0IE=0;//Se deshabilita el timer0 y se deja de tomar datos
465                VERDE=1;//Se deja el LED fijo para indicar que ya esta la memoria llena
466             }
467             AMARILLO=0;//Mirar al principio de este else if
468          }
469          else if(PIR1bits.TMR1IF&&PIE1bits.TMR1IE)
470          {
471             //Ejecucion de la secuencia de cálculo de offset (con el sensor apoyado en una superficie plana)
472             PIR1bits.TMR1IF=0;//Se resetea el flag de interrupcion
473             TMR1H=offsetH;
474             TMR1L=offsetL;
475             /*En el caso de que no se desee hacer un ajuste de offset, se ha de pasar de modo de calculo
476              * de offset a modo standby-despues-de-offset antes del tiempo indicado por "transicion"*/
477             if(!calibrado)
478             {
479                if(espera<transicion)
480                {
481                   if(espera%5==0)
482                   {
483                      AMARILLO=!AMARILLO;//Para que parpadee primero a intervalos de 1 segundo
484                   }
485                   espera++;
486                }
487                else //Ha pasado el tiempo determinado por "transicion"
488                {
489                   situacion++;
490                   //El parpadeo es mas rapido (0.1 segundos, indicando que se esta calibrando el offset)
491                   AMARILLO=!AMARILLO;
492                   if(situacion<2)//Primero hay que activar el sensor (y esperar [10+1/F] segundos)
493                   {
494                      com(0x2D,0,0x08);//encendido del sensor (sirve la configuracion estandar ya escrita)
495                      for(k=0;k<3;offset[k]=0,k++);//Primero hay que borrar los offsets anteriores
496                   }
497                   else if(situacion<muestras+2)//Hay que recoger al menos 100 muestras(o el doble)
498                   {
499                      for(k=0;k<3;k++)
500                      {
501                         capturado2=com(toma[k],2,0);
502                         offset[k]+=capturado2;
503                      }
504                   }
505                   else
506                   {
507                      /*Una vez recogidas todas las muestras, se calcula la media y se envia a los registros
508                       * de offset de cada eje*/
509                      //Ahora se adaptan los valores a complemento de 2
```

```
510                 /*No es necesario adaptar los valores a complemento de 2, porque el numero negativo
511                  * en la variable es ya un complemento a 2 a nivel de bit*/
512                 //Ahora se mandan los valores a los registros de offset del sensor
513                 offset[0]=offset[0]/(sensibilidad*muestras);
514                 offset[1]=offset[1]/(sensibilidad*muestras);
515                 offset[2]=((offset[2]/muestras)-256)/sensibilidad;
516
517                 for(i=0;i<3;i++)
518                 {
519                    if(fabs(floor(offset[i])-offset[i])>fabs(ceil(offset[i])-offset[i]))
520                    {
521                       offset[i]=-ceil(offset[i]);
522                    }
523                    else
524                    {
525                       offset[i]=-floor(offset[i]);
526                    }
527                 }
528                 com(0x1E,0,offset[0]);//Offset eje X
529                 com(0x1F,0,offset[1]);//Offset eje Y
530                 com(0x20,0,offset[2]);//Offset eje Z
531 //                 com(0x1E,0,-offset[0]/(sensibilidad*muestras));//Offset eje X
532 //                 com(0x1F,0,-offset[1]/(sensibilidad*muestras));//Offset eje Y
533 //                 com(0x20,0,-((offset[2]/muestras)-256)/sensibilidad);//Offset eje Z
534                 com(0x2D,0,0x00);//Se deja el sensor como estaba (apagado)
535                 //PIE1bits.TMR1IE=0;//Se deshabilita el Timer1
536                 calibrado=1;
537                 INTCON3bits.INT2IF=1;//Se activa el flag del boton para cambiar de estado
538              }
539           }
540        }
541        else
542        {
543           INTCON3bits.INT2IF=1;//Se salta directamente al siguiente modo
544        }
545     }
546     else if (INTCON3bits.INT2IF)
547     {
548        INTCON3bits.INT2IF=0; //Se pone a 0 el flag de la interrupcion
549        if(PIR2bits.TMR3IF)
550        {
551           PIR2bits.TMR3IF=0;
552           TMR3H=offsetH;
553           TMR3L=offsetL;
554           //En caso de que se quiera saltar del estado de ajuste de offset a otro, hay que deshabilitar el
555 Timer1
556           if(estado!=0)
557           {
558                PIE1bits.TMR1IE=0;
559                espera=0;
560                situacion=0;
561           }
562           switch(estado)
563           {
564              case 0:
565                 estado=1;//Estado de calculo de offset (con espera)
566                 ROJO=0;
```

```
567                 VERDE=0;
568                 AMARILLO=0;
569                 //espera=0;
570                 //situacion=0;
571                 PIE1bits.TMR1IE=1;//Se habilita el Timer1
572                 break;
573               case 1:
574                 estado=2;//Estado de standby post offset
575                 PIE1bits.TMR1IE=0;//Se deshabilita el Timer1
576                 ROJO=1;
577                 VERDE=0;
578                 AMARILLO=0;
579                 break;
580               case 2:
581                 estado=3;//Estado de captura y guardado de datos
582                 //Se activa el sistema
583                 //Se manda la accion y direccion de memoria a escribir
584                 CE=0;//CE a nivel bajo
585                 com(58,0,0x06);//Instruccion de habilitacion de escritura
586                 CE=1;//CE a nivel alto
587                 /*Hay que hacer una primera escritura en la direccion 0x00 0x00 0x00 para que luego en
588                   el bucle principal solo sea 0xAD y los dos bytes*/
589                 CE=0;
590                 com(58,0,0xAD);
591                 for(i=0;i<5;i++)//Primera pareja de bytes a mandar a la direccion 0x00 0x00 0x00
592                 {
593                    com(58,0,0x00);
594                 }
595                 CE=1;
596                 com(0x2D,0,0x08);//Para encender el sensor
597                 INTCONbits.TMR0IE=1;
598                 ROJO=0;//Led rojo OFF
599                 VERDE=1;//Led verde ON
600                 contadorT=0;
601                 break;
602               case 3:
603                 estado=4;//Estado de PC
604                 //Hay que deshabilitar primero la escritura continuada
605                 CE=0;
606                 com(58,0,0x04);
607                 CE=1;
608                 com(0x2D,0,0x00);//Para apagar el sensor
609                 ROJO=1;
610                 VERDE=1;
611                 //Se detiene el sistema
612                 INTCONbits.TMR0IE=0;
613                 break;
614               case 4:
615                 estado=0;//Estado de Standby pre-offset
616                 //Se borra primero la memoria para poder escribir de nuevo nuevos datos
617                 CE=0;
618                 com(58,0,0x06);//Se manda un write enable
619                 CE=1;
620                 CE=0;
621                 com(58,0,0x60);//Se manda la instruccion de borrado de chip
622                 CE=1;
623                 AMARILLO=0;
```

```
624                     CE=0;
625                     com(58,0,0x05);//Se manda instruccion de leida continuada del registro de estado
626                     /*Hasta que el bit BUSY no pase a 0, no se sale de ahi (cuando la memoria se hubiera
627                      * borrado del todo)*/
628                     do{
629                        capturado=com(58,1,0);
630                     }while(capturado&0x0001);
631                     CE=1;
632                     trama=0;
633                     //Esto se hace para asegurar visualmente que se ha borrado la memoria
634                     AMARILLO=1;
635                     ROJO=1;
636                     VERDE=0;
637                     break;
638                 }
639               }
640             }
641     }
642
643     void main(void)
644     {
645       //16 MHz (en el PIC18f14k22, en el PIC18F4520 son 8 MHz)
646       OSCCONbits.IRCF0=1; //(este a cero = 8 MHz en el PIC18f14k22 y 4 MHz en el PIC18F4520)
647       OSCCONbits.IRCF1=1;
648       OSCCONbits.IRCF2=1;
649       /*A 16MHz se consigue una duracion de la rutina de captura de datos y guardado en memoria
650        de 2.6 ms (1/2/2016). Esto abre la posibilidad de que se pueda muestrear a mas de 100 Hz.*/
651
652       //Configuracion pines de los LEDS e INT2
653       ROJOConfig=0;
654       VERDEConfig=0;
655       AMARILLOConfig=0;
656       ANSEL=0x00;
657       ANSELHbits.ANS11=0;
658       ANSELHbits.ANS10=0;
659       ANSELHbits.ANS8=0;
660
661       //Configuracion comunicaciones UART
662       pinTX=0;  // Se configura la línea RC6/TX como salida
663       pinRX=1; // Se configura la línea RC7/RX como entrada
664       /*Se inicializa la transmision con 8 bits ,en modo asincrono, sin envio del BREAK y con velocidad de
665        * comunicación alta (BRGH='1')*/
666       TXSTA=0x20;
667       RCSTA=0x90;  // Se inicializa la recepción con 8 bits y se configuran RC6 y RC7 como pines TX y RX
668       SPBRG=25;  // para 9600, 5.5 a 4MHz, 12 a 8MHz, 25 a 16MHz
669
670       //Configuracion comunicaciones SPI software (1=entrada 0=salida)
671       CEConfig=0;//Pin de seleccion de la memoria
672       MISOConfig=1;
673       SCLConfig=0;
674       MOSIConfig=0;
675       CE=1;//Estado inicial al que poner el pin de seleccion de la memoria
676       //Configuracion comunicaciones I2C
677       //Hay que poner la opcion SLEW_ON al usar la velocidad máxima de 400 kHz
678       OpenI2C(MASTER,SLEW_ON);
679       //Esto configura el reloj del I2C (que ha de ser de 400 kHz (limitando la captura a 800 Hz)
680       SSPADD=9;
```

```
681     //Configuracion inicial SPI software
682     MISO=0;
683     MOSI=0;
684     SCL=1;
685
686     //Configuracion timer0
687     // Timer 0 modo temp. de 16 bits. Prescalar on de 64 para 16MHz y de 32 para 8MHz. TIMER OFF
688     T0CON=0b10000101;
689     // Se carga el valor de TMR0H y TMR0L para un intervalo a escoger (1s, 100ms o 10ms)
690     TMR0H=registroT[0][rT];
691     TMR0L=registroT[1][rT];
692
693     //Configuracion timer1
694      //Timer 1 en modo temporizador de 16 bits. Preescalar de 8 para 16 MHz (4 para 8 MHz y sucesivo)
695     T1CON=0b10111001;
696     TMR1H=offsetH;
697     TMR1L=offsetL;
698
699     //Configuracion timer2
700     //Timer3 en modo temporizador de 16 bits. Preescalar de 8 para 16 MHz(4 para 8 MHz y sucesivo)
701     T3CON=0b10110101;
702     TMR3H=offsetH;
703     TMR3L=offsetL;
704
705     //Se habilitan las interrumpciones
706        INTCONbits.GIE_GIEH = 1;  // Se activan las interrupciones a nivel global
707     INTCONbits.GIE=1;
708     INTCONbits.GIEH=1;
709     INTCONbits.PEIE_GIEL = 1;  // Se activan las interrupciones de perifericos a nivel global
710     PIE1bits.RCIE=1;    // Se habilita la interrupcion de recepcion del canal serie
711     INTCONbits.TMR0IE=0; // Se deshabilita la interrupcion del Timer0
712     PIE1bits.TMR1IE=0;//Se deshabilita la interrupcion del Timer1
713     PIE2bits.TMR3IE=1;//Se deshabilita la interrupcion del Timer3
714     //Configuracion INT2 del boton
715     INTCON2bits.INTEDG2=0;//Salta con el flanco de subida
716     INTCON3bits.INT2IE=1;//Se habilita la interrupcion
717
718     //Secuencia de arranque (solo para la memoria)
719     CE=0;//Se escoge activar la memoria
720     com(58,0,iniM[0]);
721     CE=1;
722     CE=0;
723     for(k=1;k<4;k++)
724     {
725        com(58,0,iniM[k]);//La secuencia de configuracion de la memoria a arrancar
726     }
727     //Configuracion del sensor
728     for(k=0;k<3;k++)
729     {
730        com(datS[0][k],0,datS[1][k]);
731     }
732     CE=1;//Se deselecciona todo
733     VERDE=0;
734     AMARILLO=1;
735     ROJO=1;
736     for(k=0;k<3;offset[k]=0,k++);//Primero hay que borrar los offsets anteriores
737     while(1)
```

```
738     {
739     };
740   }
741   unsigned char checksum(unsigned char x[], char n)//Todos los elementos excepto el propio checksum
742   {
743     unsigned char j,r;
744     for(j=0,r=0;j<n;j++)
745     {
746       r=r+x[j];
747     }
748     return r;
749   }
750   int com(char quien, char RW, char dato)
751   {
752     unsigned char i,bufferI2C[2];
753     int y=0;
754     if(quien>57)//SPI
755     {
756       /*El dato de entrada se convierte en una secuencia de 1 y 0 en un array porque hacer
757        * desplazamiento de registro ocupa mas tiempo cuando mayor es el desplazamiento*/
758       //Esto es lo más rápido que hay
759       for(i=0;i<8;i++)
760       {
761         SCL=0;
762         MOSI=(dato&0x80)>>7;
763         dato=dato<<1;//Se hacen 8 desplazamientos no 7! (5040)
764         SCL=1;
765         y=(y<<1)+MISO;
766       }
767       //Hay que poner todo a cero para tener unas condiciones inciciales identicas en cada ciclo
768       SCL=0;
769       MISO=0;
770       MOSI=0;
771       if(RW)//Si se ha esogido leer datos del bus SPI, se procedera, si no, se salta
772       {
773         return y;
774       }
775     }
776     else//I2C
777     {
778       //De esta forma, solo cuando se usa la modalidad I2C, se resetea la variable
779       bufferI2C[1]=0;
780       bufferI2C[0]=0;
781       if(RW>0)//Lectura
782       {
783         //Proceso de comunicaciones (en base a la secuencia establecida por el "sensor")
784         StartI2C();
785         while(START);
786         WriteI2C(sensor);
787         WriteI2C(quien);
788         RestartI2C();
789         while(RESTART);
790         WriteI2C(sensor+1);
791         bufferI2C[0]=ReadI2C();//Esto es el primer byte (DAT_0)
792         if(RW==2)
793         {
794           AckI2C();
```

```
795                 while(ACK);
796                 bufferI2C[1]=ReadI2C();//Esto es el segundo byte(DAT_1)
797               }
798               NotAckI2C();
799               while(NAK);
800               StopI2C();
801               while(STOP);
802               //Transformacion de los dos bytes a un numero
803               y=bufferI2C[1]*256+bufferI2C[0];//Esto es lo mas rapido que se puede ir
804               return y;
805            }
806            else//Escritura
807            {
808               StartI2C();
809               while(START);
810               WriteI2C(sensor);
811               WriteI2C(quien);
812               WriteI2C(dato);
813               StopI2C();
814               while(STOP);
815            }
816         }
817      }
```

# Annex 2: Commands used between Microcontroller – PC

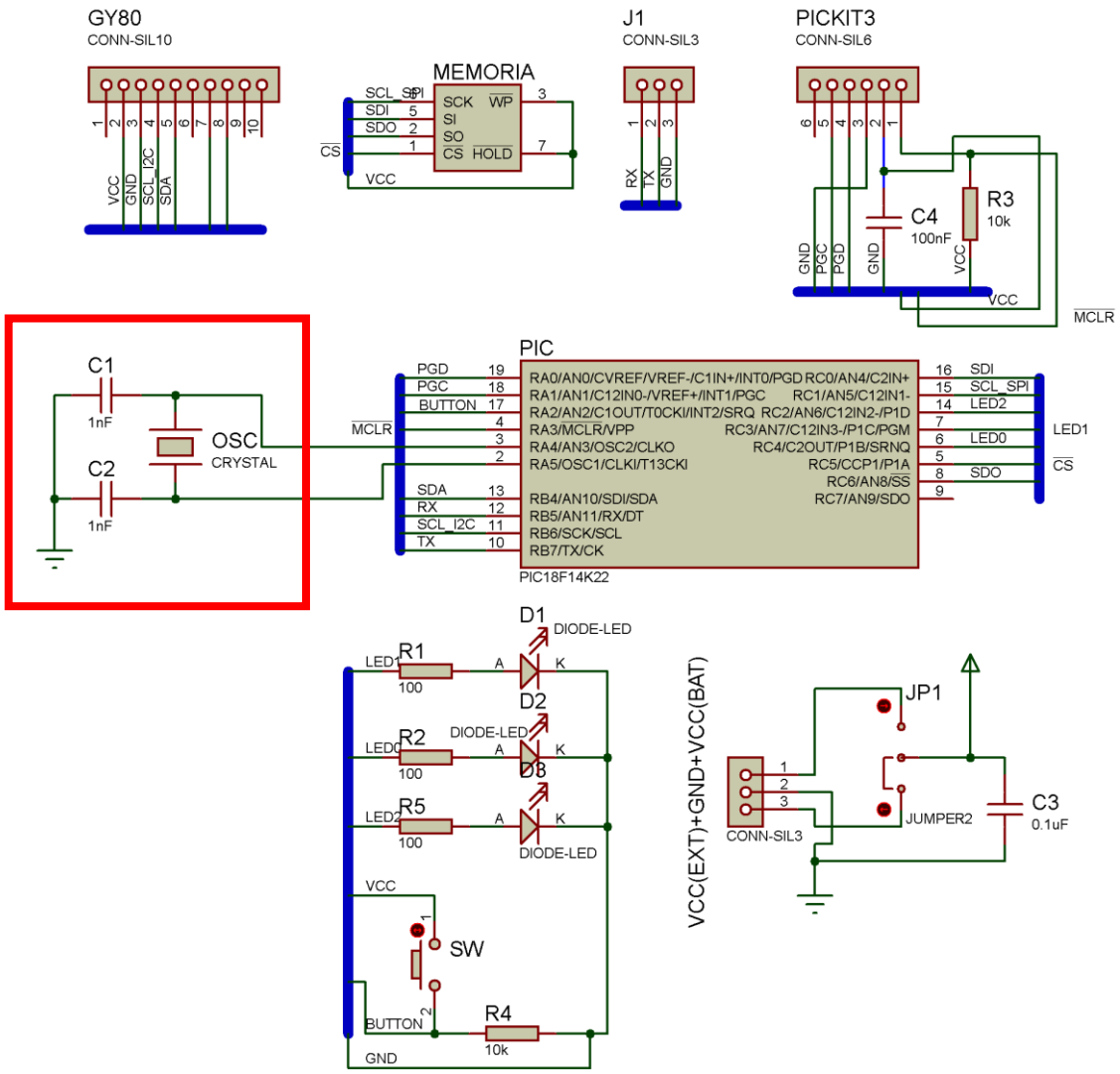
For any of the following commands to work (except for commands 15 and 9), the device must be set in computer controlled mode. Additionally, every command received will cause the orange LED to blink. Except commands 7, 17, 18 and 19, all the others were used for debugging purposes.

| Commands | Description |
|---|---|
| 0, 1 | These commands are responsible for manual communication (reading) with the **sensor** through **$I^2C$** from the computer. The first one will indicate that just one byte is expected to be read, whereas the second one indicates two bytes to be expected.<br>Instruction 0 is also used by the computer interface to retrieve on address 0x00 the ID code of the sensor. By doing this the $I^2C$ communication path is checked for proper operation.<br>It will read the data from the address specified in the third byte of the data stream received from the computer interface. |
| 2, 3 | These commands are responsible for manual communication with the **memory chip** through **SPI** from the computer. The first one will indicate that just one byte is expected to be read, whereas the second one indicates two bytes to be expected. Due to the nature of SPI communication, commands 4 and 5 have to be used too. |
| 4 | This command is responsible of controlling the chip enable pin of the manual SPI communication process. It will set the logic value of the pin based on the value (0 or 1) passed by the third byte of the data stream received from the computer interface. |
| 5 | This command is responsible of sending a single byte to the memory chip though SPI. This byte is passed by the third byte of the data stream received from the computer interface. |
| 6 | This command is responsible for the manual activation of the erase process of the memory chip. The green LED will change state before starting the erasing and again once it finishes. |
| 7, 17, 18, 19 | These three commands are responsible for the process of data recovery from the memory chip.<br>Instruction **7** is used to start the process. It prepares the memory chip for the sequential reading process.<br>Instruction **17** is sent by the computer interface asking for the next data package. The device ensures that there is a valid package available and sends it back to the computer interface. If there were no more packages available, the device sends command **18** to the computer interface.<br>Instruction **19** asks the device to send back the last data package sent. This is done when the data package received by the computer interface is not valid. |
| 8 | This command has no other purpose but to assure that communication between the computer interface and the device is working properly. This is checked thanks to the blink of the orange LED. |
| 9 | This command will cause a software reset process on the µC. It is outside the PC-mode check just in case there are any problems in any mode. |
| 10, 11 | These commands are used to obtain from the memory chip its JEDEC and ID codes respectively. |

| | |
|---|---|
| | On one hand, the JEDEC code is retrieved just to assure that the SPI communication path is working properly. On the other hand, the ID code is retrieved for debugging purposes as the process to retrieve such code is identical to the sequential memory reading process, and quite similar to the writing memory process. |
| 12 | This function was used for debugging purposes of the entire writing, reading and sending processes. All three process were included in the execution of this command and adapted to a scenario of capturing 2 bytes (0xABCD). |
| 13 | This command is responsible for manual communication (writing) with the **sensor** through **$I^2C$** from the computer. Only one byte can be written at the time as all writable register addresses were just one byte of length.<br>The address and data to be written are passed by the third and fourth byte respectively of the data stream received from the computer interface. |
| 14 | This command is responsible of toggling the functionality of the button of the device. When the device powers up, this button is enabled. |
| 15 | This command allows to change to any of the modes the device can operate based on the third byte received from the data stream from the computer interface. The external interrupt that activates the change of the device mode is software activated. |
| 16 | This command allows to change the sampling frequency (1 Hz, 10 Hz, 100 Hz, 200 Hz, 400 Hz) of the data, based on the third byte received from the data stream from the computer interface. |
| 20 | This command allows to retrieve the amount packages that have been stored in the memory chip. |

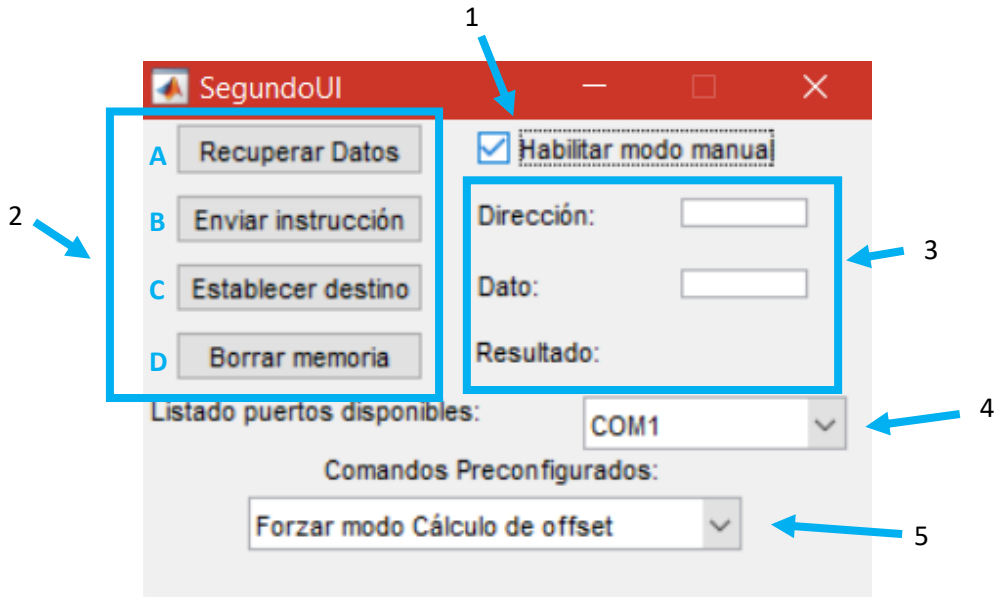
Table 5: Summary of commands used during communication with PC

# Annex 3: Device schematic




Although it was thought to include an external oscillator in the design of the device (as seen in Figure 2, pg 7) it was not included at the end as the internal oscillator of the microcontroller ended up to be sufficient for this project.

# Annex 4: Description of the Computer Interface




1) Checkbox that enables/disables all aspects of the interface except for the recovery of data button (A), the button for establishing the directory where the data will be saved (C), the memory erase button (D) and COM port selection list (4). All the other aspects are disabled because they are used mainly for debugging purposes.

2) Control buttons for multiple purposes:

   A. Recover data from the device
   B. Send instruction selected from the preconfigured command list (5) (and send with the command the required data if the command needs it)
   C. Establish the directory where the acceleration data file will be saved
   D. Erase the data in the memory chip

3) Input fields for SPI/$I^2C$ address and data to be sent (if required by the command) and the result received (if the situation required so).

4) COM port selection list, just in case there are multiple COM ports available in the computer being used.

5) Preconfigured command selection list. All these commands between the computer and the device are already established inside the interface and the user only has to select the one of his interest and send it to the device via button B.