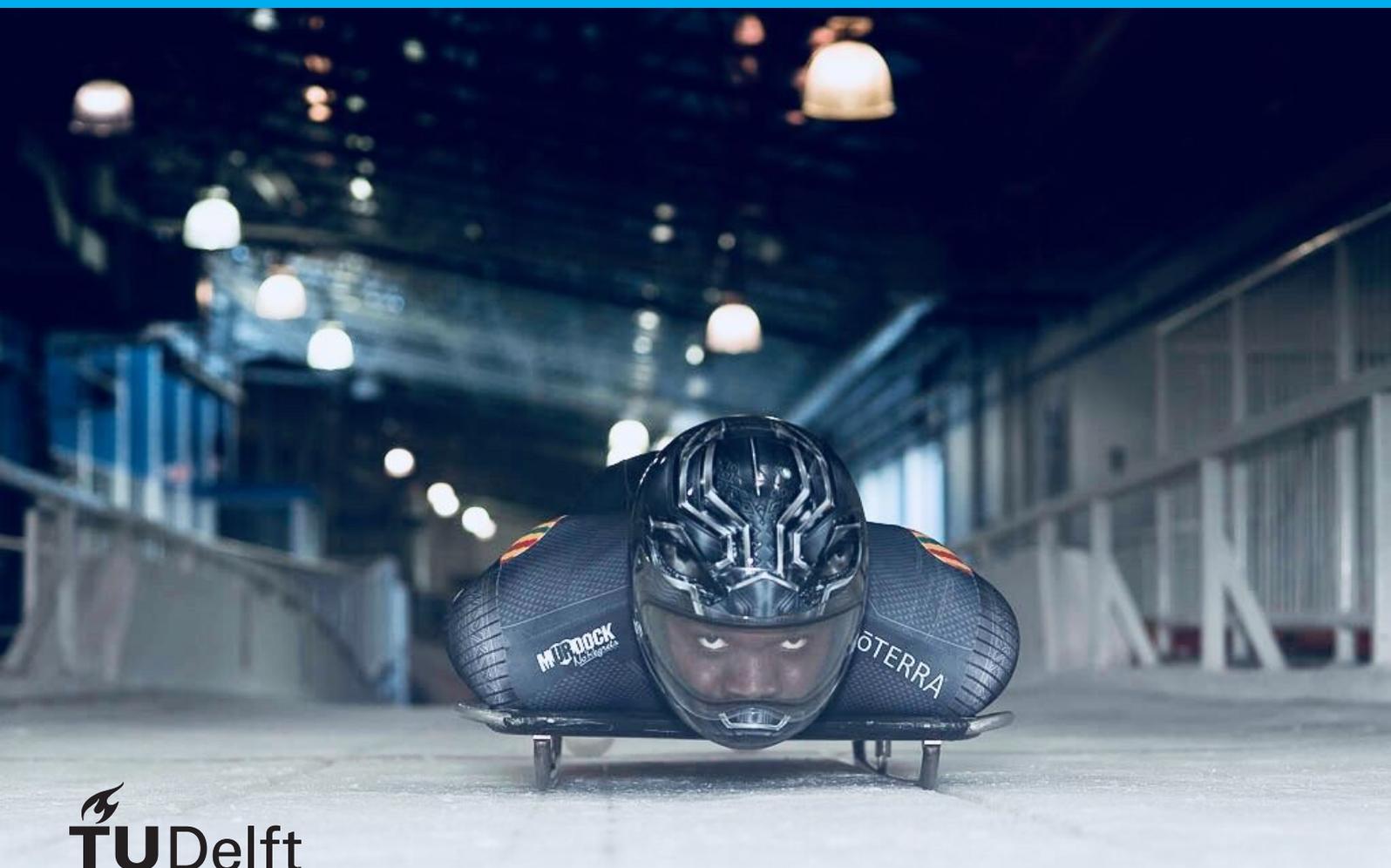


Instrumented Skeleton Sled

BSc Thesis

A. J. de Jong
M. J. Heller

Focussing on force and orientation sensing



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by

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focussing on force and orientation sensing,
as part of the Bachelor Graduation Project,
at the Delft University of Technology.

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Abstract

This report details the design of an instrumentation system to be used on a skeleton sled. The system will measure data during the run on a skeleton track using several sensors and process and visualise the data afterwards in order to shorten the learning curve of the athlete and give quantitative feedback.

The subsystem discussed in this report concerns the measurement of the forces between the body and the sled in order to analyse the steering behaviour of the athlete. This is accomplished via thin film resistive force transducers. The g -forces on the athlete and the sled and the orientation of the sled are measured as well in order to give a better insight how this influences steering and is measured using an IMU (Inertial Measurement Unit).

The data is collected using an ESP32 microprocessor.

Preface

This thesis is written in context of the Bachelor Graduation Project. The project was commissioned by Akwasi Frimpong, a professional skeleton athlete with the goal to come up with a way to provide him with quantitative information on his performance in order to shorten his learning curve.

We would like to express our gratitude to our supervisors prof. dr. Paddy French, dr. ir. André Bossche and ing. Jeroen Bastemeijer for their guidance during the project. We would like to thank the thesis committee, prof. dr. ing. Andrea Neto, prof. dr. Paddy French and dr. ir. Mottaqiallah Taouil for assessing our defence. We would like to offer dr. ir. Mottaqiallah Taouil our special thanks for his very useful feedback on our thesis. Furthermore, we would like to thank Akwasi Frimpong for the topic and wish him good luck on the Winter Olympics in Beijing in 2022. Finally we would like to thank our colleagues: Werner van Dijk, William Hunter, Tijs Moree and Karen van der Werff for an enjoyable and productive collaboration.

*Jan de Jong & Martijn Heller
Delft, June 2019*

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Introduction

1.1. Background

Skeleton is a winter sport in which an athlete lies in a prone position (face down and head first) on a small sled with two metal runners underneath, and goes down a winding track which is approximately 1800 meters long and covered in ice. An example of such a track can be seen in Figure 1.1, which depicts a computer mock-up of the track that will be used at the 2022 Winter Olympics in Beijing. The sport has a high intensity: during a run, the athlete is subject to high g-forces and speeds which can exceed 130 km/h [1]. The steering of the sled is done by pushing the shoulders or knees into the sled: “the sled contorts as a response to the athlete’s steering control movements. When this happens, the left or right runner knife is forced into the ice, creating an asymmetry in ice friction resulting in a steering moment. That is, when the left runner is forced into the ice, the sled will turn left. Athletes thus use their shoulders and knees to contort the sled; for a more dramatic steering movement, they ‘tap a toe’ onto the ice, creating a larger steering moment” [2].

A run starts with the athlete sprinting from the starting point with the sled, the so-called push start, a critical part of the run (this feature also appears in bobsled racing, but is absent from the similar sport of luge). This can be seen schematically in Figure 1.2: after about fifteen to thirty metres, the athlete mounts the sled at full running speed and manoeuvres it around a series of (often) high-banking corners in the desired path, to maximise his speed [2].

1.2. Problem definition

Akwasi Frimpong is an Olympic skeleton athlete, who aims to be the first African athlete to win a medal at the Winter Olympics. He is relatively new to the sport, with his background being track-and-field. In order to accomplish his goal, he therefore wants to shorten his learning curve in the skeleton sport. At the moment, only video imagery and visual feedback from the coach are used as feedback on his performance. Because of the high speeds at which he is traveling during the largest part of a run, the important details from the run can be very hard to spot. This is evident from Figure 1.3: grainy images like this are the best the average athlete has to evaluate his performance on the sled. Besides the previously mentioned means of feedback, there are no quantitative elements that are readily measured except for the elapsed time, measured by timing eyes mounted in set intervals on the track.

The important thing for an athlete to know is how he influences the sled during the run. This is especially relevant in curves, since the way these are traversed is the most impacting factor on the run time besides the push start [4]. As mentioned in Section 1.1, the steering of the sled is done by exerting forces on it using the shoulders and the knees. These movements of the shoulders and knees are practically impossible to



Fig. 1.1: A computer mock-up of the skeleton track to be used at the 2022 Beijing Winter Olympics [3]

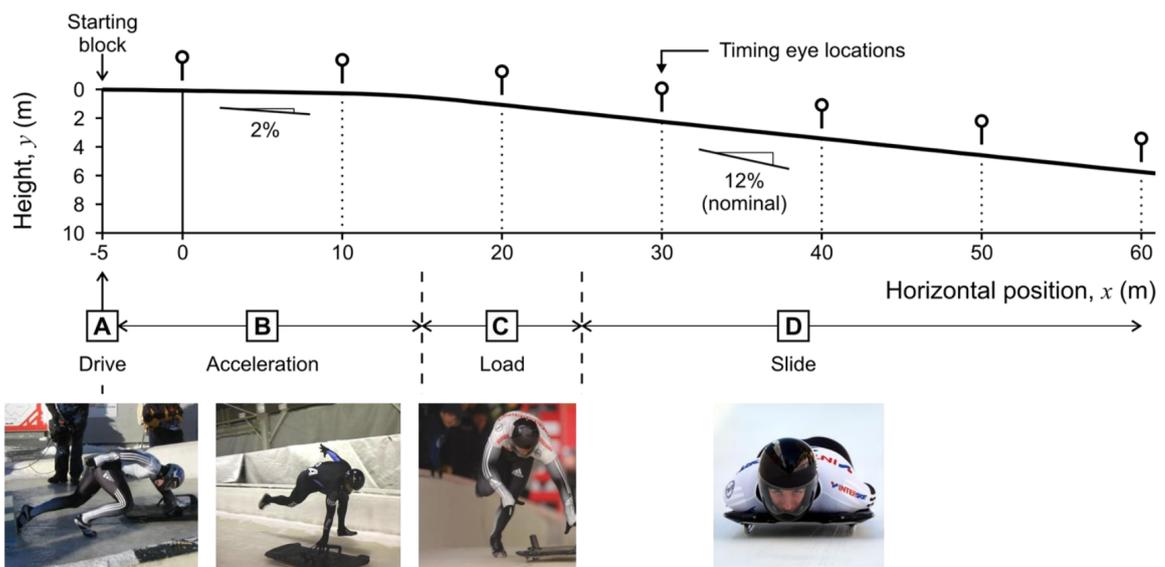


Fig. 1.2: An overview of the height profile at the beginning of a skeleton practice track, illustrating the push start [1]

see on video, or on images like Figure 1.3. The solution to this problem could be offered by integrating a measurement system onto the sled (forming a so-called “instrumented sled”). This sled can measure the forces applied by the athlete, along with other relevant performance parameters. This can then couple the measured forces to the location of the sled on the track—and all these measurements would then need to be presented to the athlete in a way that he can quickly access. The use of an instrumented sled would result in a significant increase in useful feedback that the athlete can use to improve his run time, thus increasing the chances of the athlete shortening his learning curve. The primary goal of the product would thus be providing detailed, useful feedback on an athlete’s run, in a way that is easy for both the athlete and the coach to understand and work with.



Fig. 1.3: An example of the visual feedback that is currently available to a skeleton athlete. This image was used by a coach to illustrate a momentary lifting of the shoulders off the sled, which is considered to be a bad habit (image courtesy of Akwasi Frimpong).

1.3. State-of-the-art analysis

Despite the fact that the sport of skeleton is not very widely practiced, a number of studies have been done on the measurement of the forces, speeds and acceleration involved in the sport. These studies were primarily performed in order to create a better understanding of the dynamics at play in the sport, instead of having a goal of being used to actively improve athlete performance. Roberts [1] showed in his work that from measurements of the acceleration of the sled in three axes, velocity and traversed distance can be derived, which can provide useful information about the push start of the run. This is valuable, as it has been shown that the (effectiveness of the) push start has a large impact on the eventual time taken to complete a run [5]. After the push start and later in the run, however, the noise on these measurements becomes too large due to vibrations and other factors [1], making it impossible to integrate this to obtain a meaningful speed and distance reading during the whole descent. Sawade *et al.* [2] studied the factors influencing skeleton steering, showing a correlation between the applied steering force by the athlete and measured accelerometer and gyroscope data.

The aforementioned studies examined a number of relevant parameters involved in a skeleton run by attaching sensors to the sled and logging their output data. Although this is useful data, these studies provide only a limited tangent to the solution to the problem put forth in Section 1.2, as further processing of the data and visualisation (to produce the graphs from which conclusions could be drawn) was done after the fact. No special consideration was given to making the data easily and quickly available to the athlete (and his coach) from which the measurements were sourced, relegating their results to the status of reference work for an athlete instead of a product they can use themselves. The general idea of combining computing, sensing and communication as is required for this project, however, isn't new. This way of integrating information processing into user objects without the user being actively aware of the hardware behind it is known as "ubiquitous" or "pervasive" computing and has seen a rapid increase in the past decade [6]. In sports in general, "these ubiquitous computing technologies are utilised to acquire, analyse and present performance data without affecting the athletes during training and competitions" [6].

Nevertheless, these technologies aren't yet prevalent in the skeleton world; the closest similar system was studied by Lee *et al.* for use on a bobsled. This involved fitting an elaborate system of sensors and cameras on the sled, that together produced video imagery overlaid with sensor data, which was then wirelessly transmitted to a monitor on a remote site in real time [7]. This is useful functionality, but it isn't practically usable in the skeleton case: the system is bulky, as can be seen in Figure 1.4, requiring (amongst other things) a relatively large and heavy control unit, which wouldn't fit on a skeleton sled.

It can thus be concluded that although modern research into the topic of skeleton dynamics is available, none exists that cover the scope of the system required to provide skeleton run data accurately and quickly in an (from the athlete's point of view) easy-to-understand format.

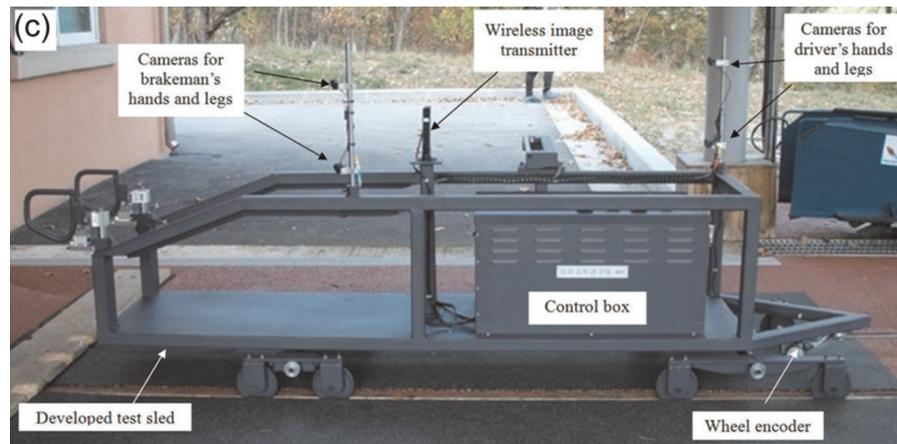


Fig. 1.4: An example of an instrumented bobsled, as developed by Lee *et al.* [7].

1.4. Subdivision of the system

In order to realise the instrumented sled system, the product is divided into three subgroups, each with its own responsibilities: a schematic overview is given by Figure 1.5. The work of each of the three groups is documented in separate theses: “Data Group” refers to the work done by Hunter and Moree [8] and “sensor group B” refers to the work done by Van Dijk and Van der Werff [9]. Group A (and thus this thesis) is responsible for the measurement of the (steering) force that is applied by the athlete and the measuring of the g-forces and orientation of the sled. Group B is responsible for the localisation of the sled, measurement of the ice temperature and power management of the system. The Data Group focuses on integration of the total system at software level, data storage, processing and visualisation at the end of a run, to produce the desired user interface.

The work of all three subgroups is eventually combined to form the instrumented sled system: the eventual prototype of the system will consist of a printed circuit board (PCB) containing all necessary parts (developed by the different subgroups) integrated into one system, along with the software required to run it and produce the visualised data. The responsibility of designing this PCB prototype and corresponding hardware-level considerations of the integrated system lie with sensor group B; the software integration falls under the responsibility of the data group.

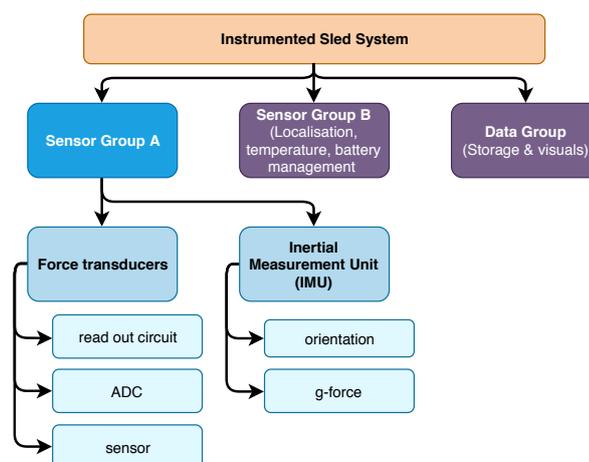


Fig. 1.5: Subdivision of the project into groups, and their responsibilities

1.5. Thesis Outline

This thesis covers the choices made regarding the sensors used for measuring the force applied by the athlete and the g-forces on and orientation of the athlete and his sled. First the programme of requirements is laid out and some elaborations are made on some requirements in Chapter 2. Then the design process is described. First the force transducers is discussed followed by the discussion of the measuring of the orientation and g-forces. This can be found in Chapters 3 and 4. Then results of tests are described in Chapter 5. After that a conclusion is made, the programme of requirements is validated and recommendations for future work in Chapter 6.

2

Programme of Requirements

The deliverable is a system that can be integrated on a skeleton sled. The system must be able to measure data, processing and visualising it to a point where a skeleton athlete and his/her coach can understand it and use it to improve training. The subsystem discussed in this report has the task of measuring the force of the athletes body on the sled at the steering points and the g-forces experienced by the athlete and its sled, as well as the orientation of the sled.

2.1. General requirements

General requirements are those requirements that are relevant for the entire system and that should be met by every subgroup. They can be listed as follows:

- G.1** The product must be able to measure g-forces, rotation, force applied by the athlete, ice temperature of the track and must be able to determine the location of the skeleton sled.
- G.2** The product must be able to work in a temperature range from $-20\text{ }^{\circ}\text{C}$ to $40\text{ }^{\circ}\text{C}$, since it will be used in an area with temperatures in this range.
- G.3** The product must be able to withstand momentary accelerations of up to 5 g [4, p. 198].
- G.4** The complete system should not weigh more than 1.5 kg , to prevent that the characteristics of the skeleton sled are different from match conditions during training.
- G.5** The dimensions of the product cannot exceed a box of dimensions $31.5 \times 14.7 \times 2\text{ cm}$, since this is the size of the available box inside the skeleton sled.
- G.6** The update rate of the force sensors and localisation system should be such that data points are at most 1 meter apart. Working with a maximum speed of 147 km/h [1], this gives a minimum frequency of 41 Hz .
- G.7** It should not be necessary to open the space inside the skeleton sled, where the circuitry will be located, in between runs. Therefore the user must be able to start and stop the measurement from the outside.
- G.8** The product must be easily installed or removed from the sled, without leaving any (permanent) traces on the sled.
- G.9** The product should influence neither the aerodynamic properties nor the mechanical properties, apart from the weight, of the sled.

- G.10** The product can not have any wired connections outside the sled and must be able to operate for the time it takes to do 3 runs and the time in between runs.
- G.11** The system must be robust, being able to handle the vibrations of the sled during a run.
- G.12** The acquired data must be available within 5 minutes after each run for the athlete and the coach to use.
- G.13** The product should be easy to use.
- G.14** The total cost of making the prototype must fit in the budget of €250,-.

2.2. Specific requirements

There are several requirements specific for the subsystems described in this thesis. For the subsystems of the force measurement and G-force and orientation the following specifications must be met:

S.1 Force measurement between body and sled

- (a) The force measurements must be performed at a large enough surface area to measure the force applied by the shoulder or knee of the athlete, an area of approximately 5×5 centimeters is chosen.
- (b) The weight measurements in order to determine the applied force must be done in a range of 0 to 2.5 kg under normal conditions (1 g).
- (c) The weight measurement range increases to a range of 0 to 15 kg due to the sled being subject to g-forces of up to 5 g.
- (d) The weight measurements must have a resolution of at least 100 grams.
- (e) The weight measurements must be done with an accuracy of at least 50 grams.
- (f) The measurements of the force must not hinder the position of the athlete on the sled or his behaviour.
- (g) The measured values should not be dependent on temperature.
- (h) The measured values must be suited as an input to an *ESP32* microprocessor.

S.2 G-force and orientation measurement

- (a) The acceleration in all three dimensions has to be measured
- (b) The roll and pitch of the sled are to be measured.
- (c) The measurements must be able to be performed when subject to g-forces of up to 5 g.
- (d) The measured values must be suited as an input to an *ESP32* microprocessor.

3

Force transducers

The most important quantity to measure on the instrumented sled is the force applied by the knees and shoulders of the athlete. This chapter describes the decisions that have been made for the system of the force transducers, i.e. the location of the transducers, the considerations made when choosing the force transducers and the circuits used to read out the force applied to the transducers.

3.1. Placement of the transducers

In order to measure the forces we must first take a look at where these forces need to be measured. For each run the position of the athlete on the skeleton is almost exactly the same. This means force transducers can be applied in all of the four areas where the force is applied by the athlete, the places where the shoulders and knees touch the skeleton. Also a fifth transducer can severely help to give insight in the order of the forces that the athlete experiences, for instance in corners of 5g. This sensor is placed in a place where the force applied by the athlete is constant. The fifth sensor is therefore placed in the middle of the sled. The transducers are attached to the sled via double sided tape and connected to the main board using two wires.

3.2. Selection of force transducers

There is a great variety of transducers available, each with its advantages and disadvantages. The instrumented sled, however, has specific requirements which have to be met as specified in Chapter 2. Criterion S.1a states that the transducer needs to be large enough to cover the area where the force is applied, this area is chosen to be 5×5 cm. Criterion S.1f requires that the transducers do not hinder the athlete in his normal behaviour. The fact that the transducers can not hinder the athlete, require the transducers to be as flat as possible, limits the options when choosing transducers. This means that mechanical load cells are no viable option since they are bulky and can not be made in the flat dimensions that are necessary. Strain gauges need some kind of lever construction to know what forces act upon them. Capacitive transducers are susceptible to noise, can be hard to read out [10] and can not be found for a low price, which is a constraint because of requirement G.14. These constraints result in the choice for pressure-sensitive films. These sensors are readily available, affordable, proven to work by other studies on skeleton [1], have the dimensions that are needed (flat and 5×5 cm), have the range that is needed and are simple to read out. Therefore two kind of pressure sensitive films are bought. The Interlink Electronics Force Sensing Resistor[®] model *FSR 406* and the *Flexiforce* sensor by Tekscan model number *A502*. This in order to compare which one is better suited for our application. Both sensors can be seen in Figure 3.1.

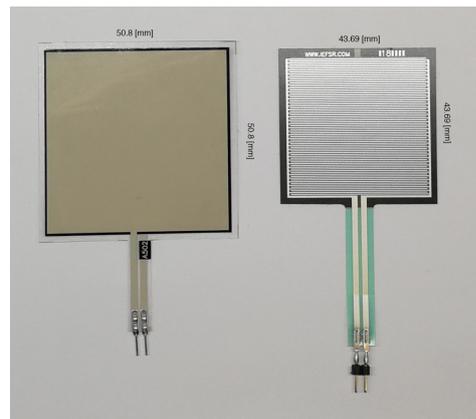


Fig. 3.1: The *Flexiforce A502* by Tekscan (left) and the Interlink Electronics *FSR[®] 406* (right)

3.2.1. Pressure-Sensitive Films

Pressure-sensitive films work on the principle of conductance. According to The Handbook of Modern Sensors [11] the workings of a pressure sensitive film can be explained as follows. A typical film consists of five layers. A pressure-sensitive layer captured between two conductive layers (electrodes) and on the bottom and the top a protective layer. The pressure-sensitive layer consists of a piezoresistive ink with a predefined pattern that has a thickness of 10 to 40 μm . Inside of the piezoresistive ink there are two types of oxides, one that is conductive and one that is insulating. When force is applied to the sensor it causes the conductive particles to touch and form conductive paths. Besides this, a tunneling effect appears when the inside ink come in very close proximity to each other, in the order of 1 nm, electron hopping appears at 10 nm. The operation principle is illustrated in Figure 3.2. The conductive paths, the tunneling effect and the electron hopping cause the sensor to essentially act as a resistor where its conductance is linearly dependent on the force that is applied to the film. This results in a sensor of which the resistance is in the order of mega ohms when uncompressed. The resistance drops when a force is applied to the sensor.

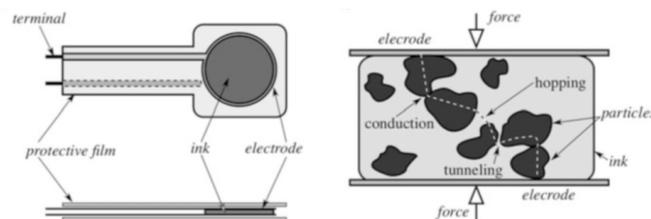


Fig. 3.2: The working principle of a thin film transducer [11]

When it comes to pressure-sensitive films we can further differentiate between thru mode and shunt mode sensors. They both work using the principle as described above however the structure of the sensor can deviate from the above described structure. The thru mode sensor is almost the same as the above described sensor, however two ink layers are present, joined together by an adhesive layer [12][13]. The *Flexiforce A502* uses this sensor structure. This structure can be seen in Figure 3.3a.

The shunt mode sensor consists of a top surface with interdigitated electrodes facing down, a layer of air and a bottom substrate with conductive ink. When external force is applied to the sensor, the top surface is deformed against the bottom substrate. This causes the two interdigitated electrodes to conduct more from one electrode to the other [12]. The principle of shunt mode is incorporated in the design of the *FSR 406* by Interlink electronics and this principle can be seen in Figure 3.3b. Both technologies can be seen incorporated in the sensors in Figure 3.1.

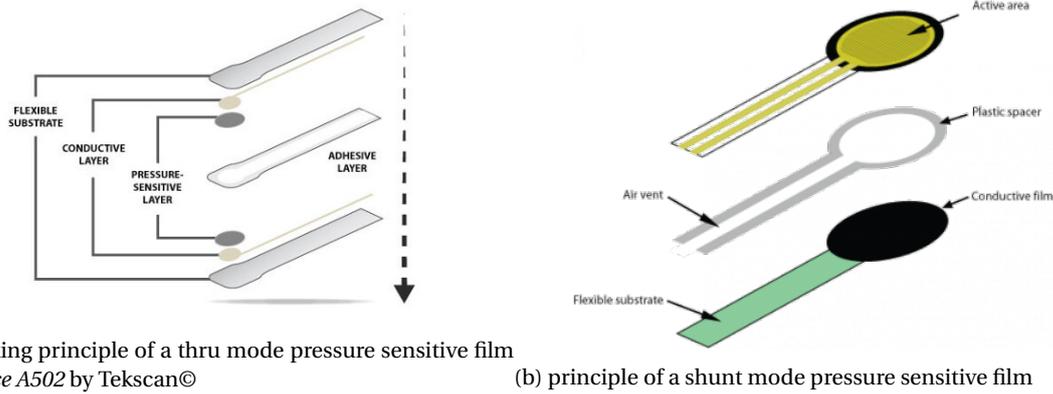


Fig. 3.3: Film transducers

3.2.2. Characterisation

Having introduced the Interlink Electronics *FSR*[®] 406 and the *Flexiforce A502* by Tekscan, measurements can be done in order to characterise the sensors and make a choice in order to see which of the two is best suited for the instrumented sled. The measurement that were performed made use of weight plates to apply a force to the sensors. The measurements were done by increasing the weight on the sensors with 250 gram until 11 kg. At every mass the resistance of the sensor was measured by a multimeter. In Figure 3.4a the applied weight can be seen set out against the resistance, this figure shows the resistance is in logscale. The lines depicts the point where 95% of the measured range of resistance is used. From the figures, a steep decline of resistance for the first 0-1500 grams can be seen. If the force would be measured by determining the resistance the *Flexiforce* is the one that has the most dynamic range. However, as Section 3.2.1 describes, the conductance is the quantity that is linearly dependent on the force. In Figure 3.4b the conductance of both sensors can be seen plotted against the applied weight.

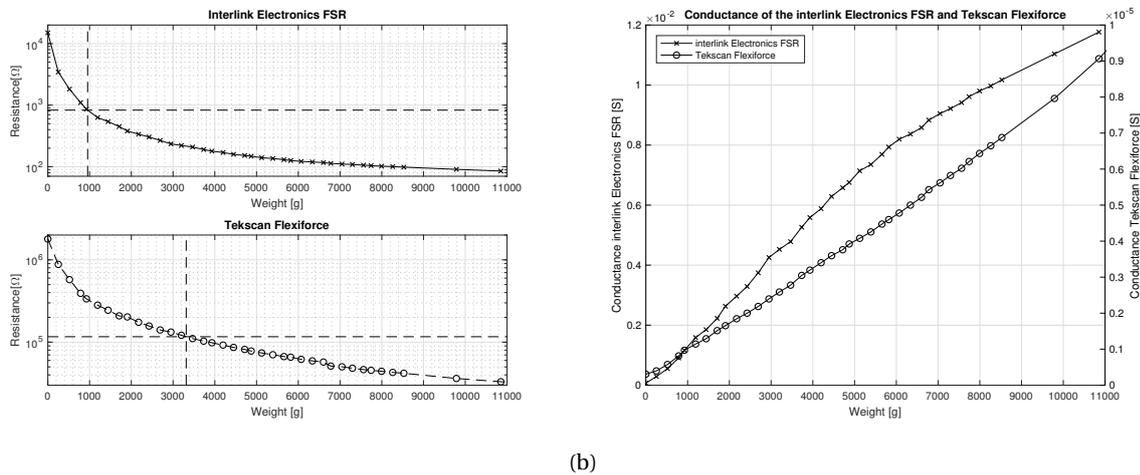


Fig. 3.4: Resistance (a) and conductance (b) as a function of the applied weight for the Interlink Electronics *FSR*[®] and the Tekscan *Flexiforce*

From this figure, it is evident that the conductance of the *Flexiforce* is more linearly correlated to the applied force than the Interlink Electronics *FSR*[®]. For this reason, the *Flexiforce* is chosen as the force transducer to be used.

3.3. Read out circuit

The resistance of a force sensitive resistor does not change linearly with changing applied force, as can be seen in Figure 3.4a, however the conductance of the force sensitive resistor does, see Figure 3.4b. In order to obtain an output from the force transducers, a read out circuit is required. This read out circuit has to relate the input resistance or conductance to an output voltage that is preferably linearly related to the applied force. In the case of a transfer function that is dependent on the resistance of the sensor the microprocessor is used to convert the output voltage of the circuit to the resistance of the sensor using the transfer function of the read out circuit. In turn, the resistance can be converted to a conductance, resulting in a value that is linearly correlated to the applied force. In the case of a transfer function that is dependent on the conductance of the sensor, the measured output voltage is already linearly correlated to the applied force.

3.3.1. Current-to-voltage converter

The Integration guide of the Interlink Electronics *Force Sensing Resistor*[®] [14] suggests various read out circuits, three of which are current-to-voltage converters. Since the use of these circuits results in an output voltage that is dependent on the conductance of the sensor, and thus linearly dependent on the applied force, one of these circuits is used in the system. The used circuit can be seen in Figure 3.5. The range of the output voltage is regulated by the feedback resistance. In order to optimally use the voltage range of 0 to 3 V for a weight range of at least 0 to 15 kg, as dictated by requirement S.1c, the feedback resistance, $R_{feedback}$, at room temperature is chosen to be 33.05 k Ω .

Figure 3.6 shows a plot of the applied weight against the output voltage measured using this circuit. The operational amplifier used in this circuit is the *MCP6024*, containing 4 rail-to-rail single supply op-amps [15]. The choice for the *MCP6024* over for example the *MCP6021* is its small form factor, where the *MCP6021* has 8 pins and contains only one op-amp, the *MCP6024* has 14 pins while containing 4 op-amps. The *MCP6024* was chosen due to the fact that it is an affordable rail-to-rail op-amp with DIP technology. The choice for a rail-to-rail amplifier, which is an amplifier that is able to produce an output voltage which is very close to the supply voltages, will be further explained in Section 3.3.2. The DIP technology is chosen since it makes for easy prototyping.

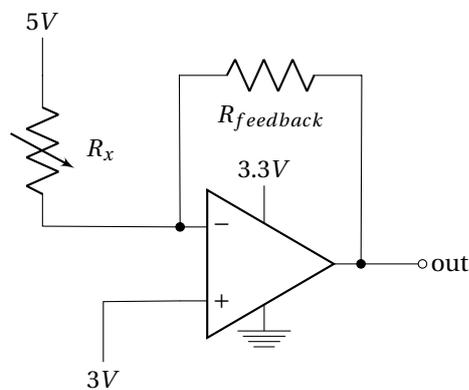


Fig. 3.5: Schematic of the current-to-voltage read out circuit

The transfer function of the current-to-voltage circuit is found to be:

$$V_{out} = \max((V_{ref} - V_{in}) \cdot R_{feedback} \cdot G_x + V_{ref}, 0) \quad (3.1)$$

Where G_x is the conductance of the sensor.

The fact that the output voltage can not be lower than 0 V is because a single supply op-amp is chosen, the *MCP6024-I/P*. As can be seen from 3.1, this read out circuit is dependent on the conductance of the sensor, which is assumed to be linear, as discussed earlier.

Figure 3.6 shows a plot of the output voltage of the read out circuit against applied weight. As is evident from the figure, the output voltage can be assumed to be linear with applied force.

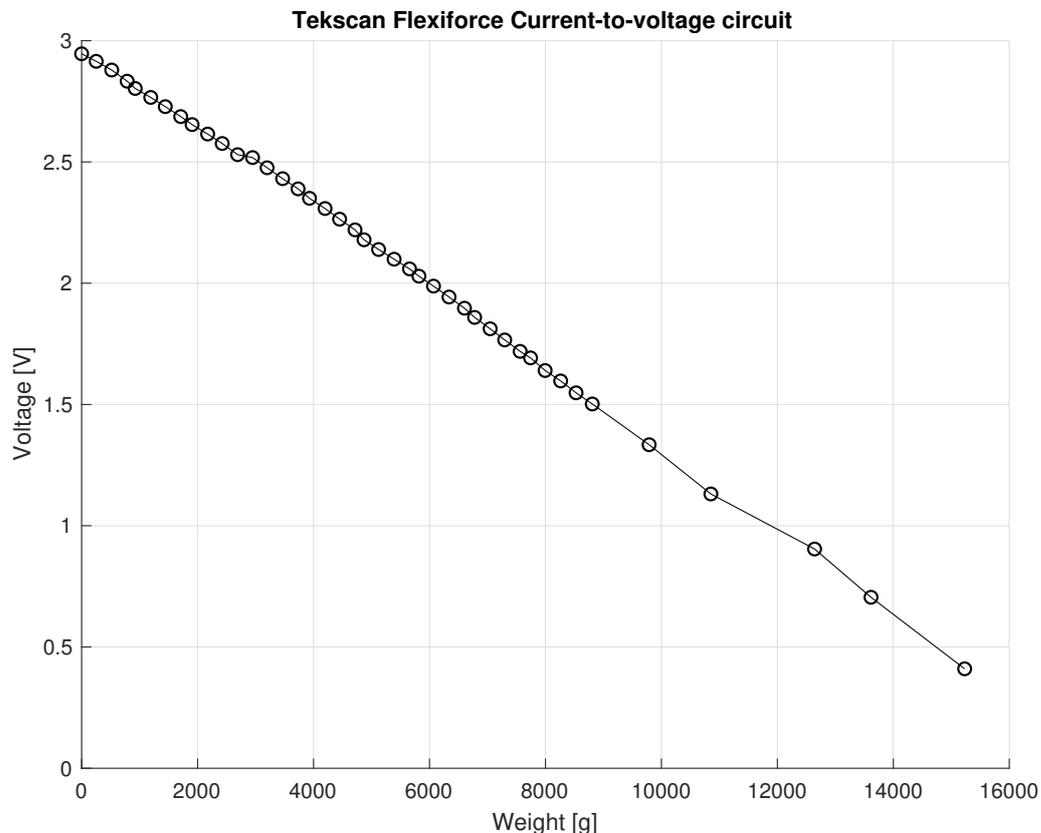


Fig. 3.6: Output voltage of the read out circuit for different values of applied force. $R^2 = 0.999$

3.3.2. Load independence, over voltage protection and noise filtering

In the system, the read out circuit that is shown in Figure 3.5 is followed by a voltage follower. This voltage follower is in place for two reasons, the first reason being to make sure the output of the current-to-voltage converter is independent of the load. Without this voltage follower, the output voltage of the read out circuit would be dependent on the input load of the Analog to Digital Converter.

The second reason for having a voltage follower in place is the maximum input voltage that is allowed by the Analog to Digital Converter, which is equal to its supply voltage +0.6 V [16], in this case the supply voltage is 3.3 V, which results in a maximum input voltage of 3.9 V. Since the output of the current-to-voltage converter is connected to the 5 V source via the feedback resistor and the sensor, the voltage follower is needed to make sure no higher voltage than the maximum of 3.9 V is connected to the Analog to Digital Converter in the case of a short somewhere in the circuit.

The voltage follower is implemented using a single supply rail-to-rail op-amp, the *MCP6024-I/P*. A rail-to-rail op-amp is chosen so that the supply voltage of this op-amp can be chosen very close to the 3 V that is chosen to be the maximum output voltage of the circuit. The supply voltage is chosen to be 3.3 V, this is an additional part of the over voltage protection for the Analog to Digital Converter, which makes sure that the maximum voltage on the input of the Analog to Digital Converter is 3.3 V in the unfortunate case of a short between the output of the op-amp and its supply. The read out circuit, including the voltage follower, is shown in Figure 3.7.

Originally, the circuit was tested without the capacitor in place. When connecting the output of the circuit to an oscilloscope it was found that there was a large amount of high frequency noise present on the output signal. In order to filter out this noise, a capacitor is placed in parallel with the feedback resistor to create an active low-pass filter. The cut-off frequency of the filter is given by Equation 3.2, and with $R_{feedback} = 33.05 \text{ k}\Omega$ and $C_{feedback} = 47 \text{ nF}$ the cut-off frequency can be found to be 102.46 Hz.

$$f_c = \frac{1}{2\pi \cdot R_{feedback} \cdot C_{feedback}} \quad (3.2)$$

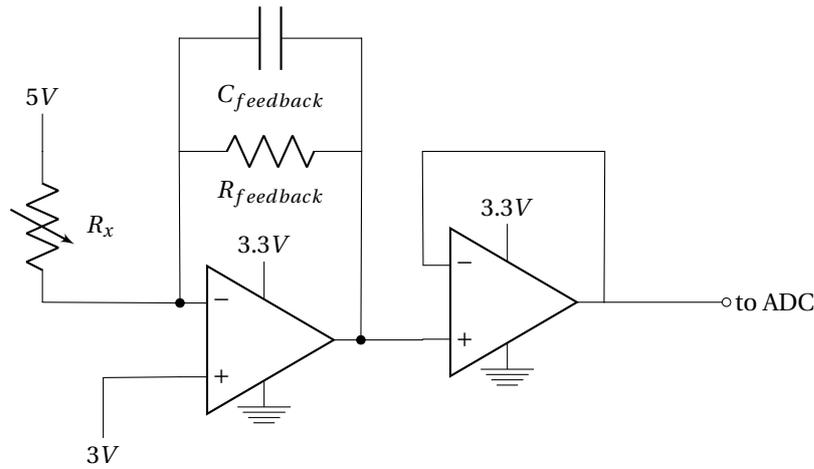


Fig. 3.7: Schematic of the current-to-voltage read out circuit with voltage follower

3.3.3. Temperature independence

Since the system is to be used during decent on a skeleton track, it should be temperature independent, as stated in requirement S.1g. All components used in the system have a minimum operating temperature of -40°C , however, the resistance of the feedback resistor used in the circuit, as well as that of the sensor itself are temperature dependent. This said, it is not known how much influence the temperature has on the resistance of the sensors, especially since the heat of the athlete's body could influence this as well. At this point we do not have the means to examine this.

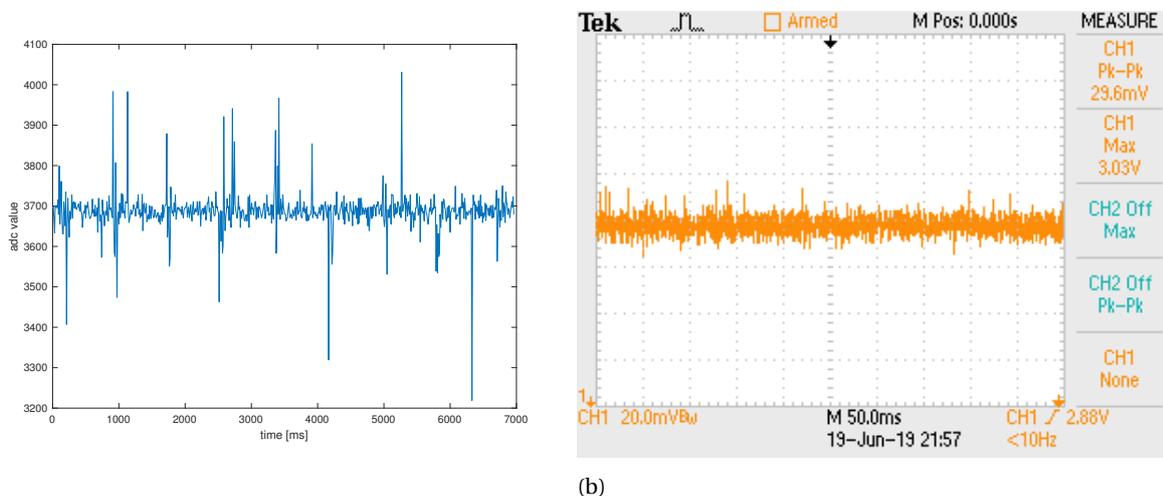
In an attempt to measure the temperature dependence of the force sensor, it was put in a freezer along with the read out circuit and when it had reached the temperature of -18°C the sensor and the circuit were taken out of the freezer and hooked up to the necessary power supplies and measurement equipment. However, since the sensor is very thin and the components in the read out circuit are fairly small as well, their temperature would have risen to a temperature close to room temperature before effective measurements could be made.

In order to have the system be totally temperature independent, it should be characterised for each temperature, mapping each output voltage to the corresponding applied force, then when measuring forces, the current temperature would have to be sent to the microprocessor to make sure the correct mapping of output voltage to applied force is used. In order to use the voltage range as efficiently as possible, a digital potentiometer should be used in order to adjust the range for the given temperature. For now, the mapping of voltage to force and the voltage range is calibrated for room temperature.

3.4. Analog to digital converter

In order for the microprocessor to be able to read the output voltage of the read out circuit, an Analog to Digital Converter, or ADC, is needed. The *ESP32* that is used in the system is implemented on the *Adafruit Huzzah32 Feather Board* which maps 12 of the 16 available ADC ports [17] to the input pins [18].

When characterizing the ADCs of the *ESP32*, it was found that the output was very unstable, Figure 3.8 shows plots of the output of a channel of the ADC and its input voltage, each ADC channel showed this behaviour. As can be seen from Figure 3.8b, the input voltage is fairly stable, while the output of the ADC takes on values with a difference of as much as approximately 700, which, with a 12-bit ADC with a minimum input value of 0 V and a maximum value of 3.3 V, corresponds to a fluctuation of approximately 0.56 V. Looking at Figure 3.6 this corresponds to a difference in weight of approximately 1500 grams.



(a)

(b)

Fig. 3.8: (a) The output of one of the ADC channels on the *ESP32*, (b) The input voltage of the ADC

Since a fluctuation of 1500 grams is simply unacceptable, an external ADC is used instead of the ADCs available on the *ESP32*. In this system, the *MCP3208* is used.

The *MCP3208* [16] was chosen due to the fact that it is a fairly cheap ADC, with at least 5 channels. The *MCP3208* is one of few affordable ADCs that has enough channels and also one of few affordable ADCs using DIP technology, making it easy to use it for prototyping. The *MCP3208* has the same resolution as the ADCs on the *ESP32*, namely 12-bit. Looking at Figure 3.6, it can be seen that the effective weight range of 0 to 15.23 kg uses a voltage range of $2.946 - 0.41 = 2.536$ V. Since the ADC divides 4096 values over a total input range of 3.3 V, 1 V contains approximately $\frac{4096}{3.3} = 1241$ values, this means that the effective force range of 0 to 15.23 kg is represented by approximately $1241 \cdot 2.536 = 3147$ values, so the resolution is $\frac{15230}{3147} = 4.8$ grams, which is more than enough according to requirement S.1d.

The sample rate of the *MCP3208* is 50000 samples per second with a supply voltage of 2.7 V and 100000 samples per second when using a supply voltage of 5 V [16]. Since the *MCP3208* in this system uses a 3.3 V supply, it can be assumed that the samplerate of the ADC is at least 50000 samples per second, this is well within the specifications of requirement G.6.

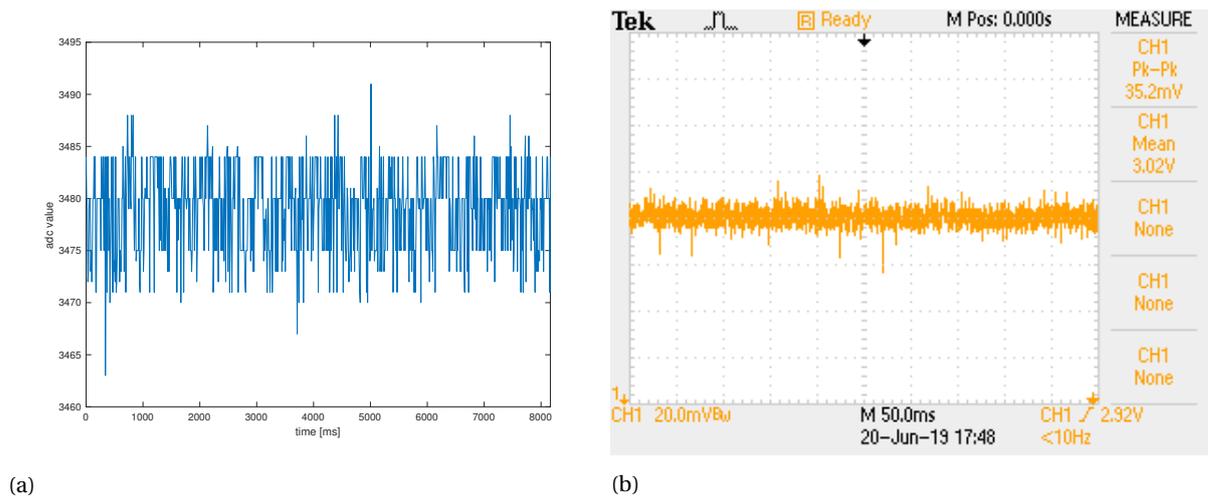


Fig. 3.9: (a) The output of one of the channels of the *MCP3208*, (b) The input voltage of the *MCP3208*

Requirement S.1h demands that the ADC produces an output that is suited as an input to an *ESP32* microprocessor. The *MCP3208* makes use of the Serial Peripheral Interface, or SPI, protocol. The *ESP32* also has the option to communicate via SPI [17]. The SPI setup in this system uses a “master” device, in this case the *ESP32* microprocessor, which is connected to the “slave” devices by two datalines and one clockline, along with a chipselect line for each “slave” device. The clockline carries a clocksignal and the chipselect line is normally high. One dataline is used to send data from the *ESP32* microprocessor to the “slave” device and the other dataline is used to send data from the “slave” device to the *ESP32*. The clockline is used to make sure the data transfer is synchronised. A “slave” device is only allowed to send or receive data when its chipselect line is made low, this is why the SD-card, which also uses SPI [8], and the ADC can be connected to the same data- and clock lines. The code used by the *ESP32* to read out the ADC is shown in Appendix A.1.

Figure 3.9 shows plots of the output of the external ADC and its input signal. The difference in values is approximately 30, which corresponds to a fluctuation of approximately $\frac{30}{4096} * 3.3 = 24$ mV. As can be seen from Figure 3.9b this is mostly due to the fluctuating source voltage.

Looking at Figure 3.6, it can be seen that the fluctuation of 24 mV results in a fluctuation of approximately 150 grams. This is not in line with requirement S.1e. However, as is shown in Figure 3.9, this is mostly due to the noise on the power supply. The supply voltage that will be used in the final system might be more stable, this is still to be determined.

4

G-Force and Orientation

G-force is a measure of acceleration, relative to the gravitational force. The g-force is of interest to the athlete, since he wants to see whether the g-force influence his steering behaviour. In order to measure the g-force in all directions, a tri-axial accelerometer is needed.

The Assessment of an empirical Bob-Skeleton steering model [2] describes a model that correlates the measured force applied by the athlete to a measured orientation. Since both quantities are measured in our case to illustrate the motion of the athlete in the analysis on the mobile device, this model could be of help to give further insight in the data. The slope of the track is also of interest, in order to assess whether this could be influencing the effectiveness of the steering motions made by the athlete. The orientation of the sled is found by measuring the roll, the slope is found by measuring the pitch. Both these quantities can be measured by using a gyroscope. Figure 4.1 illustrates the directions of these motions.

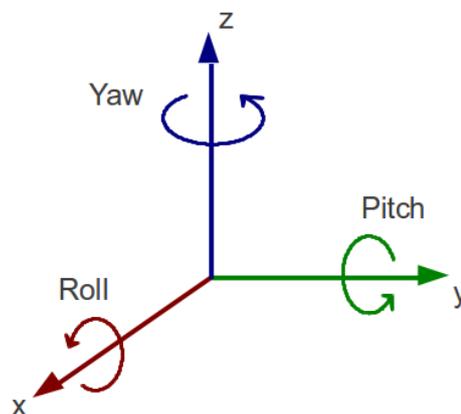


Fig. 4.1: The roll, yaw and pitch. In this case the front of the sled is in the positive x direction.

4.1. Selection of the accelerometer and gyroscope

A separate tri-axial accelerometer and a separate gyroscope can be used to measure the previously mentioned quantities, however, a device called an Inertial Measurement Unit, or IMU, combines these sensors, along with a magnetometer. The IMU that will be used in the system is the *MPU-9250 Breakout circuit* by Sparkfun Electronics. This circuit contains the IMU itself, along with the necessary components for a correct

read out of the measurements [19].

The *MPU-9250* allows for the export of the measured data via I²C or SPI. In this system, I²C is used for the communication between the *ESP32* and the IMU. Similar to SPI, as discussed in Section 3.4, I²C allows for the connection of multiple “slave” devices to a single bus. Rather than using 4 datalines, I²C only uses 2 datalines, a clock line and a bidirectional dataline. The distinction between multiple “slave” devices is made by the fact that each device has its own address. Requirement S.2d is satisfied by using the I²C protocol.

The implementation of the *MPU-9250* was largely done by subgroup B, since their system uses it to implement a Kalman filter in order to increase the accuracy of the localisation. More about this can be read in their thesis [9]. All the code needed to read the measured values with the *ESP32* was also provided by subgroup B and can be found in their thesis [9].

The choice for the *MPU-9250* was made due to availability of extensive documentation on the device, such as a hook up guide [20], which also refers to a pre-build arduino library that can be used by the *ESP32*. The fact that the implementation of the *MPU-9250* required little to no attention meant that the main focus of this subsystem could be put towards the measurement of the forces of the body on the sled. Other reasons for choosing the *MPU-9250* are its affordable price and the fact that its specifications meet the requirements mentioned in Section S.2. The *MPU-9250* has a measurement range of up to 16 g [21], meaning requirement S.2c and with that also requirement G.3 are met.

5

Discussion

During the design of this system, many tests were performed. This chapter will list the test setup and results of the most important and most relevant tests.

5.1. Resistance and Conductance of pressure sensitive film

Multiple measurements were done to the *FSR 406* and the *Flexiforce A502* sensors in order to characterise these two sensors. For both this included a measurement setup as follows. The sensor was laid flat onto a flat surface. On top of that a piece of blank PCB with an area a little bit smaller than the area of the sensor was placed, followed by a glass plate. The weight of the blank PCB and the glass plate was a total of 201 gram. The reason for including the PCB and the glass plate was to evenly distribute the force onto the transducer, create a platform to load more weights upon and create a preload on the sensor. Both of the sensors when completely uncompressed have resistances in the order of hundreds of mega Ohms. The sensor itself was connected to a *Fluke 177* multimeter that was set to the resistance measurement mode. The setup was loaded with weights, increasing the weight by 250 grams between measurements in order to measure the corresponding resistance for each mass. Now this mass is known the force can also be calculated by applying Newtons first law $F = m \cdot a$, in which a is in this case the gravitational constant g because the force is directed down towards the earth. When measuring the resistance for the *FSR 406* it was seen that sensor clearly needed time to settle to a final resistance value. This made it difficult to measure and repeat measurements. With the *Flexiforce A502* this effect was almost non-existent. For the lower masses it showed some settling behaviour but this quickly vanished as the mass increased. Measurements for the *FSR 406* and *Flexiforce A502* were both done two times in order to show repeatability. These two sets measurements deviated at a maximum 5% for the *FSR 406* However this sensor also had a settling behaviour so it is difficult to pinpoint where these inaccuracies come from. The *Flexiforce A502* showed much higher repeatability, the maximum deviation was around 1%. The results for resistance and conductance measurements can be found in Figure 3.4a. Later on two additional Tekcan *Flexiforce A502* sensors were characterised. As can be seen in Figure ?? there is a difference between the sensors. In impacts the choice of the feedback resistors. However there is chosen to equally choose the feedback resistors for all read out circuits and give each sensor an individual characterisation formula in the software.

5.2. Read out circuits

When all the measurements of the resistance were available it was possible to convert this to a signal that can be presented to the ADC which expects a voltage between 0 and 3.3 V. In Section 3.3.1 a circuit is described that can convert the input force into a voltage. Using the resistances measured before, a feedback resistor is

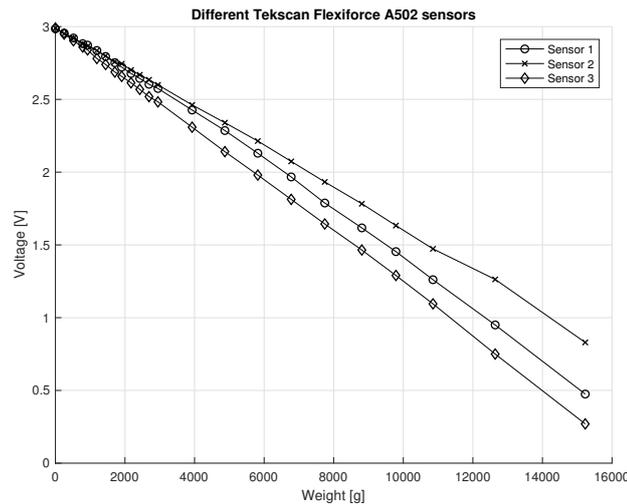


Fig. 5.1: Multiple *Flexiforce A502* sensors characterised

calculated for this circuit in order to get all of the information from the sensor into the voltage range that was available. This was done using the transfer function of the circuit and the known minimum and maximum resistance. Due to the more linear behaviour of the conductance the *Flexiforce A502* was chosen. The circuit was now measured in order to confirm the transfer function and to see if other factors influenced the output. A second op-amp was also added in voltage follower configuration in order to protect the ADC, as mentioned in Section 3.3.2. The 5 V, 3.3 V and 3 V were provided by three *Tektronix PWS4205 programmable power supplies*. The output was measured by a *Fluke 177* multimeter in DC voltage measurement mode. This provided 4 decimal place accuracy so this would be more than the 12-bit resolution of the ADC. The measurements were compared to the expected output as calculated using the transfer function. The first chosen feedback resistor was unfortunately chosen to be too high. This feedback resistor caused the voltage at the output of the circuit to decline too quickly, causing the output voltage to be too low for a mass that was still in the range that had to be measured according to requirement S.1c. Choosing a resistor of a lower value solved this problem and in the second prototype this resistor was replaced by a potentiometer. The accuracy of these measurements are still dependent on the accuracy of the power supplies and the temperature the room.

5.3. Temperature dependence

An effort was done to measure the circuit and sensor under cold (-18°C) conditions. However, it was found that when the whole circuit was placed in a freezer for a night they would heat back up to room temperature within 30 seconds. It was concluded that in order to get an accurate measurement of the circuit and the sensor the whole measurement setup has to be placed into an environment that is the desired temperature. However a climatic cabinet or an equivalent environment was not available during the project.

The manual of the *Flexiforce A502* states: "Force reading change per degree of temperature change = $0.36\%/^{\circ}\text{C}$ " [22]. Since the force is linearly correlated to the conductance, it is not clear how this effects the resistance in particular. This means it is hard to know how exactly the temperature has an effect on the reading and how the feedback resistor can be chosen in order to compensate for this.

5.4. Measurement and characterisation of the ADC

In order to characterise the ADCs, both the one on board of the *ESP32* and the *MCP3208*, a measurement setup was build. The characterisation of the on board ADC was done with some code that read the ADC output and then sent over to the computer via USB. A constant voltage was provided to the ADC pin by a

Tektronix PWS4205 programmable power supply that was set at different voltages to see what voltage corresponded to each ADC value. The same is done with the *MCP3208*, but this time, the ADC is connected to the SPI bus of the *ESP32* that sends this data again to the computer via USB. The reference voltage and the power supply were provided by a constant voltage from a *Tektronix PWS4205 programmable power supply*. During the tests it was noticed that the power supply had some noise despite being in constant voltage mode and showing a three decimal place accuracy on the screen. The fluctuations in voltage were measured by an *Tektronix TDS2022C* digital oscilloscope. The results can be seen in Figure 3.8b.

5.5. Measurement and characterisation of the IMU

After the IMU was selected it could be characterised. With the help of a library that was available for the Arduino IDE, the IMU could be easily read out using the *ESP32*. The working of all of the axes of the accelerometer and the gyroscope were checked. Karen from group B did a measurement in which the IMU was tilted from a rest position in every axis. First at 45 degrees and after that at 90 degrees. This can be seen in the shift in gravitational constant of 9.81 in the 3 top figures of Figure 5.2. In the bottom 3 figures this difference in angle can be seen as well. The test was done at an update rate of 10 Hz.

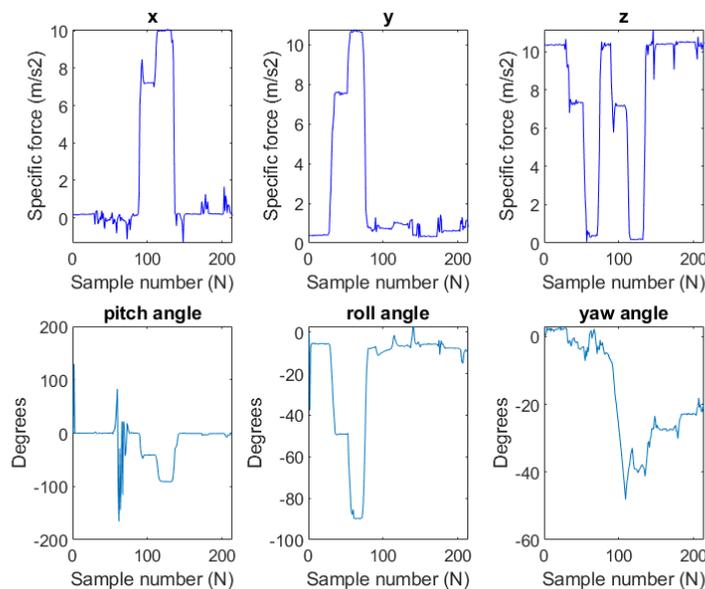


Fig. 5.2: X, Y and Z axis of the accelerometer and the yaw, pitch and roll

5.6. IMU in Duinrell

On Monday afternoon June 17th 2019, measurements were done with the complete system excluding the force sensors in several attractions at the Duinrell entertainment park. Several runs were done in a roller coaster in order to acquire data in a high g-force environment. This would be the same magnitude of g-forces that an athlete would experience on the track [23]. The runs were also measured as a reference by a mobile phone with the Matlab mobile app that recorded the orientation, acceleration and location (GNSS) at an update rate of 100 Hz for the acceleration and orientation and 1 Hz for the location. However the total system was not configured correctly. The whole system only updated at an update rate of 1 Hz and this was not enough to show meaningful data. There also errors introduced by the GNSS because of which the time in between data points could be delayed up to 4 seconds. At this moment it is not known if the data was incorrect due to the slow update rate or due to the interaction between the GNSS receiver and the IMU. Further testing and tweaking of the code is necessary in order to prove the full update rate of the IMU in order to meet requirement G.6.

6

Conclusion and Recommendations

A lot of the requirements from Section 2 were met. In this section it will be discussed which requirements were and were not met.

6.1. Specific requirements

S.1 Force measurement between body and sled

- S.1a The sensors were chosen in such a way that they are large enough (5x5 cm) to measure the force applied by the athlete. This is described in Section 3.2.
- S.1b and S.1c are met by choosing the Tekscan Flexiforce A502 that can measure masses from 0-20kg. And choosing the appropriate feedback resistor in the read out circuit. This is found in [22] and Section 3.3.
- S.1d The chosen read out circuit maps the force in the a way that the *MPC3208* 12 bit ADC can provide the resolution that is necessary. This is described in Section 3.4.
- S.1e Due to the noise on the supply line of the readout and ADC circuit the precision of 50 grams is not yet reached. This can be found in Section 3.4.
- S.1f The force transducer was chosen in such a way that this was a thin film sensor and does not hinder the athlete on the sled or his behaviour. This is described in Section 3.2.
- S.1g The components that were selected for the force measuring system were chosen in such a way that they would work in the temperature range but it is not verified if the system is independent on temperature. This is described in Section 3.3.3.
- S.1h The read out circuit is designed in order to provide the ADC with a suitable signal. This is then successfully transferred to the ESP32 via the SPI bus. This is described in Section 3.4.

S.2 G-force and orientation measurement

- S.2a The acceleration in all three dimensions can be measured by the *MPU-9250* as described in Section 4.1 and 5.5. However the total integrated system still has some issues as can be found in Section 5.6.
- S.2b The roll and pitch of the sled can be measured by the *MPU-9250*. This is described in Section 4.1 and validated in Section 5.5. However the in the total integrated system it still has some issues as can be found in Section 5.6.
- S.2c The IMU is selected in order to measure at least 5 g but can measure upto 16 g. This is described in Section 4.1.

S.2d The measured values are presented to the *ESP32* via the I²C bus and this is described in Section 4.1.

6.2. General requirements

All quantities stated in requirement G.1 can be measured individually, however due to an error in the code for the GNSS, the sample time sometimes gets delayed resulting in a sample time of several seconds, this is explained in more detail in the thesis of subgroup B [9]. Because of this, the sample rate is not high enough to satisfy requirement G.6.

Since the means to measure the influence of the temperature of the environment in which the product will be used and the vibrations on the track due to irregularities in the surface of the ice are not available, it can not be checked whether requirements G.2 and G.11 are met. However, as mentioned in Section 5.6, a prototype of the system was tested during several roller coaster rides. The prototype was not mounted on the dedicated PCB that was designed by subgroup B [9], while with the final product this will be the case. This means that the final product will be even more robust.

The product must be easily removed and installed on the sled, as dictated by requirement G.8. The inside of the sled is fairly easily accessible, therefore the product can be easily removed or installed. As mentioned in Section 3.1, the force transducer are attached to the sled using double-sided tape, they could leave some easy to remove traces on the sled. The measurements, however, should be started without accessing the circuitry inside the sled, as stated in requirement G.7. Just like the force transducers and the GNSSreciever [9], a momentary switch is mounted on the outside of the sled. This momentary switch sends a signal to the *ESP32* to start the measurements. The dimensional requirements listed in G.5 and G.4 have been met, the dimensions of the part of the product that should fit inside the sled are $11.5 \times 12.5 \times 1.8$ cm and the weight of the total system is 261 grams. The product, however, does have minimal influence on the aerodynamics of the sled due to parts of the system being mounted on the outside of the sled, such as the GNSS [9] and the switch for starting the run [8]. This means the product partially meets requirement G.9.

As discussed in Section 5.6, the system has been tested at g-forces of up to approximately 5 g. The system was able to acquire data in these conditions, however, due to an error in the code, the measured data could not easily be interpreted. This means it can not be said whether requirement G.3 is met.

As described by the other subgroups, the power is provided by a battery [9] and the processed information is sent to a mobile device via Wi-Fi [8], meaning no external devices have to be connected to the product in order to use it, in accordance with requirement G.10.

All that is needed to use the product is a press on the button to start the measurements and after the run a mobile device to read the data, satisfying requirement G.13. According to requirement G.12, the acquired data should be available to the athlete and the coach within 5 minutes. As described in the thesis of subgroup C [8], the time it takes to process the data and present it on the web page takes less than 20 seconds.

The final general requirement, requirement G.14 states that the total costs of making the prototype should be within the budget of €250,-. This requirement was not met, the overall costs of the prototype are approximately €400,-.

6.3. Recommendations and future work

In order to end up with a better system, the following things still have to be done:

1. Making the system temperature independent
2. Testing the force sensing circuit with the battery voltages
3. Investigating the effects of vibrations during the run due to the surface of the ice not being perfectly smooth
4. (Optional) increasing the accuracy of the force measurements by using an array of sensors per steering point

5. Further testing of the integrated system
6. Characterise the other Tekscan Flexiforce sensors

6.3.1. Temperature independance

First of all, it should be examined how much influence the temperature has on the resistance of the sensors, especially since the heat of the athlete's body could influence this as well. Once this is assessed, a suitable temperature compensation can be implemented.

In order to be able use the system at different temperatures and still extract useful data, the system has to be calibrated and characterised for various different voltages. As was mentioned in Section 3.3.3 the best option to do this is to integrate a system that uses a digital potentiometer to change the value of the feedback resistor to change the utilised voltagerange. The digital potentiometer would be configured using the microprocessor, by providing the temperature at which the run is going to be taking place.

In order to enable the microprocessor to chose the correct setting of the digital potentiometer, the circuit will have to be characterised for the temperature range in which the sled is to be used. In order to do this, a lab setup similar to that described in 5.2 is needed, however, it must be possible to control the temperature of the room in which the measurements are made, the controllable temperature range should be between -21°C and 40°C.

6.3.2. Testing the read out circuit with the battery

Since the measurements and characterisation of the ADC values were done using a fairly noisy supply, as mentioned in Section 5.4, in order to accurately characterise it and see whether the fluctuation is within the specifications of requirement S.1e, the output should be examined while using the battery voltages that are to be used in the final system instead of the lab bench power supply.

6.3.3. Investigating the effect of vibrations

In order to investigate the influence of the vibrations of the sled due to irregularities in the surface of the ice on the track on the measurements, the system should be tested on a skeleton track. After a few runs, the data should be analysed and a conclusion should be drawn about the influence of these vibrations.

If the vibrations turn out to be of significant impact to the measurements, a low-pass filter should be implemented in order to filter out these rapid fluctuations in the measured data. This can be done digitally in the *ESP32*.

6.3.4. Using more sensors or sensorarrays

More data could be extracted about the steering movement of the athlete if multiple sensors or sensorarrays were used at each of the steering points to measure the forces of the body on the sled. With multiple sensors or sensorarrays, the distribution of the force at each could be visualised for at each steering point individually. This would mean that the athlete has a better idea of the exact position of his shoulders and knees during the steering motion.

6.3.5. Further testing of the integrated system

As mentioned in Section 5.6 the system is not yet well integrated and the IMU does not yet give useful data that can be used to give an orientation feedback to the user. It is therefore necessary to further test and improve

the code to read out all of the sensors at the update rate that is specified in G.6. Due to the implementation of the IMU together with the localisation with the GNSS receiver, group B and the Data group will further investigate these implementation problems.

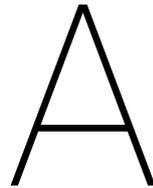
6.3.6. Characterise the other Tekscan Flexiforce sensors

At the moment the mass is determined by the characteristics from the Flexiforce sensor that we have. In order to implement the other two sensors in the system these have to be characterised as well. This because there can be irregularities between the individual sensors. After that the feedback resistor can be tuned to the characteristics of the individual sensor. And after that the impedance characteristic function for the individual sensor can be implemented in the code.

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Appendix

A.1. Code for reading out the ADC

```
1 #include <SPI.h>
2
3 #define ADC_SELECT_PIN 5 //Selection Pin
4
5 void setup() {
6 //set up chipselect and SPI
7 pinMode(ADC_SELECT_PIN, OUTPUT);
8 digitalWrite(ADC_SELECT_PIN, HIGH);
9 SPI.begin();
10 }
11
12
13 void loop() {
14 int SL = 0, SR = 0, B = 0, KL = 0, KR = 0;
15 //shoulder left
16 SL = read_adc(0);
17 //shoulder right
18 SR = read_adc(1);
19 //belly
20 B = read_adc(2);
21 //knee left
22 KL = read_adc(3);
23 //knee right
24 KR = read_adc(4);
25 }
26
27 double adcRead(int channel) {
28 // Enable ADC reading from SPI
29 digitalWrite(ADC_SELECT_PIN, LOW);
30
31 // Request data
32 SPI.transfer(0x06 | (channel >> 2));
33 int firstrequest = SPI.transfer(channel << 6);
34 int secondrequest = SPI.transfer(0);
35
36 // Disable ADC reading from SPI
37 digitalWrite(ADC_SELECT_PIN, HIGH);
38
39 // Turn raw data into kilograms
40 return 17.6066 - 0.00482858262 * (((firstrequest & 0x0F) << 8) + secondrequest);
41 }
```