EE2011 Group Report

Mark Fitzgibbon - 122319381 - Team Leader
Ian Kenny - 122339163
James Crotty - 122362063
Fearghal Desmond - 122380651

March 2024

Abstract

The use of a microcontroller's I/O capabilities to program a primitive autoranging mulitmeter represents an interesting design challenge. A microcontroller is a cost-effective tool for investigating embedded systems, giving insight into the interface between the digital and analog domains. Beyond its pedagogical utility, this assignment highlights the complexity of digital measurement tools and raises an important question: is a breadboard-based multimeter design feasible? If so, over what range will it be sufficiently accurate? This report details one such design, with a particular emphasis placed on the electrical and electronic principles underlying each of four modes of operation: voltmeter, ohmmeter, capacitance meter and frequency counter. Key learnings from the assignment include an appreciation for the non-ideal nature of practical circuit components, a basic understanding of C-based coding languages, experience in configuring embedded systems for precise measurement and user input, and an understanding of the relationship between accuracy and complexity in electronic design. This report also briefly evaluates the commercial viability, environmental impact and safety implications of the design. More thorough investigations are required for a more comprehensive discussion of these points. - James

Contents

1 Introduction - Mark **1**
1.1 Project Goals 1
1.2 Work Organisation 1
1.3 Team Tasks 1
1.4 Code References 1

2 Frequency Counter - Mark **2**
2.1 Design Principle 2
2.2 Design implementation 2
2.2.1 Circuitry 2
2.2.2 Code 3
2.3 Results 3
2.3.1 Discussion and Conclusion 4

3 Voltmeter - James **5**
3.1 Design Principle 5
3.1.1 Voltage Level Shift 5
3.1.2 Analog Measurement and Conversion 5
3.2 Design Implementation 6
3.2.1 Circuitry 6
3.2.2 Hardware Specifications 6
3.2.3 Code 7
3.3 Results 7
3.3.1 Discussion and Conclusion 7

4 Capacitance Meter - Fearghal **8**
4.1 Design Principle 8
4.1.1 Principle of Operation 8
4.2 Design Implementation 8
4.2.1 Circuit Setup 8
4.2.2 Choice of Resistance Value 9
4.2.3 Code Design Overview 9
4.3 Results 9

5 Ohmmeter - Ian **10**
5.1 Design Theory 10
5.1.1 Mathematically 10
5.1.2 Application 10

5.2 The Circuit 10
5.2.1 Parts Required 10
5.2.2 Diagram And Explanation 11
5.3 Measurement Results 11
5.3.1 Attempted Designs 11
5.3.2 Final Design 12

6 Health and Safety, Standards and Ethics **13**
6.1 Relevant National/International Standards - Mark 13
6.2 Life cycle - Ian 13
6.3 Health and Safety - Mark 13
6.4 Ethics 14
6.4.1 Nucleo Board 14
6.4.2 ADALP/ADALM components and assembly - Ian 14

7 Appendix **15**
7.1 Interface Design - Fearghal 15
7.1.1 Overview 15
7.1.2 Implementation 15

List of Figures

2.1 Circuit design for the digitisation of the input waveform . . . 2
2.2 Plot of the frequency measured, normalised as the gain of the output against the input, in decibels vs. Input frequency . . . 3

3.1 Circuit design for the voltage level shift 6

4.1 RC Circuit for capacitance meter 8

5.1 Ohmmeter Original design 12

Introduction - Mark

1.1 Project Goals

The design requirement for this project was to design and implement an autoranging multimeter, based upon the Mbed Nucleo-F446RE microprocessor board. The specifications that the design had to meet included:
- Measuring ± 5V
- Measuring resistances between 10Ω and $10\text{M}\Omega$.
- Measuring capacitances in the nF and μF ranges.
- Measure frequencies.

1.2 Work Organisation

A joint GitHub repository was used to host the team's code and manage version control, in order to ensure a smooth workflow during the course of the project. To accelerate integration of the various functions required for the multimeter to perform, it was established by the team that each seperate function of the multimeter would be written within an independent .cpp file.

To further assist integration, each individual function of the multimeter was designed to be a void return type callable from main, which would print to the serial monitor. This allowed for a quick integration process towards the end of the project, and minimised conflictions within the code.

1.3 Team Tasks

James - Voltmeter, filming and video production.
Fearghal - Capacitance meter, Ohm meter, GUI and front end design.
Mark - Frequency counter, integration testing, collation of report.
Ian - Ohm meter.

1.4 Code References

Throughout the report, the code for the project will be referenced. The document containing the code, Group_7_EE2011_Code_Doc, has been uploaded alongside this report.

Frequency Counter - Mark

2.1 Design Principle

In order to simplify measuring the frequency of the signal, the input signal is digitised, enabling the detection of binary transitions. The digital waveform is then output to a digital in pin on the Nucleo board.

To begin measuring the frequency, a rising edge detector is used. When a rising edge is detected, a timer is started, and runs until the signal falls again. The reciprocal of double this time duration will then be equal to the frequency of the input signal.

2.2 Design implementation

2.2.1 Circuitry

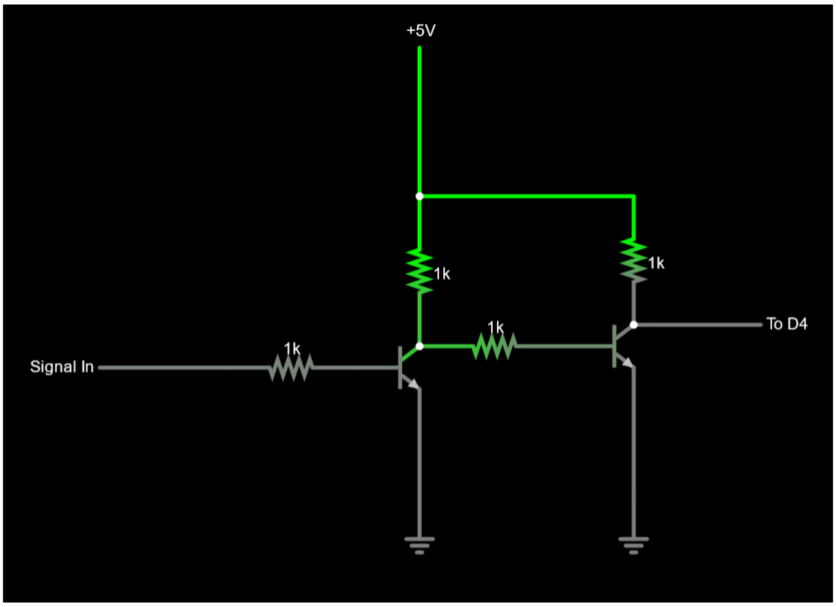

Figure 2.1: Circuit design for the digitisation of the input waveform

To digitise the input signal, it enters the base pin of a 2N3904 transistor, through a 1kΩ resistor. The output voltage, though square, is out of phase with the input. To remedy this, the output voltage, taken from the collector pin, enters the base of an identical transistor. The final output signal is then connected to a digital in pin.

2.2.2 Code

In order to increase accuracy, ten samples of the signal are measured, and the mean is calculated. The sample is taken by continually measuring the digital in pin, and once a 0 and 1 are measured sequentially, the timer is begun. The timer is then halted once a 0 is detected on the digital in pin, and the time elapsed is cast, in microseconds, to a float.
See Group_7_EE2011_Code_Doc, freq_counter.cpp, float sample()

The frequency is calculated by first taking the average of the accumulated sample durations, and then finding the reciprocal of twice this average. The implication of this approach is that as the duty cycle of the input signal deviates from 50%, the accuracy of the sampling decreases linearly.

2.3 Results

Using a square wave input, a range of frequencies were tested, from 1Hz up to 1MHz.

Input Freq. (Hz)	1	10	100	1k	10k	100k	150k	200k	1M
Measured Freq. (Hz)	1	10	100	1k	10k	100k	135k	166k	167k
Accuracy (%)	100	100	100	100	100	100	90	84	17

Table 2.1: Measurement readings, and accuracy, for an input frequency sweep from 1Hz - 1MHz

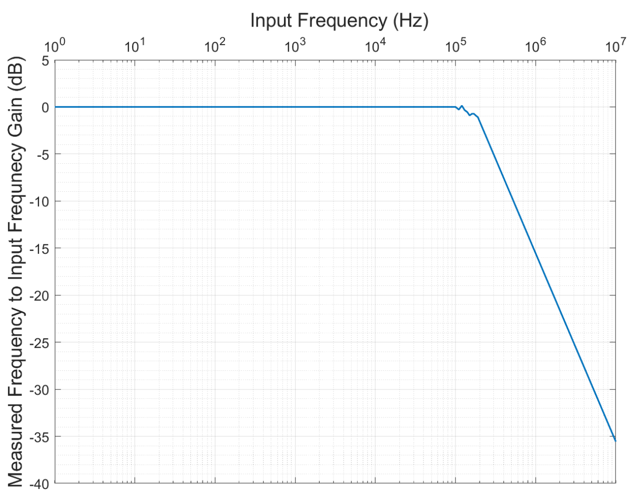

Figure 2.2: Plot of the frequency measured, normalised as the gain of the output against the input, in decibels vs. Input frequency

From table 2.1, the frequency counter solution can be seen to be accurate for frequencies up to 100kHz, above which there is a steep decline in accuracy. This trend is quantified by figure 2.2, where an accuracy drop of 20dB dec^{-1} is observed above 100kHz.

2.3.1 Discussion and Conclusion

There is a clear limitation with the design, in that it is unable to reliably measure frequencies above 100kHz. This appears to be a limitation of the measuring speed of the digital in pins on the NUCLEO-F446RE. One potential solutions to this constraint would be to selectively choose a microcontroller designed for high-frequency digital reads.

A potential improvement for the design implemented would be for the timer to halt on the next rising edge, instead of on the falling edge of the same pulse. In this way, accuracy for waves with duty cycles greatly deviating from 50% could theoretically be improved.

Voltmeter - James

3.1 Design Principle

3.1.1 Voltage Level Shift

The idea behind a level shifting circuit is to take some input range and, by combining this with a supply voltage in a resistor network, to transform it into a different output range. There are two relevant considerations here:

1. The input is specified as $\pm$**5V** in the assignment brief.

2. The NUCLEO-F446RE analog-to-digital converter can only read values over a small, positive voltage range.

Examining Figure 3.1 below, three resistors come together at a single node. The input voltage is fed through one branch, the 5V V_{cc} through another and the GND through the third. The voltage output is taken into the microcontroller from this node.

The crucial decision is the ratio of the three resistors, as this will determine the output shift of the circuit. For our design, three *equal* 10 kΩ resistors were chosen, as this transforms the signal from -5 – 5V to 0 – 3.333V. Hence, the ADC only receives positive voltages.

It is worth noting that the actual resistance values are immaterial; it is only their ratio that determines the range of the outputted voltage. We chose relatively high resistances to avoid the possibility of exposing the sensitive ADC pin to excessive current.

3.1.2 Analog Measurement and Conversion

The NUCLEO-F446RE ADC has 12-bit resolution and a default reference voltage of 3.3V, which we increased to 3.333V to match the maximum voltage output of the level shift circuit. Therefore, the microcontroller will take any voltage between 0V and 3.333V and represent it with 12 bits of floating-point accuracy.

There exists a simple linear relationship between the input voltage and the output voltage, allowing us to infer V_{in} from the voltage read by the ADC. To three decimal places, the relationship is:

$$V_{out} = \frac{V_{in}}{3} + 1.666$$

Rearranging for V_{in} ...

$$V_{in} = 3 * (V_{out} - 1.666)$$

Using this relationship, the software maps back from the nodal voltage to the input voltage.

3.2 Design Implementation

3.2.1 Circuitry

As mentioned in Section 3.1, the voltage shift circuit is a remarkably simple configuration consisting of three equal resistors and a 5V supply.

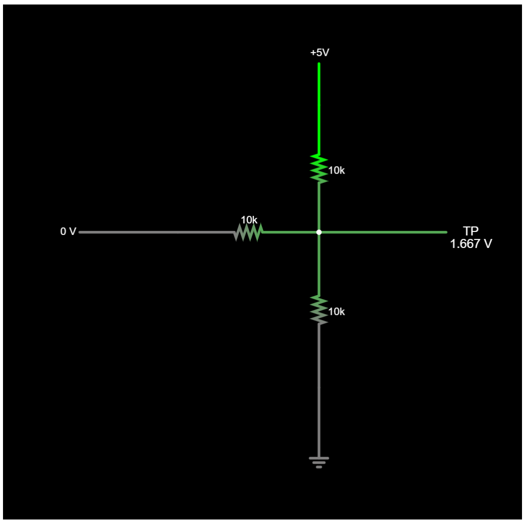

Figure 3.1: Circuit design for the voltage level shift

3.2.2 Hardware Specifications

- NUCLEO-F446RE microcontroller
- breadboard
- 3x 10 kΩ resistors
- 5V power supply
- wired connection to AnalogIn pin of microcontroller
- variable voltage supply (input), ranging from -5 – 5V

3.2.3 Code

Much like the physical circuit, the Mbed programme for the voltmeter is simple. The function will return a float representing the input voltage. Lines 5 and 6 set pin A3 to AnalogIn and configure the reference voltage of the built-in ADC as 3.333V. Line 8 reads in the nodal voltage using the ADC, and Line 9 uses the linear function described previously to calculate the input voltage. Line 10 attempts to account for error in the system by adding 30 mV to the result. Finally, the adjusted result is returned.
See Group_7_EE2011_Code_Doc, voltmeter.cpp, void get_voltage()

3.3 Results

The error of the voltmeter design varied between +/- 20 to 30 mV over the input range. These errors were exacerbated at the high and low limits of the range, likely due to nonlinear resistor behaviour within the ADALM2000 voltage supply.

Overall, the design exhibited high accuracy and surpassed performance expectations. Despite losing a small amount of resolution due to the compression of the input range into a smaller output range, these losses were largely compensated by the high resolution of the NUCLEO board's ADC.

3.3.1 Discussion and Conclusion

Though the voltmeter gave accurate readings within the required range, it is worth considering the implications of a larger input range. The aforementioned signal compression would lead to more significant errors due to limited resolution. Moreover, the ADC would be driven into saturation at the upper and lower ends of its range.

It is clear that, though this design is striking in it's simplicity, a more comprehensive approach would be required to achieve a more robust and accurate product. One possible approach is the use of an inverting op-amp to invert negative voltages. This design was considered in the course of our planning, but was rejected due to its relative complexity and the insufficient quality of available components (e.g.rail-to-rail op-amps only giving out 3.5V with a 5V supply).

Capacitance Meter - Fearghal

4.1 Design Principle

4.1.1 Principle of Operation

An RC circuit has a characteristic time constant $\tau = RC$. The voltage dropped across the capacitor can be modelled by the equation:

$$V_c = V_{in} e^{\frac{-t}{\tau}} \tag{4.1}$$

Therefore by measuring the voltage on the capacitor at a given time, with a fixed resistor, the capacitance can be determined using the following formula.

$$C = \frac{-t}{R \cdot ln(V_{in} - V_c)} \tag{4.2}$$

4.2 Design Implementation

4.2.1 Circuit Setup

Our circuit consists of a simple RC circuit with a known resistance and unknown capacitance. The input voltage is provided by a digital output pin. Initially it is held low and a timer starts when it is set to high. The output voltage is measured using an analog input pin at the positive terminal of the capacitor.

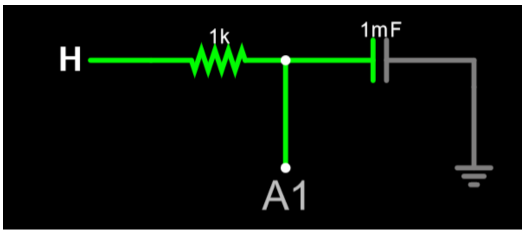

Figure 4.1: RC Circuit for capacitance meter

4.2.2 Choice of Resistance Value

A large resistance value was chosen in order to increase the size of the time constant. For low nanoFarad or picoFarad capacitors capacitors, choosing a resistor in the order of MΩ means that the time constant will be in the order of milliseconds. The exact resistance is measured using an LCR meter to ensure maximum accuracy. This is several orders of magnitude greater than clock speed of the microncontroller, which is in the order of MHz. A precise value can be gotten in the low nanoFarad range as a result.

4.2.3 Code Design Overview

The tradeoff of high resistance it takes a long time for high farad value capacitors to charge; in the order of minutes. Initially, the code was structured such that when the voltage reaches $0.632 * V_{cc}$ i.e. one time constant the program terminates and the calculation in equation 4.2 is performed. However, this led to very long program times for high capacitance.

Instead the code was structured such that it ran for 10ms and checks the voltage. If the voltage is greater than 0.1V, the calculation is done and the capacitance is outputted. Otherwise, the capacitor is left to discharge, and the duration of charge is increased by one order of magnitude.
At 10 seconds, the percentage error for high capacitance capacitors is quite low. Hence the loop terminates and even if the voltage drop is less tha 0.1V, the capacitance is calculated.
See Group_7_EE2011_Code_Doc, capacitance.cpp, void capacitance()

4.3 Results

Rated Cap. (F)	1n	10n	47n	100n	1μ	10μ	47μ	220μ
Measured Cap. (F)	1.1n	10.2n	43.2 n	84.8n	0.94μ	9.3μ	46.1μ	187.1μ
Accuracy (%)	94.34	98.23	91.87	84.76	93.6	93.1	98.04	85.1

Table 4.1: Measurement readings, and accuracy, for a range of capacitors varying from 1nF to 220μF

The capacitance meter was accurate to within 90% for values from the 10s of picoFarad range upwards. At low values, the time to get this reading was less than 1s.

The capacitor was able to measure any arbitrary capacitance to within approximately 90% . However, for values above approximately 100μF the time taken to measure capacitance using the above method was approximately 2 minutes and there was a slight decrease in accuracy due to higher initial capacitances. Efforts were made to put a hard cutoff at approximately 12 seconds, however at high capacitances error rates were up to 30%. At higher capacitances there was a slight increase in error, This was because the initial charge on higher capacitors was found to be greater.

Ohmmeter - Ian

5.1 Design Theory

5.1.1 Mathematically

The ohmmeter is built using an RC circuit that follows the same principle as the capacitance meter (see section 4.1). The final equation use as the base of the code is reorganised for a new purpose:

$$R = \frac{-t}{C \cdot log(1 - (V_{in} - V_c))} \tag{5.1}$$

Therefore by measuring the voltage on the capacitor at a given time, with a fixed capacitor, the resistance can be determined.

5.1.2 Application

The circuit makes use of the RC time constant by measuring the voltage and time while using a known capacitor to calculate the value of an unknown resistor in series with the capacitor.
See Group_7_EE2011_Code_Doc, resistanc.cpp, void resistance()

5.2 The Circuit

5.2.1 Parts Required

The parts required for the ohmmeter were:

Part Name	Amount Required
Nucleo F446RE	1
1mF Capacitor	1
An Unknown Resistor	1

Table 5.1: Ohmmeter Parts List

5.2.2 Diagram And Explanation

The circuit is set up the same way as in figure 4.1. The known capacitance was initially chosen to be 1mF to improve accuracy at lower resistances. However, it was later discovered through experiment that a 1μF capacitor provided a greater range. A digital output provides the voltage and the output is read using an analog pin.

5.3 Measurement Results

Rated Res. (Ω)	10	100	1k	10k	100k	1M	10M
Measured Res. (Ω)	30	79	930	9.1k	89.3k	870k	9.2M
Accuracy (%)	33.3	79	93	91	89.3	87	92

Table 5.2: Measurement readings, and accuracy, for a range of resistors between 10Ω and 10MΩ, using a 1μF capacitor for τ

Rated Res. (Ω)	10	100	1k	10k	100k	1M	10M
Measured Res. (Ω)	43.4	101.27	0.88k	8.9k	93.3k	680k	4.85M
Accuracy (%)	23.0	98.7	88.0	89.0	93.3	68.0	48.5

Table 5.3: Measurement readings, and accuracy, for a range of resistors between 10Ω and 10MΩ, using a 1mF capacitor for τ

It was experimentally determined that the 1mF capacitor gave poor results at high resistance. The time constant in the MOhm range becomes incredibly high - in the order of hours. As a result, cutting the time after seconds, or even minutes leads to massive percentage errors. The large time constant also means that any parasitic capacitances or resistances have a significant impact on the time constant. At low values of resistance, the real resistance of the capacitor makes it difficult to get accurate readings regardless of the choice of capacitor. Therefore the decision to try to increase tau to hedge for low values was unjustified and a smaller capacitor would be more appropriate.

5.3.1 Attempted Designs

Initially, an effort was made to build an ohmmeter based on the voltage divider. A series of BJTs would be used to switch between different known resistors to try to find a suitable known resistance to perform the calculation. The design is shown in figure 5.1. The design could not be successfully implemented, and it was decided to use the functioning code and setup from the capacitance meter in order to have a working ohmmeter, even if the range was compromised slightly.

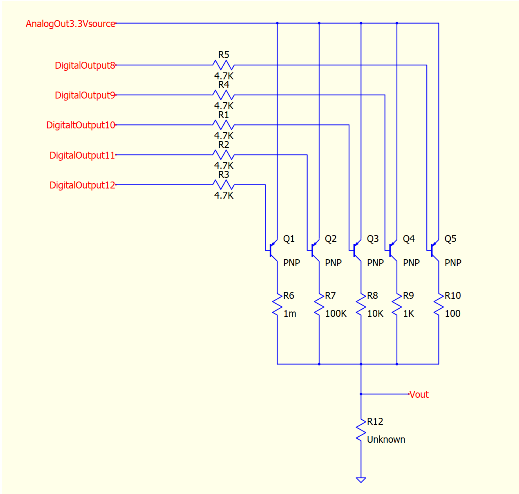

Figure 5.1: Ohmmeter Original design

5.3.2 Final Design

Although the ohmmeter did not work over the entire operating range, it provided accurate results over a several order of magnitude range and was easy to implement. If the user wanted to build an ohmmeter that works over a relatively small range, they can choose a suitable capacitor value and will get accurate readings for their resistor.

Health and Safety, Standards and Ethics

6.1 Relevant National/International Standards - Mark

The main source of components used for the project, the ADALP2000 parts kit, produced by Analog Devices, is marketed as being “RoHS Compliant”. RoHS, the “Restriction of Hazardous Substances in Electrical and Electronic Equipment”, is an EU directive to restrict the presence of substances hazardous to life, including “heavy metals”, “flame retardants” and “plasticizers.” [1] In particular, the directive seeks to prevent the escape of these hazardous materials into the environment, following the disposal of components at the end of their life cycle.

6.2 Life cycle - Ian

All components from the digital multimeter can be reused, as they can easily removed from the breadboard and returned to the ADALP2000 parts kit. The microcontroller can likewise be reused, resulting in a fully reusable implementation.

Since the components are RoHS compliant, once they are no longer fit for use, they can safely be disposed of with minimal environmental impact.

6.3 Health and Safety - Mark

In order to avoid damage to the components of the multimeter, it is advised that the consumption of food and drink in the vicinity of the multimeter is avoided. To avoid injury to the user of the multimeter, the user is advised to keep their hands away from the circuitry while it is in operation, in order to prevent electrical shocks, which could also damage the circuitry.

6.4 Ethics

6.4.1 Nucleo Board

Sustainability

STMicroelectronics, the manufacturer of the Nucleo-F446RE, outline in their Sustainability Charter [2] their commitments and goals for operating a sustainable business and production line. These include:

- Implementing a strategy for responsibly sourcing minerals, developing packaging materials that are free of hazardous substances, and by using 100% recyclable packing.
- Implementing an environmentally friendly design process for all products developed by their company since 2015.
- Continuously reducing direct emissions, with an intermediate goal of reducing emissions by 50% by 2025 compared to 2018, to be compliant with the 1.5°C scenario aligned with the COP21 Paris agreement.

6.4.2 ADALP/ADALM components and assembly - Ian

ADALP

The ADALP kit used to build the multi-meter circuits was manufactured in the Philippines. The Philippines is a source of cheap labour, where workers are often forced to undergo harsh working conditions to satisfy the demands of large multinational corporations. We were unable to find specifics about any factories employed by Analog Devices, so it is unknown whether they are contributing to the above issues and thus poses an ethical question about our use of these components.

ADALM

The ADALM device is manufactured in China, where working conditions have many similar issues to the Philippines when it comes to working conditions and therefore its use in the building and testing of our multi-meter could pose a similar ethical question over its use.

Appendix

7.1 Interface Design - Fearghal

7.1.1 Overview

In order to control the microcontroller a browser based user interface was developed. The design of the interface was a selector to choose which measurement to take, a button to request the measurement, and a display for the measurement.

7.1.2 Implementation

The backend for this application was written using javascript. It involved two functions. Firstly, communication over the serial port was done using the node serialport library. Secondly, an expressJS server was used to communicate with the frontend.

When the user presses the button to request the measurement, a POST HTTP request is sent to the backend containing the required measurement. A character representing the desired measurement is written to serial. The main function in the c++ code waits to read characters. Depending on which character it receives it executes the necessary function.

The POST endpoint waits for data to be written to the serial port. Once data is written, it then sends the data back to the frontend where it is displayed.

The interface was found to be easy to use, with very low latency and offering high control over which functions were to be operated.

Bibliography

[1] European Parliament (2011) - *Directive 2011/65/EU*
https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32011L0065

[2] STMicroelectronics - *Sustainability Charter*
https://www.st.com/resource/en/corporate_brochure/ST_Sustainability_Charter.pdf