Technische Universität München

Lehrstuhl für Bioverfahrenstechnik

Semesterarbeit

Development of a Low-Cost Electrical Conductivity Meter for Liquids

Sebastian Plamauer

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Betreuer: M.Sc. Timm Severin
Prof. Dr.-Ing. Dirk Weuster-Botz

Selbstständigkeitserklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbstständig verfasst und keine anderen als die angegebenen Hilfsmittel verwendet habe.

Ort, Datum	Unterschrift

Abstract

Contents

1. Introduction

Fossil fuels play a large role in the worlds energy production and as energy source for transportation vehicles. Especially for vehicles, their high energy density and liquid form at room temperature enabled the construction and operation of cars and airplanes otherwise not possible. At the same time, there are fundamental problems in using fossil fuels as energy source. Be it oil, coal or gas, the formation of these resources is a natural process spanning millions of years. This means that once the current reserves are depleted, they will not be refilled. And even without depleting all the reserves, the depletion of the easily reachable reserves means that ever greater effort has to be taken to find and use less accessible fields, using methods with severe impact on the environment. In addition to that, burning fossil fuels for energy also releases a slew of gases in the atmosphere, of which CO2 is the most prominent. CO2 is a greenhouse gas and as such influences the worlds climate tremendously.

In light of those problems, renewable energy sources are needed. For electricity production there are a some attractive technologies already in use that directly or indirectly generate power using the sun. For vehicles, using electrical power can be problematic. The electricity has to be stored in batteries, and even with the higher efficiency of electrical motors, the lowered energy density reduces range drastically. Batteries also have to be charged, as opposed to be refilled like tanks, which takes substantially more time. While for some vehicles, like cars, this technology still can be made feasible, it is much less suitable for airplanes.

For these application a more direct replacement for fossil fuels has to be found. A possible solution are bio-fuels. Bio-fuels are generated from bio-mass, for example plants. An important requirement for the growing of bio-mass to process to bio-fuel is to avoid competition over land and resources with food production. A low price is also important to make the process economically viable.

One technology to potentially fit these needs are open photobioreactors growing algae. The algae produces lipids, which can be processed to fuel. To improve and optimize these reactors experiments and models are needed, among those is a computer fluid dynamics (CFD) simulation. In order to validate the simulation, experiments have to be conducted where the flow conditions in the reactor have to be measured. To do so, a sensor system needs to be developed. The next chapter details the objectives and criteria of this system.

2. Objectives

The goal of this project is the development and test of a low-cost electrical conductivity meter for liquids to be used as an aid to measure and analyze the flow in a photobioreactor.

The method chosen beforehand was to measure the fluids electrical conductivity, which can be changed easily by adding water with differing salt concentrations. Commercially available conductivity meters are built to measure with high accuracy in order to obtain information about a liquids absolute salinity and are relatively expensive. Our use case however does not need to create high accuracy absolute measurements, but measure a relative change allowing to distinguish two different liquids by their salinity. However, this needs to happen very fast and at a lot of different points in the stream. The more positions measured, the more complete the picture of the flow becomes. Therefore, the cost per sensor has to be low, to not put a restraint on the total number of points that can be measured.

The actual flow analysis is not part of this work, but rather the creation of a tool to make it possible. As such, the system needs to be designed to be used by others, not the creator himself. This thesis therefore describes a product development process rather than a scientific study.

The following sections describe and detail the requirements the sensor system has to fulfill in order to meet the objectives. These requirements translate the objectives into discrete and verifiable units, serving as the base for development and benchmark for the later performance analysis.

2.1. Spacial and Time Resolution

The spacial resolution $\mathrm{d}s$ and the time resolution $\mathrm{d}t$ decide the granularity of the flow image. Both resolutions are connected by the velocity v of the stream flowing over the sensor as shown in equation (5.1).

$$v = \frac{\mathrm{d}s}{\mathrm{d}t} \tag{2.1}$$

With both resolutions connected, only one of them has to be defined.

The information gathered by the sensor has to be granular enough to enable the verification of the simulation. As it is not possible to derive a hard number from that, the following list shows different deliberations to establish a first estimate.

- The granularity of the simulation is determined by the mesh size and is in the order of about 1 mm to 5 mm. A resolution better than that would be unnecessary, making this the lower limit.
- The data collected by the sensor system shows salinity of the liquid passing a certain position over time. By extracting the same data from the simulation, a graph can be compiled comparing the measured to the simulated values. The flow becomes visible when comparing data from different positions. The first sensor to show a spike in salinity is further up the stream then sensors spiking later. The distance between two sensors has to be big enough for a given velocity of the stream so that the time delay can be clearly seen. At a flow speed of v in the order of 1 m/s, a resolution in the order of centimeters would yield time differences of hundredths of a second. Whether or not this is sufficient depends on noise and delay in the sensor system, however hundredths of a second is a conservative estimate likely to be achieved.
- The geometry of the forebay as shown in figure 2.1 also influences the needed resolution. It has to be an order of magnitude smaller as the basins characteristic length, in this case the width of 850 mm, to enable gathering data about the flow conditions within.

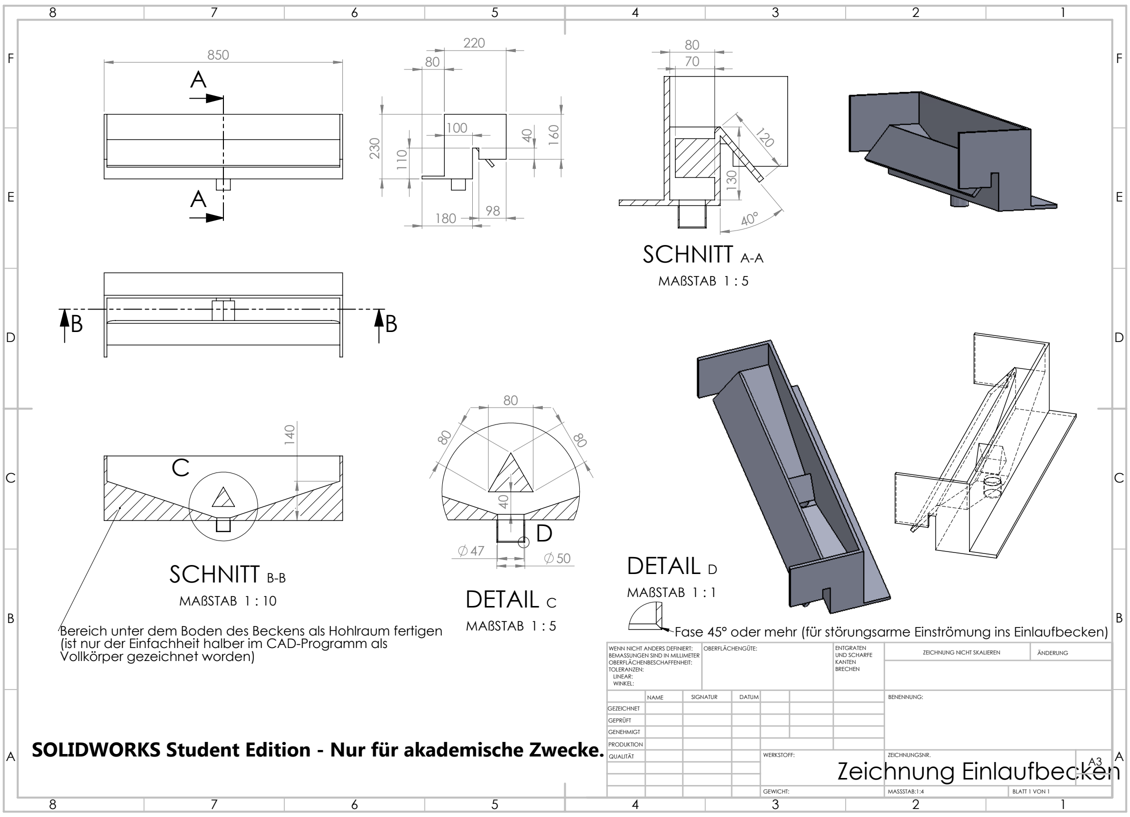

Figure 2.1.: Forebay

Derived from all that, a spacial resolution in the order of centimeters is chosen as requirement.

2.2. Electrical Conductivity Resolution

To measure the arrival of the new water stream after switching the water feed, the system has to be able to distinguish between water with different salinity. The water used normally in the reactor is tap water with a salinity of about 0.2 %. The salinity of the added saltwater can be chosen freely. Water with a salinity of about 5 % is easily available in the facilities and offers a sensible choice. Assuming a reactor with 65 l in circulation and an added saltwater impulse of 5 l, the resulting salinity after perfect homogenization would be approximately 0.5 %. The system has to be able to clearly distinguish between all those salinities. The sensors sensitivity therefore shall be better than 0.1 % salinity with a range from 0 to 5 %.

2.3. Cost

The more sensors used, the more points in the stream can be measured and the better the image of the stream gets. Therefore, the cost per sensor has to be low enough to not be prohibitive of adding more sensors. The cost of a high quality lab conductivity meter is in the range of €1000 and was set as the goal of maximum cost for the sensor system. The number of sensors needed to cover all interesting regions of the bioreactors is about 40. A maximum cost per sensor of €25 results from those figures.

2.4. Usability

The sensor system is meant to be used in the algae reactors of the algae cultivation center at the Ludwig Bölkow Campus. It has to be possible to easily mount and remove the system to and from the reactor without having to dismantle it.

The system also has to be easy to use, so it can be helpful to the researchers working on the reactor. It has to work reliably and act according to expectations of the users. The chance of handling errors that lead to loss of data has to be minimized. All operations have to be documented in a minimal set of written instructions, so the system can still be used even if the designer isn't available anymore.

Table 2.1.: Requirements

Nr.	Requirement	Verification
1	The system shall have a spacial resolution in the order of 1 cm.	Inspection
2	The system shall have a sensitivity of 0.1 % salinity.	Test
3	The system shall have a range from 0 to 5 % salinity.	Test
4	The cost per sensor shall be less than €25.	Analysis
5	The system shall be deployable in the algae reactor.	Demonstr.
6	The system shall be usable with a minimal set of written instructions.	Test, Review

3. Background

In this chapter a theoretical background of electrical conductivity measurement will be established. After that, a market research takes a look at the commercially available solutions of sensor systems and parts that could be used to develop one.

3.1. Theoretical Background

The following section is translated and summarized from the books [7] and [6].

The conductivity κ is the ability of a certain volume of a substance to conduct electricity. It is measured in the unit $^{\mathrm{S}}/_{\mathrm{m}}$ and is a specific parameter normalized to the length and cross section of the volume. Conductivity in a liquid is depended on ions as charge carrier and can therefore be used to measure concentration of such. Temperature plays a large role in the mobility of the ions and thus influences the conductivity.

To better understand conductivity, an equivalent circuit diagram, shown in figure 3.1, of an electrode system, shown in figure 3.2, can be used. This method is called conductometry. In this measurement configuration, two electrodes are submerged in the liquid to be measured and a voltage is applied. The resistance R of the substance is determined by measuring the potential drop U_R given a constant voltage U, current I and internal resistance R_i.

The resistance R is

$$R = \frac{U_R}{I} \tag{3.1}$$

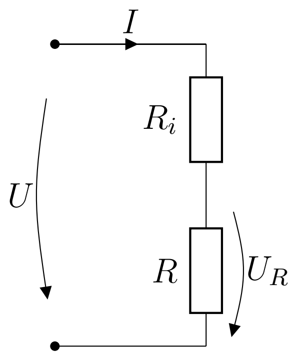

Figure 3.1.: equivalent circuit diagram

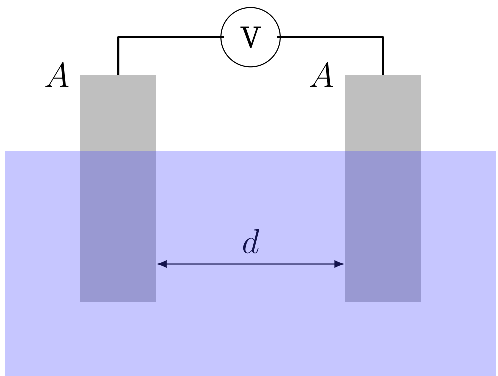

Figure 3.2.: electrode configuration

The inverse of the resistance R is the conductance G

$$G = \frac{I}{U_R} \tag{3.2}$$

Considering the cell constant C yields the conductivity

$$\kappa = G \cdot C \tag{3.3}$$

The cell constant C depends on the geometry of the sensor

$$C = \frac{d}{A} \tag{3.4}$$

where d is the distance between and A the surface area of the electrodes.

In electrolytes, the electrical conduction is a result of mass transfer, where ions are carrying the charges. If the measurement is conducted with direct current, this mass transfer leads to changes in the measured solution and the electrode surface, negatively impacting the measurement. Furthermore, polarization effects create additional resistance, leading to lower than actual results. To avoid this, alternating current is used. The fast, periodical swap of polarity eliminates the net mass flow and it's effects. Polarization is a result of the current flowing through the electrode, thereby its effects can be minimized by minimizing this current. One method to do this is replacing the two-electrode-cell with a four-electrode-cell. This separates the current flow from the potential measurement by using one electrode pair to apply the current, and a separate pair to measure the potential drop.

The electrolytes temperature has a big influence on the conductivity and has to be taken in account when comparing two measurements. If the temperature T is known, the conductivity at that temperature κ_T can be normalized to a reference temperature T_{ref} using equation (3.5), resulting in the reference conductivity κ_{ref}.

$$\kappa_{ref} = \kappa_T \frac{1}{1 + C \cdot (T - T_{ref})} \tag{3.5}$$

The temperature coefficient C assumes a linear correlation and is only valid in a narrow temperature range. For bigger ranges the denominator can be replaced with a polynomial using higher order coefficients, resulting in equation (3.6).

$$\kappa_{ref} = \kappa_T \frac{1}{\sum_{i=0}^{n} C_i \cdot (T - T_{ref})^i} \tag{3.6}$$

3.2. Market Research

Conductivity meters can be readily bought and range from prices of over €1000 for lab equipment [4] to €100 for simple field water quality monitors [5]. Even cheaper water quality testers from no-name manufacturers can be found for as little as €10 from online vendors.

Figure 3.3 shows a field conductivity meter from a quality manufacturer as example for the typical traits most available solutions share:

- a single electrode pair
- a display to report measurements
- designed to perform singular reads with high quality

While field conductivity meters have the electrodes integrated to form one compact device, the more expensive lab equipment often has the electrodes attached to the device with a cable, allowing for a more flexible use.

A different option was found in the MinieC I2C eC interface from Sparky's Widgets [3]. The MinieC interface is an Open Hardware project providing a conductivity sensor that easily interfaces with a microcontroller, licensed under Creative Commons. This license means that the schematics, CAD files and software are available, granting the user the right to modify and build custom versions of the board, as long as the original creator is attributed and the modified material itself is also released under the same license [1]. Ready-made boards can be purchased for about €25.

The design approach is also more modular than that of the more professional equipment. The MinieC offers an interface to connect external electrodes and can be controlled and read by a microcontroller.

Figure 3.3.: Fisher Scientific™ Traceable™ Salinity Meter Pen [5]

4. Design

This chapter describes the design of the sensor system and all components involved. The system consists of several parts playing different roles. The System Design gives an overview of these parts, their purpose and their communication with each other. Afterwards, these subsystem are described in detail.

4.1. System Design

On the user-facing side there is a personal computer (PC). This PC runs software that visualizes a live data stream and provides a control interface for the sensor system. It is connected via USB to a microcontroller. This microcontroller controls the MinieeC interface via I2C, reads the measurement data from it and sends it to the PC. It also controls the matrix switches. The MinieC Interface provides the signal and ground between which the resistance is measured. Both lines are connected to one matrix switch each. These matrix switches are able to connect one input to 8 different outputs. On each of those outputs, one electrode is connected. The matrix switches can thereby connect the MinieC interface to one of 8 electrode pairs.

Using the matrix switches, 8 electrodes can be used with just one MinieC interface. Increasing the number of electrodes can be done in two ways:

- by chaining up multiple stages of matrix switches, the number of electrodes can be increased eightfold with each stage
- by connecting another MinieC Interface with it's own set of matrix switches to the microcontroller, 8 more electrodes can be added with each of these subsystems

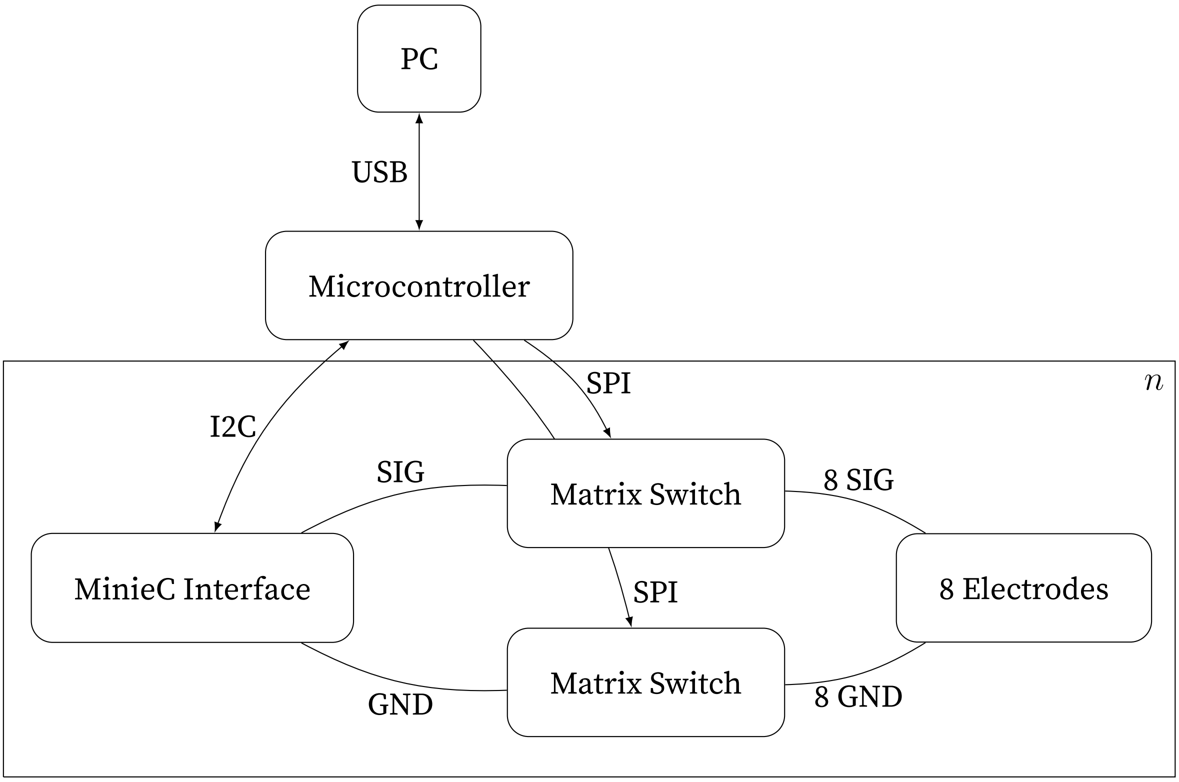

Figure 4.1.: System Design

The first option results in lower cost per added electrode, as the MinieC interface is reused. However, with a system like that, all electrodes have to be read in serial, while with the second option each MinieC interface can read in parallel, resulting in higher sample rate. Practically the second option is also easier to achieve. For the first option, a board with 18 matrix switches and 80 connections is needed, while the second option only uses 2 switches per board resulting in 16 connections. The simpler board greatly reduces complexity and can also be made smaller.

4.2. Electrodes

The electrode pairs are the actual sensors in contact with the fluid to be measured. Their material and geometry influence the measuring range of the system. According to information in the book [7] a cell constant C of 1 enables a range from $2 \cdot 10^3$ $\mu S/\text{cm}$ to $10 \cdot 10^3$ $\mu S/\text{cm}$. For a water temperature of 18° C this corresponds to salinities of

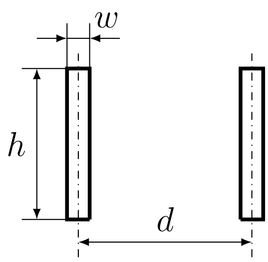

Figure 4.2.: Electrode pair forming a sensor

0.66 % and 0.12 %. While this theoretical range is not sufficient for our purpose, first tests showed that the achievable range is much bigger than described in the book. The book doesn't specify the materials influence on the range and it also doesn't qualify how the usable range is defined. As our application has much lower demands on accuracy as the usual ones, this might be an explanation for the discrepancy.

Figure 4.2 shows the geometry of the sensor. To achieve a cell constant C of 1, a width w of 1 mm, height h of 10 mm and distance d of 10 mm were chosen.

As a first proof-of-concept a the sensor was built as a sensor array, containing multiple electrode pairs on a strip 4.3. A 5 cm wide and 25 cm long band of Kapton adhesive tape served as the base. 4 electrode pairs made from 0.2 mm platinum wire were arranged equidistant on the strip. 0.4 mm enameled copper wire runs along the tape to connect each electrode pair to the left end of the strip, from which insulated cables run to the sensor node. After soldering the joints, two smaller strips of tape were used to cover the wiring, exposing only the electrodes to fluid.

First tests with this sensor array showed the viability of the concept, however a simple look at it shows the inherit problems. Instead of a uniformly flat strip with minimal influence on the flow, the assembly forms several irregularities. Soldering 0.2 mm platinum wire to 0.4 mm enameled copper wire on a piece of adhesive tape per hand also did not result in clean solder joints. And while with the experience of the first array, the second array turned out a bit cleaner, the fundamental problem remains: it is a tedious manufacturing process resulting in a low quality product.

As an alternative to these handmade strips, industrially produced Flex-PCBs were

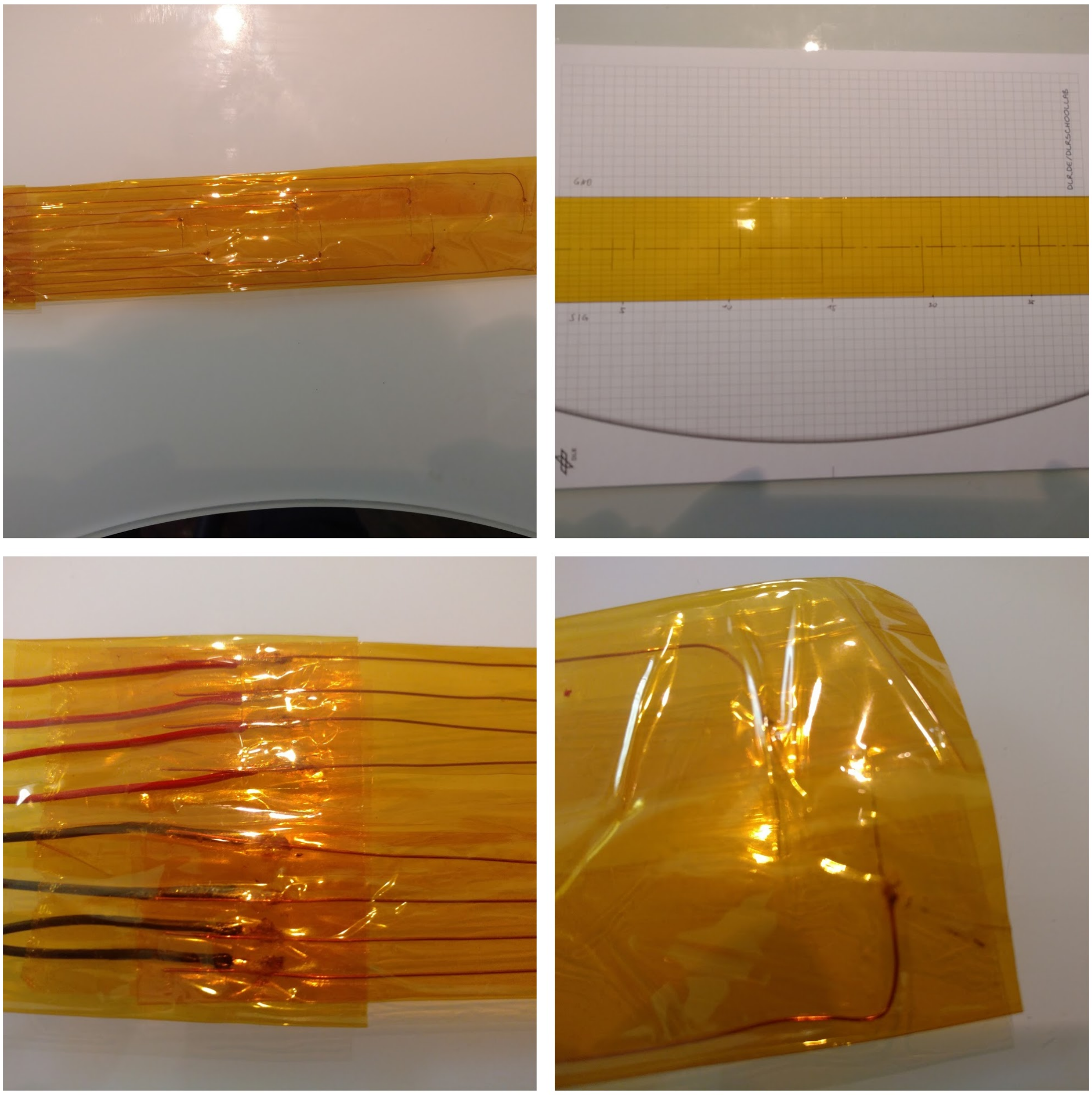

Figure 4.3.: Handmade Sensor Strip

Figure 4.4.: Design of FlexPCB

identified. Flex-PCBs are flexible printed circuit boards that are very close to the handmade arrays described above. They also use Kapton as base, on which a copper coating gets applied and partially removed by etching to form the conducting paths. On top, another layer of Kapton is applied, with cutouts in the places where the copper is supposed to be exposed. The exposed copper is then plated with ENIG (Electroless nickel immersion gold) to protect the copper from oxidation and provide the landing pads for electrical components to be soldered on.

For our purpose those exposed and plated landing pads can be used as electrodes, being nicely embedded in a FlexPCB that also runs the wiring up to an interface from where cables can be run. Using the FlexPCB itself as cable is not viable due to the high cost per area.

The cables are soldered directly to the PCB and silicone is used to create a waterproof seal around the connection.

4.3. Matrix Switches

The matrix switches are an essential part of the system, enabling it use multiple sensors with a single MinieC Interface, thus lowering the cost per sensor. The part used is an ADG738 from Analog Devices. It is an 8-channel CMOS analog matrix switch controlled via a 3-wire serial interface. The following information is taken from the data sheet [2].

Figure 4.5 shows the functional block diagram. The switch has one drain pin (D) and 8 source pins (S1..S8). Despite the naming of drain and source, the internals provide simple switches between the drain and each source pin. The switches work in both directions without any restriction on the signal beyond a maximum current of 120 mA

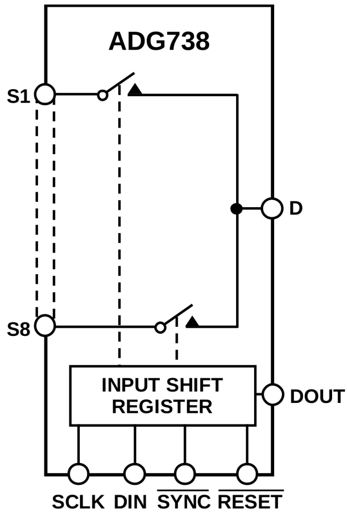

Figure 4.5.: Functional block diagram of ADG738

that far exceeds our needs. By sending control commands via the 3-wire interface, each of the 8 internal switches can be turned on and off individually.

The example timing diagram 4.6 describes the data transmission process. The microcontroller sends one byte of data to the matrix switch. Each of the 8 bits of this byte controls one switch. The first bit controls the first switch and so on. If the bit is 1, the switch is closed, if 0, the switch is open. To send the byte, first the synchronization pin (SYNC) has to be pulled low from it's usual high level. A clock signal is provided to the clock pin (SCLK). At each falling edge of the clock signal, the data input (DIN) is read - where high leads to a 1-bit and low to a zero-bit. After 8 cycles, SYNC is pulled high again marking the end of data transmission with a full byte transferred. After that, the switches immediately take their instructed states with switching times in the order of 100 ns. In the example shown, the first switch is on, while all others are off.

Multiple matrix switches can be controlled at once by daisy-chaining the data output pin (DOUT) of the first device to DIN of the second one, and on so forth. Both SYNC and SCLK are connected to the same bus. This assures that all matrix switches are set in the same state and at the same time.

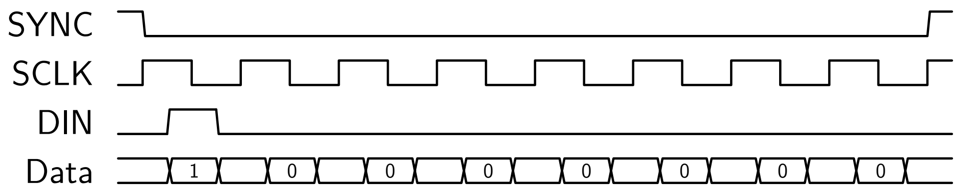

Figure 4.6.: Timing diagram

4.4. MinieC Interface

The MinieC Interface contains the electronics to perform the resistance measurement. It contains sever parts used to generate an electrical signal, run it through a circuit in which the liquid to be measured serves as a resistor and measure the voltage drop over it.

The first part is a TPS6040 charge pump voltage inverter. It's purpose is to generate a negative output voltage from a positive input. This negative voltage and the positive voltage are needed to drive a Wien bridge oscillator. This oscillator outputs a sine wave voltage oscillating between the positive and negative input voltage. This whole first stages purpose is to generate an alternating current to be used in the measurement, avoiding polarization effects describe in the background chapter.

The AC signal provided by the first stage is then fed into an OpAmp. An OpAmp is a part that has two input signals and one output, where the output is proportional to the difference of the input signals. In our use case, the OpAmp's output is pulled to ground via a voltage divider. The first resistor R_i in the divider is fixed, while the second one R is the liquid to be measured. The output voltage of this divider is depended on the liquids resistance. This voltage is then fed back into the second input of the OpAmp. Via this feedback, the output (OUT) of the OpAmp is now the input signal (SIG) modulated in amplitude by the resistance of the liquid.

In the last step, the modulated output is amplified in two stages, and the measured by an analog-digital-converter (ADC). The ADC measures the voltage and provides the measurement to the microcontroller via I2C.

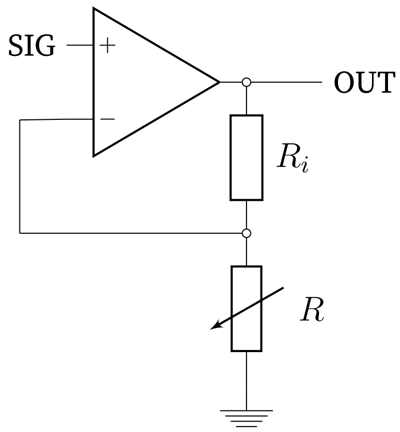

Figure 4.7.: OpAmp

4.5. Microcontroller

The Data Processing Unit has to be able to control the functions of the sensor nodes attached to it, read the data from them, log it and serve it to the user-interface. Typically, any micro-controller is is fit for those tasks. Micro-controllers usually are programmed in C or C++, however nowadays there are other options, too. One of those is Micropython, which is an implementation of the Python 3 programming language designed to run on micro-controllers. Python is a vastly easier language than C/C++, and this is especially true when the involved persons are not from a computer science or electrical engineering background, but i.e. mechanical engineering or other sciences. In those fields, Python is often familiar from usage for data processing and visualization. Using Micropython enables us to design a system where it is more likely that the people using it are able to understand the code, enabling them to improve it and adapt it to alternate use-cases. It does however limit our choice of Hardware to supported platforms and it requires more powerful and thereby expensive micro-controllers. But as the system only requires one Data Processing unit to drive a very large amount of sensors, the added cost is relative and outweighed by the benefits of the better usability. While the factor of the expensive controllers to cheaper ones is about 10, the cost in the end is still only about €7. For prototyping, a development board named ”Espruino Pico” was chosen. It is a very small and simple board that provides the electrical boilerplate to use a micro-controller without needing to deal with the lowest level of electronics, like cleaning power supply, etc.

4.6. User-Interface

5. Results

The velocity v of the stream flowing over the sensor is approximately 1 m/s. This allows us to create a relation (5.1) between the spacial resolution $\mathrm{d}s$ and the time resolution $\mathrm{d}t$.

$$v = \frac{\mathrm{d}s}{\mathrm{d}t} \tag{5.1}$$

For example, a spacial resolution of 1 cm would require a time resolution of 0.01 s. However, this assumes the size l of the sensor and the time τ a measurement takes to be infinitesimal small, while in reality it is not. While the sensors measures, the flow continuous and instead of measuring the conductivity of a certain volume at a certain time, an average is measured. Figure 5.1 visualizes this issue.

To accommodate for that, factors n (5.2) and k (5.3) are introduced, describing the ratio of the resolutions to the actual sizes.

$$n = \frac{l}{\mathrm{d}s} \tag{5.2}$$

$$k = \frac{\tau}{\mathrm{d}t} \tag{5.3}$$

Inserting k and n in formula (5.1) yields

$$v = \frac{\mathrm{d}s}{\mathrm{d}t} = \frac{k \cdot l}{n \cdot \tau} \tag{5.4}$$

The ratio r

$$r = \frac{k}{n} \tag{5.5}$$

is the ratio of the time it takes a control volume to enter and leave the sensor area to the time a measurement takes. To avoid a smearing of the measurement over multiple

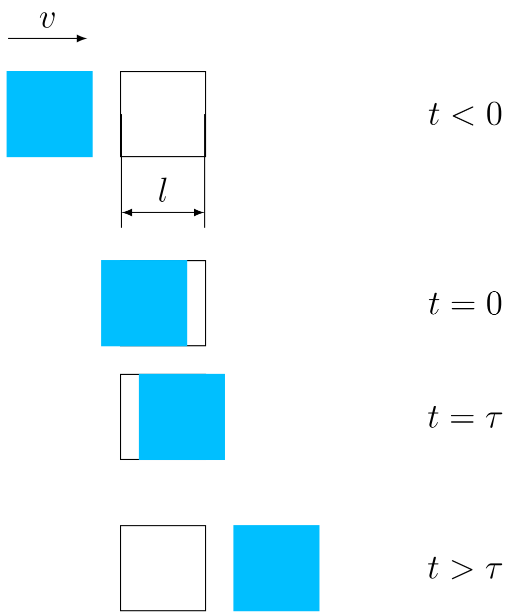

Figure 5.1.: control volume moving over sensor

control volumes, r should be 10. This can be achieved with a sensor that has a size l of 1 cm, and a measurement time τ of 1 ms.

5.1. Verification

Test for each requirement.

5.1.1. Time Resolution

Test if smaller then 1 ms.

5.1.2. Spacial Resolution

Inspect if smaller then 1 cm. [physical size of sensor is 1 cm, sensor can be directly next to each other. show via drawing]

5.1.3. Electrical Conductivity Resolution

Test if able to distinguish liquids with a conductivity of 5 S/m and 5e-3 S/m.

5.1.4. Cost

Analyse if less than €10 per sensor.

5.1.5. Deployment

Demonstrate that deployable in the algae reactor.

5.1.6. Usability

Test if easy to use by anybody with only a minimal set of written instructions. [find a victim to try to perform a measurement with only written instructions provided]

5.2. Validation

Check, if Timm can use it to measure flow and compare with simulation. [?]

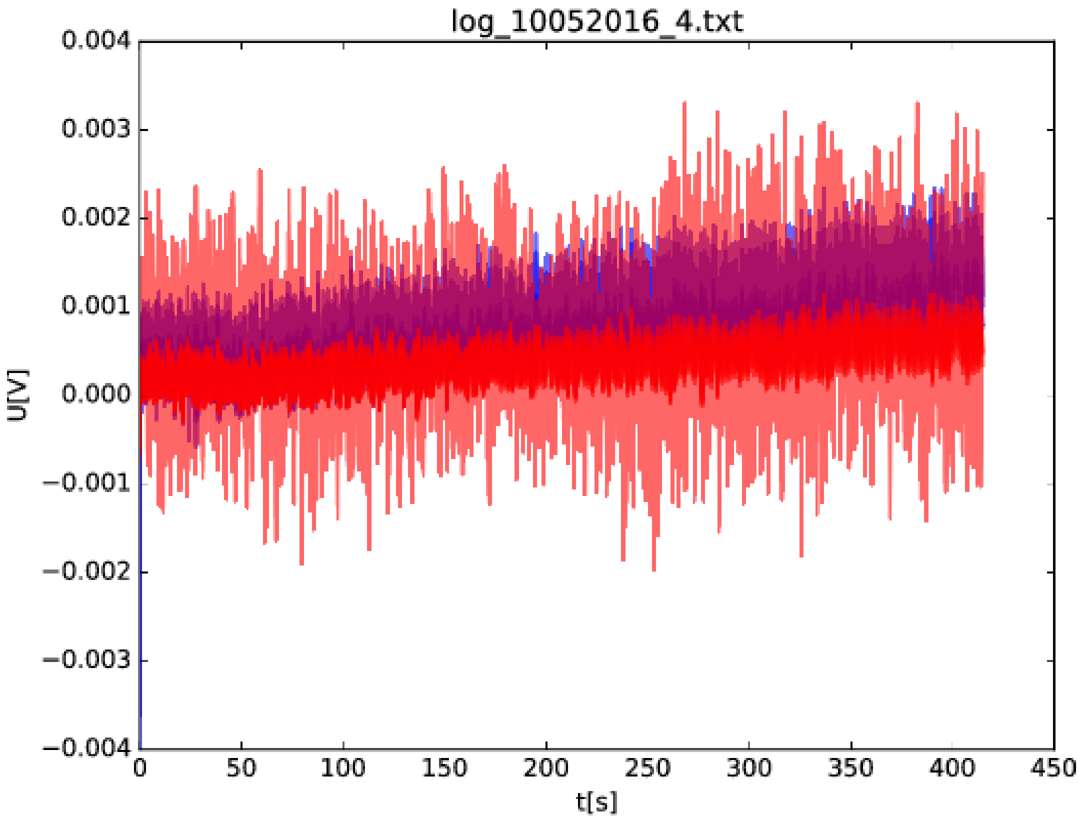

Figure 5.2.: noise

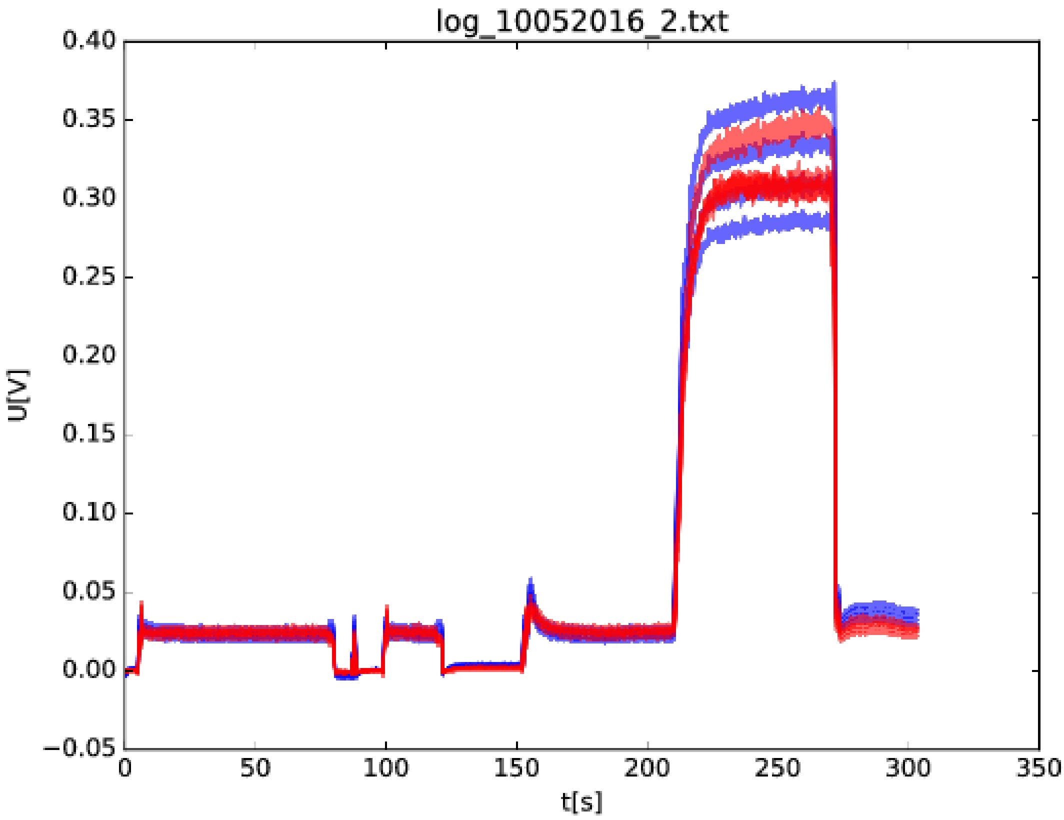

Figure 5.3.: feed switch

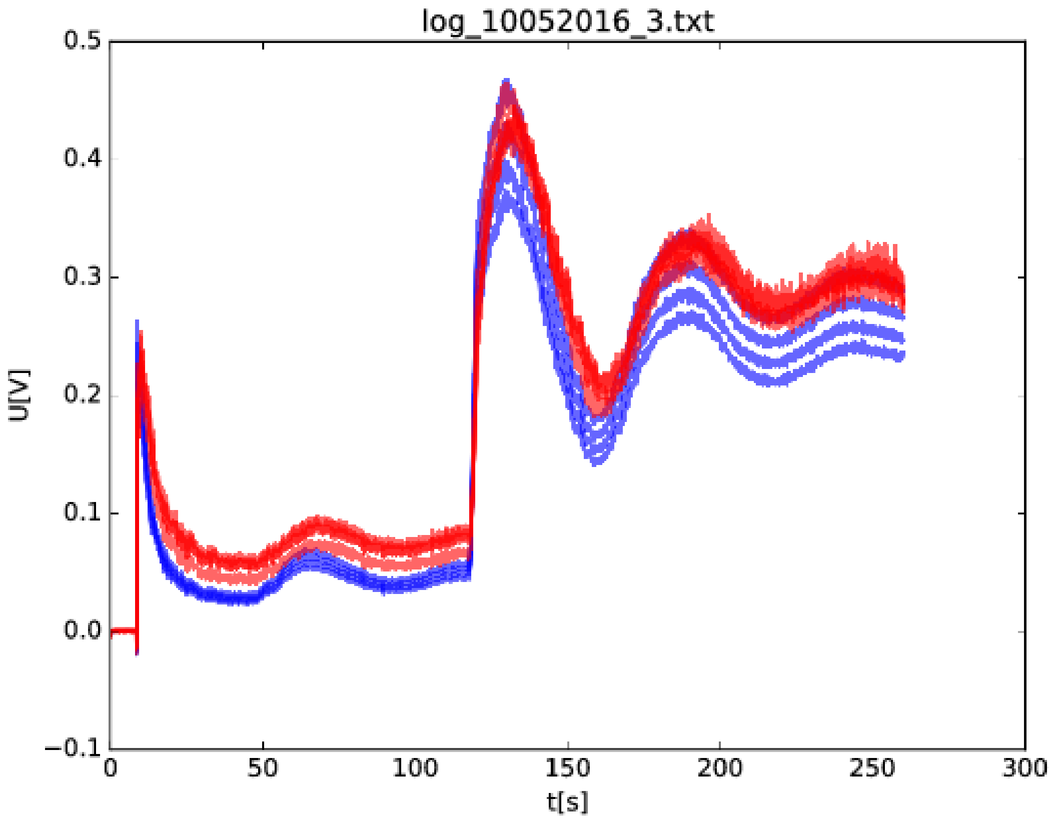

Figure 5.4.: feed add

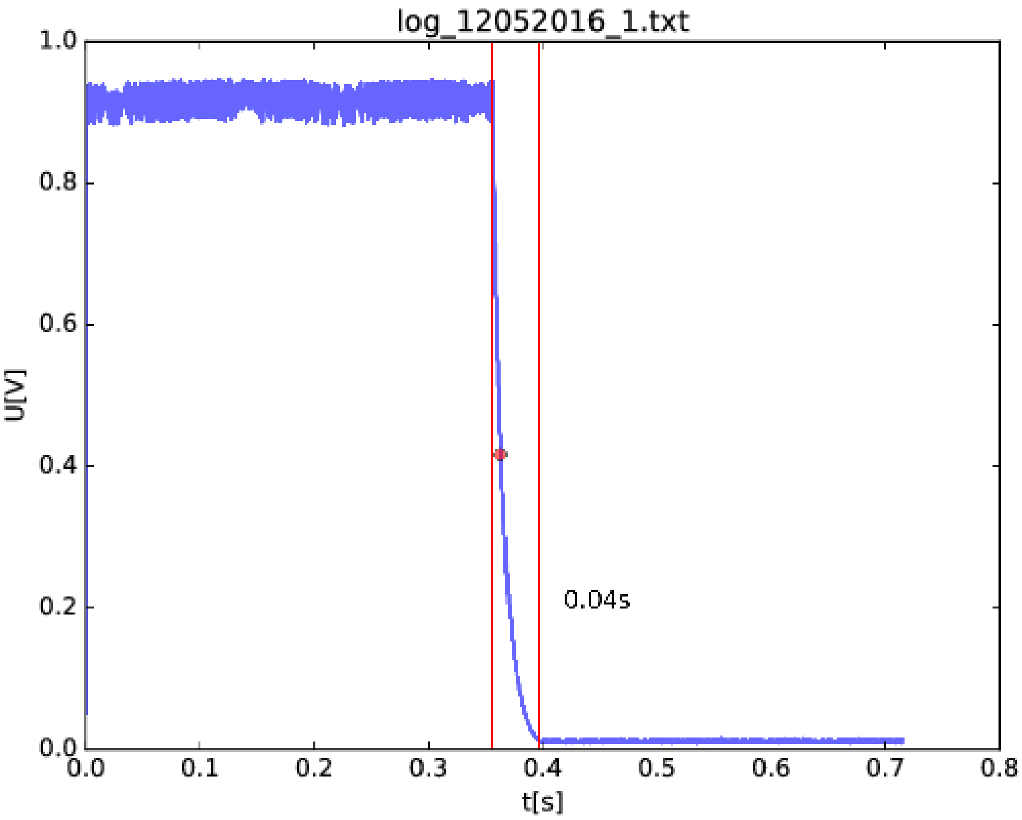

Figure 5.5.: switch cap

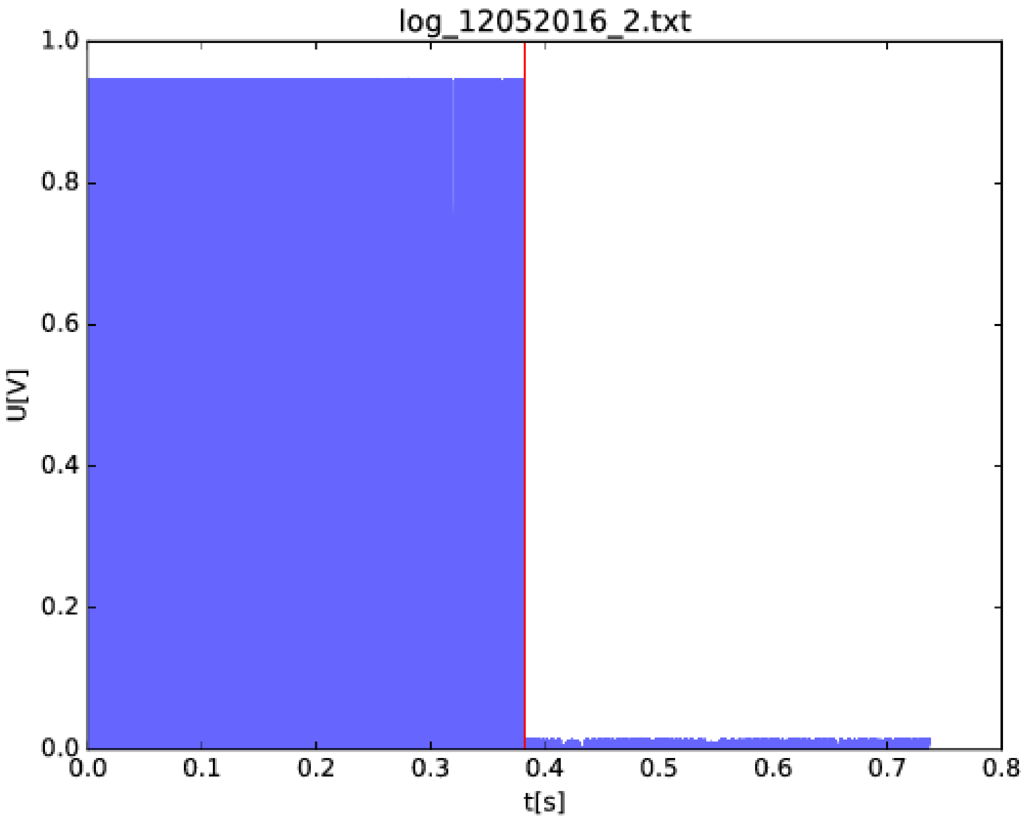

Figure 5.6.: switch no cap

6. Conclusion

The conclusion is it works.

Appendix

A. Abbreviations

CFD	Computational Fluid Dynamics
PBR	Photobioreactor

B. List of Figures

C. List of Tables

D. Bibliography

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