Technische Universität München

Lehrstuhl für Bioverfahrenstechnik

Semesterarbeit

Development of a Low-Cost Electrical Conductivity Meter for Liquids

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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

65% of the worlds energy is produced using fossil fuels []. Those fuels have to main problems: they are not renewable, meaning that the resources might be depleted one day, and they have a negative CO2-balance [], resulting in a green house effect that changes the climate of the world[].

Due to this problems, alternatives are needed. Renewable production of energy using wind or solar combined with energy storage in batteries is a promising method already in use, but it can not replace fossil fuels in all situations. Generating biofuels from biomass allows for a direct replacement of fossil fuels, keeping all their benefits while still being renewable and C02 neutral. However, biomass production for fuel is not to compete with food production [...] .

One method to generate biomass without competing with food production is to grow algae in photobioreactors.

This photobioreactor is used to grow algae that produce lipids from carbon dioxide via photosynthesis. These lipids can be processed to biofuel and other oil-derivatives, replacing crude oil as precursor. In order to be economical viable, the reactor has to feature minimal investment and operating cost.

This means open bioreactors that would be located in regions where conventional farming isn't possible. By using saltwater there would also not bee competition for freshwater [?].

To better develop, compare and optimize different reactor concepts, a computational fluid dynamics model is being developed. In order to validate this model, and to generate data to feed into it, the real flow conditions in an actual reactor have to be studied. The scope of this work is the development and test of a sensor system to make that possible.

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.

This photobioreactor is used to grow algae that produce lipids from carbon dioxide via photosynthesis. These lipids can be processed to biofuel and other oil-derivatives, replacing crude oil as precursor. In order to be economical viable, the reactor has to feature minimal investment and operating cost.

To better develop, compare and optimize different reactor concepts, a computational fluid dynamics model is being developed. In order to validate this model, and to generate data to feed into it, the real flow conditions in an actual reactor have to be studied.

The scope of this work is the development and test of a sensor system to make that possible. 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 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.

2.1. Requirements

The method to explore the flow conditions in the bioreactor used in this project is to measure the conductivity of the flowing water on multiple points with a high frequency. The conductivity is then changed by adding saltwater to the streaming freshwater, or by replacing the freshwater feed with a saltwater feed. The sensors then measure the increase in conductivity, signaling the arrival of the saltwater at certain positions. By mapping out the positions and the conductivity over time, an image of the flow can be generated. To get a usable image of the flow, the system has to meet certain requirements, which are described in this section.

2.1.1. Spacial and Time Resolution

The spacial and time resolution decide the granularity of the flow image.

The flow speed v of the stream is approximately 1 m/s. This allows us to create a relation 2.1 between the spacial resolution $\mathrm{d}s$ and the time resolution $\mathrm{d}t$.

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

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. To accommodate for that, factors n 2.2 and k 2.3 are introduced, describing the ratio of the resolutions to the actual sizes.

$$n = \frac{l}{\mathrm{d}s} \tag{2.2}$$

$$k = \frac{\tau}{\mathrm{d}t} \tag{2.3}$$

$$v = \frac{\mathrm{d}s}{\mathrm{d}t} = \frac{k \cdot l}{n \cdot \tau} \tag{2.4}$$

Using 1 for n and 0.1 for k results in a sensor that has a size l of 1 cm, and a τ of 1 ms. This ensures that the time for a measurement is only a tenth of the time it takes a control volume of fluid to flow over the sensors, as shown in 2.1 , avoiding a smearing

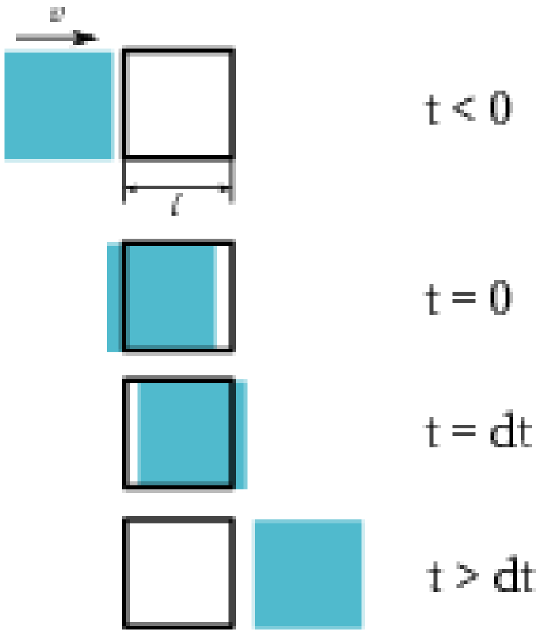

Figure 2.1.: Control volume moving over sensor [redo in tikz]

of the measurement over multiple control volumes.

2.1.2. 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 5e-3 S/m. The salinity of the added saltwater can be chosen freely. Sea water has a salinity of about 5 S/m and offers a sensible choice. [sources for salinity]

2.1.3. 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. [Why 10 bucks?]

Nr.	Requirement	Verification
1	The system shall have a time resolution of 1 ms.	Test
2	The system shall have a spacial resolution of 1 cm.	Inspection
3	The system shall cost less than €10 per sensor.	Analysis
4	The system shall be deployable in the algae reactor.	Demonstr.
5	The system shall be able to distinguish liquids with a conductivity of 5 S/m and 5e-3 S/m.	Test
6	The system shall be easy to use by anybody with only a minimal set of written instructions.	Test, Review

Table 2.1.: Requirements [nicely colored table vs. standard table?]

2.1.4. Usability

The sensor system is meant to be used in the algae reactor in the algae lab at Airbus [insert correct name]. 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.

3. Background

3.1. Market Research

Conductivity meters can be readily bought and range from prices of €500 for lab equipment to €10 for simple field water quality monitors. All available solutions are standalone devices using a single sensor and a display to report measurements. They also are designed to perform singular, high quality reads.

All of these traits are detrimental to the requirements of this project. A device is needed, which can perform fast measurements on multiple points in the stream, with the data exposed in a machine-readable format for further processing. Precision of the measurement can be compromised on, as long as a minimal standard is met. A custom design is necessary.

— [stub. detailed description of electronics] As base for this design, two solutions were found. [mini-eC Interface] Open Hardware implementation of simple signal generator and signal reader for a two electrode sensor providing raw voltage drop output. [AD5933] A simple signal generator and signal reader for a two electrode sensor, providing impedance with real and imaginary part. [this is the circuitry from the mini-eC-Interface on a single chip! awesome! base for version 2!] —

3.2. Theoretical Background

[subsections?]

The conductivity κ is the ability of a substance to conduct electricity. It is measured in the unit $^{S}/_{m}$ and is a specific parameter normalized to length. To better understand conductivity, an equivalent circuit diagram 3.1 of the experiment design 3.2 can be used. In this experiment, the resistance of a substance is determined by measuring

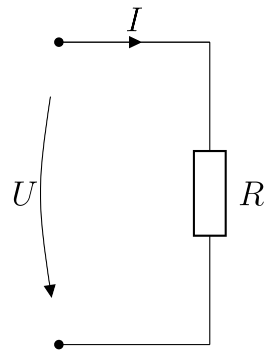

Figure 3.1.: equivalent circuit diagram

the potential drop. [update figures with voltage divider]

The resistance is

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

The inverse of R is the conductance

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

Considering the cell constant C yields the conductivity

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

The cell constant depends on the geometry of the sensor

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

where d is the distance between and A the size of the electrodes. [add figure of sensor geometry]

[paragraphs with line inbetween?] The principle of determining conductivity of a substance by measuring it's resistance in a defined geometry is called conductometry. In electrolytes, the electrical conduction happening 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 ad-

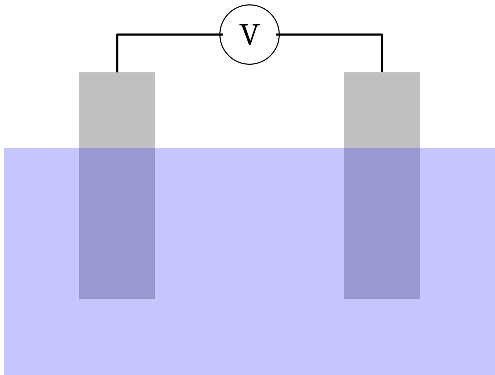

Figure 3.2.: electrode configuration

ditional 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 through the electrode, thereby it's effects can be minimized by minimizing this current.

The electrolytes temperature has a big influence on the conductivity and has to be taken in account when comparing two measurements. If the temperature is known, the conductivity can be normalized to a reference temperature.

The system described above is called a two-electrode-cell. In order to minimize current through the electrode, it is possible to separate the current flow from the potential measurement by using four electrodes. One pair is used to apply the current, a separate pair is used to measure the potential drop. This system is called a four-electrode-cell.

[everything up to here is translated and paraphrased from] **trankler2015sensortechnik** [how do I make that clear?]

4. Design

4.1. System Design

To establish common language for this thesis, following terms are defined:

- sensor - the electrode pair that is submerged in the solution
- signal generator - the source of the AC signal
- signal reader - the Voltmeter measuring the voltage drop
- sensor node - a signal generator, reader and a number of ports to connect sensors
- data processing unit - a unit providing all of the above with power, controlling their functions and capturing their data to log it and make it available to a user-readable output
- user-interface - the interface for the user to control the system and view the data
- sensor system - the sum of the described subsystems

4.1.1. Sensors

The sensor is a pair of electrodes submerged in the fluid. Waterproof wiring from these electrodes to the electrical interfaces is needed.

[electrode design - i.e. size, distance, form]

The first version of the sensor was made from two platinum electrodes that were wired to the sensor node via jumper cables. This was good enough to verify the function of the circuitry, but could not be deployed in the reactor in this form.

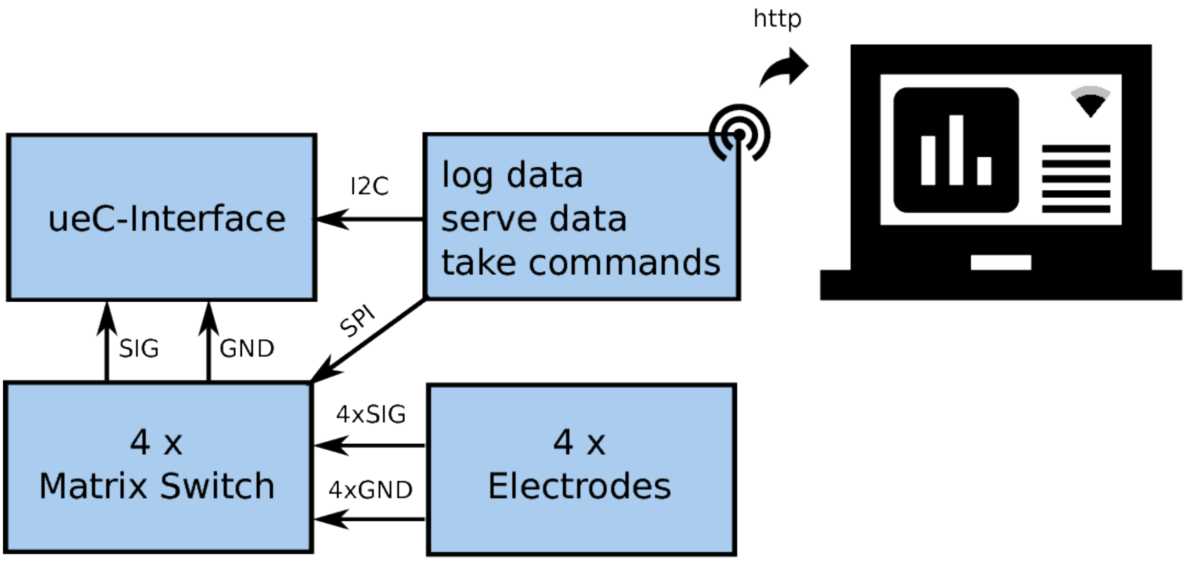

Figure 4.1.: System Design [why is this so ugly]

The second version of the sensor was built as a sensor array containing of multiple sensors on a sensor strip 4.2. A 5 cm wide and 25 cm long strip 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, it provides 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 problems stay.

As an alternative to these handmade strips, industrially produced Flex-PCBs were identified. Flex-PCBs are flexible printed circuit boards that are very close to our hand-made arrays. They also use Kapton as base, on which a copper coating gets applied and partially removed to form the conducting paths. On top, another layer of Kapton is applied, with cut outs in the places where the copper is supposed to be exposed. The exposed copper is then plated with ENIG (Electroless nickel immersion gold) to

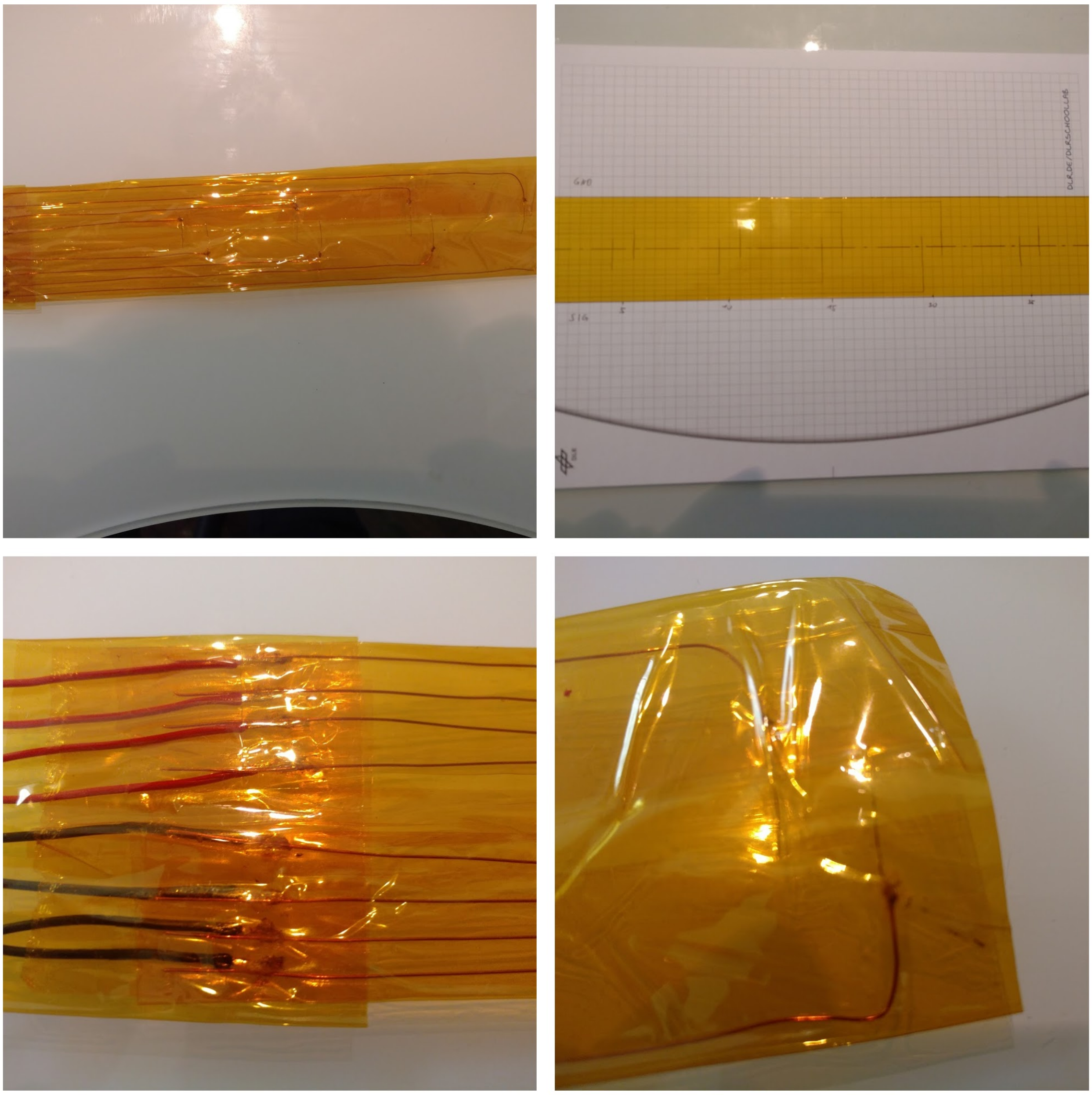

Figure 4.2.: Handmade Sensor Strip

Figure 4.3.: Design of FlexPCB

protect the copper from oxidation and provide the landing pads for electrical components to be solder 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 to the sensor node.

[image flexpcb]

[platinum vs. ENIG a electrode material]

4.1.2. Sensor Node

The sensor node logically consists of the signal generator and the signal reader, practically both parts are tightly integrated.

[Describe mini-eC-Interface] [also where i.e. the change with the filter cap and the tests that surfaced the issue is described]

The mini-eC-Interface provides two channels to connect to the electrodes, but multiple sensors should be driven by one interface. The method to this is called demultiplexing and the component able to this is the Matrix-Switch. A Matrix-Switch is an electrical component containing a multitude of switches, where the switches can be electronically closed and opened from a controller. The Matrix-Switch chosen consists of 8 switches, where all switches have the same input, but separate outputs. Thus, they allow applying an input signal to different outputs. The input in our case is the signal and reference from the minie-eC-Interface, applied to 8 different electrode pairs making up the sensors. A separate Matrix-Switch is need for signal and reference.

[name of matrix switch]

This allows us to use one mini-eC-Interface to drive 8 sensors.

Data Processing Unit

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.

4.1.3. User-Interface

4.1.4. Sensor System

[pcb, assembly]

5. Results

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. [?]

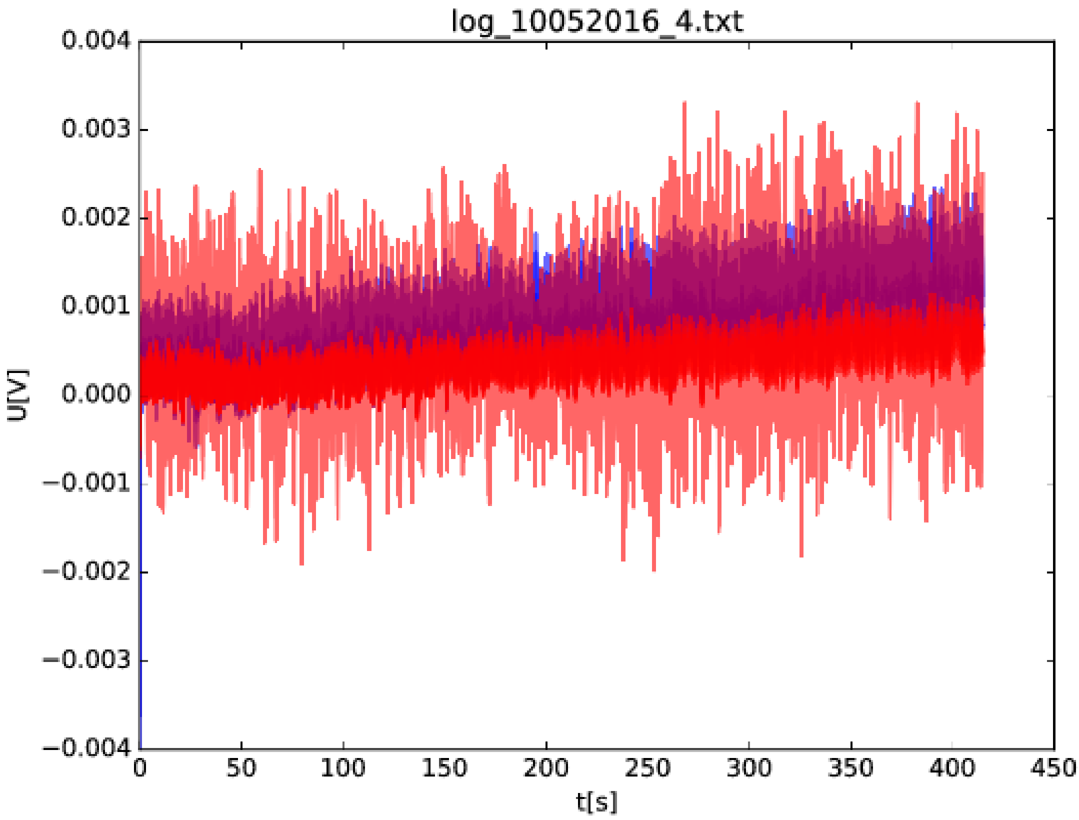

Figure 5.1.: noise

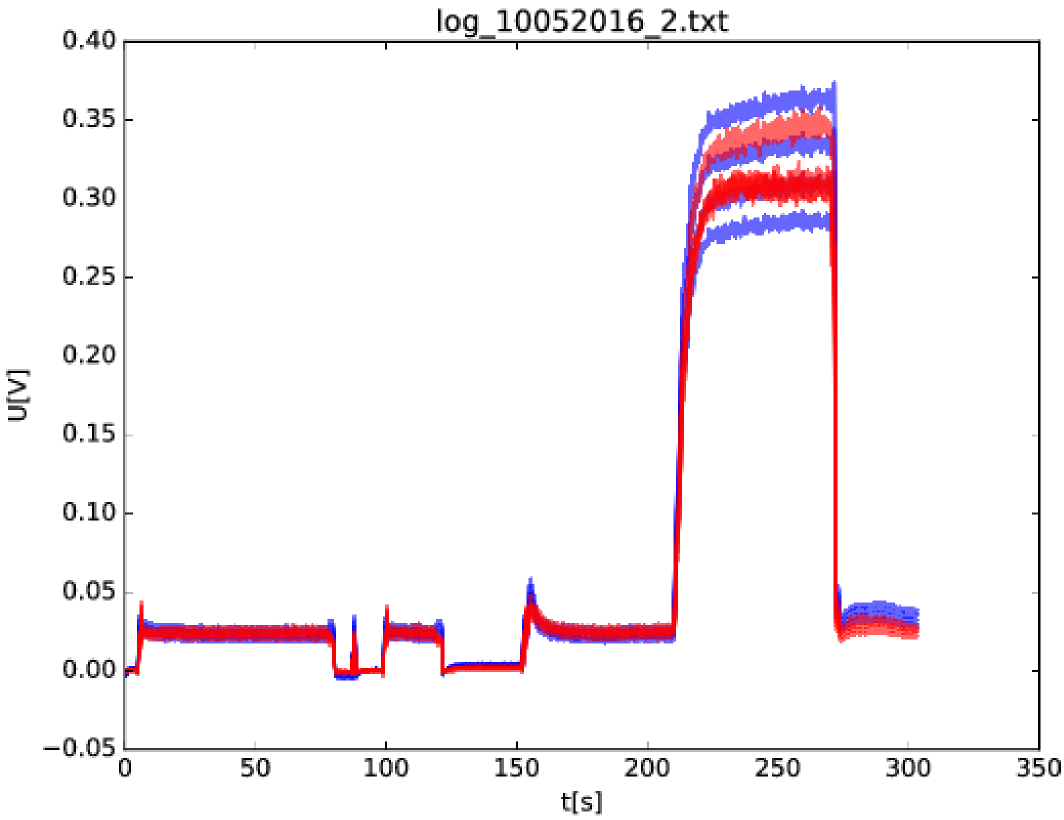

Figure 5.2.: feed switch

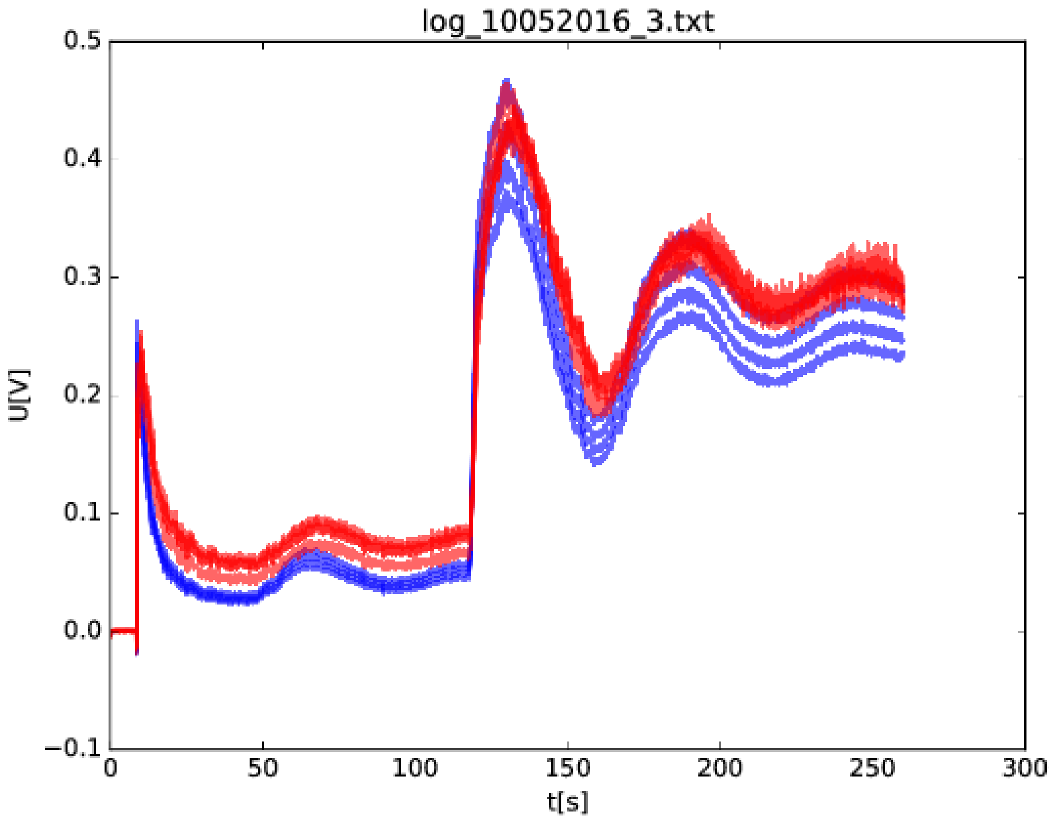

Figure 5.3.: feed add

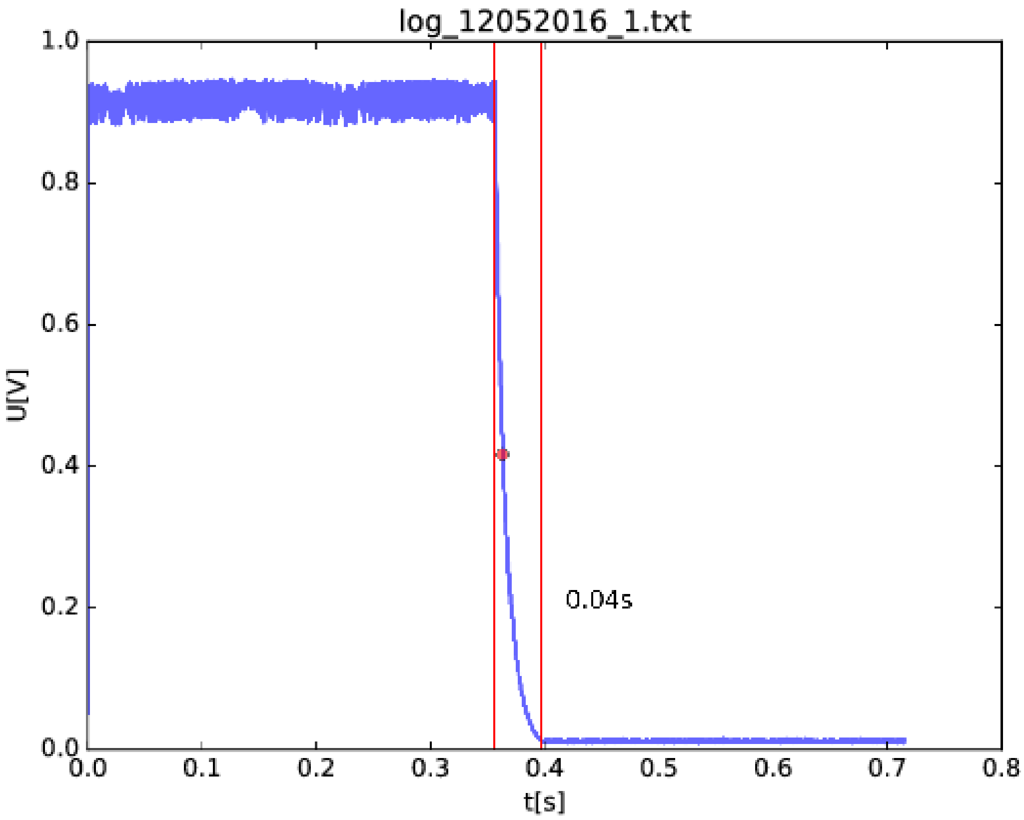

Figure 5.4.: switch cap

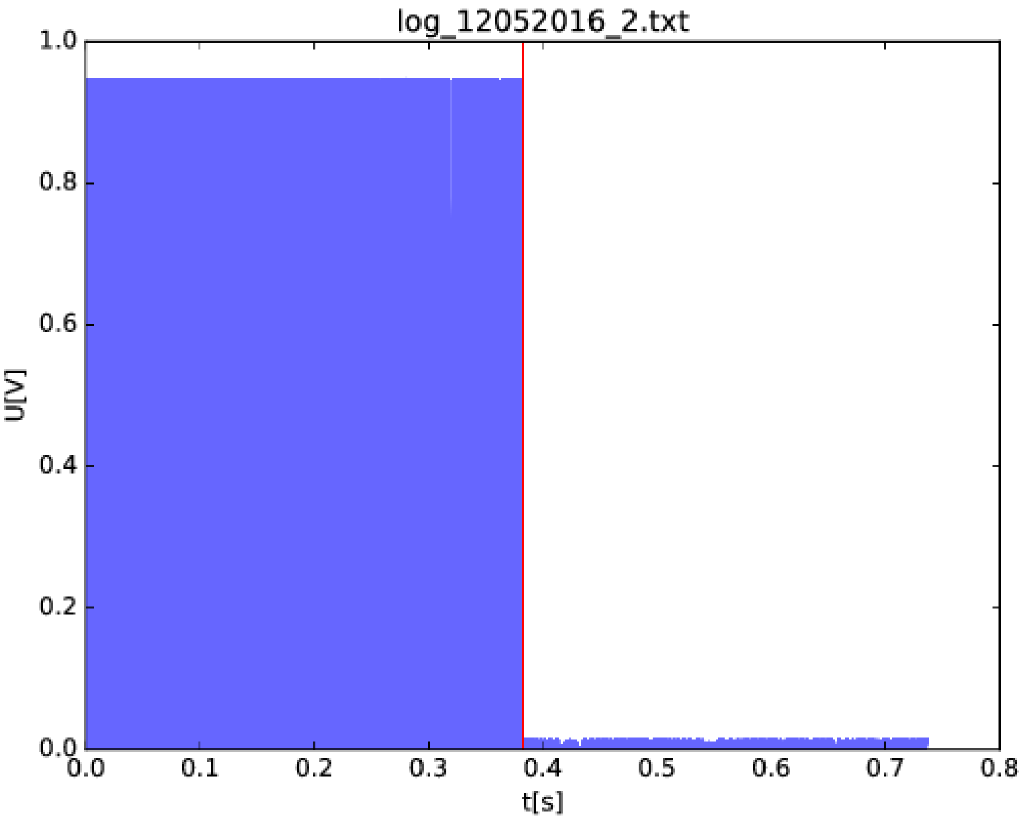

Figure 5.5.: switch no cap

6. Conclusion

The conclusion is it works.

Appendix

A. Abbreviations

CFD	Computational Fluid Dynamics
PBR	Photobioreactor

B. List of Figures

C. List of Tables