EHDA closed loop control system based on real time non-visual spray mode classification

Report

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Contents

Abstract

Electrohydrodynamic Atomization (EHDA), also called electrospray, is a liquid atomization technique that produces micro- and nanometric charged droplets within a narrow size distribution by using high electric fields (kV/cm). According to Cloupeau and Prunet-Foch[1] (1994), electrosprays can generate droplets in different ways, which the authors named "electrospray modes". These modes may be adjusted by varying the strength of the electric field and flow rate, but also depend on liquid properties and system geometry. In their work, the authors proposed four possible EHDA modes: dripping, intermittent, cone-jet and multi-jet, which are generally distinguished visually. Verdoold et al.[2] (2014) recently suggested a classification approach based on the behavior of the electric current of the electrospray process.

This project develops a closed-loop control method for EHDA devices that uses real-time, electric current-based (hence non-visual) spray mode classification. The proposed electrospray system is entirely automatic, where all the peripherals, such as HV power supply and syringe pump, are controlled by a computer which executes their routines. The system classifies spray mode dynamics using real-time current data and changes EHDA operating parameters such as liquid flowrate and applied voltage to achieve and maintain the chosen spray mode. The electrospray modes are validated in real time by using a high-speed camera. As compared to conventional manual approaches, the implemented control algorithm achieves higher accuracy and lower transient time. Therefore, a completely autonomous EHDA system opens the door to potential industrial applications. In addition, the use of the electric current signal will be useful to further study electrospray processes, leading to better control on droplet generation (frequency, size and charge). The incorporation of Machine Learning to improve mode categorization will be a future development.

Chapter 1

Introduction

Electrohydrodynamic Atomization (EHDA) is a way to disintegrate a liquid into droplets by exposing it to a strong electric field.[1] The balance beetween capilary forces and the eletric field on the charged liquid defines the spraying dynamics and droplet size. The electric current transported by the spray reveals characteristic shapes for different spray modes. Signal processing techniques can allow a non-visual classification of the spray mode based on the electric current shape.[2] The spray process imposes noise and random sequences on the measured signal making its classification not a trivial task. Industrial applications demand automated stabilization of a spray mode. This can be achieved by a closed-loop control system. This project is about to develop an application that can classify what dynamics the EHDA experiment is current in and control the variables to stabilize in the desired mode.

1.1 Motivation and Justify

As pesquisas de EHDA têm contribuído como uma importante ferramenta para o desenvolvimento da tecnologia . Embora existam aplicações de EHDA em indústria, a estabilização do modo de pulverização de jato cônico é feita empiricamente e com base em medições de corrente média. A corrente elétrica que flui transportada pelo spray revela formas características para diferentes modos de atomização. Essas formas não podem ser simplesmente resumidas por seu valor médio. Na figura um podemos ver um exemplo de cone-jet modo eletrospray.

Figura 1: exemplo de EHDA

As técnicas de processamento de sinal podem permitir uma classificação não visual do modo de pulverização com base no elétrico forma atual. O processo de pulverização impõe ruídos e sequências aleatórias no sinal medido tornando-o classificação não é uma tarefa trivial. Aplicações industriais exigem estabilização automatizada de um modo de pulverização. Isso pode ser obtido por um sistema fechado sistema de controle de circuito. A classificação automatizada do modo de pulverização é uma parte crucial de um sistema de controle, assim como o desenvolvimento de um algoritmo de controle apropriado.

1.2 Project objectives

Tendo em vista o exposto acima, este projeto tem por objetivos:

a) Item 1;

b) Item 2;

c) Etc.

O conteúdo desta seção pode se sobrepor um pouco com o da seção anterior, podendo ela ser um sumário dos pontos expostos anteriormente. A escolha do título da seção talvez seja mais apropriada para a fase de proposta do projeto. Afinal, nesta fase se conhecem os objetivos e não os resultados. Por outro lado, fará pouco sentido discutir objetivos quando o projeto está finalizado, especialmente se tais objetivos não foram alcançados.

1.3 People envolved

Implementações de processamento de sinal de projetos anteriores do grupo NHL Stenden Water Technology estão mostrando bons resultados de classificação. Mais pesquisas são necessário para melhorar a precisão da classificação e pesquisa e implementação de uma classificação adequada algoritmo. Por causa disso, o trabalho será feito pelo Water Technology Group da NHL Stenden University de Ciências Aplicadas e em combinação com empresas holandesas para combinar possibilidades de análise com conhecimento e disponibilidade de infraestrutura.

Chapter 2

System Description

2.1 EHDA

The electrospraying of liquids herein is referred to as electrohydrodynamic atomization (EHDA). The atomization by primarily electrical (electro) forces of a liquid (hydro) that is moving (dynamic) during the atomization captures the essence of the phenomena.[3] That motion applies to the liquid certain velocity that is not enough to create the spray alone. Therefore, the eletric field itself is the responsible for the spraying dynamics.[1]

The stable balance between the capilary and field forces on the liquid suggest a *quasi static* dynamics. For this reason with a controlled enviroment we can reach a certain stable spraying mode as can be seen in the Figure 2.1.

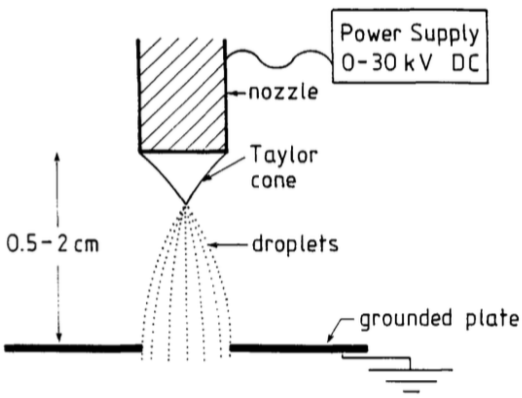

Figure 2.1: EHDA physical concept [4]

2.2 Spraying modes

Since 1915 with his pioneering work in EHDA, Zeleny observed several functioning modes with very different characteristics. Years later the same phenomena was noticed by other scientists but the classification of these modes were still not well defined by the community. For that Cloupeau and Prunet-Foch proposed spray mode classifications based in what they have seen experimentally and it's still being used as basis for EHDA researchs.[1]

The Figures 2.2, 2.2, 2.2 shows the 3 spraying dynamics that we are most intersted in this project.

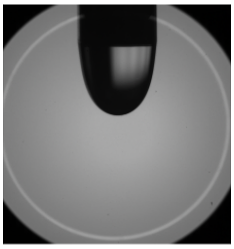

Figure 2.2: Dripping

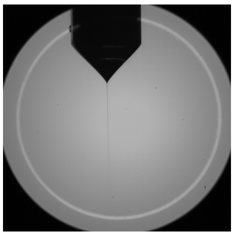

Figure 2.3: Cone Jet

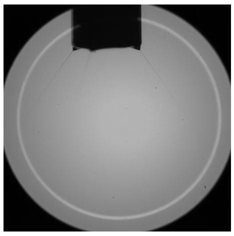

Figure 2.4: Multi Jet

Through the various classifications defined we are going to work aggregating some of them and separating beetween 5 modes as shown above:

2.2.1 Dripping

In Dripping mode the eletric field applied is not enough to change the meniscus shape, phenomena called field enhanced dripping. In that situation the liquid droplet has, in general, size bigger than the capilary and low frequency intervals between each drop.

2.2.2 Intermittent

Intermittent mode is defined when the eletric field forces starts to have a considerable effect in the meniscus and droplet formation. In this mode the droplet size is smaller than the nozzle, phenomena called microdripping, and the dripping frequency increases with the increasing of the field applied.

2.2.3 Cone Jet

2.2.4 Multi Jet

2.2.5 Corona sparks

2.3 Instrumentation

2.3.1 Setup Organization

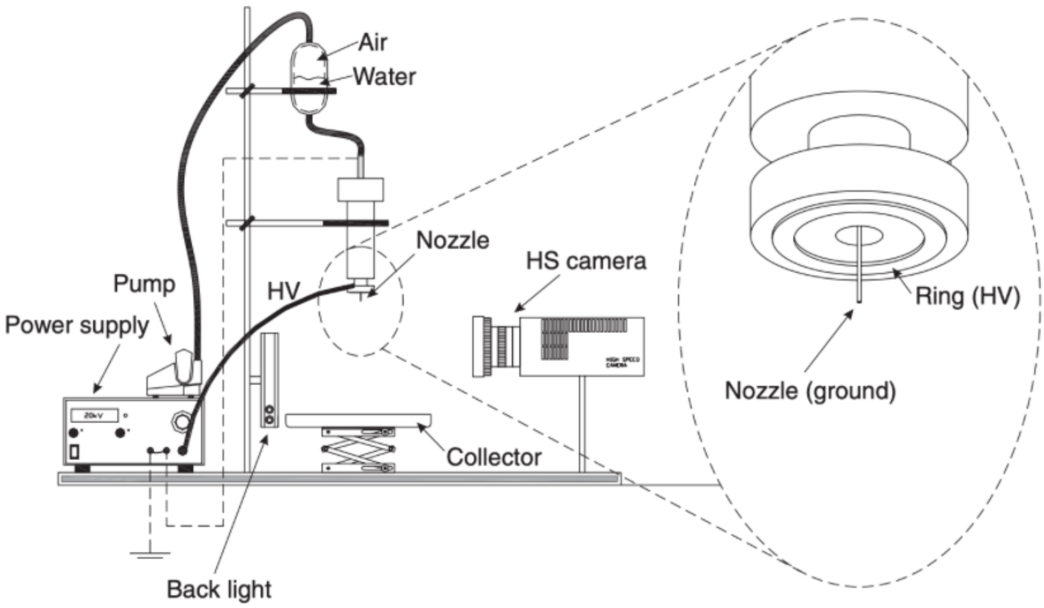

Figure 2.5: EHDA experiment setup [5]

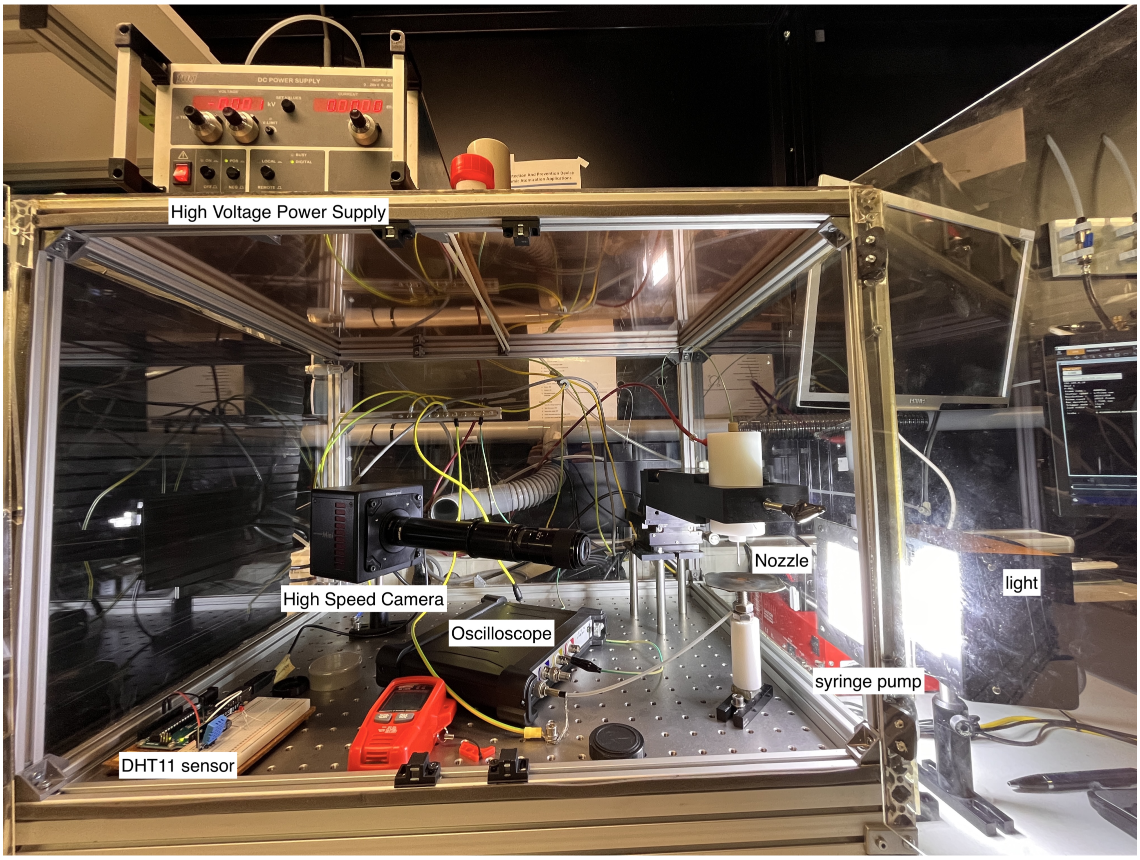

Figure 2.6: EHDA automation system setup

2.3.2 Instruments Used

The peripherals automation routine was already developed by another student. In order to continue the research I took some time to understand the physical concept behind EHDA experiments and the project knowledge. I made upgrades in the routine to include the high speed camera with a hardware triggering routine using an arduino microcontroler. This will be usefull to validate the further classification of the spray dynamics.

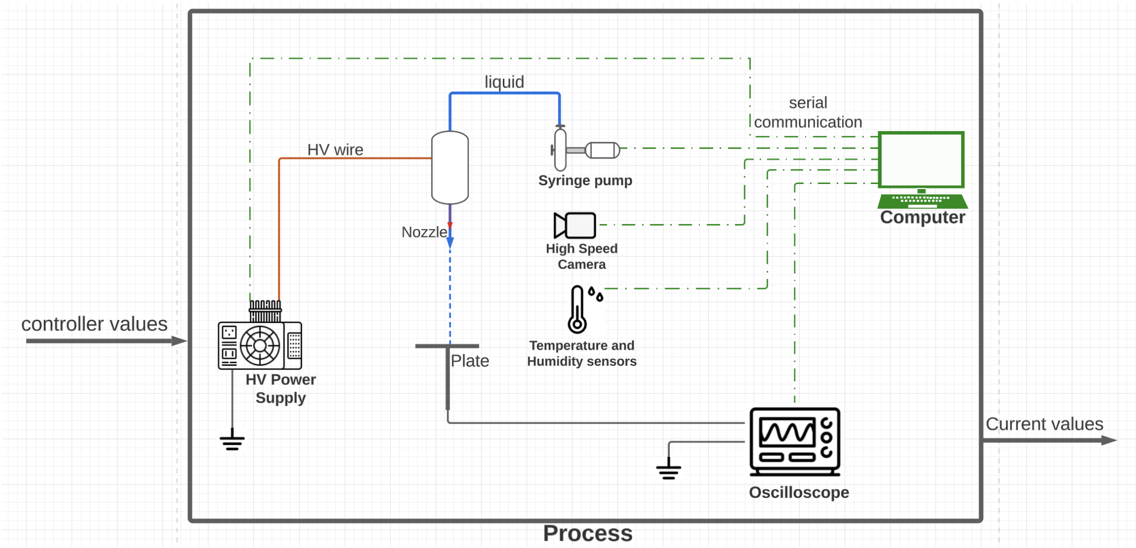

Figure 2.7: EHDA automation system setup

2.4 First Experiments

Initial tests were made to verify the setup assembly and the automation routine integration. In this step I could unterstand in practise how electrospray works. I noticed that we need a large set of variables in the range to produce the desired dynamics of electrospray, which most of the time is cone-jet mode. Those variables can be the liquid properties such as surface tension, dielectric constant, viscosity, density, electrical conductivity and vacuum permitivity. And also physical variables such as flowrate, system impedance, system temperature, system humidity, nozzle to plate distance, nozzle dimensions and applied voltage. The instruments used in the setup are:

a High Voltage Power Supply (FUG)

b Oscilloscope TiePie WS6 DIFF

c Humidity and Temperature sensor (DHT11 + Arduino Uno)

d High Speed Camera - Photron fastcam mini

e Syringe pump

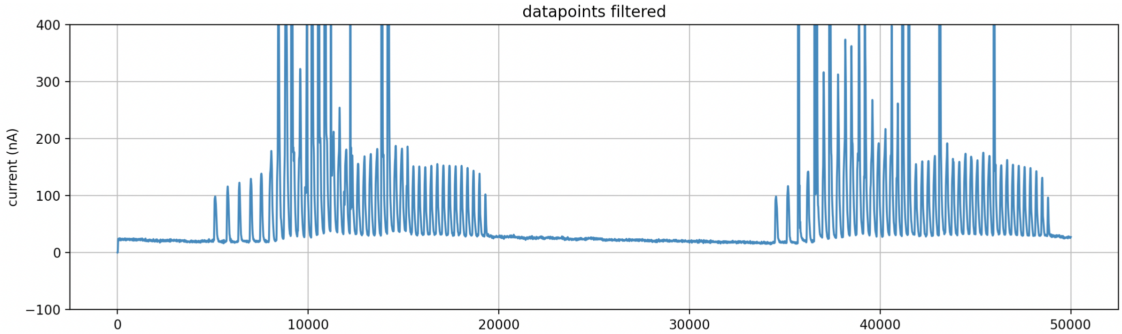

Figure 2.8: EHDA automation system setup

Chapter 3

Metodology

3.1 System Model

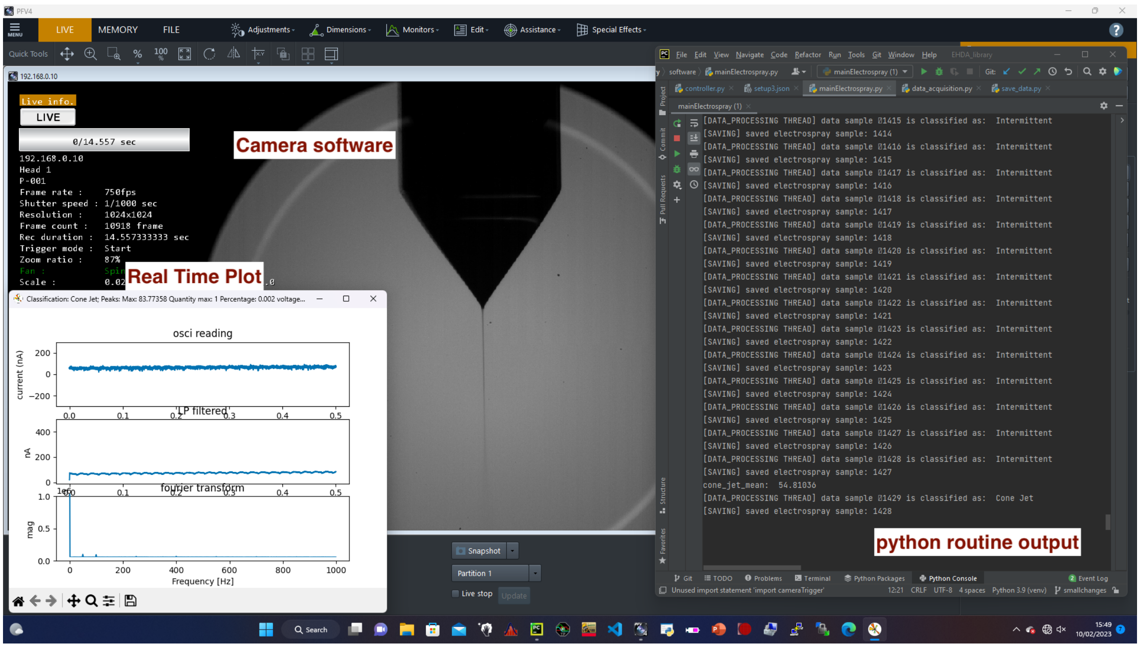

Figure 3.1: EHDA automation system setup

ilustramos o processo com a Figura 3.2.

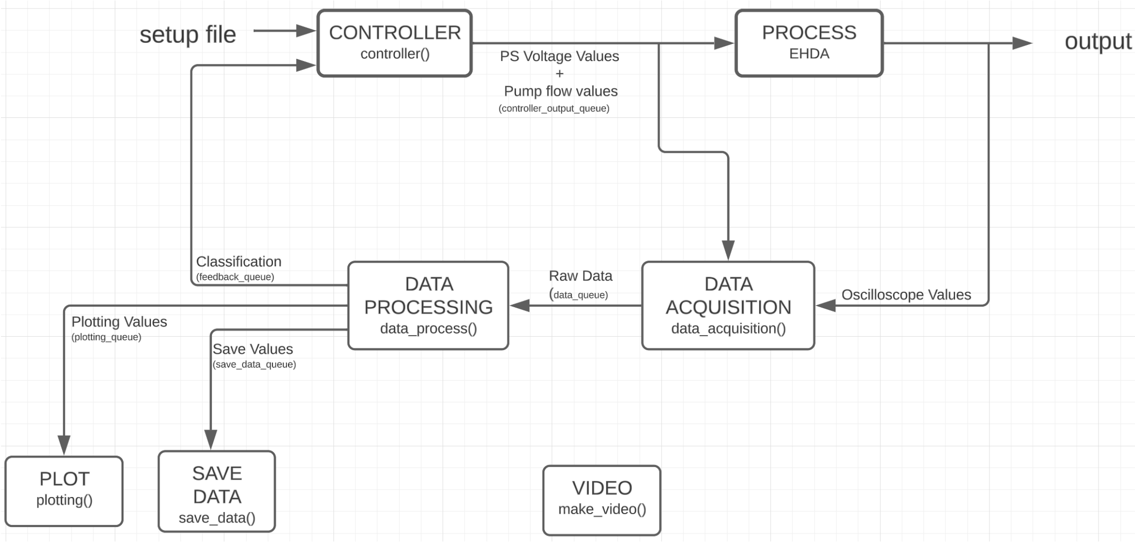

Figure 3.2: EHDA automation system setup

3.2 Threading and Queues

In order to implement this system model to the software and explore parallel processing each system in the model was developed as a separate Thread. For cuncurrency on flux of data beetween threads was used queues structures. A queue is an abstract data type that holds an ordered, linear sequence of items. You can describe it as a first in, first out (FIFO) structure.

3.2.1 Controller Thread

It is responsible of sending the power supply set voltage values and the syringe pump the flow rate set values according to the sequence selected. Also responsible of sending the finish event command that end the routine and trigger the threads to close their routines. As input we have the setup config file and the *feedback_ queue*. As output we have the values in the emphcontroller_output_queue().

3.2.2 Data Acquisition Thread

It is responsible for reading the current data from the oscilloscope, humidity and temperature data from the DHT11 sensor, voltage from the powersupply, flowrate from the pump and concatenate into one sample data. As output we have the values in the emphdata_queue().

3.2.3 Data Processing Thread

It is responsible for calculating the statistical values from the raw data and classify it in the respective spray mode for that sample. As output we have the values in the emphsave_data_queue(), emphplotting_queue() and emphfeedback_queue().

3.2.4 Save Data Thread

After the processing the data is saved in real time in a json file using *jsonstreams* library to save one sample structure at a time.

With the new streamming model of saving a new structure of the collected data were created. Instead of having all data measurements values and after all data processing values we now are saving for each sample the measurements and processing values. The structure of the

```
"sample 0": {
    "name": "setup/liquid/ethanol",
    "data [nA]": [⋯
    ],
    "flow rate [m3/s]": "1.1",
    "voltage": "5001.66",
    "current PS": "1.31785e-08",
    "temperature": 19.20,
    "humidity": 43.00,
    "date and time": "Fri_10 Feb 2023",
    "target voltage": 5000,
    "mean": 46.43349075317383,
    "variance": 1328.3770751953125,
    "deviation": 36.44690704345703,
    "median": 27.421382904052734,
    "rms": 59.029197692871094,
    "spray mode": [
        "Intermittent"
    ]
},
```

Figure 3.3: Output data json structure

To work with this data I'm using pandas Dataframe. With the command:

pandas.read_json('PATH', orient='index').

The json file is good to store the data and to read the file. But as it is getting a lot of data working with pandas Dataframe is being way faster. Also saving the dataframe in a compressed type of file called feather is much faster to work with the data.

3.2.5 Video Thread

Normally deactivated, that thread is responsible for triggering the camera in case we want to save a video of that sample.

3.2.6 Plot

The only running function that is not a thread because of the plotting library *matplotlib* incompatibilites of running outside of the main function. It is responsible of plotting in real time the current sample acquired and it respective fast fourier transform to evaluate the sample frequency spectrum.

- plotting data queue

3.3 Classification

3.3.1 Statistical Analisys

According to [2] evaluating the current data flowing through the nozzle to the plate we can analyze the signa that represents the spraying dynamics. through statistical analysis in this signal such as mean value and standart deviation we can analyze if the signal is stable or not.

Our classification by statistical analysis was implemented in the automation library made by the previous student [6].

Each current sample is 0.5s of current data in 10kHz sampling frequency. By the processing thread we take this sample and evaluate the followings statistical values.

- Sjaak Classification -> Classifies Dripping, Intermittent and Cone Jet
- Monica Classification -> Classifies Corona Sparks
- João Classification -> Classifies Multi Jet

The algorithm implemented works in the following way:

3.3.2 Machine Learning

3.4 Routine Sequences

The software was previously developed as a electrospray multipurpose library[6]. Continuing this methodology, in the setup json file there is a "sequence" atribute which can chosen beetween "ramp", "step", "map" or "control". The controller thread will manage what the algorithm must do for each sequence.

Algorithm 1 Statistical Classification

```
function STATISTICAL_CLASSIFICATION(sample)
    spray_mode ← "Undefined";
    mean ← sample.mean;
    std_deviation ← sample.std_deviation;
    median ← sample.median;
    if mean/std_deviation > 2.5 then                                  ▷ Sjaak classification [2]
        spray_mode ← "Dripping";
    else if 2.5 < mean/std_deviation < 2.5 & mean/std_deviation > 0.3 then
        spray_mode ← "Intermittent";
    else if mean/std_deviation < 0.3 then
        spray_mode ← "ConeJet";
        cone_jet_mean ← mean;
    end if
    if mean/std_deviation > 2.5 then                                  ▷ Monica classification [6]
    end if
    if spray_mode == "ConeJet" then                                   ▷ João classification
        if cone_jet_mean > 1.14 × mean then
            spray_mode ← "MultiJet";
        end if
    end if
    return spray_mode;
end function
```

Algorithm 2 STEP sequence in controller thread

```
procedure STEP(voltage_start, voltage_stop)
    voltage ← voltage_start
    while voltage ≤ voltage_stop do                                   ▷ scanning voltage range
        SEND_VOLTAGE_COMMAND(voltage)
        SLEEP(step _time)
        voltage ← voltage + step_size
    end while
end procedure
```

3.4.1 Ramp

3.4.2 Step

3.4.3 Map

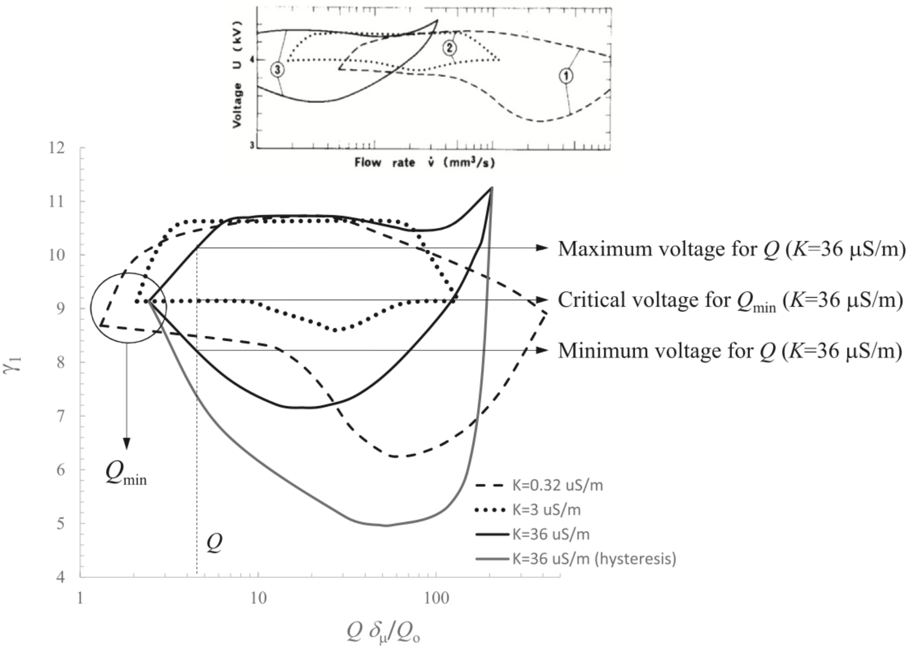

Figure 3.4: Domains of existence (stability) of Taylor cone-jets. [7]

Algorithm 3 MAP sequence in controller thread

procedure MAP($flowrate\_values$)
    for all flowrate_values **do** ▷ scanning in the flowrate range
        SEND_FLOWRATE_COMMAND(flowrate)
        $voltage \leftarrow voltage\_start$
        while $voltage \leq voltage\_stop$ **do** ▷ scanning in the voltage range
            SEND_VOLTAGE_COMMAND(voltage)
            SLEEP(step _time)
            $voltage \leftarrow voltage + step\_size$
        end while
    end for
end procedure

In the figures 5 and 6 we can see the results of this mapping experiments. The liquid used is pure ethanol. Each figure has 3 graphs with shared x axis representing the samples collected. The first is the current values collected through all the experiment. The second is the voltage values applied in each window of data collected. The colors represent the spraying classification defined by our routine. The third graph shows the current mean value of each data sample. Note that the experiment is composed of loops that increase voltage, change flowrate and repeat.

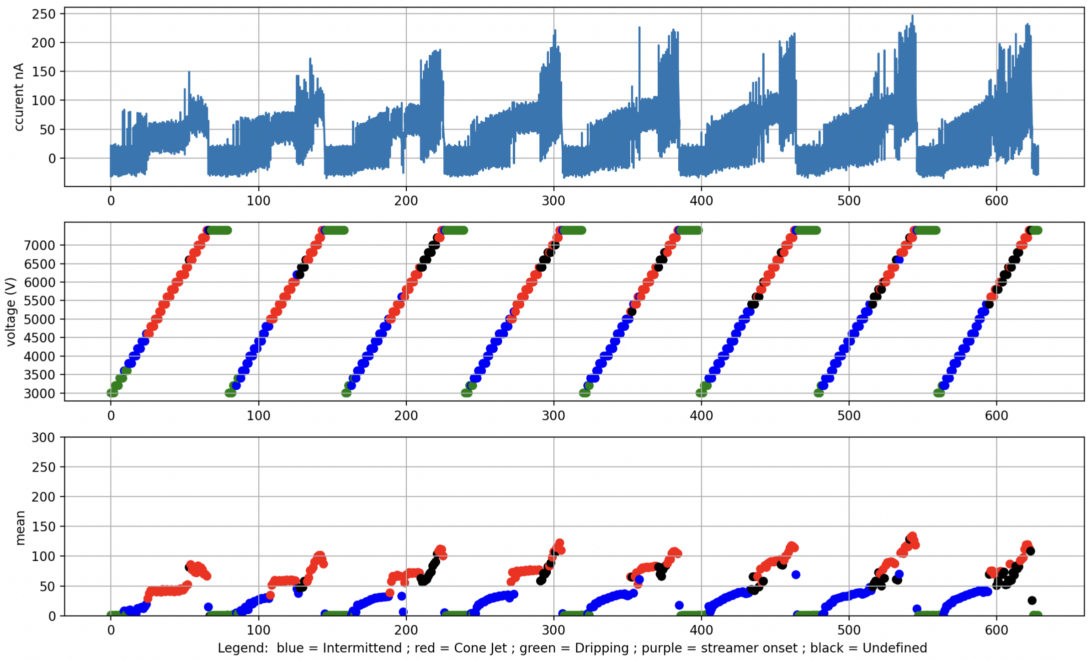

Figure 3.5: Mapping Experiment example 1

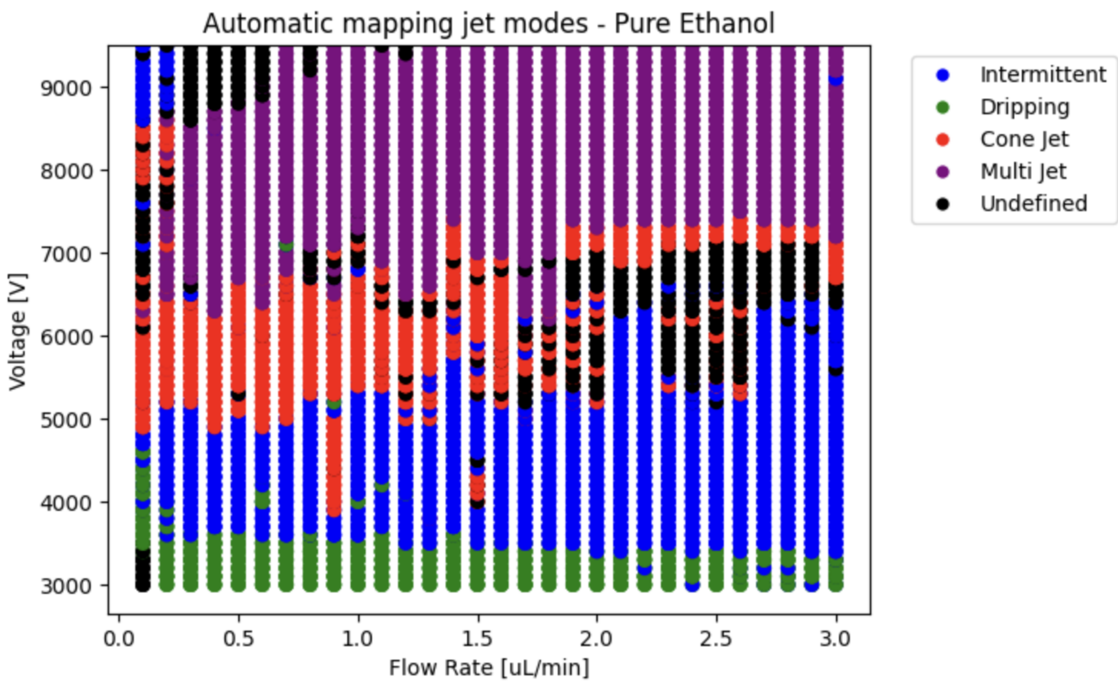

Figure 3.6: Mapping Experiment example 1

3.4.4 Control

The control sequence is the only from our list of sequences that actually uses the feedback value. As it is a closed loop control system the controller must be able to stabilize the system in the desired conditions.

3.5 Optimizations

About the python algorithm to turn the experiment autonomous it was made a study and modelling of the software architecture to optimize it for further control loop application to be implemented. From the changes made until now it highlights:

- Integrate high speed camera to the experiment routine.

- Remodel the software to support threads in order to separate the sensoring and controlling routines.

- Reduce the data collected size.

- Synchronize the power supply step commands and voltage sensoring.

- Reestructure the setup file in order to make it more intuitive to use the experiment.

- Improvements in code organization and readability.

About the setup,integrate was changed the liquid, nozzle diameter and distance to the plate in order to make the experiment the most stable and easy to reach cone-jet mode as possible. For example, while doing experiments we discovered that the frequency of the pump machine internal motors was creating an interference in the flowrate. Therefore compromising the stabilization in cone jet mode. A solution for that was to increasethe flowrate wich smooths this pumping noise. For that was also necessary to increase the nozzle diameter to balance with all other variables from the experiment.

3.5.1 Pump Integration

The pump integration in the automation algorithm bring us a new controllable variable, the Flowrate. Now we can control the spraying mode with the two main variables that afect the system. It will bring more complexity for the system since now we are dealing with multivariable control. Controlling also the flowrate gives to this project a new dimension in the system giving us freedom to explore the flowrate properties.

About the pump interface. As I could not find a good ready-to-use library for this pump I developed an simple and intuitive interface to be our software routine. The communication protocol used is RS-232. In the software routine the communication used is python serial interface. The pump commands list were found in the user manual.

Chapter 4

Results

4.1 Map Sequence

4.1.1 Manual experiments

For better understand the effects of both voltage and flowrate in the spraying dinamycs manual experiments were made. Also in order to find the stability region of cone jet mode for the liquid and setup used.

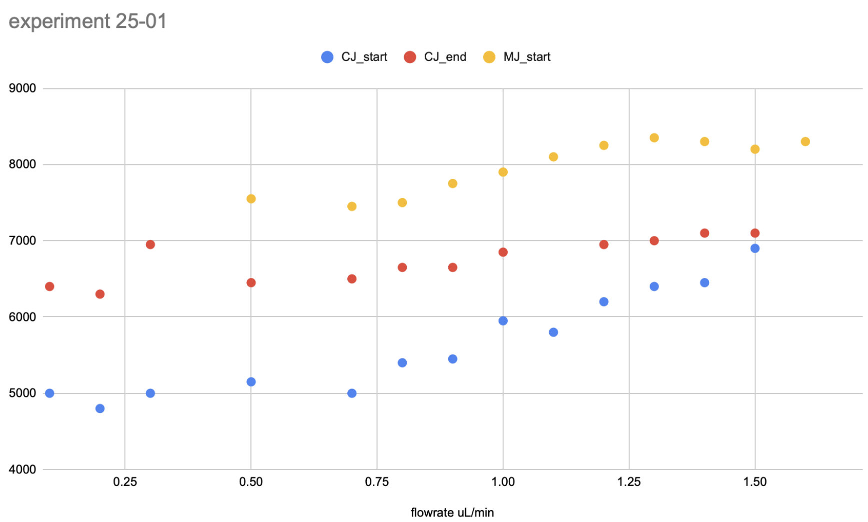

Figure 4.1: exp25-01-1 (V x Q)

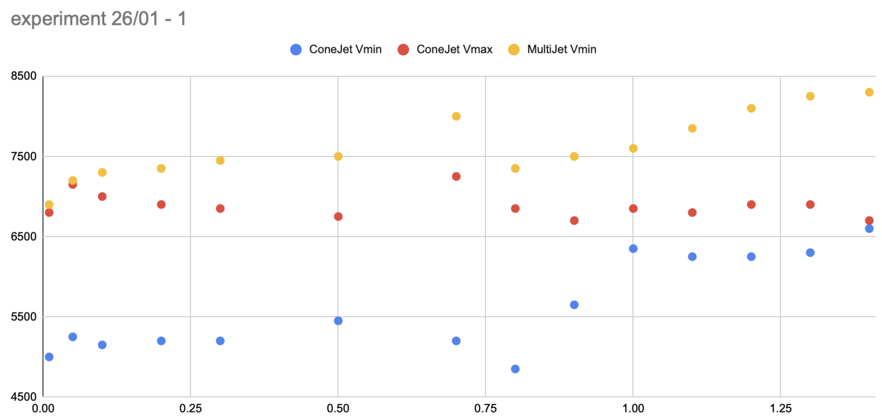

Figure 4.2: exp-26-01-1 (V x Q)

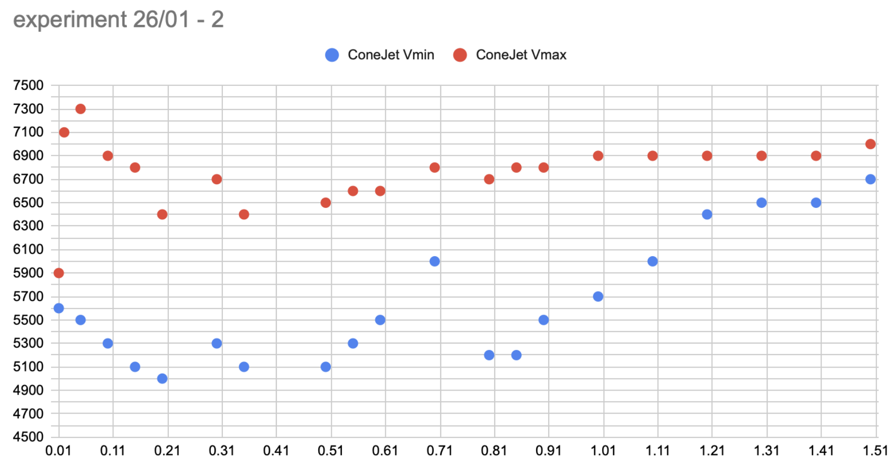

Figure 4.3: exp-26-01-2 (V x Q)

4.1.2 Automatic experiments

With the desired voltage and flowrate range defined for the automatic experiment the next part is to define how many datapoints will be collected in both x and y axis. Since we are introducing a new dimension for our experiment it is also increasing fast the amount of data collected. The goal of this part is to find the ideal combination of voltage step size, voltage step time and flowrate step size in order to get the most accurate results without exceding the separate memory for each experiment.

In the further improvements of the routine it's ideal to apply a real time file writing with all experiment data. This will prevent that any crashes in the program lose all data and not overflow the memory allocated for the program.

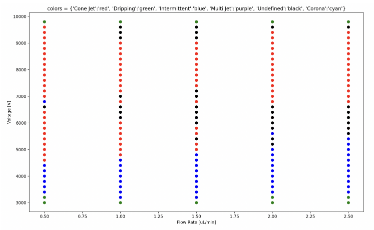

Figure 4.4: First mapping trial

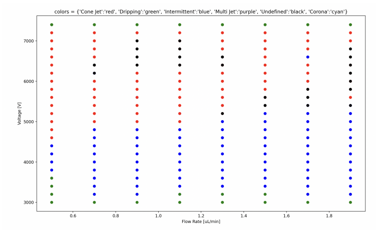

Figure 4.5: Second mapping trial

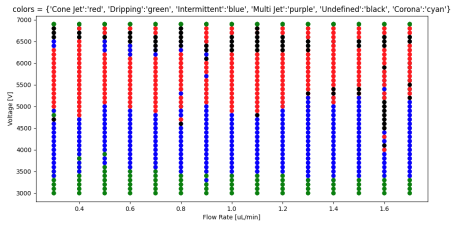

Figure 4.6: third map - better result

4.1.3 Manual x Automatic Cone Jet stability island maps

For validation of the automatic system and classification some experiments were made having both manual and automatic data collecting.

The Figure 13 shows a printscreen of how the experiment looks like in real time. We can see the image generated by the camera in the back. The routine code running in pycharm software on the right. And also real time signal plottings of the current data on the left.

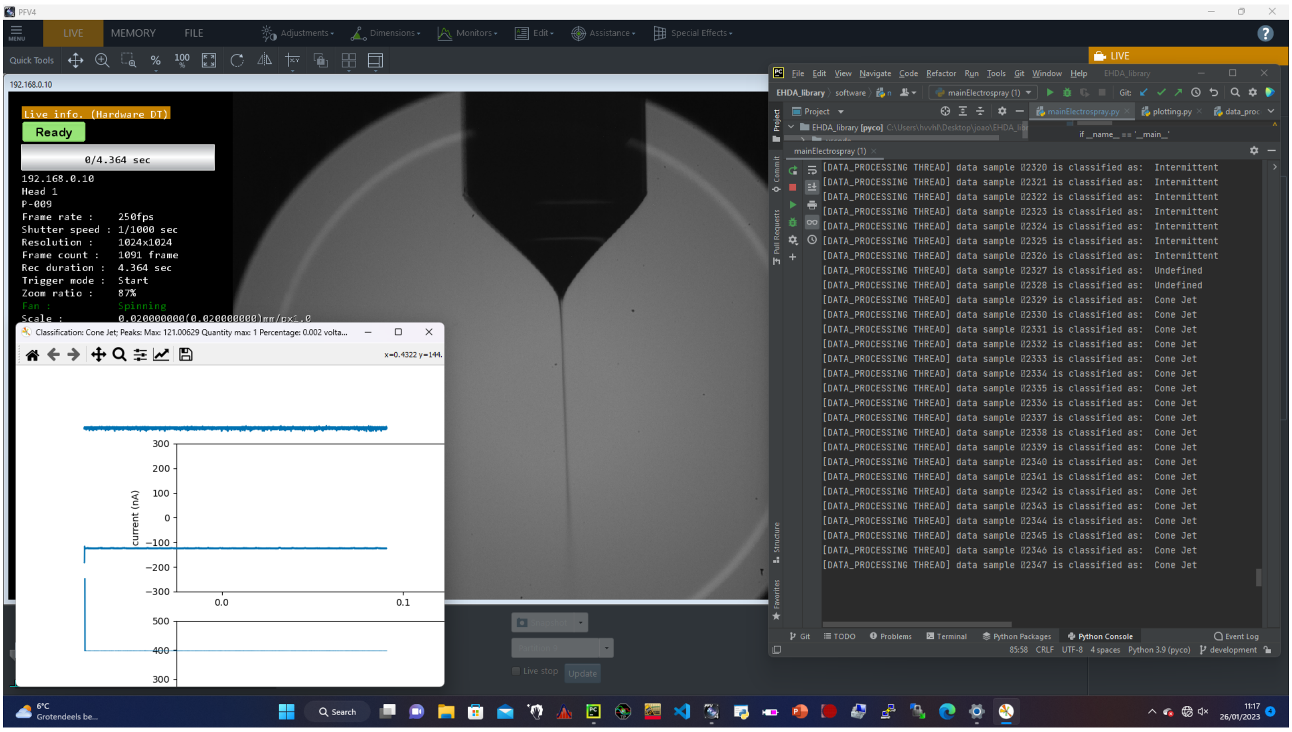

Figure 4.7: running experiment print screen

In Figure 14 we can see a result of the map generated by the automatic classification in this experiment.

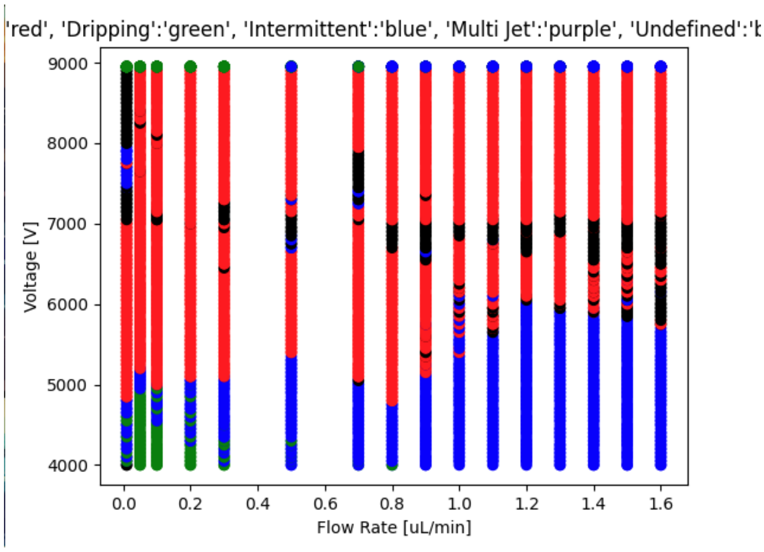

Figure 4.8: exp-26-01-23

Figures 15 and 16 shows that we could achieve a stable cone jet region map with similar shape and values in both manual and automatic classification of the same experiment.

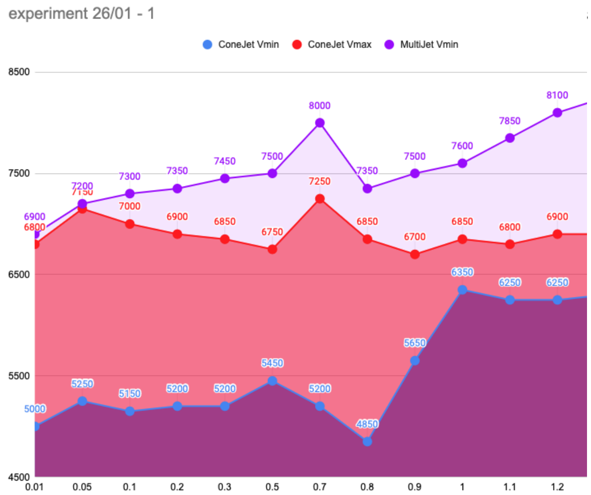

Figure 4.9: exp-26-01 manual classification

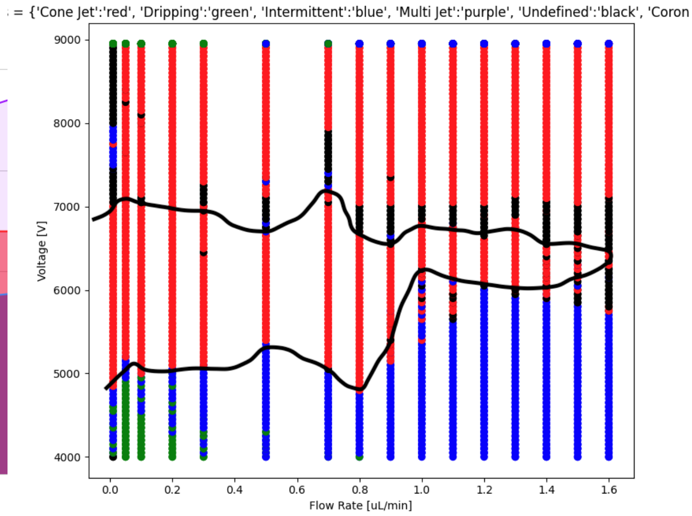

Figure 4.10: exp-26-01 automatic classification

4.2 Atividades do Projeto

4.3 Requisitos do Sistema

Chapter 5

Conclusion

References

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Appendix A

O que ficou para depois

Inclua aqui informações que não sejam tão relevantes para o entendimento do projeto mas que ainda sejam importantes para documentá-lo.

Appendix B

O que mais faltou

Inclua aqui informações que não sejam tão relevantes para o entendimento do projeto mas que ainda sejam importantes para documentá-lo.