



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

Monography

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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.

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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 between capillary forces and the electric 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

EHDA research has contributed as an important tool for the development of technology. The advantage of using EHDA is precision and uniform size and shape of droplets creation. Specially in certain spraying modes.

Although there are applications of EHDA in industry, the stabilization of the conical jet spray mode is mostly done empirically and based on average current measurements.

The flowing electrical current carried by the spray reveals characteristic shapes for different atomization modes. Signal processing techniques may allow non-visual classification of spray mode based on electrical current form.

The spraying process imposes noise and random sequences on the measured signal making it sorting is not a trivial task. Industrial applications require automated stabilization of a spray mode. This can be achieved by a closed system loop control system. Automated spray mode sorting is a crucial part of a control system, as well as the development of an appropriate control algorithm.

1.2 Project Goals

This project aims to give continuity to the previous student work[6], Mônica, who focused in detecting undesired discharges (sparks) in the system accusing high electric potential. For that, she developed a python software routine to connect most of the peripherals and analyzed the current data. Her work corroborates the validation of this project motivating its development and optimization.

Above is shown the main goals listed:

Multipurpose applications for both scientific and industrial approaches.

Fully automated and intuitive system for EHDA.

Real Time non-visual classification of spraying modes.

Control and stabilization on a desired dynamic.

System portability and versatility.

1.3 People involved

The NHL Stenden Water Technology group has been involved in previous projects that have successfully implemented automated signal processing techniques, resulting in highly ranked outcomes. However, further research is required to enhance the accuracy of the classification algorithm. In order to achieve this, the Water Technology Group at NHL Stenden University of Applied Sciences, in collaboration with Dutch companies, is conducting extensive research and implement appropriate classification algorithms. The aim is to combine analytical capabilities with infrastructure knowledge and availability to achieve optimal results. As a student from UFMG, I am now actively involved in this research project to improve the automation usability, classification accuracy and system stabilization with signal processing techniques.

1.4 Document Structure

Chapter 2

Literature Review

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.[7] That motion applies to the liquid certain velocity that is not enough to create the spray alone. Therefore, the electric field itself is the responsible for the spraying dynamics.[1] A stable balance between the capillary and field forces on the liquid suggest a *quasi static* dynamics. The feeding liquid is pulled through a small orifice by means of the applied voltage. The droplets are accelerated towards the grounded electrode by the electric field. The resulting spray is electrically charged, and the droplets repel one another. For this reason, with a controlled environment we can reach a certain stable spraying mode as can be seen in the Figure 2.1.

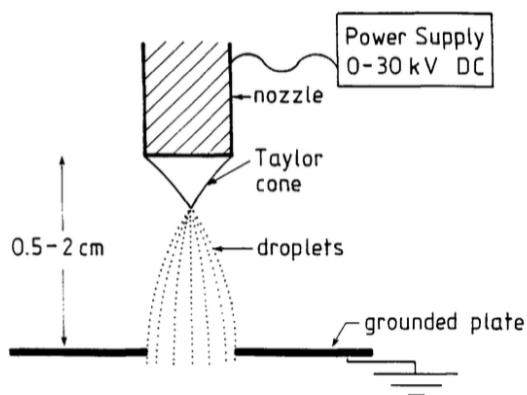


Figure 2.1: EHDA physical concept [3]

2.2 Non-visual classification

From the inception of EHDA until the present day, research has been carried out through manual means, involving the use of visual classification to determine the spraying mode either through cameras or by direct observation. It is advisable to employ a high-speed camera (HS) to accurately capture the spraying process as certain intermittent or dripping states may occur at a high frequency and be erroneously perceived as a stable condition. The setup in figure 2.2 shows the most common setup used for EHDA researchers.

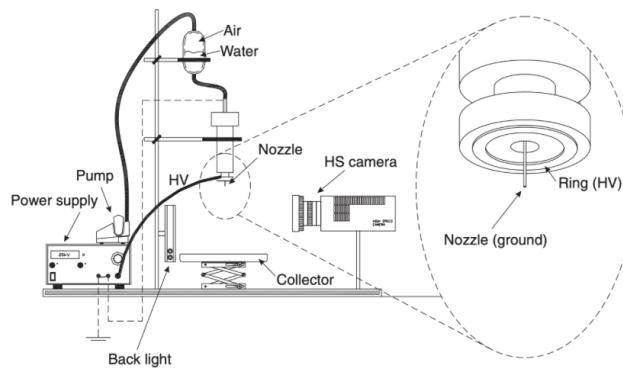


Figure 2.2: EHDA experiment setup [4]

Therefore, researches were made about the classification of the spraying mode measuring the current flowing through the nozzle to plate[2][8]. Evaluating the current data can give us valuable information about the spraying behavior. Figure 2.3 illustrate a sample of current measured in our system during a dripping of a charged liquid. We can visually identify the signal of two droplets generated in this time frame.

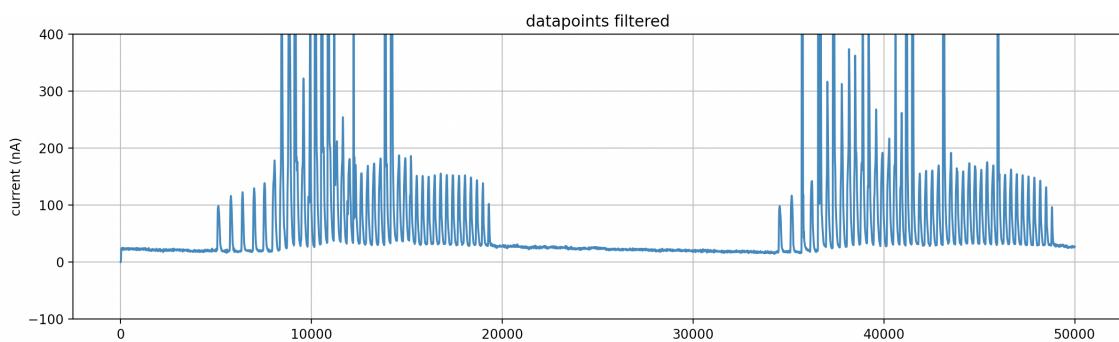


Figure 2.3: Current measurement sample of dripping spraying mode. This graph represents 0.5s sample.

The existing signal contains valuable data not only about dripping but also other modes of spraying, thus it can serve as a non-visual classifier. This report draws significant inspiration from Sjaak's[2] work, which identifies distinct statistical characteristics of electrical current for various spraying modes. A profound use of his method will be explained in section 4.1. Together with the current characteristics, visual observations and results from literature it was investigated whether generic trends are present that can be related to the actual spraying modes.

2.3 Scaling Laws

The electric spray current is a critical variable that has been extensively researched by multiple authors[1][8][5], resulting in scaling laws that express the relationship between liquid flow rate, conductivity, surface tension, density, and droplet diameter. These scaling laws can predict the size and charge of emitted droplets, making them useful tools for electrospraying practitioners. Obtaining scaling laws is necessary for characterizing an electrospraying system and gaining a better understanding of the process mechanisms. In equation 2.1 we have the current flowing through the charged liquid.

$$I = \left(\frac{\gamma K Q}{\kappa} \right)^{1/2} \quad (2.1)$$

2.4 Spraying modes

Since 1915 with his pioneering work in EHDA, Zeleny[9] 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[1] proposed spray mode classifications based in what they have seen experimentally, and it's still being used as basis for EHDA researches.

Figures 2.4, 2.4, 2.4 shows 3 spraying dynamics that we are most interesting in this project.

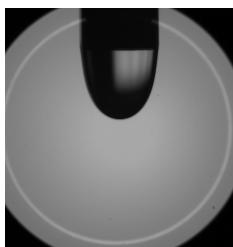


Figure 2.4: Dripping

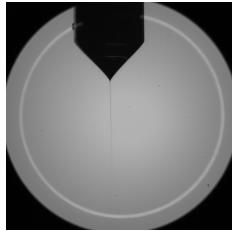


Figure 2.5: Cone Jet

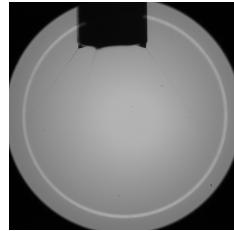


Figure 2.6: Multi Jet

Through the various classifications and sub-classifications of spraying defined in literature we are going to aggregate some of them and separate between 5 modes as referred below in order of growing electric potential:

2.4.1 Dripping

Dripping mode happens when the electric 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 capillary and low frequency intervals between each drop.

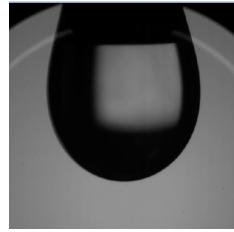


Figure 2.7: Dripping

2.4.2 Intermittent

Intermittent mode is defined when the electric field forces start to have a considerable effect in the meniscus and droplet formation. This mode can be identified by its pulsating manner. 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. Figures 2.4.2, 2.4.2 and 2.4.2 illustrates 3 different dynamics herein considered as intermittent.

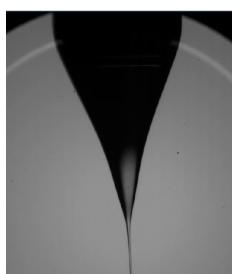




Figure 2.9: Intermittent



Figure 2.10: Microdripping

2.4.3 Cone Jet

Taylor (1964)[10] was the first to demonstrate that electrostatic pressure and capillary pressure can be balanced at any point on the surface of a liquid cone. The electrified meniscus can take on a conical shape within a certain range of applied voltage and injected liquid flow rate.

In Taylor cone, here referred as Cone Jet, the direction of the cone apex also varies depending on the balance of forces. With a fixed flow of liquid it is noticeable that the pointing direction curves and the meniscus reduce volume as we increase the electric potential until the moment the jet breaks into two or more jets going to the next classification.

Figures 2.4.3, 2.4.3 and 2.4.3 shows three cone jets in different circumstances.



Figure 2.11: Cone Jet



Figure 2.12: Cone Jet

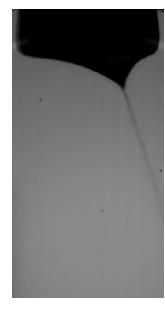


Figure 2.13: Cone Jet

2.4.4 Multi Jet

Zeleny's (1915)[11] paper was the first reference to multi-jet phenomena. In his experiments was observed: *"for voltages well above that for which the steady conical surface changed into a blurred agitated one, the appearance became a number of fine points with their attendant dark streaks arranged along the circumference of the raised edge"*.

In recent times, researchers have made significant advancements in understanding multi-jet technology and have identified various profiles with distinct characteristics. Because of that, some authors can divide what we call multi jet in more classifications. The multi jet mode is considered in this work when two or more spraying jets can be visualized in the HS camera and the current shows a stable profile. Figures 2.4.4, 2.4.4 and 2.4.4 shows three different variations of multi jet spraying mode.

C.N. Ryan (2012)[12] focused his work in multi jet spraying mode, and its current properties. He detected that for a low number of jets emitted, seen in figure 2.4.4 and 2.4.4, the meniscus is not bound to the rim of the capillary. This mode is seen to be less stable, in that each jet in multi-jet mode is unable to support the same volumetric flow as in the single jet mode.

As the number of jets increases the mode becomes what Ryan refers at rim-mode electrospray, seen in figure 2.4.4. In this work, all modes with more than one stable jet will be classified as multi jet.

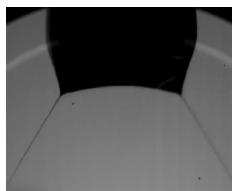


Figure 2.14: Multi Jet - double jet

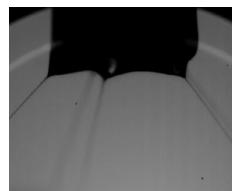


Figure 2.15: Multi Jet - low number of jets



Figure 2.16: Multi Jet - rim spraying mode

2.4.5 Corona

At even higher electric potentials, above of multi jet, the insulation between the electrodes start to breakdown, and we achieve a phenomenon of discharge. Those can be easily classified because of its high current value.

This mode is also divided by other classes such as streamer corona or transient sparks discharges, but it's not in the scope of this work. Mônicas[6] work was focused on how

to predict that mode with the current analysis for safety in industrial applications.

Chapter 3

System Description

In this chapter, we will discuss the equipment used in detail, including its integration and how it was modeled and implemented in both hardware and software. The python automation routine that is the focus of this project was started by a previous student[6], and the software itself was originally created as an electrospray multipurpose library [6].

3.1 Hardware model

3.1.1 Instrumentation

The main instruments used for this project are listed below:

- a) High Voltage Power Supply (HVPS)
 - brand: FUG
 - model: HCP35-20kV

The HVPS provides the electrical potential to the liquid, which can be applied by connecting the HVPS directly to the liquid feeding capillary or needle to a grounded electrode (usually a plate or a ring) located downstream.[6] The setup has the USB serial interface for controlling and polling measurements.

The software has an interface to integrate the HVPS to our routine. This interface can be found in *FUG_function.py* file where is located the functions used to control and collect data from this instrument. In case of change of equipment, a new interface must be created within this file to match another manufacturer specifications.

b) Wireless Oscilloscope

- Brand: *TiePie engineering*
- model: TiePie WifiScope WS6 DIFF

The signal analysis with an oscilloscope using WiFi technology allows an in-depth case study of the electric current signal. The current is measured via a TiePie WifiScope WS6 from TiePie engineering that is a battery powered oscilloscope capable of transmitting data via a WiFi connection allowing it to be placed in the high voltage or ground path.

Wireless communication allows us to make measurements disconnected to an external power supply, which gives us more safety when using high voltage potential references and also reduce the signal noise collected from external power lines. The current is routed directly via the input, hence the oscilloscope measures the voltage dropped via its input resistance (which can be switched between 1 or 2 Mohms). TiePie WifiScope WS6 has a resolution of up to 16 bit at a minimal input range of 200 mV, sufficient to measure currents down to 1 nA.

The interface with the software was made using the TiePie Library[13] and can be found in *configuration_tiepie.py*. Note that is also important to have the *print_info.py* file in the project folder in order to work.

c) Humidity and Temperature sensor

The stability of the system is affected by many physical effects. Evidently having the more parameters analyzed favors the system control. The surface tension force is dependent of the liquid-gas interface on the meniscus. Hence, the surrounding gas must be constantly the same and so its humidity. Also, temperature is a variable that interfere in many phenomena in the system. Specially the liquid properties such as viscosity.

For that, a standard microcontroller development board (*Arduino Uno*) with a temperature and humidity sensor (DHT11) was configured to add that data in real time in the routine. The Arduino code can be found in the */peripherals* folder.

d) High Speed Camera

- Brand: *Photron*
- model: Photron fastcam mini

e) Syringe pump

- Brand: *Master dual*

- model: WPI AL-1000

The pump integration in the automation algorithm brings us a new controllable variable, the Flow rate. Now we can control the spraying mode with the two main variables that affect the system. It will bring more complexity for the system since now we are dealing with multivariable control. Controlling also the flow rate gives to this project a new dimension in the system giving us freedom to explore the flow rate properties. With this new input variable our control is a MISO (Multiple Inputs Single Output) system.

About the pump interface. As I could not find a good ready-to-use library for this pump I developed a 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.

In figure 3.1 we illustrate a diagram with all the key components of our system. The peripherals are connected to a computer running the software routine via serial communication. This diagram encapsulates our process system and will be used as a sub-system in our control model. The input of our process system are power supply voltage and pump machine flow rate, referred here as the controller values. The output is the oscilloscope current sample.

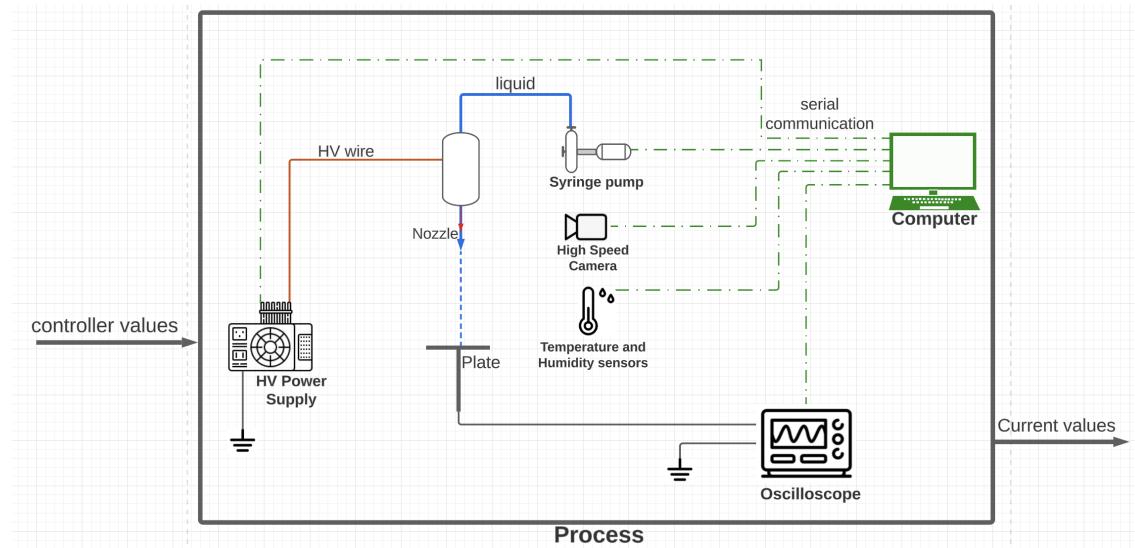


Figure 3.1: EHDA automation system setup

There are also many minor variables that affects the experiment stability. More details are explained in B.1.

3.2 Software Model

The software was reformulated on top of the control model represented in figure 3.2. The process of the control loop is the same as represented in 3.1. Each other subsystem in the control loop is a separate thread that will be explained below.

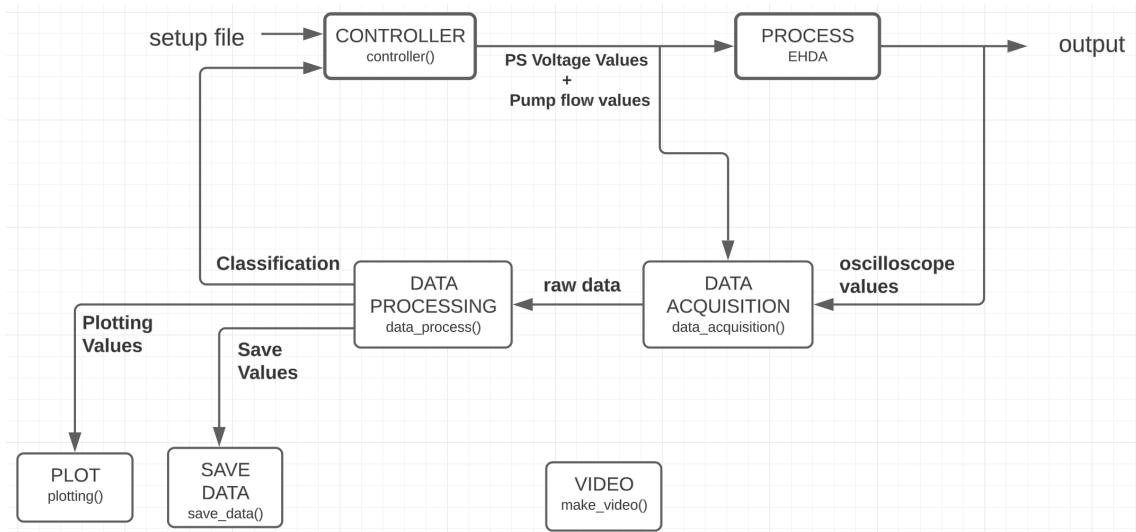


Figure 3.2: EHDA automation system setup

3.2.1 Threading and Queues

In order to implement this closed loop control model to the software and explore parallel processing, each sub-system was implemented as a separate Thread. For concurrency on flux of data between 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.

3.2.2 Controller Thread

It is responsible for sending the power supply set voltage values and the syringe pump the flow rate set values according to the sequence selected. Also, responsible for 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 *controller_output_queue()*.

3.2.3 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 power supply, flow rate from the pump and concatenate into one sample data. As output, we have the values in the *data_queue()*.

3.2.4 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 *save_data_queue()*, *plotting_queue()* and *feedback_queue()*.

3.2.5 Save Data Thread

After 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 streaming 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 data acquired in each sample of 0.5s is shown in figure 3.3.

```

"sample 0": {
    "name": "setup/liquid/ethanol",
    "current": [...],
    "flow_rate": "0.97",
    "voltage": "4001.62",
    "current_PS": "-2.79252e-09",
    "temperature": "0",
    "humidity": "16.0",
    "date_and_time": "2023-03-16 14:26:53.012518",
    "target_voltage": 4000,
    "mean": 18.687360763549805,
    "variance": 506.2657470703125,
    "deviation": 22.500349044799805,
    "median": 9.559748649597168,
    "rms": 29.248645782470703,
    "spray_mode": "Intermittent"
},

```

Figure 3.3: Output data json structure

This new way of saving the measurement and processing data altogether separate by enumerated samples prevents loss of data in case of error during experiments and, specially improve in the usability of the data for further deep analysis. One experiment of around 1 hour collects around 6 GB of data. Organizing that amount of data to make it fast and easy to use was an important improvement in the software. To work and analyze the data we can use pandas Data frame. A python widely used framework for data analysis. With the command:

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

It will construct a Data frame with all data organized by samples.

To conclude, json files are good as a system output because of its human readability. But as the database gets bigger json becomes to be a slow to read and heavy way to store the data. For that, saving the data frame in a compressed type of file called feather is much faster to work with the data.

3.2.6 Video Thread

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

3.2.7 Plot

The only running function that is not a thread because of the plotting library *matplotlib* incompatibilities of running outside the main function. It is responsible for plotting in real time the current sample acquired, and its respective fast Fourier transform to evaluate the sample frequency spectrum. It takes as input the *plot_data_queue* from the *processing_thread()* and displays three graphs updated in real time on the screen during the experiment.

3.3 Chapter conclusion

In this chapter we described the system description detailing the hardware instruments, how it was modelled and its implementation in the software. Figure 3.4 shows a print screen of the user interface during an experiment.

3.3. CHAPTER CONCLUSION

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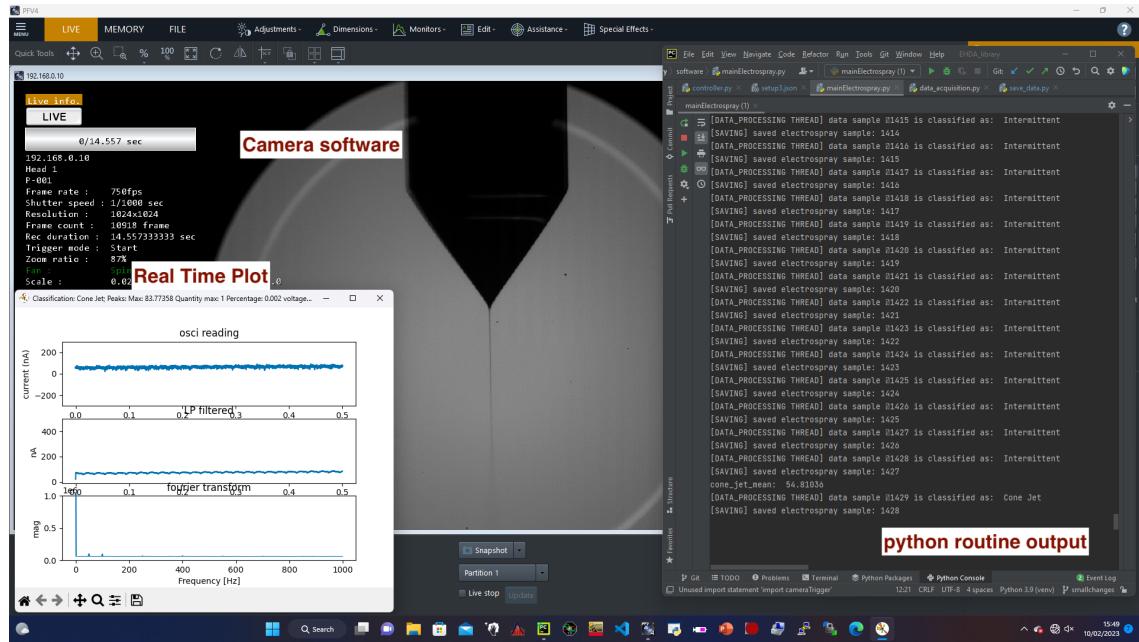


Figure 3.4: EHDA automation system setup

Chapter 4

Methodology

This chapter is about describing the methodology and developments to achieve the project goals. Firstly, I begin by elaborating on the workings of the classification process in the processing thread. Moving on, I will then delve into the operational sequences of the controller thread. Lastly, I will provide an explanation on the implementation of the controller.

4.1 Classification

The classification is a key step in our routine. For being able to be used in multipurpose applications our classification routine must be able to run in real-time. Which means it must be fast and automatic classification. Our goal is to improve and apply in our routine different approaches of non-visual spraying classification using the current data collected from the system.

4.1.1 Statistical Analysis

In Sjaaks[2] work, the author exposed signal characteristics that can be used to classify the actual spraying mode with a sample of measured current using both time and frequency domain analysis. We acquire the current data frame of 0.5s with 100 KHz as sampling frequency. With that each current sample as 50 thousand current values. Through statistical analysis in these values such as mean and standard deviation we apply in our automatic classification the relative standard deviation. Which is referred as the sample standard deviation divided by the sample mean values. Figure 4.1

illustrate data samples being classified using Sjaaks method.

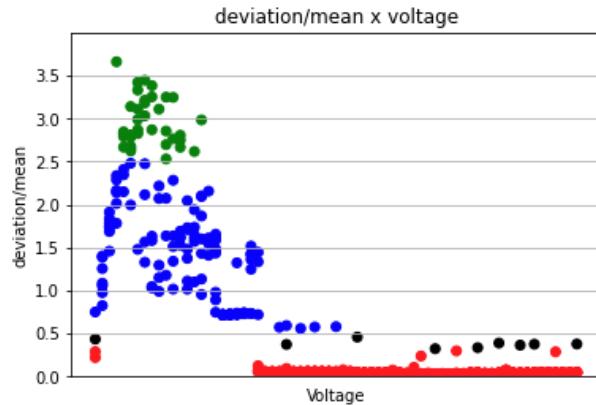


Figure 4.1: Sample classification using statistical values. Colors: Green = Dripping; Blue = Intermittent; Red = Cone Jet

This classification by statistical analysis was already implemented in the software library made by the previous student [6]. This method was capable of only classifying dripping, intermittent and cone jet modes. Also in her work, Monica extended the classification to corona or discharge detection. My contribution was to integrate her work on my control loop model and extend the classification for the multi jet.

To classify the multi jet, after running many steps experiments as shown in figure 5.4 I noticed that the multi jet signal has a similar shape as the cone jet but with a step in its current mean. I also noticed that the cone jet current was almost fixed all its spectrum. These effects were exposed by Ryan[12]. In his work he defines the relation between current per jet in both cone jet and multi jet modes.

With that, I implemented the classification of the multi jet when the current mean is 1.14 above the expected cone jet current mean. The cone jet current can be calculated by the scaling laws^{2.3} formula. The value 1.14 was found by repeating a lot of experiments with the same liquid, but varying the flow rate and the voltage. This means this value is just defined for pure ethanol, the liquid used in all those experiments. The classification in the algorithm was divided in three steps as shown below. The algorithm is shown in 1.

- 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:

Algorithm 1 Statistical Classification

```

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

```

4.2 Routine Sequences

The program developed is capable of running different types of routines. The code is also easy to implement new routines. Continuing the methodology, in the setup json file there is a "sequence" attribute which can be chosen between "ramp", "step", "map" or "control". The controller thread will manage what the algorithm must do for each sequence. Following our control model 3.2, the controller outputs are the actuators signal. The sampling rate is fixed to 0.5 seconds for all the experiments, and it's managed by the data_acquisiton thread 3.2.3.

4.2.1 Ramp

The ramp sequence is simply done by sending one command to the power supply to perform a ramp in the voltage with initial, final and slope values. The flow rate for this sequence is constant, and the experiment consists in a voltage range scan.

4.2.2 Step

The step sequence is done by the same command send to the power supply but with the maximum slope value in order to proximate of a step signal. By waiting a certain defined *step_time* and repeating the command in a loop until it gets into the final voltage. This algorithm is represented in 2.

Algorithm 2 STEP sequence in controller thread

```

procedure STEP(voltage_start, voltage_stop)
    voltage  $\leftarrow$  voltage_start
    while voltage  $\leq$  voltage_stop do                                 $\triangleright$  scanning voltage range
        SEND_VOLTAGE_COMMAND(voltage)
        SLEEP(step_time)
        voltage  $\leftarrow$  voltage + step_size
    end while
end procedure

```

4.2.3 Map

The map that will be explained below is the most relevant sequence in this work. This type of experiment saves human work and time, create a precise analysis and can be compared with previous works for validation of methodology. The purpose is to map the operational window, seen in Figure 4.4, that can be defined where the spraying mode can be stabilized based on the flow rate, voltage and the setup configuration.

The map was inspired in Gañan-Calvo[5] work where he points how liquid conductivity influences the cone jet stability island.

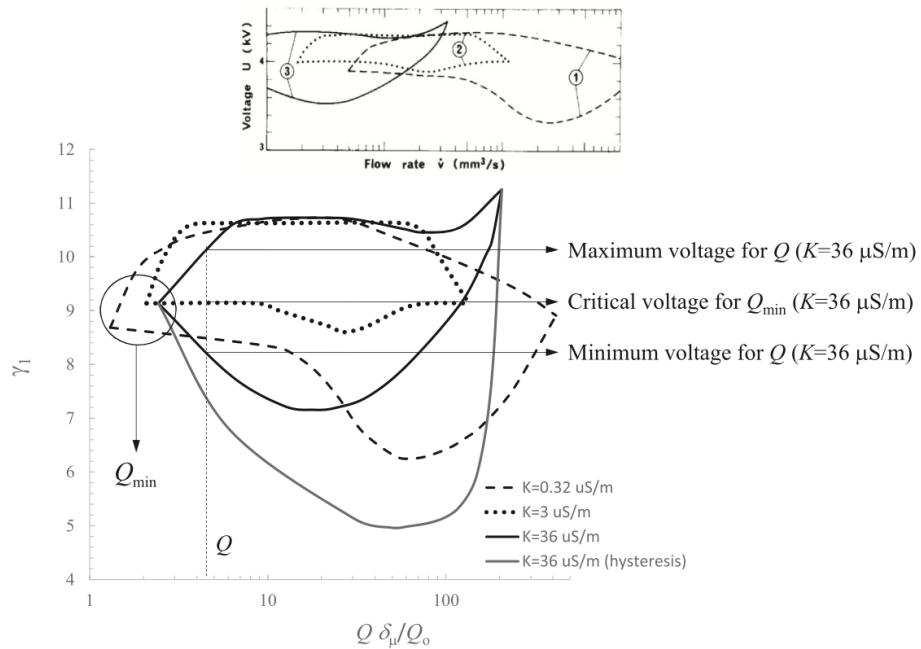


Figure 4.2: Domains of existence (stability) of Taylor Cone Jets. [5]. The window formed by these points is where the system operated in the stable cone-jet. Operational windows depend of the liquid and configuration setup. Different windows are represented for different liquid conductivity. The X and Y axis are non-dimensional representation of electric potential and liquid flow rate, respectively.

To reach certain map it is necessary to traverse flow rate and voltage values acquiring samples. The flow rate (X axis) and voltage (Y axis) values for each experiment can be configured in the setup.json file. The algorithm for this sequence is a loop of the step sequence 4.2.2 for each flow rate chosen. It is represented in the algorithm 3.

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 ← voltage_start
        while voltage ≤ voltage_stop do                      ▷ scanning in the voltage range
            SEND_VOLTAGE_COMMAND(voltage)
            SLEEP(step_time)
            voltage ← voltage + step_size
        end while
    end for
end procedure

```

In Figure 4.3 we can see the data acquired in this mapping experiments. The liquid used is pure ethanol. Note that the experiment is composed of loops that increase

voltage, change flow rate and repeat.

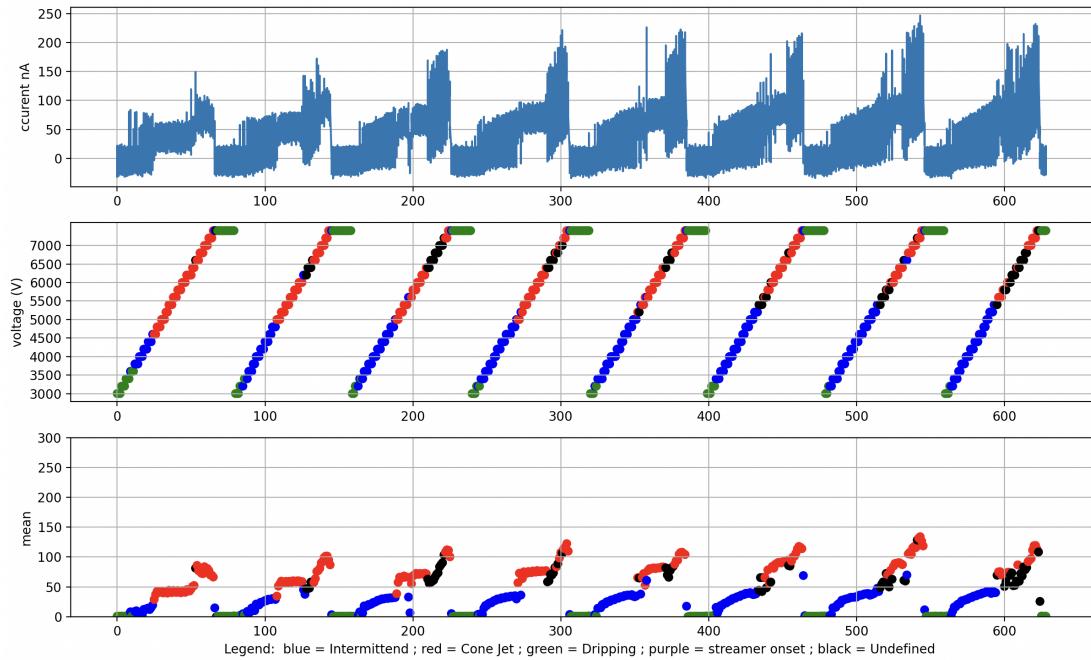


Figure 4.3: Mapping Experiment data collected. The figure has 3 graphs with shared x axis representing the samples collected. The first is the current values collected through all the experiment. The second is the voltage values applied in each window of data collected. The colors represent the spraying classification defined by our routine. The third graph shows the current mean value of each data sample.

With all the data collected, classified and saved in real time, we can do further analysis and studies. For example, Figure 4.4 illustrate the data classified by our algorithm and displayed in a Voltage X Flow rate range of spraying modes with a specific liquid setup so that we can compare the automatic results with previous researches, such as showed in figure 4.2 and validate the algorithm.

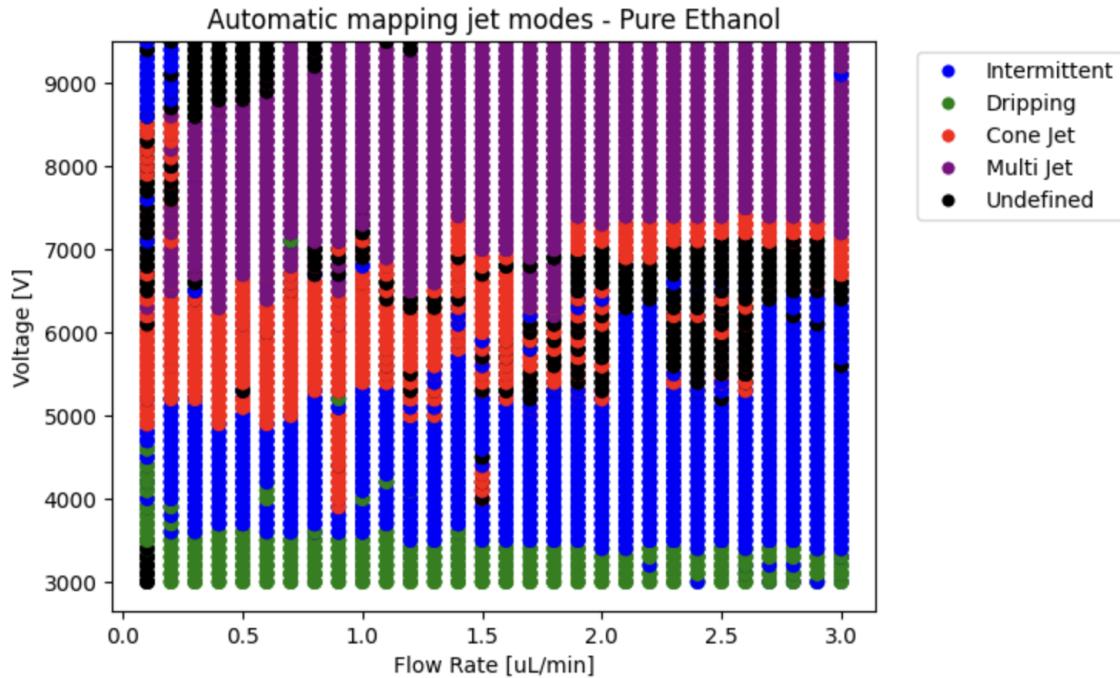


Figure 4.4: Mapping Experiment for pure ethanol in ambient conditions with our capillary setup. The map shows the stability region of each electrospraying mode in the voltage and flowrate range.

4.2.4 Control

The control sequence is the only from our list of sequences that actually uses the feedback classification value. As it is a closed loop control system the controller must be able to stabilize the system in the desired conditions. A simple controller algorithm is represented in 4, and it was used as a proof of concept.

4.2.5 Simple Controller

Algorithm 4 simple controller

```

function CONTROLLER(spray_mode)
    if spray_mode = 'Intermittent' or spray_mode = 'Dripping' then
        SEND_VOLTAGE_COMMAND(voltage + 100)
    else if spray_mode = 'MultiJet' or spray_mode = 'Corona' then
        SEND_VOLTAGE_COMMAND(voltage - 100)
    else if spray_mode = "ConeJet" then                                ▷ Keep Stable
        end if
    end function

```

4.3 Chapter conclusion

Chapter 5

Results

In this chapter, we will present the results obtained from our project. Firstly, we will demonstrate how the automation routine enhanced the research experiments. Next, we will discuss the validation of the classification results. Finally, we will showcase the performance of the implemented controller algorithms.

5.1 Automation routine

The automated experiment routine is capable of acquiring a significantly more precise and extensive amount of data than what can be achieved by a human. With the save data by streaming in saving thread^{3.2.5}, we achieved less program memory during the experiment and, specially, safety for not losing the data in case the program fail during an experiment.

Also, most power supplies rely on manual potentiometer adjustment to select the set point, which results in imprecise potential selection by a person. Moreover, manual adjustment takes some time to achieve the desired voltage. By running a computer routine that automatically sends commands to the power supply and pump machine we can achieve faster and more reliable experiment data points.

The visual interface for the user, seen in figures 5.1 and 5.2, shows all the important sensor data and signal analysis that can be interesting to the operator in real time.

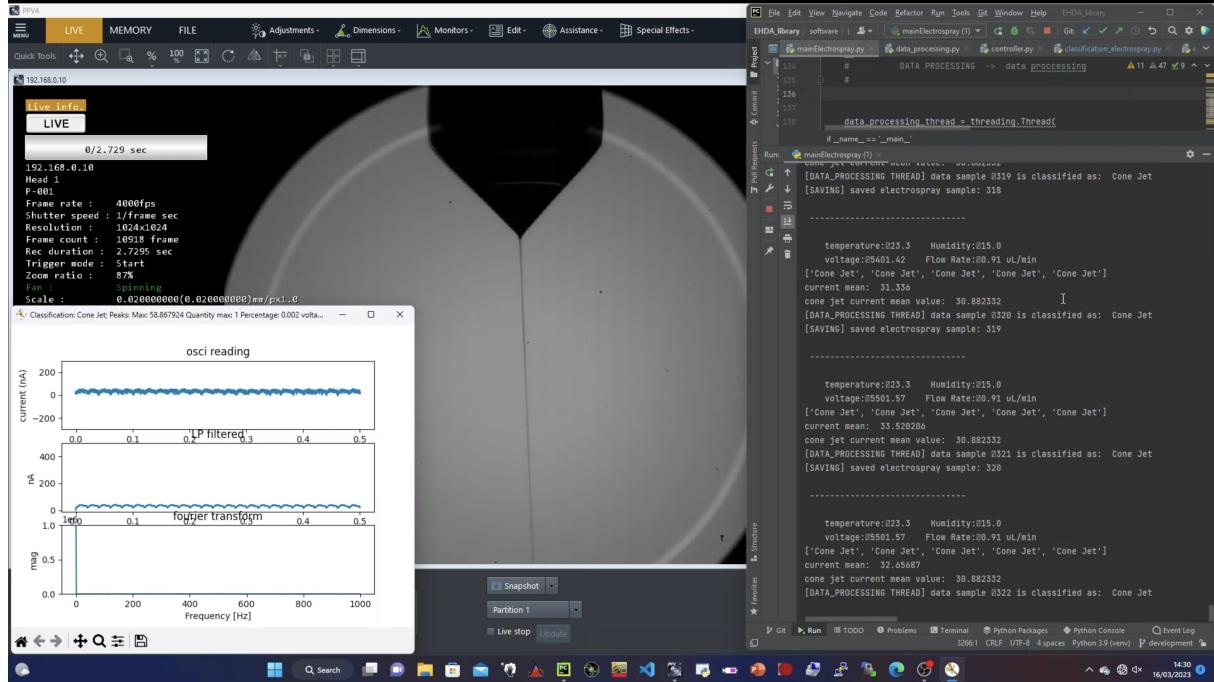


Figure 5.1: Print screen of the window shows user interface during the experiment. We can see the image generated by the camera in the background. The routine code running in pycharm software on the right side. And also real time signal plottings of the current data on the left side.

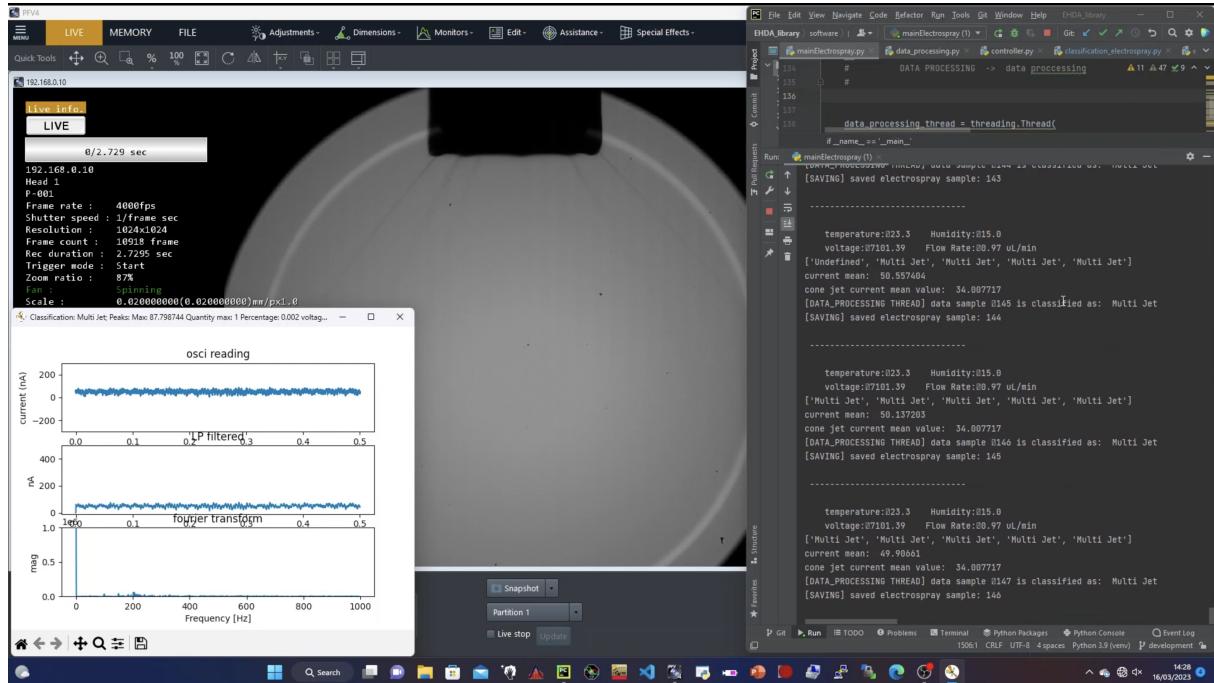


Figure 5.2: Print screen during an experiment. At this moment we are in Multi Jet spraying mode. At the left we can see the current signal has a smooth and constant curve. We can also see the automatic classification on the right side.

5.2 Classification

The classification results in our algorithm implemented as described in section 4.1 showed good accuracy for all the classifications described in section 2.4. Nevertheless, the multi jet classification made by a current value factor of 1.14 above the cone jet is just effective for pure ethanol, liquid used in all this project.

Even if the multi jet classification just works for pure ethanol, the data saved with correct classification in ethanol can be used to extract any other signal information about the multi jet or to train a black box classification algorithm.

5.2.1 Step Sequence

Our first classification results were made exploring just the voltage ranges. For that stabilized all the other parameters such as humidity, temperature and external noise. First, we fixed a flow rate to 0.7 $\mu\text{L}/\text{min}$. and ran a step routine as defined in 4.2.2. The figure 5.3 shows the step voltages during the experiment and figure 5.4 illustrates the raw data acquired with it. In figure 5.5 we see the same experiment data classified by spraying mode and separated by color.

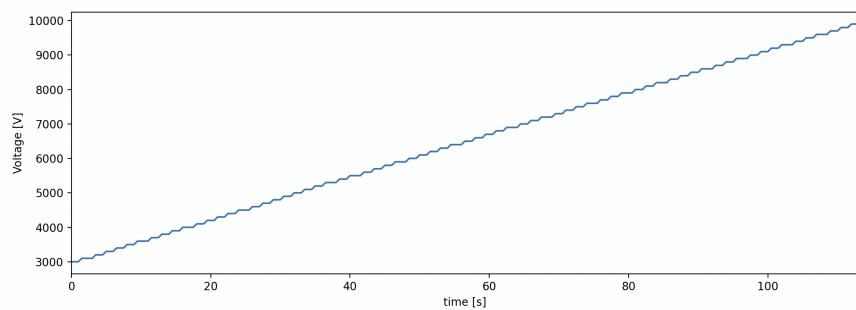


Figure 5.3: Input voltage step graph. The range is between 3K-10K Volts. Step size of 50V and step time of 5 seconds.

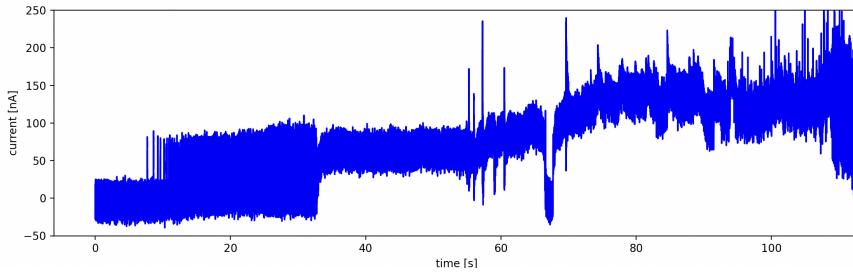


Figure 5.4: Output raw data collected in the voltage range experiment showed in 5.3. The sampling rate of the oscilloscope is 10KHz. This graph has 1.5 Million data points.

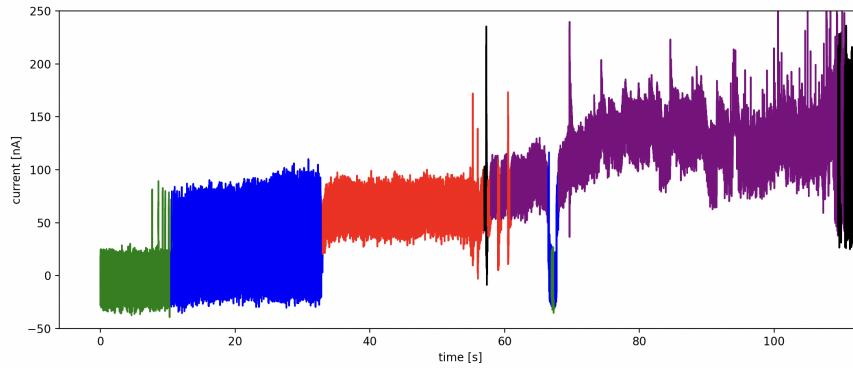


Figure 5.5: The same graph as 5.4 but after the classification procedure. The colors are green: Dripping, Blue: Intermittent, Red: Cone Jet, Purple: Multi Jet and Black: Undefined.

The graph of voltage scan as showed in 5.4 has a common shape for different liquids and parameters. After having familiarity with it is even possible to classify the spraying modes by visual analysis. For example: Dripping mode has a current mean of 0V. The Intermittent state has a high variation of values that can be seen by the thickness of the graph. The Cone jet is a thinner graph because the signal is more constant. The Multi Jet is the same as Cone jet graph but with a higher mean value than cone Jet. Corona sparks are not showed in the graph because the discharges has a high current value and will be above the axis limits.

5.2.2 Map Sequence

For validation with literature and also to expose the benefits of the automated routine and classification the map sequence proof itself the best result of this work.

Firstly, for better understand the spraying dynamics, manual experiments were done. Figure 5.2.2 shows the stability region of different spraying mode for pure ethanol in

the range of voltage and flow rate.

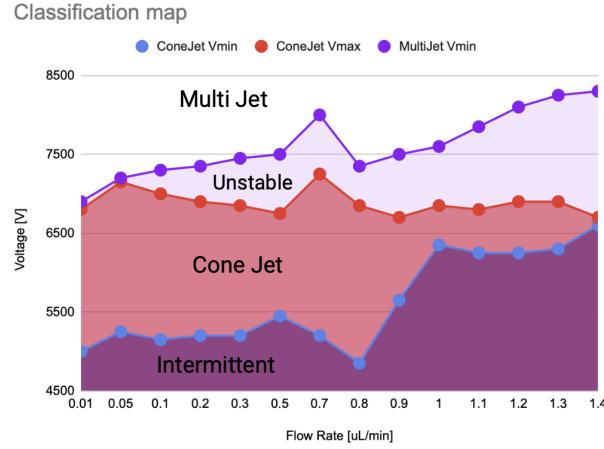


Figure 5.6: Spraying modes regions of pure ethanol

For validation of the automatic classification experiments were made comparing both manual and automatic classification. In figures 5.7 and 5.8 we can see that the cone jet stability island has a similar shape in both manual (fig. 5.7) and automatic (fig. 5.8) data collected in the same experiment.

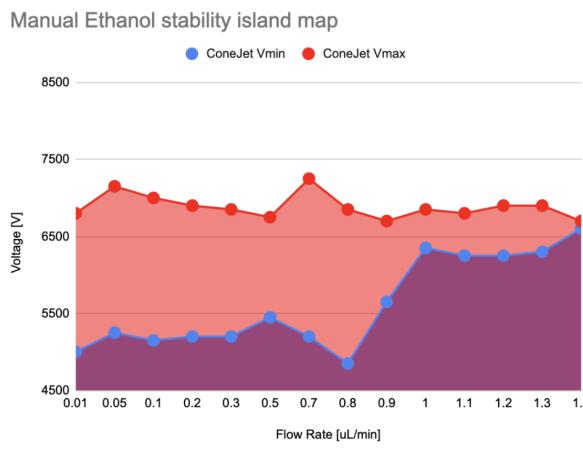


Figure 5.7: Cone jet island manual experiment 1

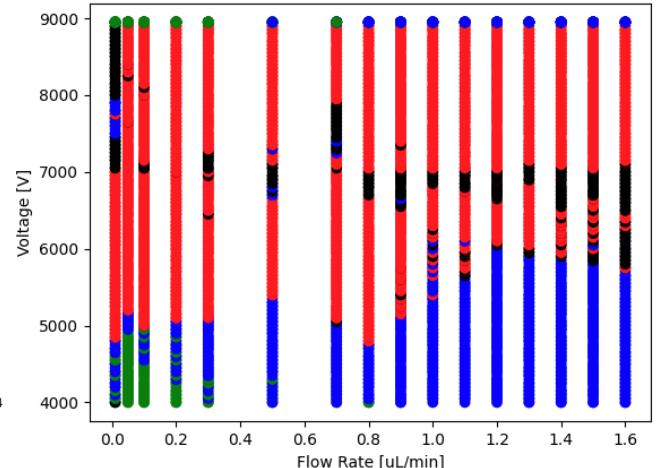


Figure 5.8: Cone jet island automatic experiment 1

We can see in figures 5.9 and 5.10 another experiment with the same liquid and a comparison on manual (visually by the high speed camera) and automatic classification.

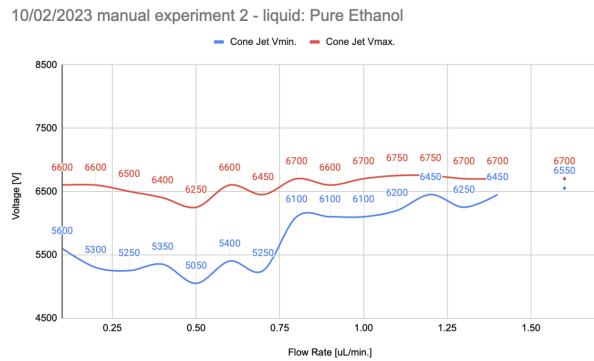


Figure 5.9: Cone jet island manual experiment 2

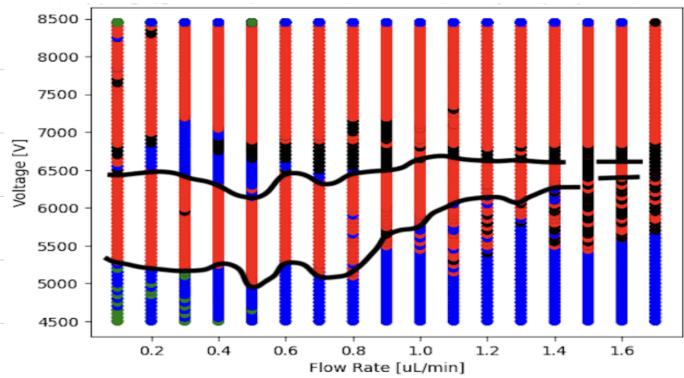


Figure 5.10: Cone jet island automatic experiment 2

We can see in figures 5.11 and 5.12 the same experiment and results as above, but with the Multi Jet classification that was a new feature in the software.

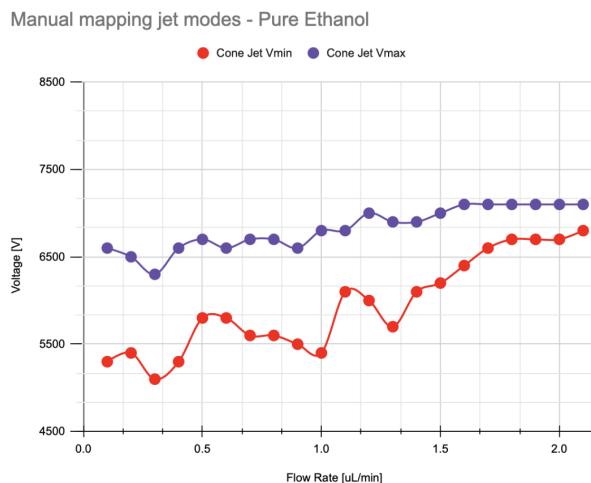


Figure 5.11: Cone jet island manual experiment 3

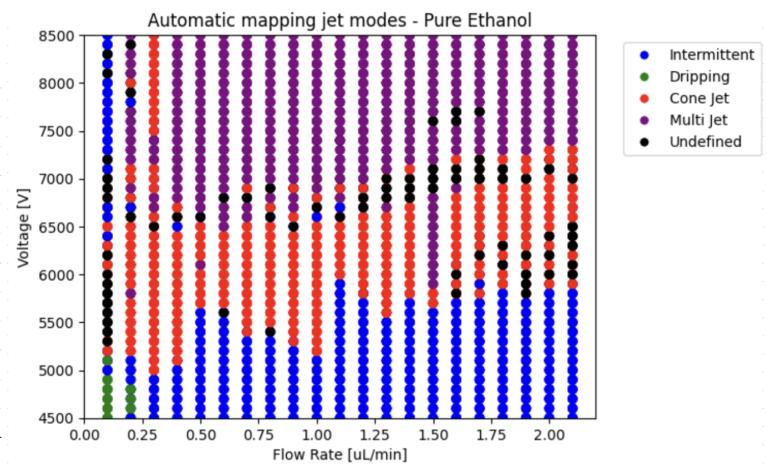
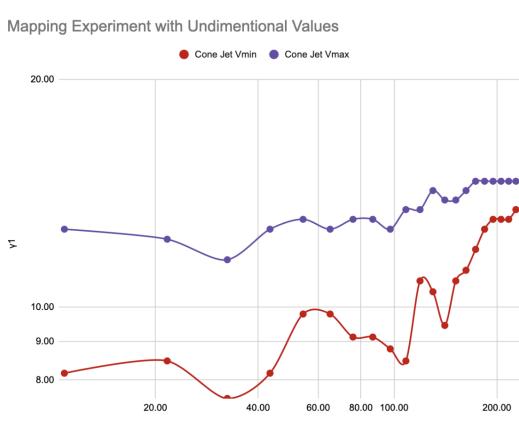


Figure 5.12: Cone jet island automatic experiment 3

Non-dimensional axis

To compare with the literature and validate the algorithm we decided to display the data using the non-dimensional numbers used in figure 4.2.



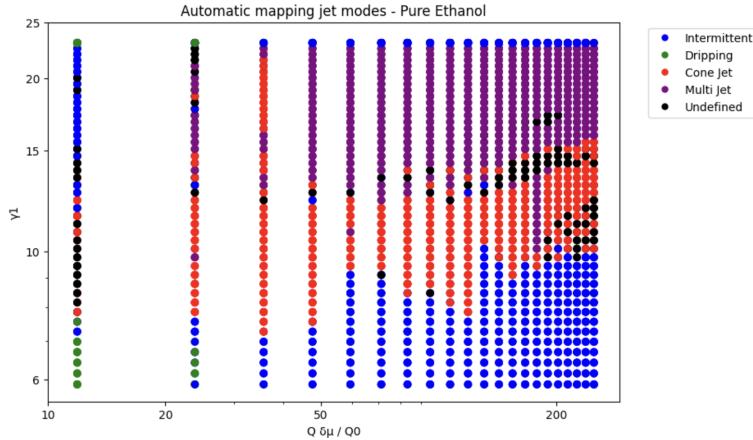


Figure 5.14: Cone jet island automatic experiment 4

5.3 Controller

The results of the classification process were favorable for experiment automation, however, they may not be as effective for optimal performance of the controller. The inaccuracy of the classification by statistical method in addition with the amount of variables that need to be syntonized for stabilize in cone jet or multi jet makes it hard to control this process.

Of particular interest in applications is the cone-jet mode, where the meniscus emits a steady microscopic jet, resulting in uniformly sized droplets.

Flow rate perturbation robustness test

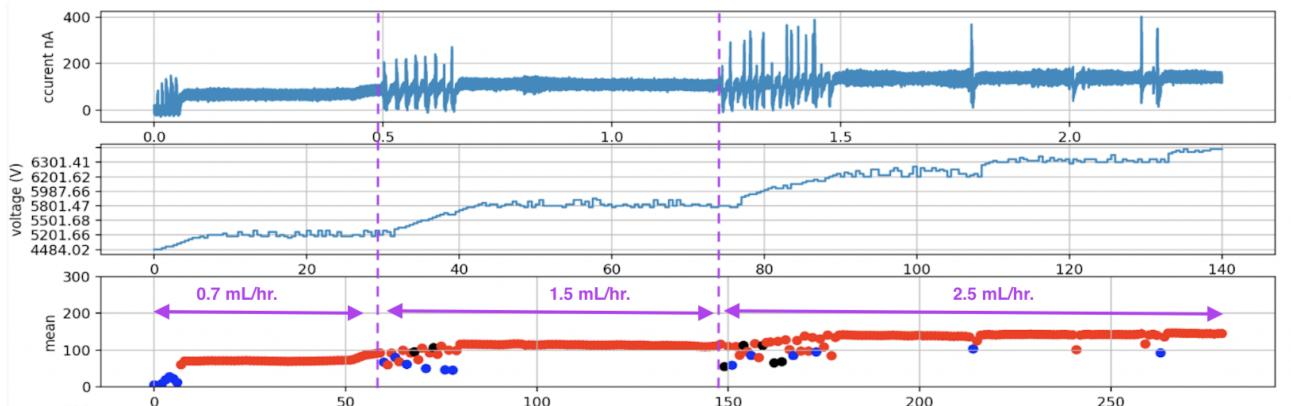


Figure 5.15: Simple controller validation experiment. For this experiment we waited the system to stabilize in the desired spraying mode. After that we made a perturbation robustness test changing the flow rate.

5.3.1 Robust Controller

Chapter 6

Conclusion

In conclusion, the implementation of a Python routine for complete automation and integration of the system has improved the precision of experiments and enabled real-time collection of extensive data without requiring the expertise and time of a specialized scientist. This project underscores the potential of automation in enhancing scientific research and accelerating progress towards achieving research goals. In addition to its potential in scientific research, the software developed in this project can also be leveraged by industrial approaches. Furthermore, the classification methods and system control implemented in this project have yielded promising results and can be further optimized in the future. Overall, this project serves as a contribution towards the advancement of automated systems and the optimization of experimental processes.

6.1 Proposal for continuing

To continue, my proposal would be to prioritize the improvement of the classification step. Ideally, we could use machine learning or another algorithm to ensure accurate classification of individual data samples.

By achieving a reliable classification, we can then implement more effective controller logic or approaches. In this regard, I would like to present the concept of a fuzzy controller as a potential solution.

To finish, I would propose a final investment in the system portability so that it can be applicable in remote applications.

6.1.1 Machine Learning

6.1.2 Fuzzy Controller

One challenge in implementing the controller is that we do not have continuous feedback. Instead, the feedback from the controller loop is a classification, which makes it difficult to apply many of the principles of control theory that are designed for continuous control. As this project involves logical control, it requires a different approach.

The fuzzy approach is an attempt to quantify the classification and fit different control models.

For that, I fuzzyfied the controller input with the data acquired in an experiment of step routine 4.2.2. With the data, I mapped the area of each spraying mode according to its potential as shown in the Figure 6.1. Figures ?? and ?? shows the steps of fuzzyfication and defuzzyfication between the input and output of the controller.

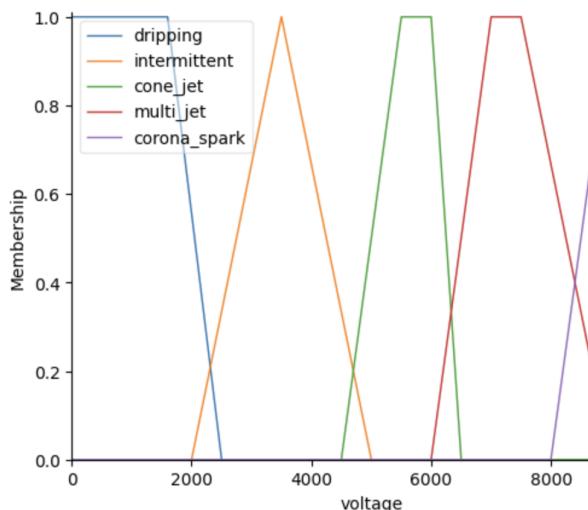


Figure 6.1: Fuzzyfication of the voltage input

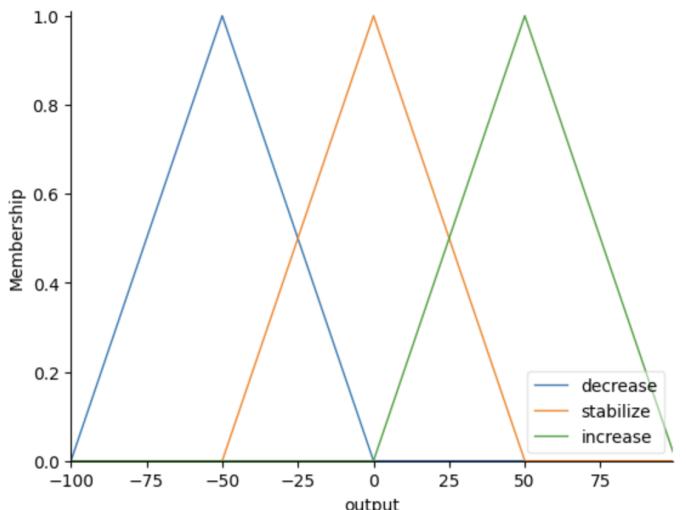


Figure 6.2: Defuzzyfication of output

Our controller is a machine that calculate the output with a geometrical calculus on the membership functions of the input and output according to our rules. The rules are listed below.

Fuzzy Rules:

- > IF dripping THEN increase
- > IF intermittent THEN increase

- > IF cone jet THEN stabilize
- > IF multi jet THEN decrease
- > IF corona THEN decrease

For testing the concept I've showed two possible states where the voltage is below the necessary to stabilize in cone jet and when is above that voltage. We can see in figures 6.4 and 6.3 that each test the output was either increase or decrease the actuator signal.

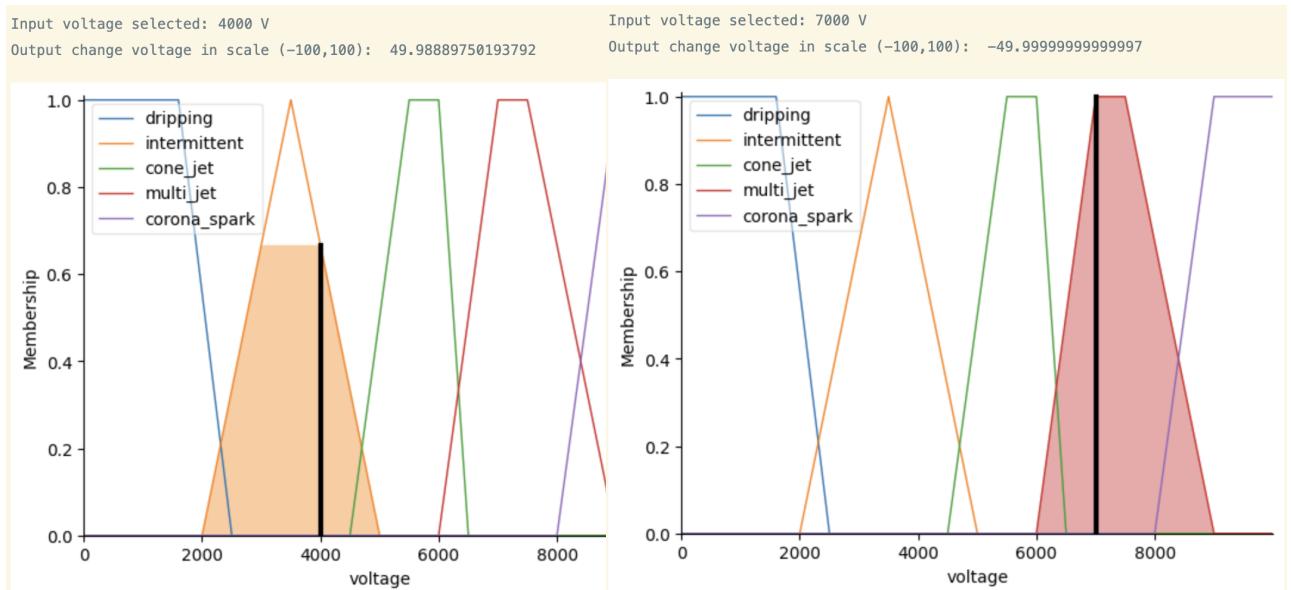


Figure 6.3: Test 1: fuzzy controller. Input voltage 4000 V the controller output to increase the voltage.

Figure 6.4: Test 2: fuzzy controller. Input voltage 7000 V the controller output to decrease the voltage.

Note that, for this method to work it is needed to run a step sequence to scan the cone jet stability island. With that data, create the input membership function. Then, run the controller routine in fuzzy mode.

6.1.3 System Portability

Raspberry Pi

6.2 Final Discussions

The works therefore presented here are a continuation and optimization of the routine to make it more precise and applicable to both industrial and research approaches. The previous student work was focused in predicting corona streamers or spark discharges, therefore her automation routine was a first version concept that proved to be valuable. From the development done by me, it highlights the results:

- Integrate liquid pump to the software and developed a routine with it.
- Modeled the software to fit a control model turning it easy to implement new control algorithms or experiment routines.
- Remodel the software to support threads in order to separate each subsystem and exchange data between them with use of queues data structures.
- Developed a classification for multi jet spraying mode.
- Developed a simple controller to proof the concept.
- Optimize the saving of data to a real time streaming together with more sensors' data.
- Restructured algorithm usability in order to make it more intuitive with the setup file.

References

- [1] CLOUPEAU, M.; PRUNET-FOCH, B. Electrohydrodynamic spraying functioning modes: a critical review. *Journal of Aerosol Science*, v. 25, n. 6, p. 1021–1036, 1994.
- [2] VERDOOLD, S. et al. A generic electrospray classification. *Journal of Aerosol Science*, Elsevier, v. 67, p. 87–103, 2014. ISSN 18791964. Disponível em: <<http://dx.doi.org/10.1016/j.jaerosci.2013.09.008>>.
- [3] MEESTERS, G. *Mechanisms of droplet formation*. Tese (Doutorado) — TU Delft Faculty of Applied Sciences, Netherlands, 1992. Disponível em: <<http://resolver.tudelft.nl/uuid:b6a2a7ad-8332-4e46-a65e-c15561037a26>>.
- [4] AGOSTINHO, L. L. et al. Morphology of water electrosprays in the simple-jet mode. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, v. 86, n. 6, p. 1–9, 2012. ISSN 15393755.
- [5] GAÑÁN-CALVO, A. M. et al. Review on the physics of electrospray: From electrokinetics to the operating conditions of single and coaxial taylor cone-jets, and ac electrospray. *Journal of Aerosol Science*, v. 125, p. 32–56, 2018.
- [6] EMEDIATO, M. *Spark Detection And Prevention Device For Electrohydrodynamic Atomization Applications*. [S.l.], 2022.
- [7] GRACE, J.; MARIJNISSEN, J. A review of liquid atomization by electrical means. *Journal of Aerosol Science*, v. 25, n. 6, p. 1005–1019, 1994.
- [8] CHEN, D. R.; PUI, D. Y. Experimental investigation of scaling laws for electrospraying: Dielectric constant effect. *Aerosol Science and Technology*, v. 27, n. 3, p. 367–380, 1997. ISSN 15217388.
- [9] ZELENY, J. The electrical discharge from liquid points, and a hydrostatic method of measuring the electric intensity at their surfaces. *Physical Review*, APS, v. 3, n. 2, p. 69, 1914.

- [10] TAYLOR, G. I. Disintegration of water drops in an electric field. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, The Royal Society London, v. 280, n. 1382, p. 383–397, 1964.
- [11] ZELENY, J. On the conditions of instability of liquid drops, with applications to the electrical discharge from liquid point. In: *Proc. Camb. Phil. Soc.* [S.l.: s.n.], 1915. v. 18, p. 71–83.
- [12] RYAN, C.; SMITH, K.; STARK, J. Characterization of multi-jet electrospray systems. *Journal of Aerosol Science*, v. 51, p. 35–48, 2012.
- [13] LIBTIEPIE SDK Python. <https://www.tiepie.com/en/libtiepie-sdk/python>. Accessed: 2023-03-31.

Appendix A

Trials and failures

A.1 Machine Learning

I've tried to create a database with the samples of current. Each sample was a vector with 50k values corresponding a 0.5s of data collected in a 100KHz oscilloscope. And in a second column its

A.1.1 Neural Network with raw data

A.1.2 Spectrogram analysis

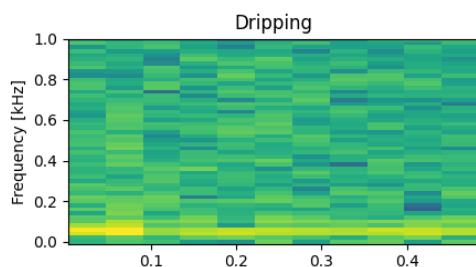


Figure A.1: Dripping

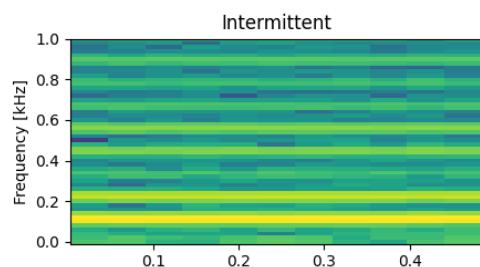


Figure A.2: Dripping

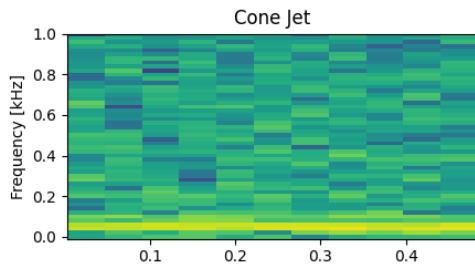


Figure A.3: Dripping

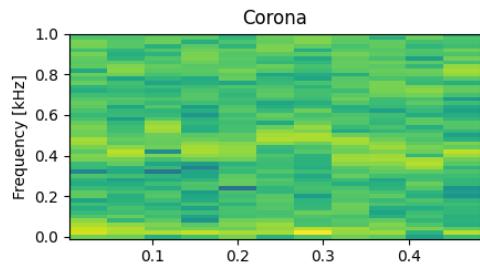


Figure A.5: Dripping

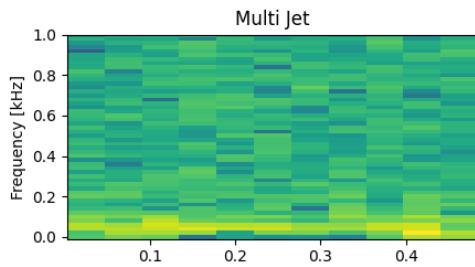


Figure A.4: Dripping

Appendix B

Details

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

put here the stability difficult about doing experiments

- syringe pump inclined - pumping liquid to avoid bubbles - mechanical noise in the pumping machine - external electrical noise collected by antennas or connections

Foto e detalhes dos instrumentos

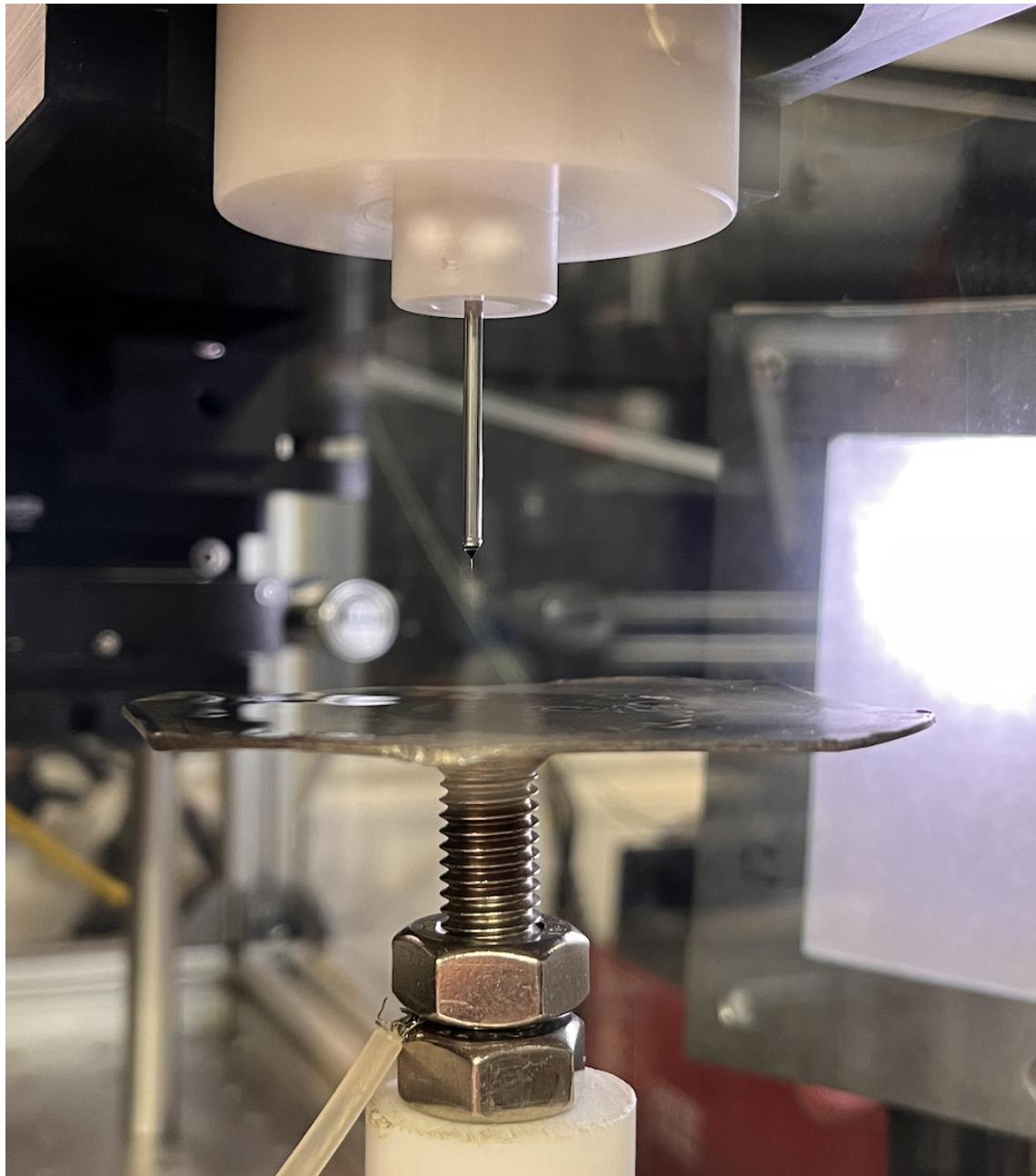


Figure B.1: EHDA physical concept

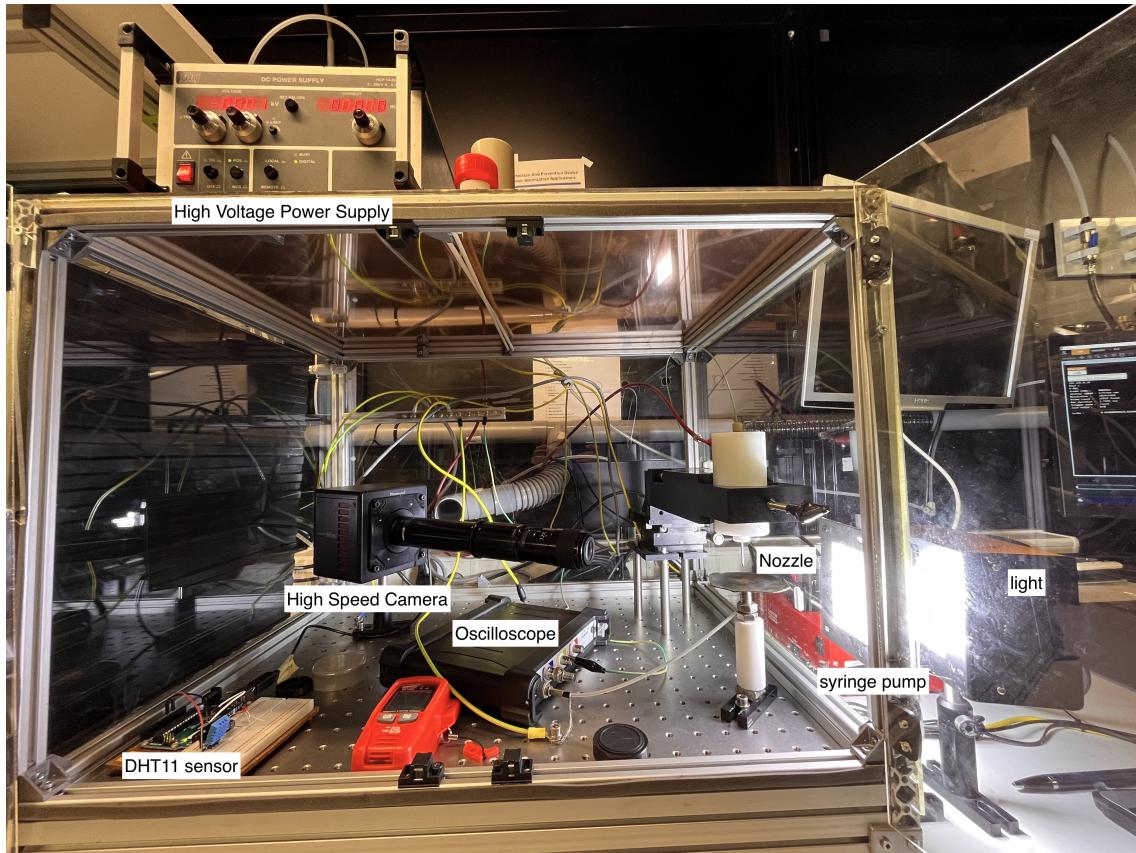


Figure B.2: EHDA automation system setup

B.1 Setup Validation

Initial tests were made to verify the setup assembly and the automation routine integration. In this step I could understand in practice how electrospray works. It was concluded that factors like geometry, polarity, material properties and occurring discharges are reflected in the system current. Also, liquid properties such as surface tension, dielectric constant, viscosity, density, electrical conductivity and vacuum permittivity. And also physical variables such as flow rate, system impedance, system temperature, system humidity, nozzle to plate distance, nozzle dimensions and applied voltage.

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 increase the flowrate which smooths this pumping noise. For that was also necessary to increase the nozzle diameter to balance with all other variables from the experiment.