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.

Acknowledgments

I would like to express my heartfelt gratitude to the following individuals and institutions who have played a significant role in shaping me into the person I am today:

First and foremost, my beloved mother, whose support and belief in my potential has been my guiding light throughout my life. Her invaluable lessons on dedication, patience, and discipline have helped me overcome countless challenges and achieve my goals.

I also extend my gratitude to my father, whose teachings on the virtues of ambition have inspired me to strive for excellence. His relentless pursuit of success has been a constant source of energy for me.

I would like to acknowledge the outstanding education and training that I received from the UFMG university, which has equipped me with the necessary skills and knowledge to thrive in the global marketplace. I am grateful for the transformative experience that has prepared me for a fulfilling career and a meaningful life.

Moreover, I cannot forget my dear friends from República Casassanta, who have made my student life such a unique and unforgettable moment. Their camaraderie and support have been a source of joy and comfort during challenging times.

Lastly, I would like to thank myself for having the courage and resilience to pursue my dreams despite my anxieties and doubts. Through my perseverance, I have been able to savor every moment of my journey and give my best to achieve my goals.

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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]

The stable balance between the capillary 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.

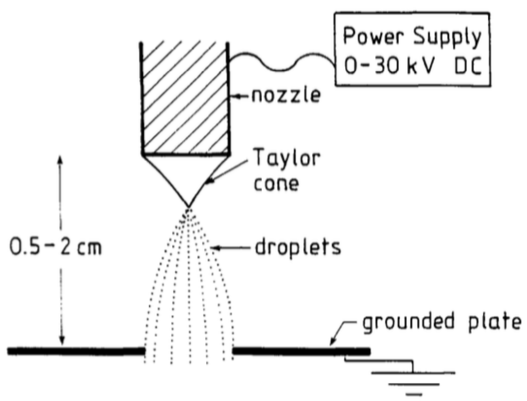


Figure 2.1: EHDA physical concept [3]

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.

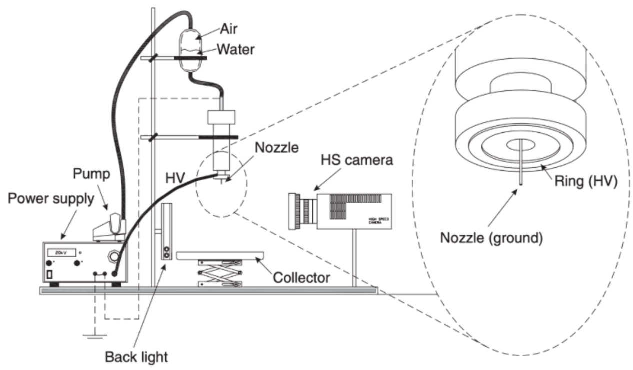


Figure 2.2: EHDA experiment setup [4]

Therefore some researchs were made about the classification of the spraying mode measuring the current flowing through the nozzle to plate[2][8]. That current signal holds a lot o information about the dynamics that is happening with the liquid. Figure 2.3 illustrate an example of that. It can be seen the signal of two droplets of charged liquid generated in this time frame.

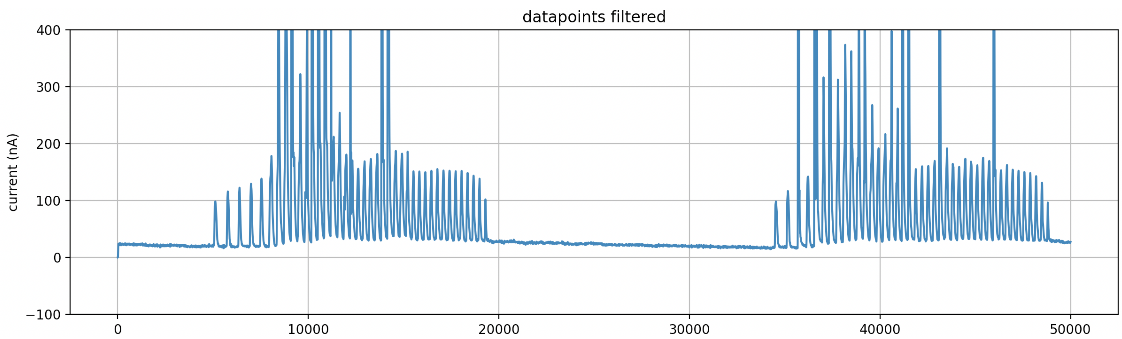


Figure 2.3: Current measurement sample of a micro-dripping spraying mode. This graph represents 0.5s sample. The sampling frequency is 100kHz. Hence we have 50000 current values.

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.

According to Sjaaks[2], evaluating the current data flowing through the nozzle to the plate can give us valuable information about the spraying behaviour. 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. It was concluded that factors like geometry, polarity, material properties and occurring discharges are reflected in the system current.

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.

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

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.

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

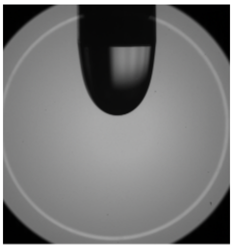


Figure 2.4: Dripping

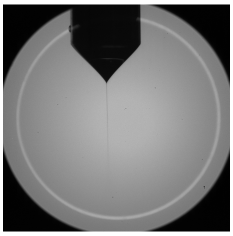


Figure 2.5: Cone Jet

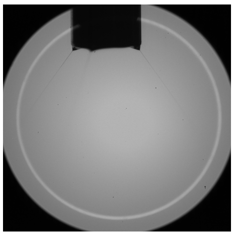


Figure 2.6: Multi Jet

Through the various classifications and subclassifications of spraying defined in literature we are going to aggregate some of them and separate between 5 modes as shown above 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.

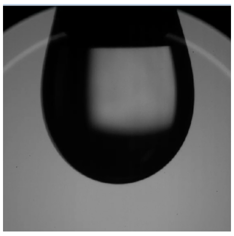


Figure 2.7: Dripping

2.4.2 Intermittent

Intermittent mode is defined when the electric field forces 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.

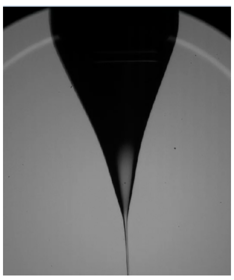


Figure 2.8: Intermittent

Figure 2.9: Intermittent

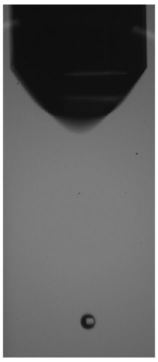


Figure 2.10: Microdripping

2.4.3 Cone Jet

The electrified meniscus can take on a conical shape within a certain range of applied voltage and injected liquid flow rate.

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. Taylor cone-jets naturally occurs under relatively limited circumstances: when the applied field and flow rate are in the appropriate range, and the electrosprayed liquid exhibits the adequate physical properties.

During the cone-jet, multiple parameters and variables influence the current, flow rate and voltage operational window.

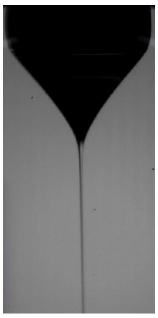


Figure 2.11: Cone Jet

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. For this work it highlights the detection 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 it will also be classified as multi jet.

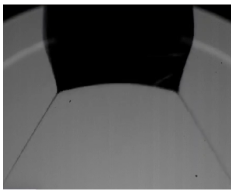


Figure 2.14: Multi Jet - double jet

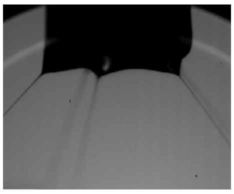


Figure 2.15: Multi Jet - low number of jets

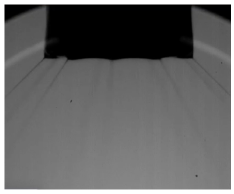


Figure 2.16: Multi Jet - rim spraying mode

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

This chapter is about to describe the equipment used and its integration explaining how it was modeled and implemented in both hardware and software sides. The python routine which this project is about was developed by the previous student that worked on it.[6] The software was previously developed as a electrospray multipurpose library[6].

3.1 System Description

3.1.1 Instrumentation

The main instruments used for this project are listed above:

a) High Voltage Power Supply (HVPS)

   - brand: FUG

   - model: HCP35-20kV

   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 future change of equipment brand 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 MTiePie 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 aftected by many physical effects. Evidently having the more parameters analysed favours the system control. The surface tension force is dependant of the liquid-gas interface on the meniscus. Hence, the gas around it must be constantly the same and so its humidity. Also, temperature is a variable that interfere in many phenomenas in the system. Specially the liquid properties such as viscosity.

For that, a standart microcontroler 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 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.

Also, the supply of constant pressure can also [1] The supply at constant pressure sometimes favours the stability of the spray. However, the flow rate depends on the applied pressure and pressure losses between the tank and the end of the capillary, which themselves are dependent on the liquid chosen and on its temperature. This volume flow rate may also depend on the applied voltage, since the electrostatic pressure on the meniscus produces a suction effect.

3.1.2 Setup Organization

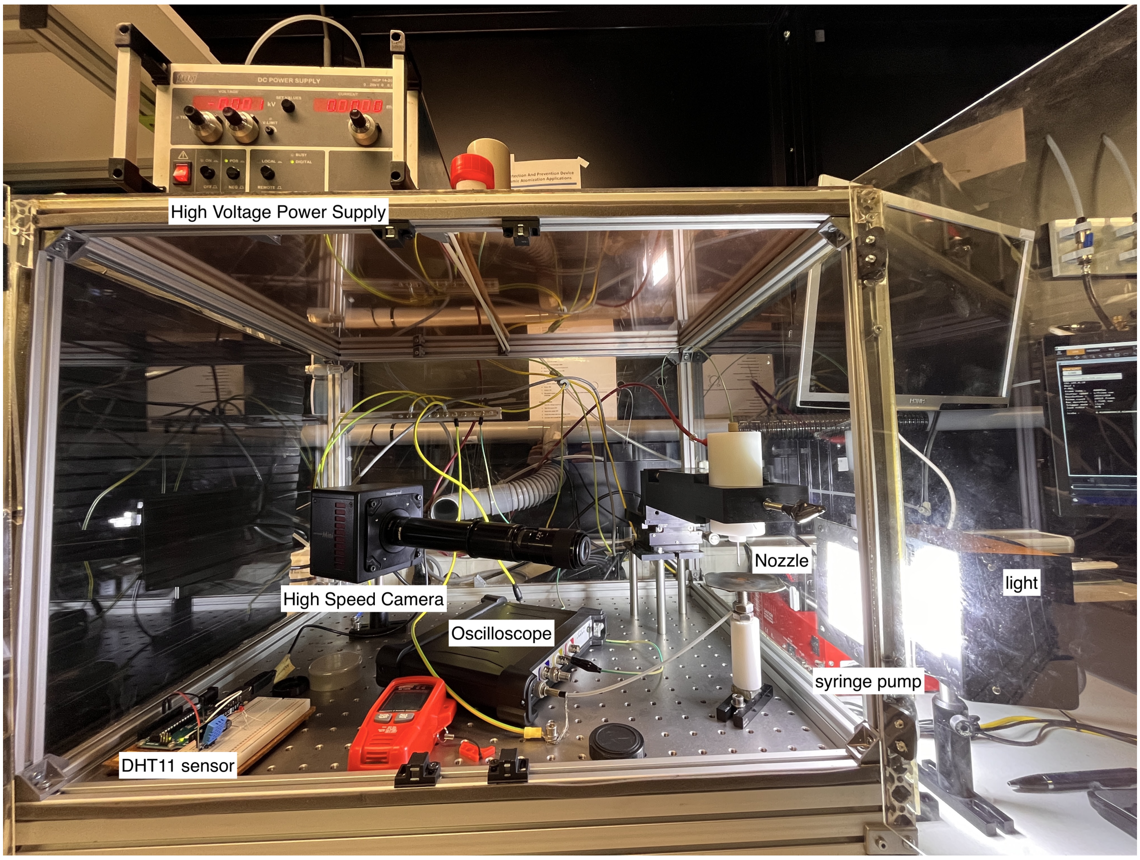


Figure 3.1: EHDA automation system setup

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.

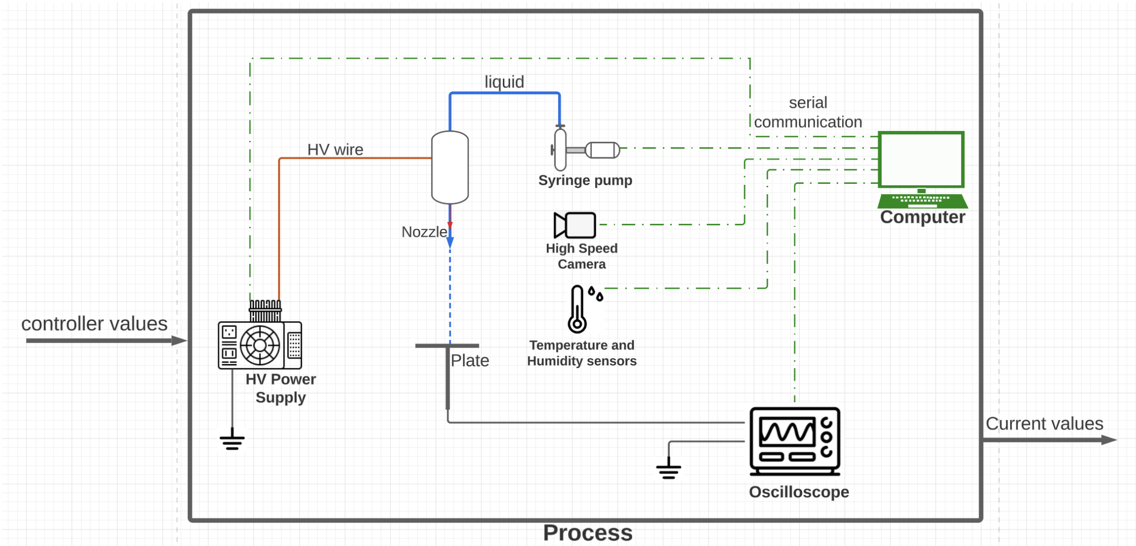


Figure 3.2: EHDA automation system setup

3.1.3 Setup Validation

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 correct 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.

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.

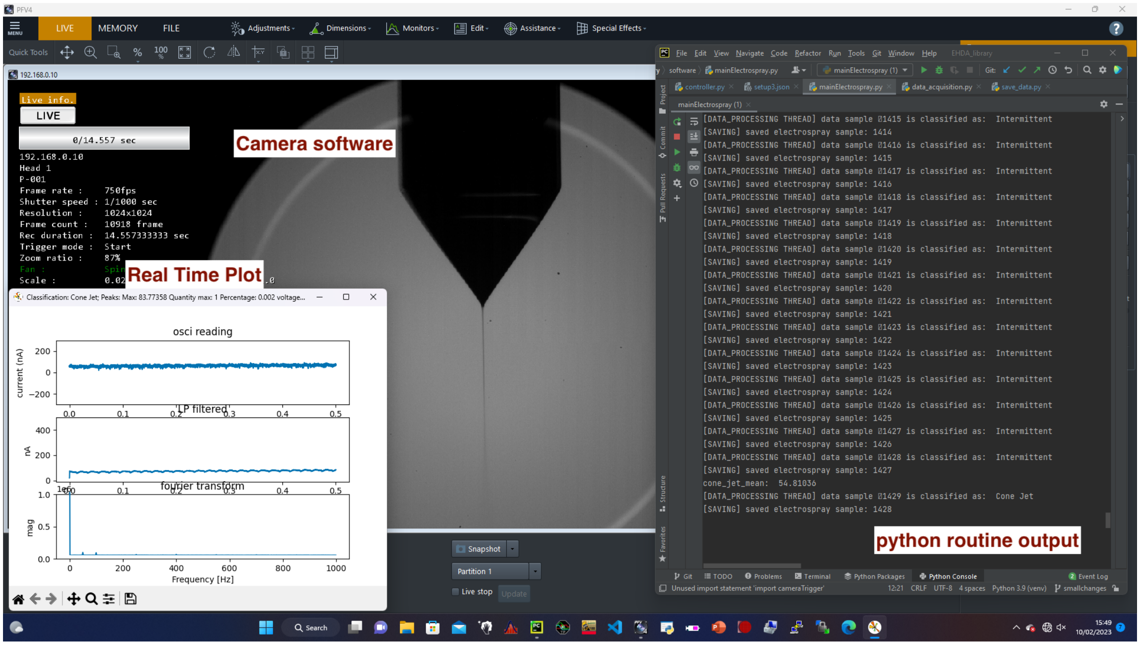


Figure 3.3: EHDA automation system setup

3.2 System Model

ilustramos o processo com a Figura 3.4.

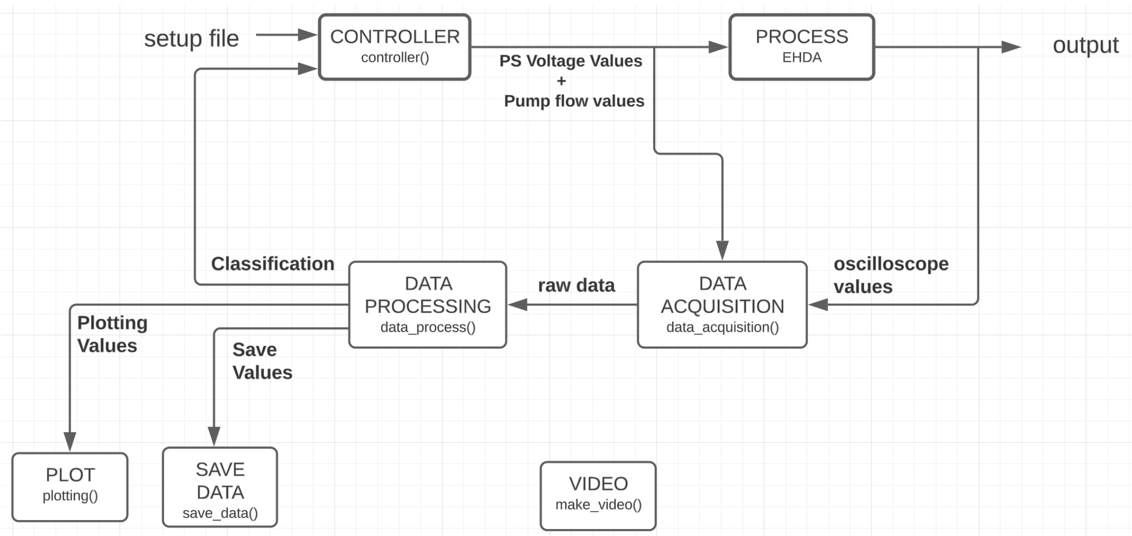


Figure 3.4: EHDA automation system setup

3.2.1 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 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 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().

3.2.3 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 powersupply, flowrate from the pump and concatenate into one sample data. As output we have the values in the emphdata_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 emphsave_data_queue(), emphplotting_queue() and emphfeedback_queue().

3.2.5 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",
    "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 3.5: 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.

3.2.6 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* 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

Chapter 4

Metodology

This chapter is about describing the methodology and developments to achieve the project goals. Firstly, let me 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 some signal characteristics that can be used to classify the actual spraying mode with a sample of measured current using both time domain and frequency domain analysis. We acquire the current data frame of 0.5s and through statistical analysis in the signal such as mean value 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.

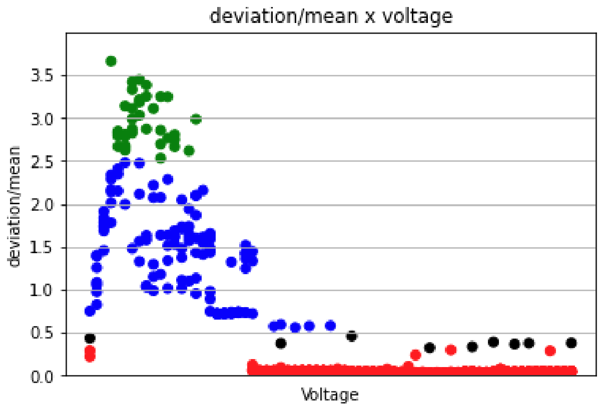


Figure 4.1: Sample classification using statistical values. Colors: Green = Dripping; Blue = Intermittent; Red = Cone Jet

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. This effect was cited 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 laws2.3 formula. The value 1.14 was found by repeating a lot of experiments with the same liquid, but varying the flowrate 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 bellow. 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 ← "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
```

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 model3.4, 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 thread3.2.3.

4.2.1 Ramp

4.2.2 Step

4.2.3 Map

The map that will be explained bellow 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

Algorithm 2 STEP sequence in controller thread

procedure STEP($voltage\_start, voltage\_stop$)
  $voltage \leftarrow voltage\_start$
  while $voltage \leq voltage\_stop$ **do** ▷ scanning voltage range
    SEND_VOLTAGE_COMMAND(voltage)
    SLEEP(step _time)
    $voltage \leftarrow voltage + step\_size$
  end while
end procedure

to map the operational window, seen in Figure 4.2, that can be defined where the cone jet spraying mode can be stabilized based on the flow rate, voltage and the setup configuration[5].

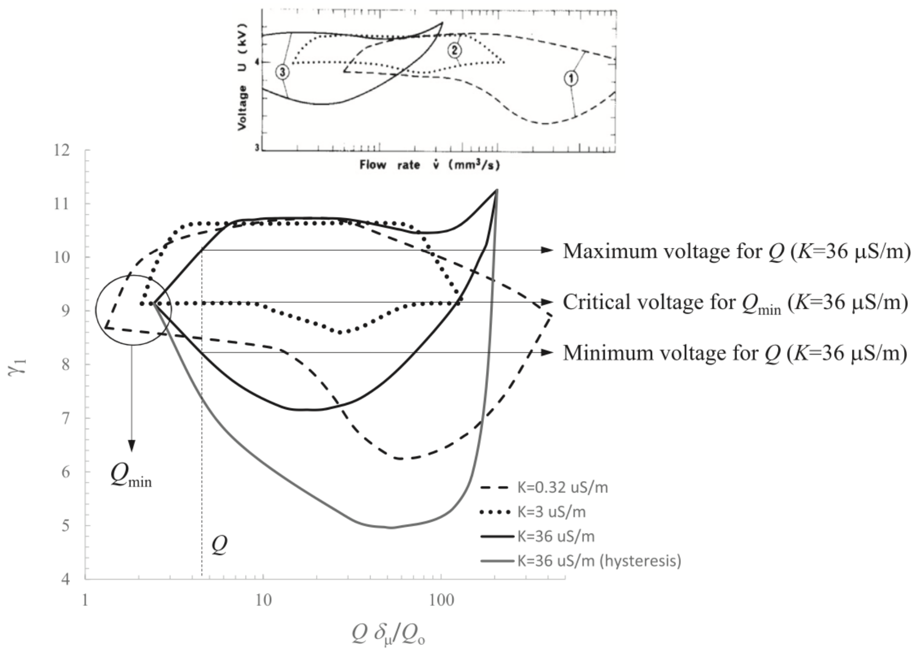


Figure 4.2: Domains of existence (stability) of Taylor Cone Jets. [5] . The window formed by these points is where the system operated in the stable cone-jet. Operational windows depend of the liquid and configuration setup. Different windows are represented for different liquid conductivity. The X and 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 copy of the step sequence4.2.2 for each flow rate chosen. It is illustrated in the algorithm 3.

In Figure 4.3 we can see the data acquired in this mapping experiments. The liquid

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

used is pure ethanol. Note that the experiment is composed of loops that increase voltage, change flowrate and repeat.

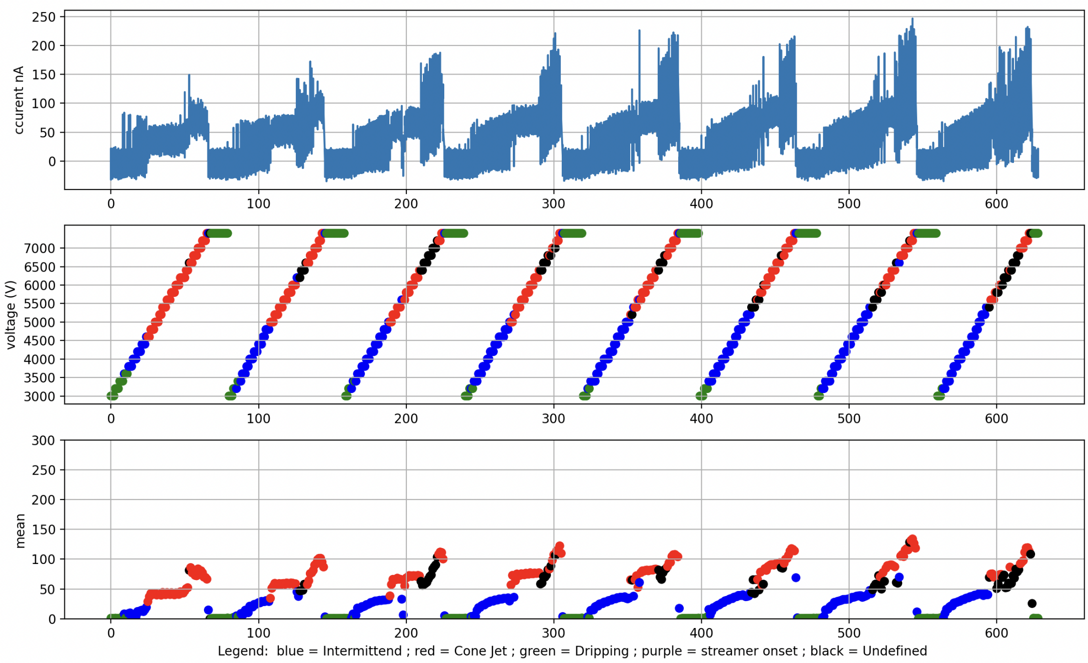


Figure 4.3: Mapping Experiment data collected. The figure has 3 graphs with shared x axis representing the samples collected. The first is the current values collected through all the experiment. The second is the voltage values applied in each window of data collected. The colors represent the spraying 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 FlowRate range of spraying modes with a specific liquid setup so that we can compare the automatic results with previous researchs, such as showed in figure 4.2 and validate the algorithm.

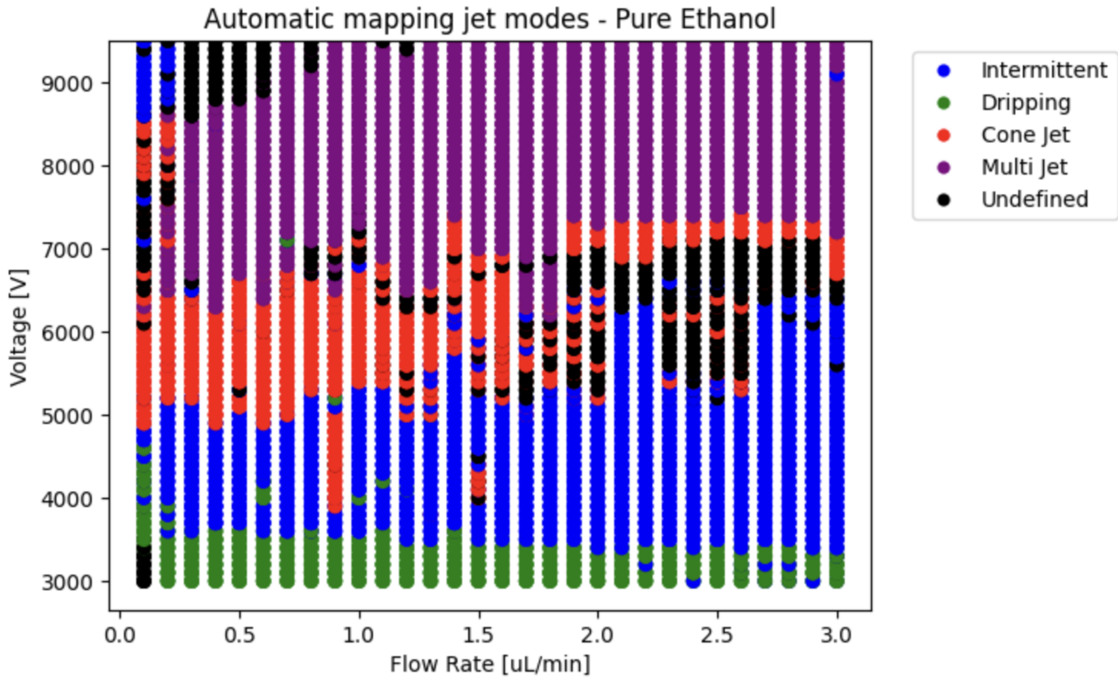


Figure 4.4: Mapping Experiment for pure ethanol in ambient conditions with our capillary setup. The map shows the stability region of each electrospraying mode in the voltage and flowrate range.

4.2.4 Control

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

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

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. Most power supplies available in the market 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. We can see in figures 5.1 and 5.2 the visual interface that the operator have during an experiment. All the important data of EHDA experiments are showed in the same screen and referring to each 0.5 seconds sampling time.

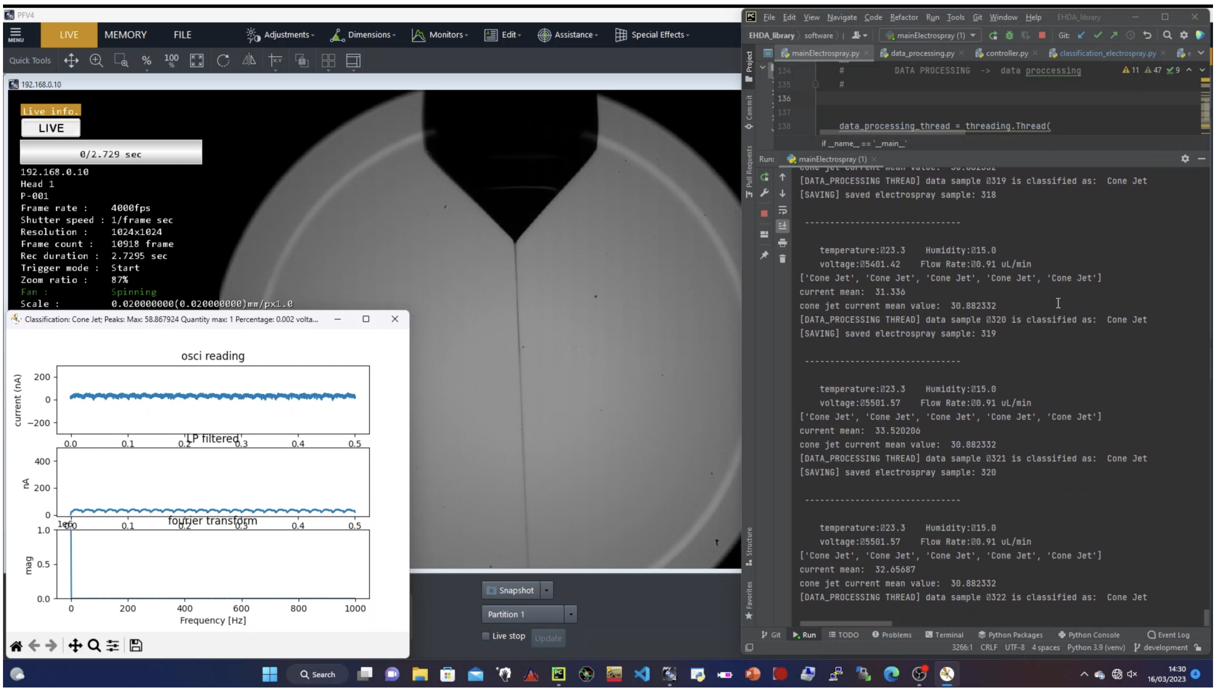


Figure 5.1: Print screen of the window shows user interface during the experiment. We can see the image generated by the camera in the background. The routine code running in pycharm software on the right side. And also real time signal plottings of the current data on the left side.

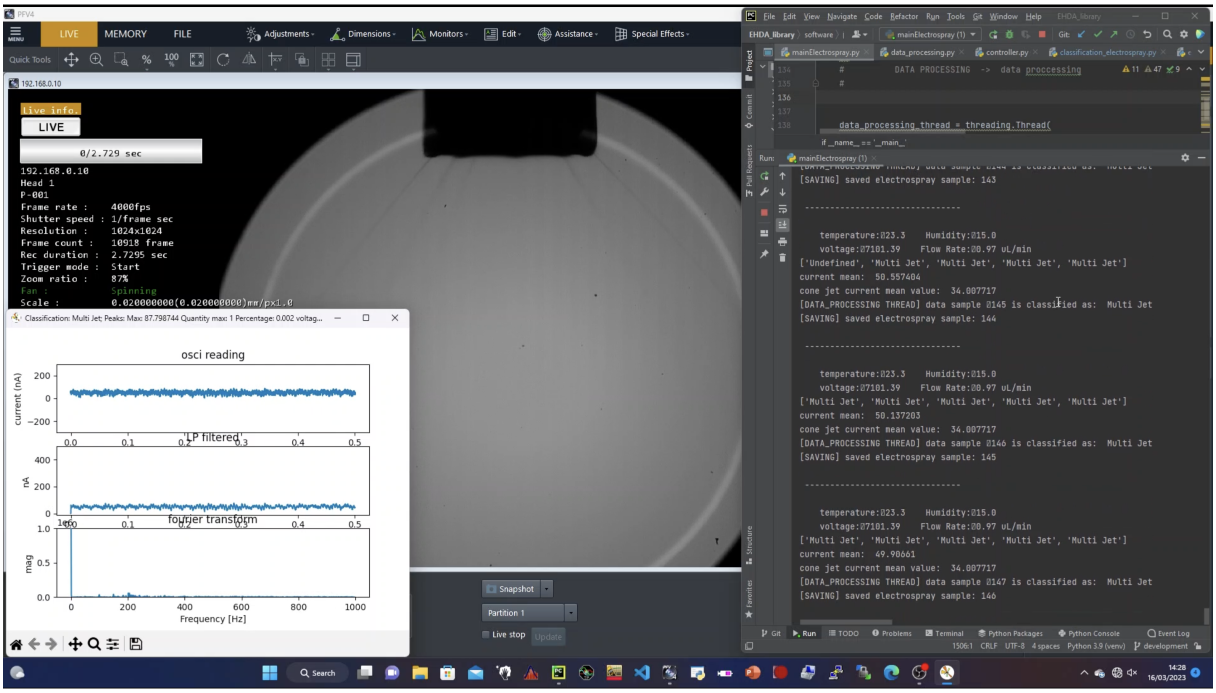


Figure 5.2: Print screen during an experiment. At this moment we are in Multi Jet spraying mode. At the left we can see the current signal has a smooth and constant curve. We can also see the automatic classification on the right side.

5.2 Classification

The 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.

5.2.1 Step Sequence

Our first classification results were made exploring just the voltage ranges. For that we tried to stabilize all the other parameters such as humidity, temperature and external noise. First, we fixed a flow rate to 0.7 uL/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.

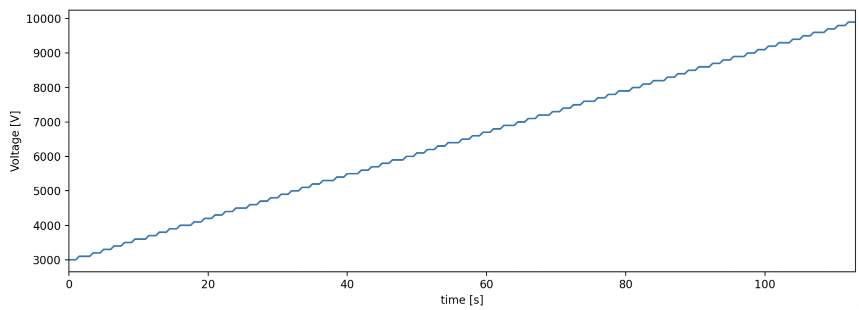


Figure 5.3: Input voltage step graph. The range is between 3K-10K Volts. Step size of 50V and step time of 5 seconds.

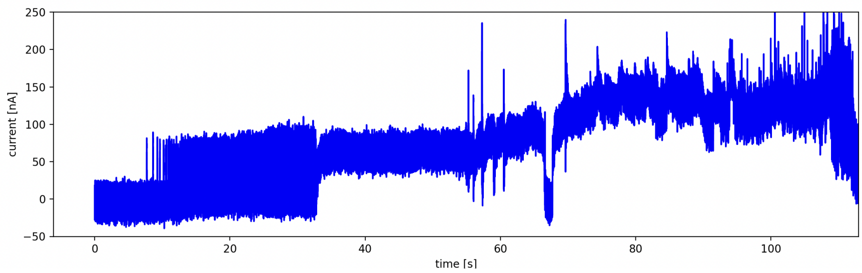


Figure 5.4: Output raw data collected in the voltage range experiment showed in 5.3. The sampling rate of the oscilloscope is 10KHz. This graph has 1.5 Million data points.

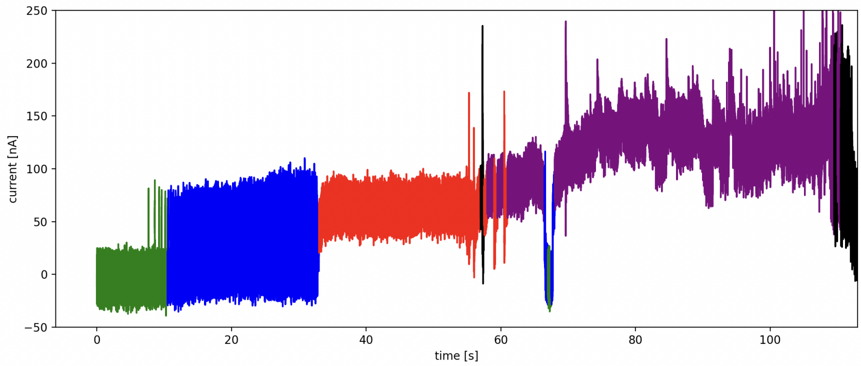


Figure 5.5: The same graph as 5.4 but after the classification procedure. The colors are green: Dripping, Blue: Intermittent, Red: Cone Jet, Purple: Multi Jet and Black: Undefined.

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 purposes 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.

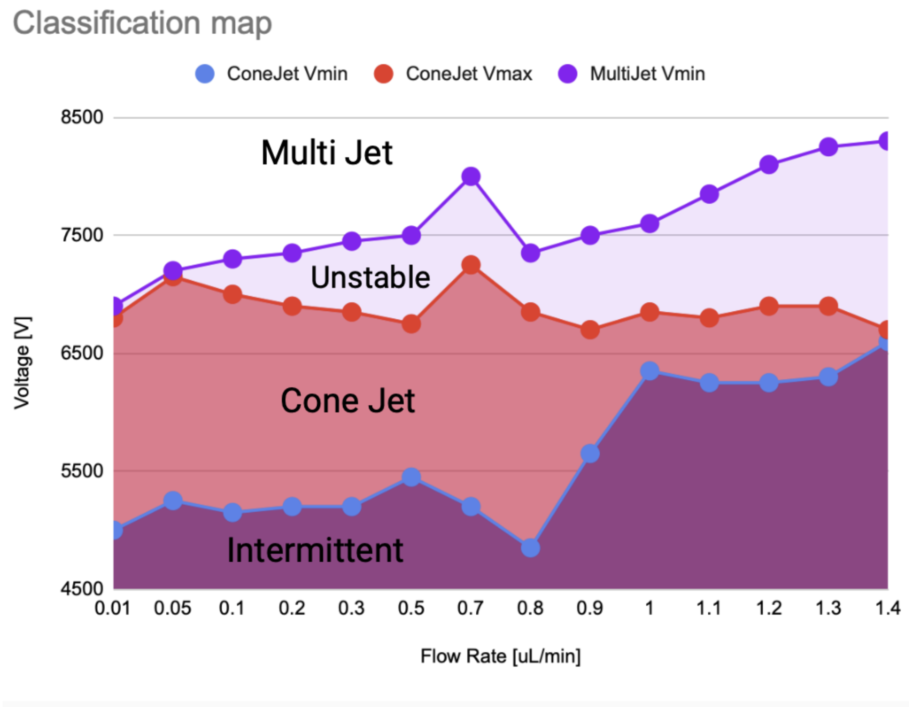


Figure 5.6: Spraying modes regions of pure ethanol

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). This

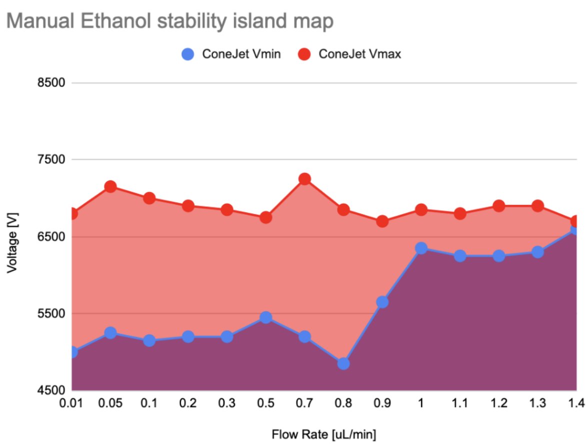


Figure 5.7: exp-26-01 manual classification

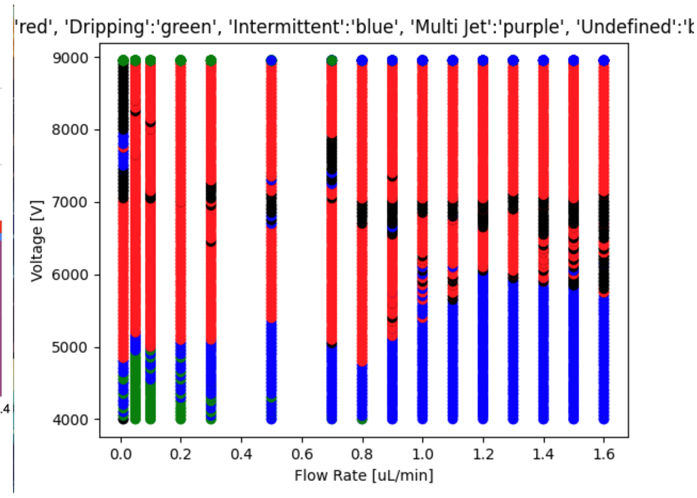


Figure 5.8: exp-26-01 automatic classification

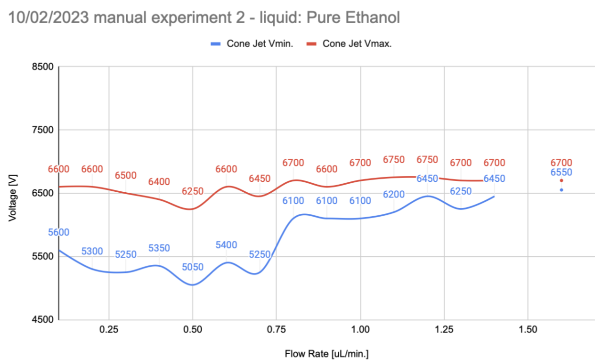


Figure 5.9: exp-26-01 manual classification

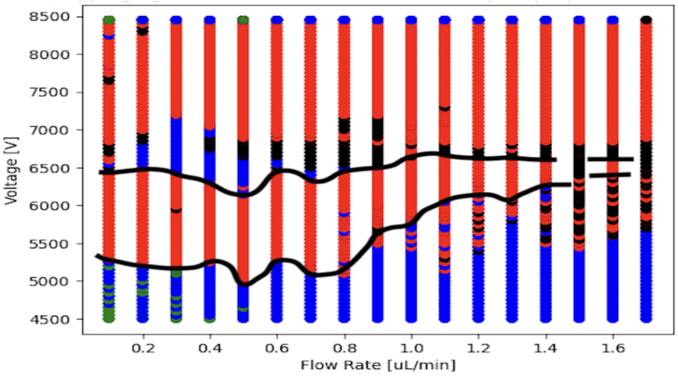


Figure 5.10: exp-26-01 automatic classification

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.

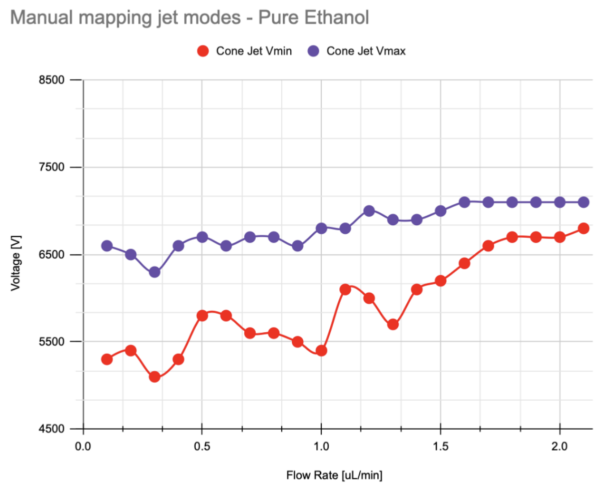


Figure 5.11: exp-26-01 manual classification

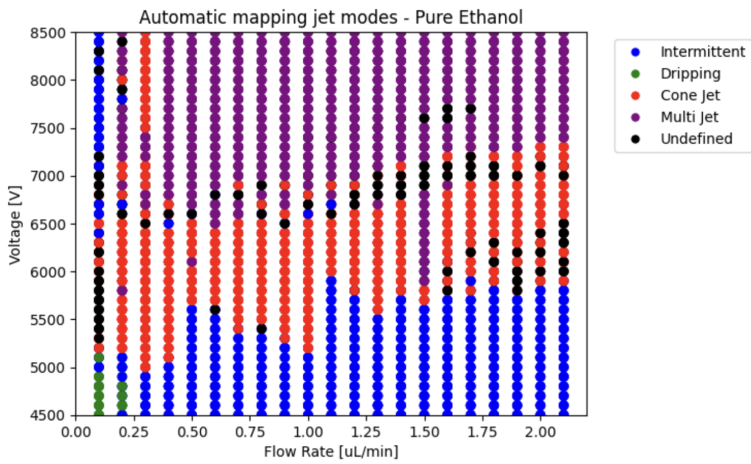
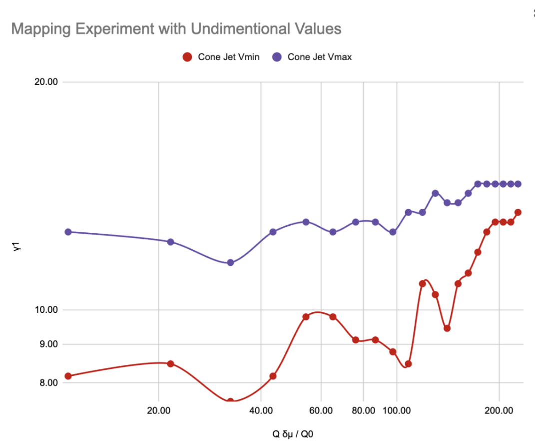


Figure 5.12: exp-26-01 automatic classification

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.



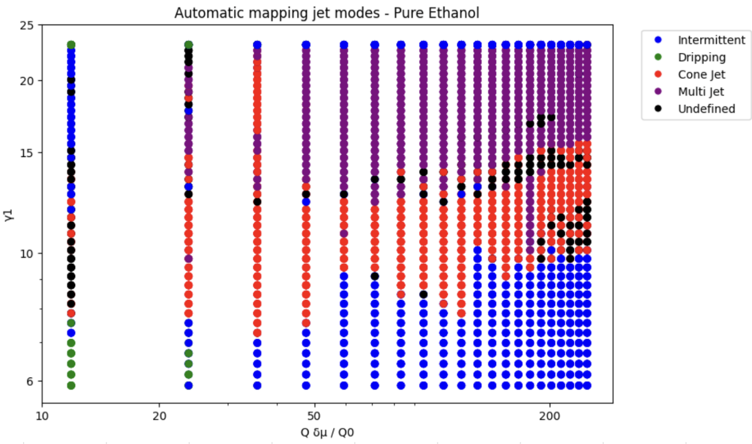


Figure 5.14: exp-26-01-2 (V x Q)

5.3 Controller

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

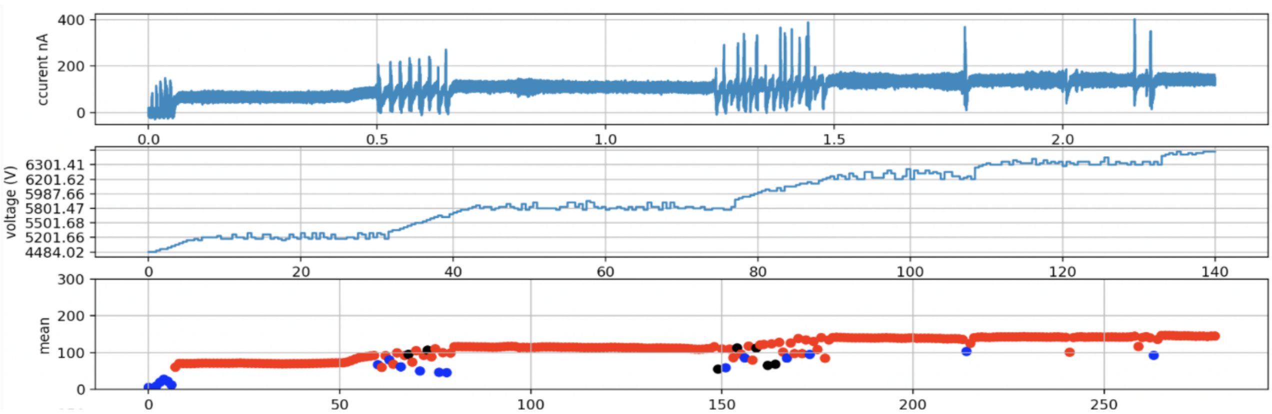


Figure 5.15: exp-26-01-2 (V x Q)

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 routine4.2.2. 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.

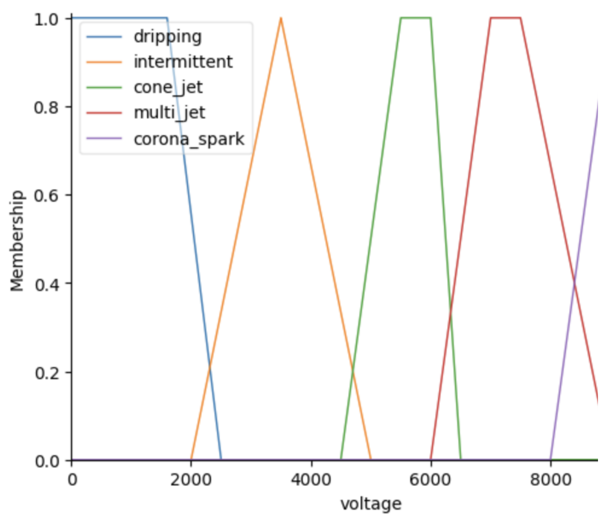


Figure 6.1: Fuzzyfication of the voltage input

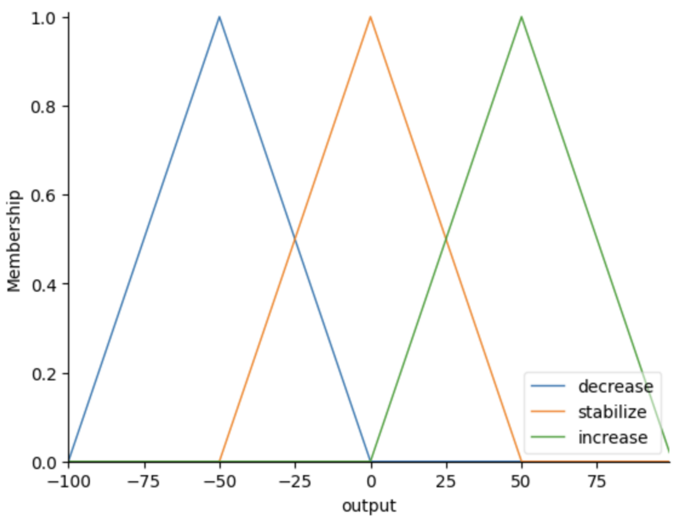


Figure 6.2: Defuzzyfication of output

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 bellow.

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 bellow 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.

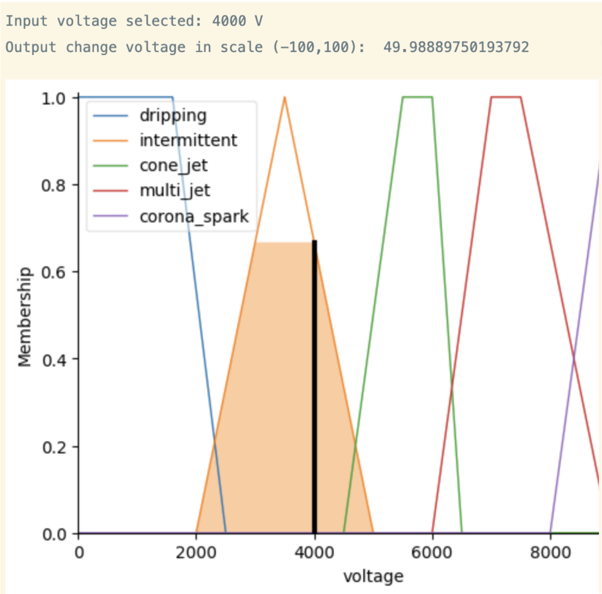


Figure 6.3: Test 1: fuzzy controller. Input voltage 4000 V the controller output to increase the voltage.

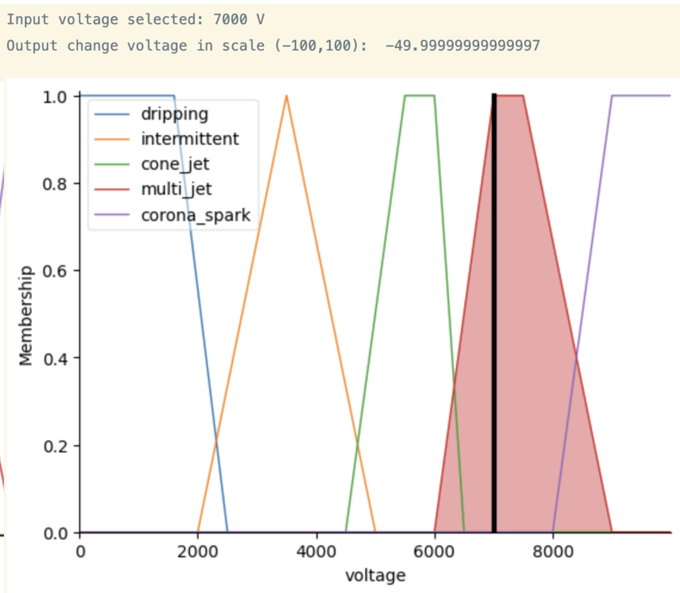


Figure 6.4: Test 2: fuzzy controller. Input voltage 7000 V the controller output to decrease the voltage.

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.

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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 Spectogram analysis

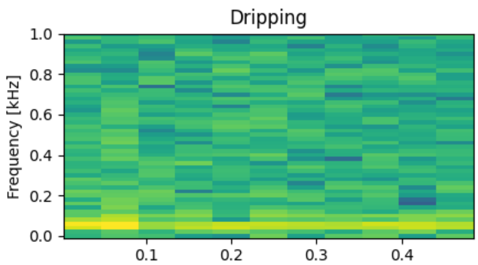

Figure A.1: Dripping

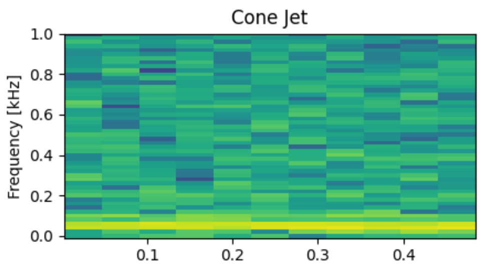

Figure A.3: Dripping

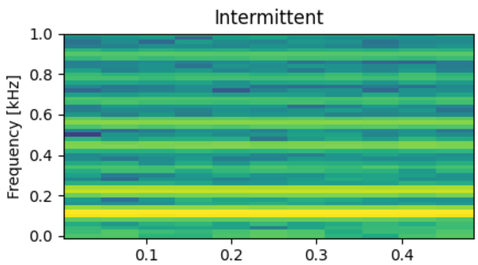

Figure A.2: Dripping

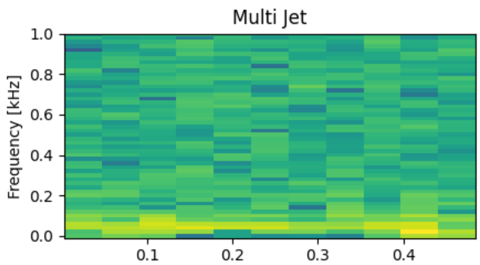

Figure A.4: Dripping

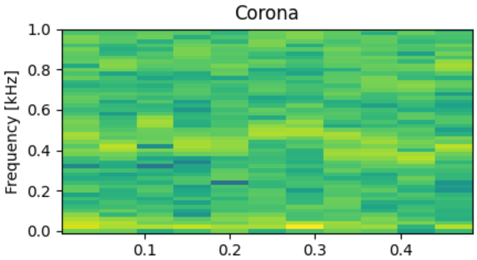

Figure A.5: Dripping

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

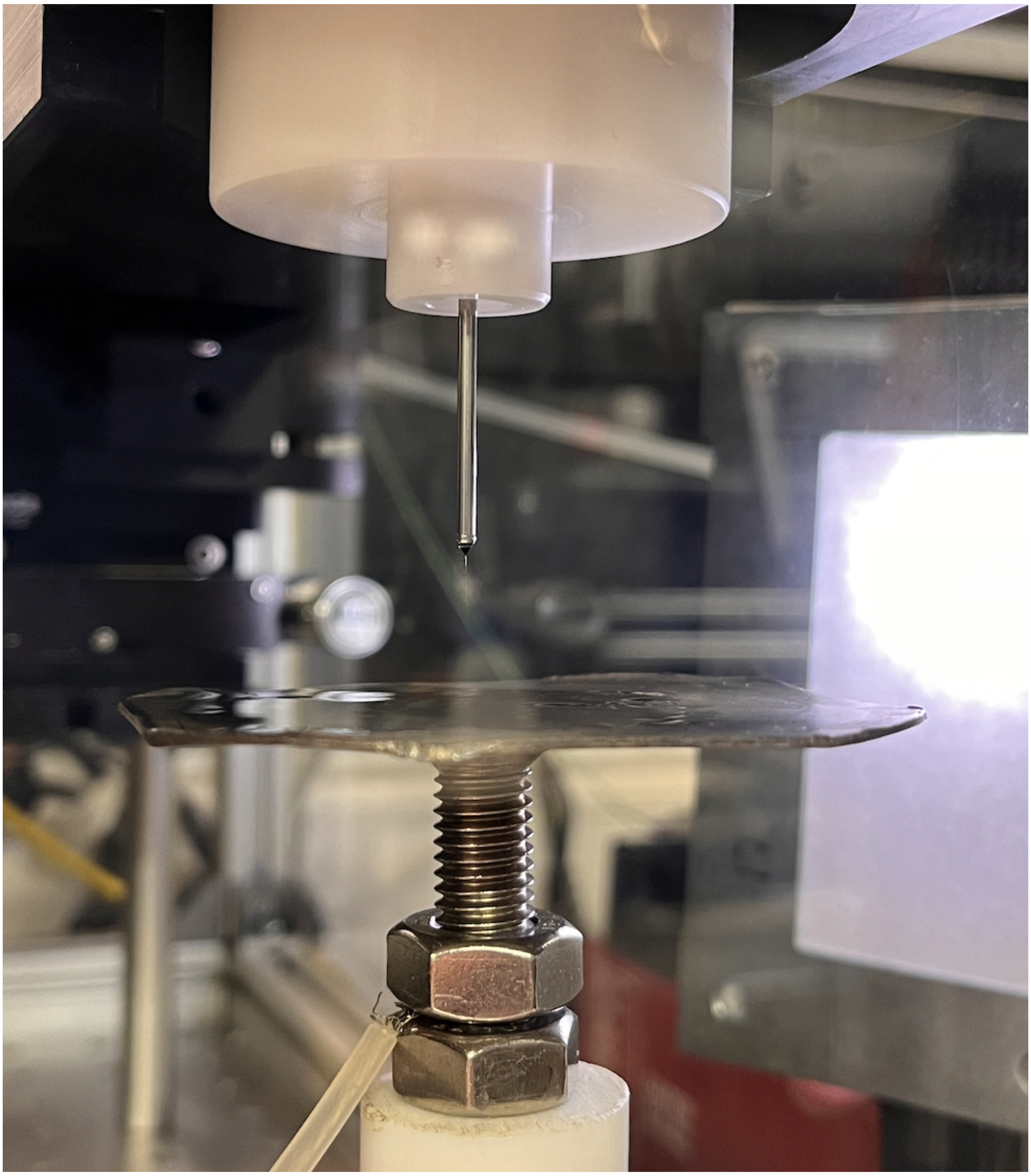

Figure B.1: EHDA physical concept