Universidade Federal de Minas Gerais
Escola de Engenharia
Curso de Graduação em Engenharia de Controle e Automação

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

Relatório 2 de Atividades PFC 1

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January 11, 2023

1 Summary

Electrohydrodynamic Atomization (EHDA), also known as Electrospray (ES), is a way to disintegrate a liquid into droplets by exposing it to a strong electric field. EHDA surveys have contributed as an important tool for the development of water technology (thermal desalination and metal recovery), material sciences (nanofibers and nano spheres fabrication, metal recovery, selective membranes, and batteries), and biomedical application (droplet encapsulation). Besides that, the project is merged with the Energy Transition strategy and Innovation Agenda Agriculture, Water, and Food, Key Enabling Technologies (KETs). Although, there are EHDA applications in industry, stabilizing the cone-jet spray mode is done empirically and based on mean current measurements.

The electric current flowing transported by the spray reveals characteristic shapes for different spray modes. Those shapes cannot simply be summarized by its mean value. In figure one we can see an example of cone-jet mode electrospray.

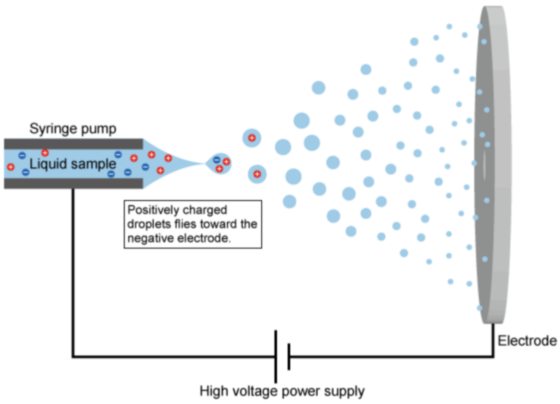

Figure 1: EHDA

Signal processing techniques can allow a non-visual classification of the spray mode based on the electric current shape. 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. Automated classification of the spray mode is a crucial part of a control system same as the development of an appropriate control algorithm. Signal processing implementations of previous projects of the NHL Stenden Water Technology group are showing good classification results. Further research is necessary to improve the classification accuracy and research and implementation of a suitable classification algorithm. Because of that, the work will be done by the Water Technology Group at NHL Stenden University of Applied Sciences and in combination with Dutch companies to match analysis possibilities with knowledge and infrastructure availability.

The setup used for this project can be seen in the Figure 2. To run the experiment automatically it is used a computational processing machine to integrate the peripherals and run their routines, system sensors such as the oscilloscope and the high speed camera and also the system actuators which is represented by the high voltage power supply and the syringe pump.

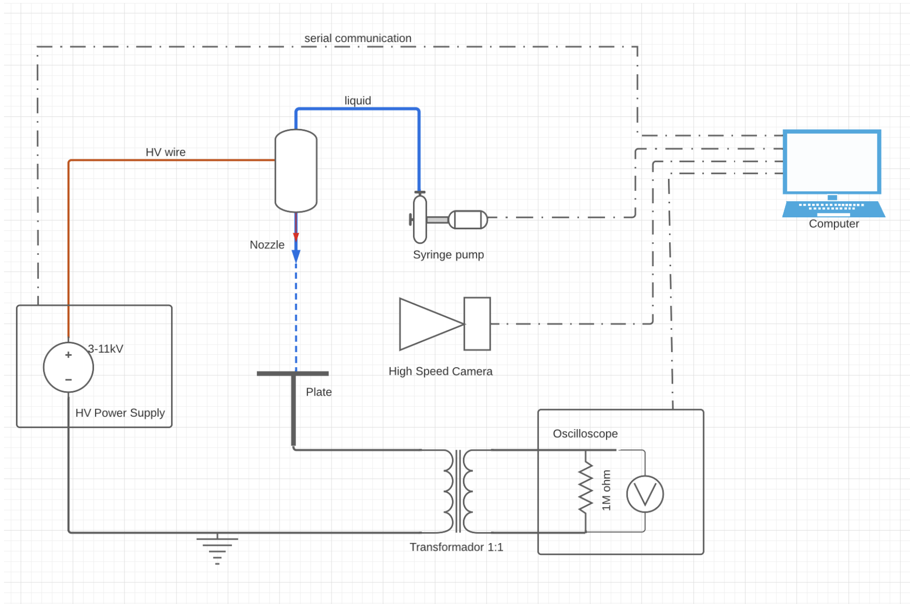

Figure 2: System Architecture

The algorithms implemented in the computer machine was developed in python by another student and it is already collecting data and classifying the spraying dynamics. In Figure 3 and Figure 4 shows pictures took by the high speed camera of some of the possible spraying dynamics we can reach. The videos took by the camera is not being used in the classification algorithm. It is used for manual validation of it.

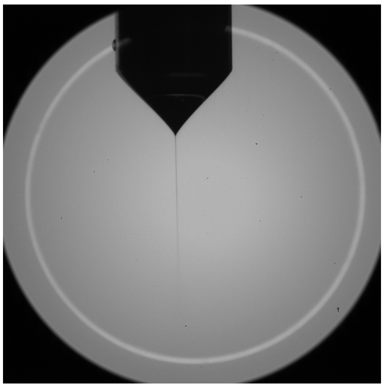

Figure 3: cone jet mode

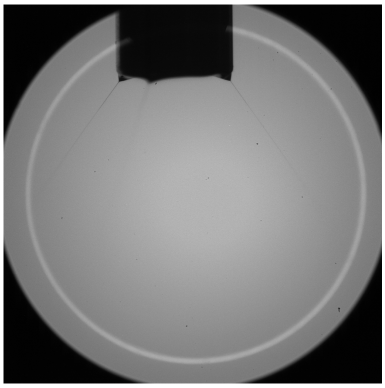

Figure 4: multi jet mode

2 Metodology and Results

3.1 Setup and Routine Algorithm Optimization

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

- Integrate high speed camera to the experiment routine.
- Remodel the software to support threads in order to separate the sensoring and controlling routines.
- Reduce the data collected size.
- Synchronize the power supply step commands and voltage sensoring.
- Reestructure the setup file in order to make it more intuitive to use the experiment.
- Improvements in code organization and readability.

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

3.2 Experiment 1

This first experiment was made using the setup:
- liquid: water60alcohol40
- flow rate min: 1.45 mL/hr
- config: nozzle to plate
- nozzle to plate or ring distance: 1.5 cm
- nozzle diameter: 0.136 mm

In Figure 5 we can see 5 graphs:
1 - current values measured by the oscilloscope. As it is a lot of data it is compressed in the figure.
2 - Voltage step sequence in order to evaluate the dynamics in each high voltage level.
3,4,5 - Statistical values measured by each window of 0.5s of data collected. This values will be used in the classification algorithm. Those values are already classified by colour and the legend is showed below.

LEGEND:
- Green = Dripping
- Blue = Intermittend
- Red = Cone Jet mode
- Purple = Streamer Onset (high current values)
- Black = Undefined

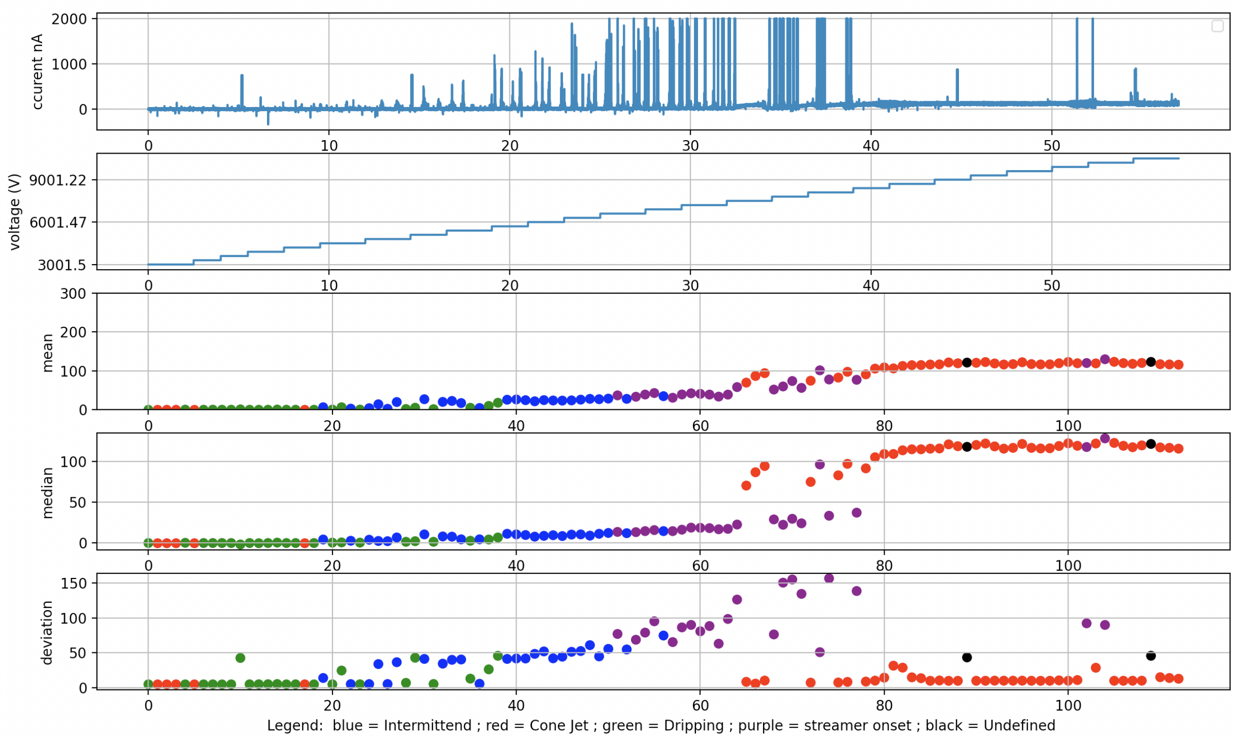

Figure 5: Data acquired in the experiment 1 - liquid: Water AND alcohol

In Figure 6 and 7 we can see one data window sample of dripping and one of cone jet dynamics. There are two graphs. The first one its the current datapoints filtered by a ideal low pass butterworth filter. In the second graph we can see the module of the fast fourier transform real values.

We can see in Figure 6 that there were two droplets expelled by the nozzle. This can be seen as the two signal waves in the current value and the amount of frequencies seen in the second graph.

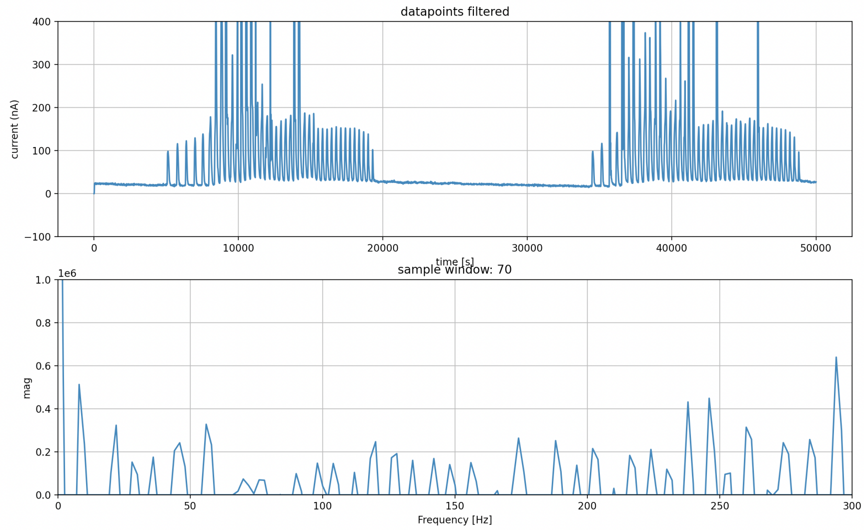

Figure 6: Dripping sample

We can see in Figure 7 that the current signal is more stable and also with an offset current arround 100nA showing that the spray is in cone jet mode. Also seen as the 0 Hz DC component value in the frequency domain graph.

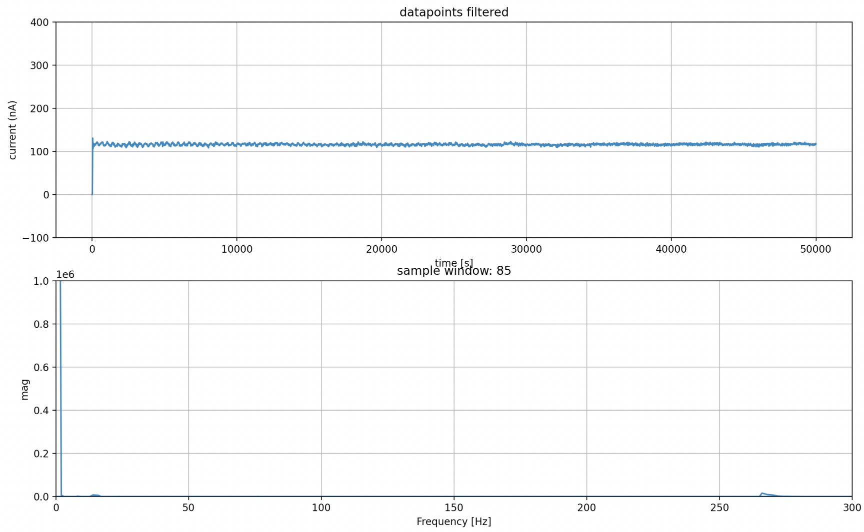

Figure 7: Cone jet sample

Other interesting grahps exposed in Sjaaks[1] paper is correlating statistical values relations to each voltage step and classification. This is also good to evaluate the separability of each classification method. Those graphs can be seen in Figures 8, 9 and 10.

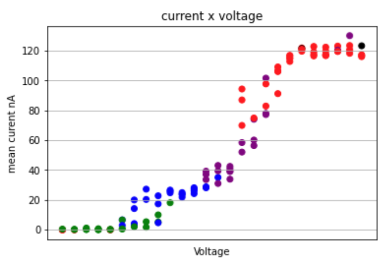

Figure 8: mean current X voltage

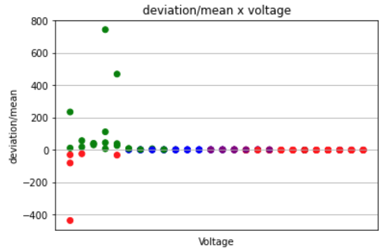

Figure 9: deviation/mean

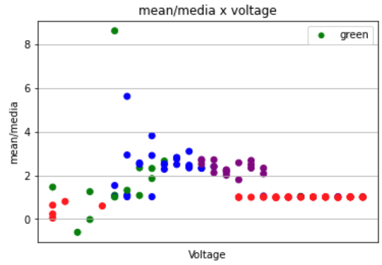

Figure 10: mean/median

3.3 Experiment 2

In this experiment the liquid was changed in order to have a bigger voltage range in the cone jet mode. Which is the most valuable mode in this project.

- liquid: ethanol pure
- flow rate min: 1.5 mL/hr
- camera to nozzle distance: 16.5 cm
- config: nozzle to plate
- nozzle to plate or ring distance: 1.5 cm
- nozzle diameter: 0.136 mm
- type of measurement:

* voltage start: 3000 V
* voltage stop: 10000 V
* step size: 100 V
* step time: 5 s

In Figure 11, the data is well classified but it also have a noise in the system that can been seen in the peak current values. Those peaks can be seen in all the voltage ranges in this experiment and also have similar distances in beetween the peaks. This is probably caused by external interference but it is still not certain what is it about.

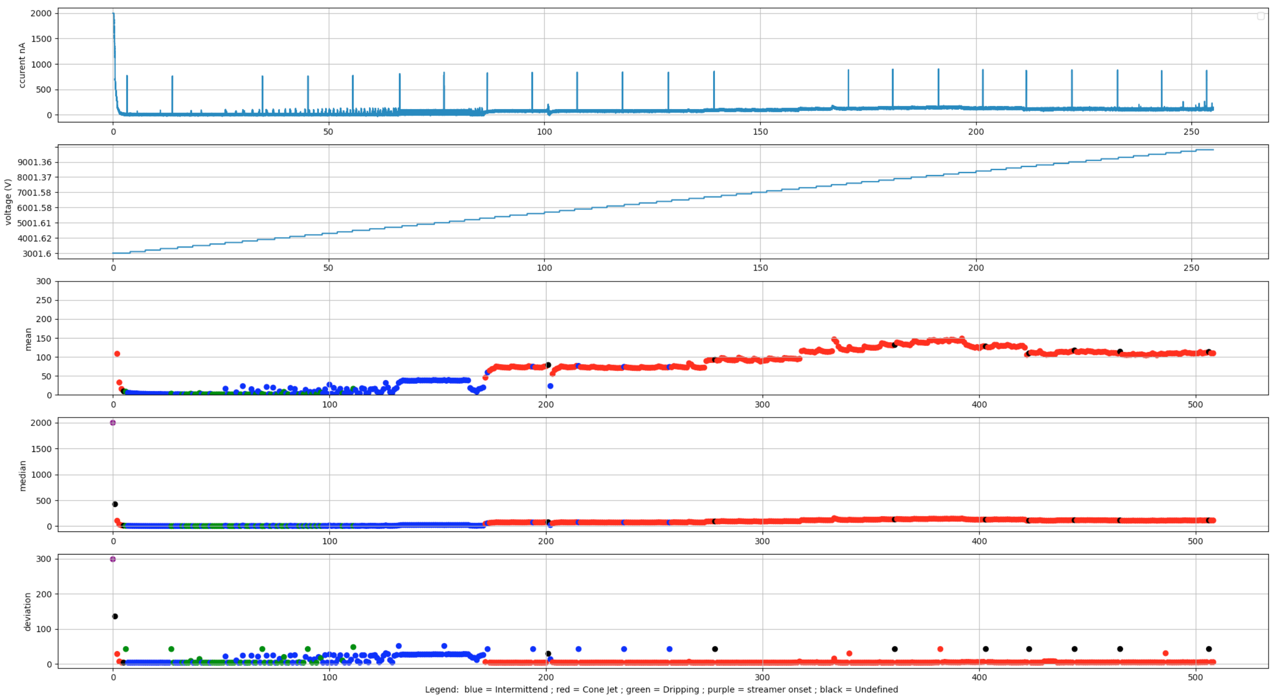

Figure 11: Data acquired in the experiment 2 - pure ethanol

The Figure 12 shows the same current x time graph but with a zoom in y axis in order to see the signal steps in the experiment. It is also classified by the same color legend as all graphs in this overview.

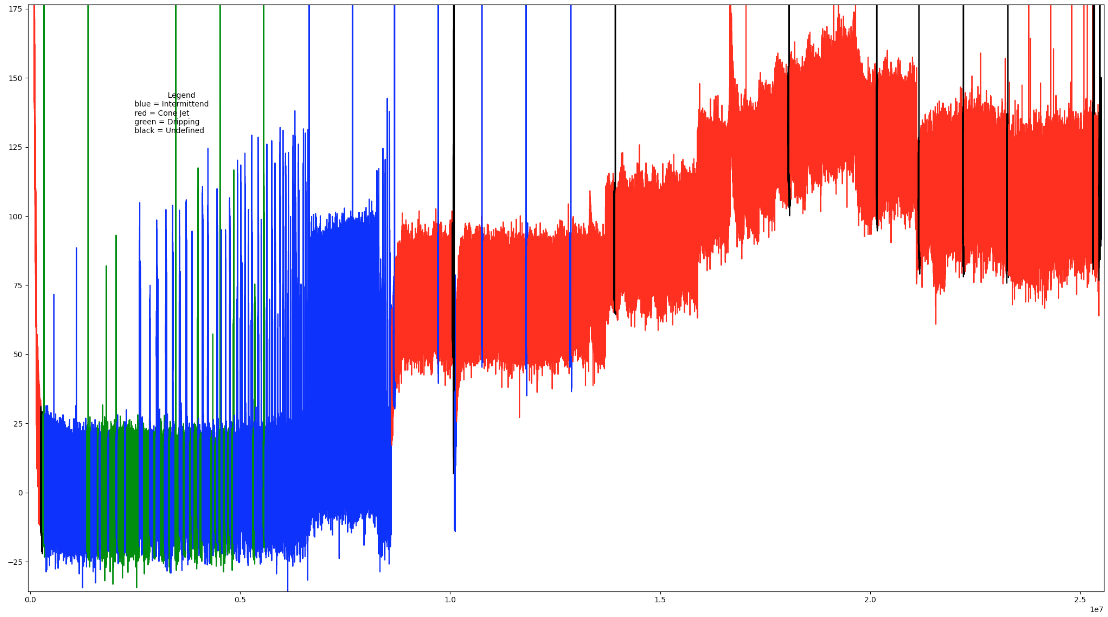

Figure 12: current graph with classification

The Figures 13, 14 and 15 shows graphs with statistical realations in the data.

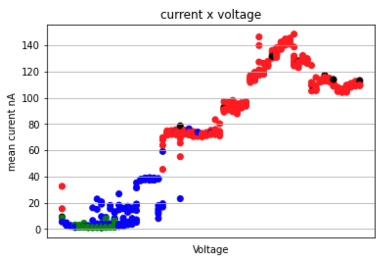

Figure 13: current mean X voltage

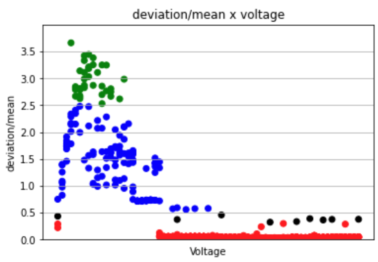

Figure 14: deviation/mean

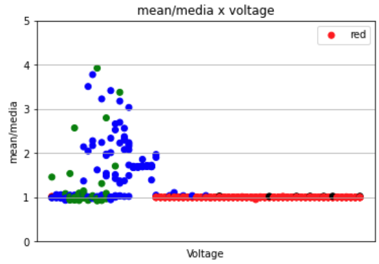

Figure 15: mean/median

3.4 Experiment 3

- liquid: ethanol pure
  - flow rate min: 1.5 mL/hr
  - camera to nozzle distance: 16.5 cm
  - config: nozzle to plate
  - nozzle to plate or ring distance: 1.5 cm
  - nozzle diameter: 0.136 mm
  - type of measurement:
  * voltage start: 3000 V
  * voltage stop: 11000 V
  * step size: 50 V
  * step time: 1 s

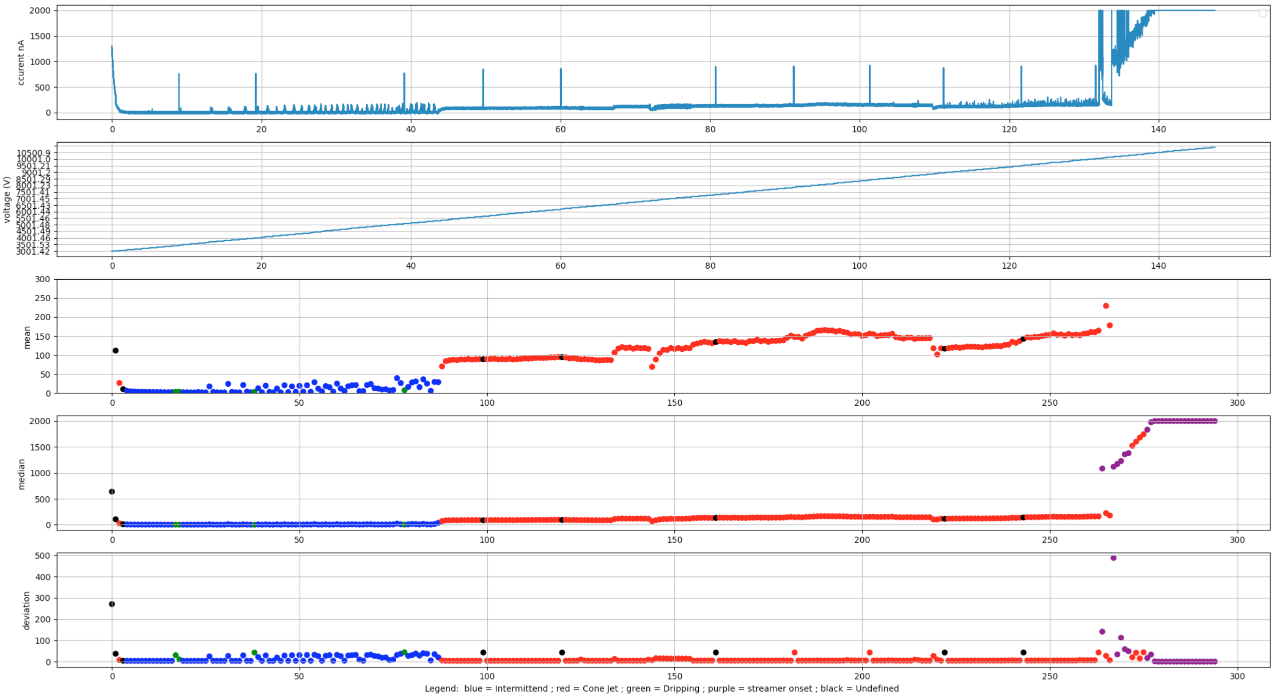

Figure 16: Data acquired in the experiment 3 - pure ethanol

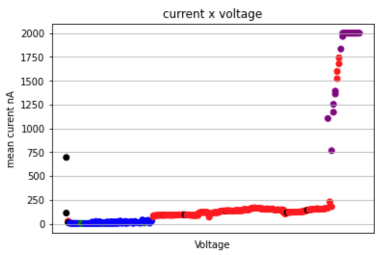

Figure 17: current mean X voltage

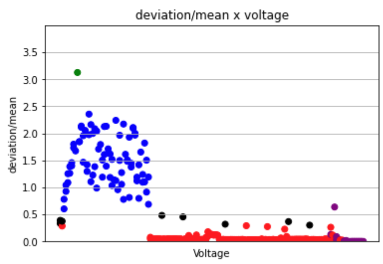

Figure 18: deviation/mean

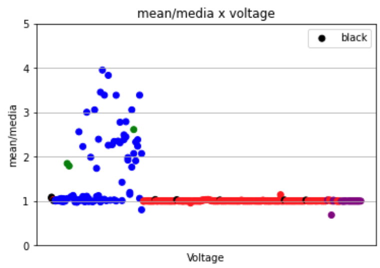

Figure 19: mean/median

3 Conclusion

In this step of the project the python code was upgraded to optimize the data acquiring, processing and saving. Also started structuring the software to fit our control model. Initial experiments was made in order to evaluate the algorithm performance and intuitivity. With the data collect in those first experiments we can notice that:

- The algorithm is not capable of separating cone jet mode and multi jet mode.
- The algorithm is not capable of sepaating intermittend and dripping.
- It has noise in the current values which are not discovered yet.

As the method proposed by Sjaak[1] classifies each spraying mode using deviation/mean and mean/median relations, we can se in Figure 14 that the colors are well separated by certain deviation/mean range.

For next steps experiments will be done varying the step size and step time of the power supply to get a better undertanding in how the change in dynamics behave. It is already known that it needs an adapting time to stabilize in a certain spraying mode. The next step will try to measure and understand this time. It is also known that the system has an histeses when changing between spraying modes. This is also another target for further studies.

References

[1] S. Verdoold et al. “A generic electrospray classification”. In: *Journal of Aerosol Science* 67 (2014), pp. 87–103. ISSN: 18791964. DOI: 10.1016/j.jaerosci.2013.09.008. URL: http://dx.doi.org/10.1016/j.jaerosci.2013.09.008.