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Instrumentation System for Liquid Drop Impact and Evaporation

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Bachelor of Engineering with Honours.

Abstract

The impact and evaporation of liquid droplets presents a complex physical process worth investigating, not only from a fundamental research perspective but for its potential for industrial application. However, in order to extract usable data from this small scale, fast phenomenon, instrumentation producing a droplet of repeatable volume and position as well as the ability to accucartly track and collect the data is essential. The establishment of an accurate drop dispensing systems forms the basis of this project. This project's approach is to add motorised automation to droplet dispensing with aims to control for droplet volume, positional variation, contact angle of the droplet. The addition of such an automated droplet dispensing system will not only improve the accuracy and repeatability of the instrumentation system, but also speed up the experimental process.

Contents

Chapter 1: Introduction

//TODO re-write in progress

1.1 Motivation

The investigation of droplet impact and evaporation is an area of interest and application to various industries. Examples of these include milk powder spray drying, ink jet printing, and applications of evaporative cooling. This project will continue on from a previous instrumentation setup, evaluating its shortcomings, and designing the next generation. This will improve the reliability and usability of the collected data from the previous setup, and introduce methods of automating the process.
Applications of interest

- Spray cooling
- powder (Milk) manufacture
- ink-jet printing
- …

1.2 Goals

Goal: To characterise behaviour of a droplet impacting and evaporating from a given substrate.

- Increase Repeatability and Reliability of results
- Increase usability of process via automation
- Produce Extendible platform that can be built upon beyond this projects scope

Chapter 2: Background and Related Work

2.1 Droplet Impact & Evaporation

Cover consideration with this kind of instrumentation/experimental measurement system and how it applied to this experimental application.

2.1.1 Other Approaches

//TODO: Go into greater detail to add context in the field of droplet instrumentation.
In literature, there exists a variety of rigs for similar experiments. These were explored to gauge a range of what factors were controlled (and measured) and with what approaches. In summary:

- Controlled environmental factors with basic box [1] or measured factors only [2].
- Controlled for droplet position and volume with hard mounted pump plus needle, but lacks environmental control or automation, and there is no top view camera [3] [4].
- Incorporated stepper motor driven automation, but no environmental control or monitoring [5].
- Full environmental chamber and fixed droplet pump, but single camera, has separate uncontrolled rig for top view [6].

2.2 Background on Stepper motor control

//TODO more passes for clarity.
This section will cover the background of controlling bipolar stepper motors via a step/direction style driver setup, as its concepts will be mentioned later in the report. This is a focused background on the key considerations and requirements when designing for and operating this specific subset, and by no means applicable to all driving and specific motor choices.
The stepper motors provide precise positioning and are capable of moving their rotor to a specified position and holding that position at a wide range of load torques. This capability makes the stepper motors popular in optics, medical instruments, factory automation, and industrial equipment.
The typical topology of a stepper driving system (based around the step/direction method) consists of a controller, driver, and stepper motor. The controller provides a direction signal and step pulses, while the driver converts these signals into actual electrical power and supplies them to the motor. The stepper motor moves in steps, each step covering one step angle, which can be described as the rotor displacement corresponding to one step pulse [7].
Stepper motors typically have a step size specification (e.g. 1.8° or 200 steps per revolution), which applies to full steps. Step/direction drivers usually provide a 'microstepping' mode which increases the resolution by allowing intermediate step locations, which are achieved by energising the coils with intermediate current levels [1].
The last major consideration in driving steppers is controlling the start-up and stopping speeds for the controller's provided pulse train to the driver. As the motor is a mechanical device in the real world, expecting a perfect impulse response will lead to driving failure.

Inertia ratio is critical to stepper motor acceleration [1]. Too great a difference in inertia ratio between system and motor risks missed steps or stalling the coils. So when starting a stepper motor, acceleration and deceleration should happen through pulses to the motor that start slowly and gradually quicken in a process called ramping.

Chapter 3: Initial Evaluation

3.1 Initial Experimental Setup at Project Start

Given that the express purpose of the project is the development of a new version of instrumentation, the first step is an examination of the prior system. This is to identify how it falls short and to determine the areas that the project will focus on.
The experimental method concerns depositing a liquid droplet upon a heated substrate. The data of note is the temperature evolution of the substrate directly under the drop, as well as image data capturing the point of impact and how the droplet changes over the course of the evaporation.

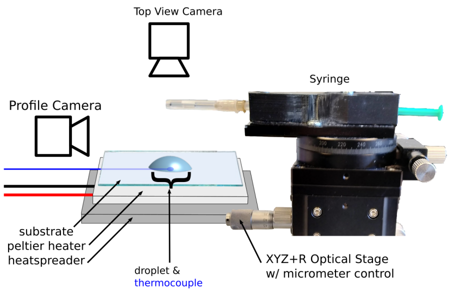


Figure 3.1: Initial Experimental Setup

The prior system uses an optical breadboard and micrometer adjustable stages as mounting platforms and positional control. A central stage holds the substrate stack, consisting of a aluminium heat-spreader, Peltier heater, and metallic substrate (copper, stainless steel, etc) with internally mounted thermocouple. To capture the image data, a pair of manual focus cameras are positioned/suspended in profile and top down view and are controlled via a USB connection. The thermocouple is sampled with LabVIEW via a USB DaQ. Dispensing the droplet itself is done by hand using a syringe mounted to another optical stage [3.1:b] with XYZ+R controls. It is rotated above the substrate and pressed to dispense a drop.
This would be perfectly fine, however the results this manual process yields had a level of inconsistency. Thus motivating the design of a new system to control for a the experiments variation.

3.2 Repeatability and Reliability

To identify more precisely the drawbacks in the performance of the prior setup and inform the requirements of the project, previously collected data was first analysed.
The data was taken from a series of five droplet runs, and was analysed to quantify the systems repeatability and reliability and to compare the affect of the drop morphology and position with the resulting temperature evolution.
First analysis is the image data. The substrate itself has a mark to represent the position of the thermocouple, this is used as a the main reference to quantify the droplet position. Reference images set calibration at 120.14 pixels/mm and 109.2 pixels/mm for the top down and profile cameras respectively, and was used to measure the droplet centre offset and

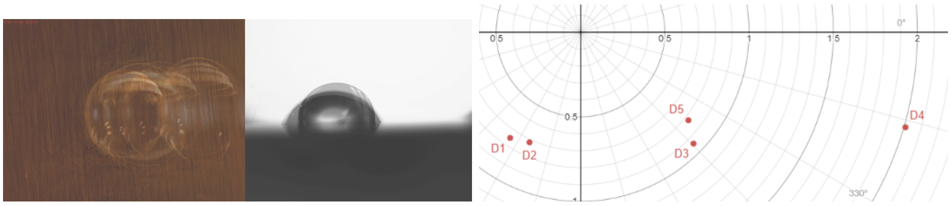
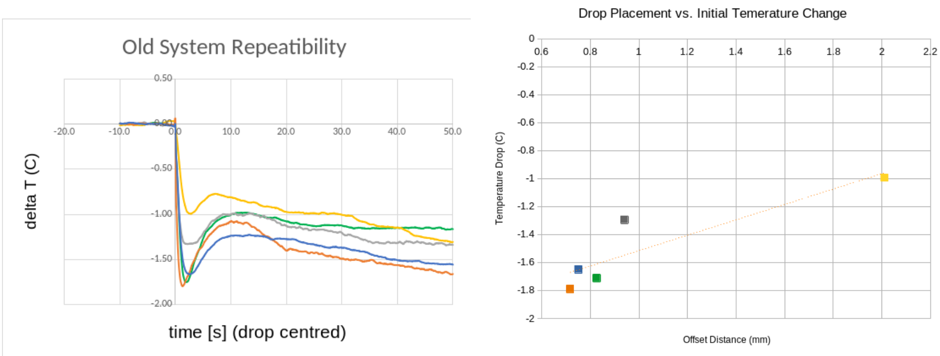


Figure 3.2: Droplet positional and shape variation; Left: Camera overlay, Right: Quantified Offsets

angle (from reference point) as well as the height, width and contact angles of the droplet on the substrate.
Seen above, the quite substantial positional variation between the runs. Ranging [0.71:2.01]mm offset and [-16:-123]° angle.

$$\frac{1}{6}\pi h(3a^2 + h^2) : a \equiv \text{half width}, \ h \equiv \text{height} \tag{3.1}$$

From the data extracted from the profile camera (height, width, contact angle) the volume of the droplets could be estimated. The method chosen was of the represent the droplet as a spherical cap and use the above equation 3.1 to compute it.



Droplet	*Offset(mm)*	*Volume(uL)*
1	0.7506	16.55
2	0.7164	17.91
3	0.9402	17.89
4	2.0104	17.57
5	0.8258	16.21
Variance	*0.2964*	*0.6288*

3.3 Summary

**Contact angle is more a function of the surface cleaning of the substrate, and is only representative of the surface area of contact with the substrate*

//TODO rewrite in prog The focus of the project is now twofold. Firstly on the automation of the process to allow for faster, pre-programmed runs to be carried out easier, and secondly

Effector	Likelihood	Effect Strength
Position	HIGH	HIGH
Volume	MODERATE	HIGH
Contact angle*	MODERATE	HIGH
Humidity	LOW	HIGH
Temperature	LOW	HIGH
Pressure	MODERATE	MODERATE

to improve on the repeatability and reliability of the results by controlling the procedural factors of the experiment.
An electronic pipette will be used to dispense a precise volume, and motorised stages will be used to provide pre-programmed, repeatable motion. The environmental factors however are not to be ignored, though controlling them is outside of the scope of this project. They will, however, be monitored, and this project will implement data collection of temperature, atmospheric pressure and humidity so these factors can be correlated to any remaining variation in data.

Chapter 4: Design

4.1 Project Specifications and Justifications

Given the results of the initial evaluation the project can now be constrained. It's main goals are to eliminate volume variation, control for droplet position, enable automation to reduced time between consecutive runs. It will not control, but provide data-logging for the environmental effectors; temperature, humidity, pressure.
From this there is a number of requirements to consider:

- **Mechanical Stability**:
- **Droplet Position Repeatability**:
- **Consistent and Variable Volume**:
- **Process Automation**:
- **System Expandability**:

The project will be evaluated on how it meets the above Specifications, its ability to control for volume and positional accuracy and repeatability as well as how it adds/improves automation, provides environmental data and allows extension.

4.2 Drop Dispensing and Volume Control

At the systems core is the liquid droplet dispensing hardware. The two core limitations of the initial setups manual syringe were fixed volume dispensing and the observed inconsistency in drop volume. In order to address these, alternative solution is required to provide a core that allows the rest of project to control and automate positioning, dispensing and liquid refilling. It was decided early on that the bulk of custom design would be focused on the motorisation hardware, custom mounting, and the driving software so the dispenser would be handled by a pre-existing product. The product selected for this is single channel electronic pipette from Labnet, P3600L-10.

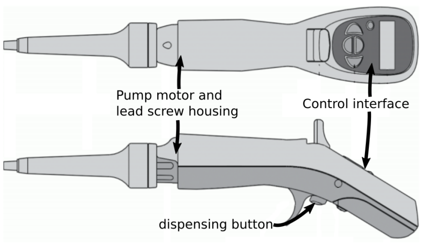


Figure 4.1: Labnet Excel P3600L-10

This product comes recalibrated and verified to dispense a droplet at a specified volume with at an accuracy of $\pm 4.0 \rightarrow \pm 1.0\%/\mu L$ over a the selection range of $0.5\mu L\ to\ 10\mu L$. This range represents the full range the pipette itself is capable of drawing and dispensing,

configured via the front panel [see 4.1], but an evaluation of the integrated system is required to confirm the mechanical stability is high enough prevent a high volume drop from prematurely detaching, as well as if its capable of depositing the minimum volume on the substrate.
Liquid refilling and dispensing is handled via the button on the back [4.1] and to enable the instrumentation to centrally control this, the planned approach was to break out the underlying switch contacts as GPIO inputs. The full process and results will be fully explored in this reports implementation system.

4.3 Mechanical Design

The goals for the mechanical aspects of this project are to provide a mounting interface to allow for the movement and positioning of the electronic pipette, mount to the optical XYZ stages, and transfer the driving force from the stepper motors to the instrumentations mechanisms.
All mechanisms share the requirements to fit compactly and correctly on the optical breadboard baseplate. Be designed in such a way to minimise backlash and prevent vibrations from propergating and resonating through the system. As this could interfere with droplet dispensing; increasing pipette tip overshoot and settling times, causes prematurely drop detachment and generally decreasing the key performance metrics.

4.3.1 Rotating Pipette Mount

The first half of the main assembly is Pipette Stage. In order to manoeuvre the pipette from reservoir to substrate stack, the pipette needs to be held at specific height and angle to roughly match the central stage (as it is Z adjustable) and rotate between these two points.
To achieve the mounting stage consists of three main parts:

- Pipette clamping and Angled mount: Responsible with securely fastening the e-pipette at the correct angle.
- Laser Cut Mounting Tower: Sets pipette height and connects pipette to motor.
- Motor shaft interface and Stage Fastening: Rotation is directly driven via the motor, thus the assembly is mounted to the motor shaft.

Dimensional Specifications: Pipette height of 130mm (from breadboard) and angle of 36.25 degrees. These specification are used to derive the full dimensions of the following assemblies.
The electronic pipette formfactor is ergonomic-hand to fit in human hand-so the clamping mechanism to fit it to the tower plate itself was challenging to design to successfully restrict its rotation and backlash. 3D printed PLA c-clamps were the perused approach to capitalise on the materials ability to deform and to aid in rapid implementation and testing.
The base design used to accomplish this was a 3D-printed ring clamp [Left:4.2] meant to be tightened and fit to the unique form of the pipette body. A variety of ring sizes and gap distance were printed and test fitted. From this it was determined that a ring diameter of 32mm and a gap of 6mm fits and deforms to the shape of the pipette. However, there was still some rotation and slip so a notch was cut into the acrylic angle plate [Left:4.2] to slot the pipettes support rest and a second ring clamp (36mm) attached lower down of the body.
//TODO More detail on motor mounting?

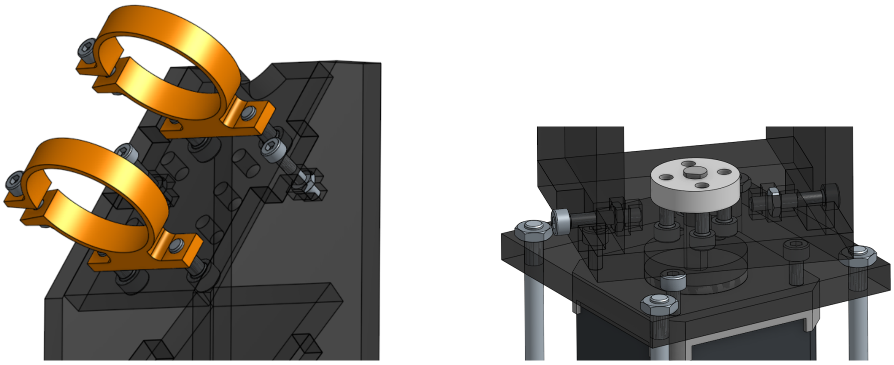


Figure 4.2: Left: Pipette Clamps and Tower, Right: Towers base mounting to motor shaft

4.3.2 Z micrometer Control

In order to control the the height of the pipette tip; to enable automated refilling and to place the dispensed droplet on to the substrate the Z height of the optical stage needs to be motorised. The Z height has a manual control in the form of an adjustment micrometer that allows for 10mm of travel, but this present the first problem in design. The micrometer travels linearly throughout the adjustment, i.e. if the stage raises 10mm the knob will retract 10mm also. Due to this a custom shaft coupler is required to interface a fixed motor to the moving knob.

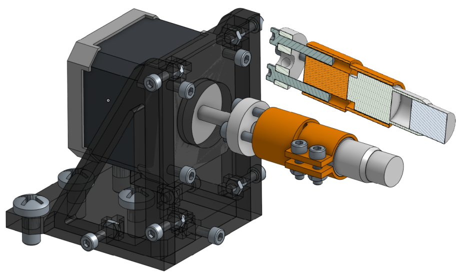


Figure 4.3: Z Driving Motor and Sliding Shaft Coupler

The figure above[4.3] shows the assembled design. One end of the coupler is an extended c-clamp that mates with the knurls knobs of the micrometer and the other is a solid piece with 4 M3 clearance holes. These holes interface with a universal shaft-hub mount with 4 M3 machine screws that transfer the motors rotation and allow the coupler and knob to slide away over the course of a movement.
The key limitation of this design is that is constrains the XY position of the stage to a single setting. This is due to the motor being fastened to the breadboard baseplate more stability, alignment and vibration reduction. Because of this it moves the fine positioning to the other stages in the setup; substrate stack and cameras.

4.4 Electronic Design

4.4.1 Motors

The motion required for the motors in this system is to provide rotation about the vertical axis to the mounted pipette, to swing from above the substrate to out of the camera view

and over a refill reservoir, as well as continuous rotation to interface the Z axis control for droplet depositing and possible refilling.
Stepper motors allow for both precise position control without the need for a feedback system and are capable of continuous rotation. In comparison, brushed/brushless DC motors require encoders for positional control and servos may do either but not both continuous rotation and positioning.
NEMA17 standard sized steppers were chosen to best fit the dimensions of the XYZ optical stage (60mm plate to 40mm motor frame) with room for fastening hardware. That left two choices for the top R stage motor; full size 38mm high frame or shorter pancake frame. Even through the pancake frame would reduce the overall height of the system, the shaft length available for this motor is less only 7mm and would greatly restrict the mounting options of the tower to the motor. For this reason 2 NEMA17x38mm Stepper motors were chosen.

4.4.2 Motor Driving

The Requirements

To drive the selected stepper motors, discrete step/direction style micro stepping drivers were chosen. This allows for the design to be flexible with its electronics placed to accommodate the experimental needs. Allows for a fairly agnostic choice for controller to supply the control signals, and standardised pinouts allow for requirement flexibility and replacements.

	A4988	**DRV8825**	**STPIN820**	**DRV8834**
Step Res	1/16	1/32	1/256	1/32
Logic Level	3V3/5V	3V3/5V	3V3/5V	3V3/5V
Current Limit	1A	1.5A	0.9A	1.5A
Drive Voltage	8-35V	8.2-45V	7-48V	2.5-10.8

Table 4.1: Comparison of considered drivers

Main consideration for device choice are: micro step resolution, driving current limit (passively cooled), and configuration pinout.

The Choice

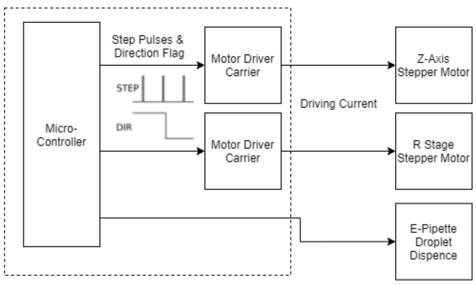
The DRV8825 was ultimately chosen.

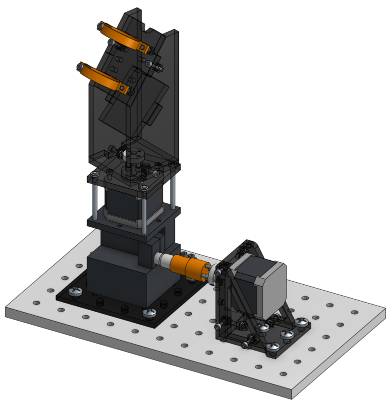
- High microstepping resolution, lower than the STPIN820 but cheap high resolution driver are prone to step skipping [1]
- Highest driving current as torque requirements are unknown for this design the headroom is nice even if it isn't use, especially as it will run cooler at lower power draw.
- It ranked above the DRV8834 due to it configuration pins (to set microstepping mode) as it provide all 3 pins without the requirement to leave pins floating as a setting thus allowing for full software control.

4.4.3 Environmental Monitoring

Although the aim of this project is to only control the position and volume of the droplet in the experiment, to at least fully address the list of affector [covered in 3] the environmental factors recorded are: **Temperature, Barometric Pressure, Relative Humidity**.
As this section of the project doesn't note share resources with the main motorised assembly it key design considerations were simplicity and function. Therefore, the environmental monitor is not required to have any integration with the main controller or data logging capabilities.
To meets these requirements the monitor was decided to be a low power microcontroller + OLED display stack that polled environmental sensor peripherals. This would be battery powered and utilised low power sleep modes to extend lifetimes
To facilitate ease

4.5 System Overview





Chapter 5: Implementation

//TODO rename sections to reflect work done

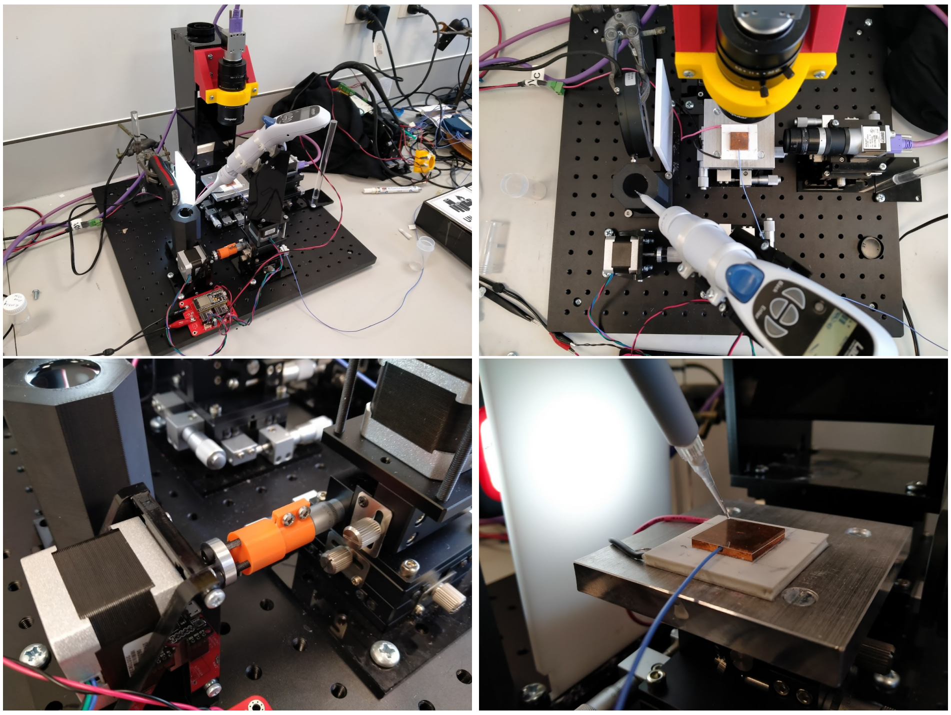
5.1 Mechanical Design

- Go into 3d printing/laser cutting refinement, testing and adjustment
- Tolerance and dimension adjustment
- Noted changed and drawback from design

5.1.1 Rotating Pipette Mount

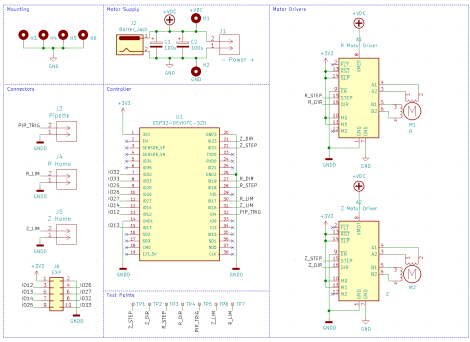
5.1.2 Z micrometer Control

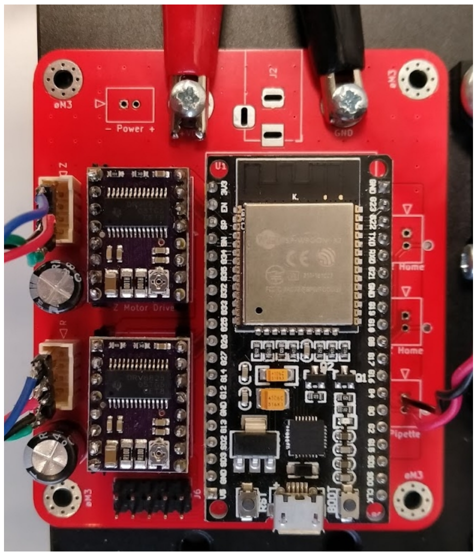
- Note initially large vibrations as z decreases, caused be loose tolerance, too small coupler. Caused droplet to prematurely detach at larger values.



5.2 Electronic Design

- full circuit
- pcb
- any and all adjustment found and made during implementation





5.2.1 Motor Driving

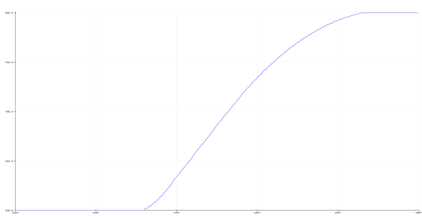
5.2.2 Setup and Requirements

- characterised skipping issue at 100Hz, 180Hz-200hz in single step
- implemted micro stepping to solve

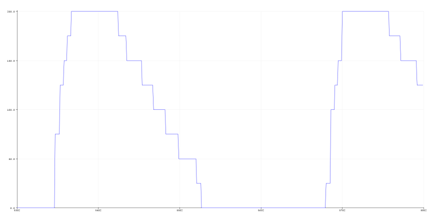
//TODO rewrite
Driving firmware was implemented on an ESP32 to validate its ability in producing the required pulse train step signal. The controller was required to produce N steps (pulses) at a set average speed, and ramp up and down that pulse speed at the head and tail of that signal.
Set values of 200 steps forward and back, at a speed of 200 steps per second, with max acceleration or 800 steps per second per second:
These pulses were captured on a second microcontroller listening for falling edges to trigger an interrupt routine to record and display that data.

5.2.3 Results

Figure 5.1:a shows a successfully produced signal of 200 pulses with an inferred acceleration at its head/tail. This speed ramping is better illustrated in figure 5.1:b showing the stepping change in pulses per second over the course of the pulse train.



(a) Pulse Count



(b) Pulses per Second

Figure 5.1

5.2.4 Pipette Triggering

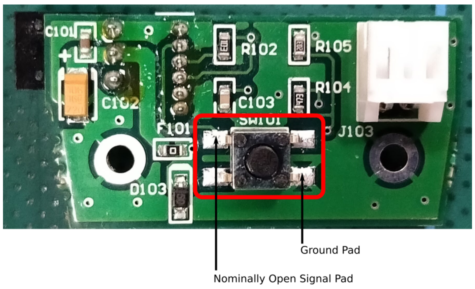


Figure 5.2: E-Pipette dispensing trigger switch daughter board with exposed pads

5.2.5 Environmental Monitoring

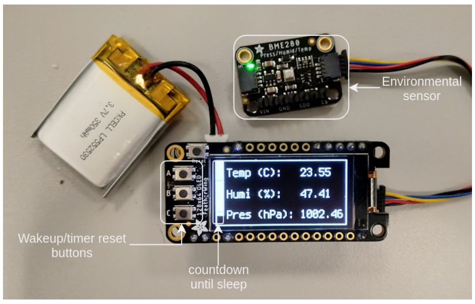


Figure 5.3: Implemented Environmental Monitor

5.3 Software

//Insert Serial Command Table (maybe only appendix)

5.3.1 Motorised Dispensing Controller

ESP32 based system controller with serial interface for issuing commands. Provides functionality to:

- Motorised stages, height and angular position
- e-Pipette droplet dispensing

5.3.2 Environmental Monitor

- Auto sleeping, button wake upon
- Circuit-Python implementation

5.3.3 LabView Temperature Logger

Chapter 6: Evaluation

6.1 Mechanical Stability

Perform Motor driving parameter sweep to optimise mechanical performance according to requirements; of minimising pipette tip overshoot and settling time.

6.1.1 Procedure

- Position tip at -1/4 revolution before zero point
- Set Speed/acceleration values
- Swing to zero position
- Repeat for value sleep=1rev/s, acc=1/rev/s/s $\rightarrow$ speed=2rev/s, acc=10/rev/s/s
- Note: acceleration is the ramp down at end/start of motion so is what we care most about
- Camera captured motion

6.1.2 Results

//insert generated figures of tip position
//generated trend lines/aggregated data (settle, overshoot) from data.

6.2 Droplet Volume

Something the previous system could not achieve was dispensing a variety of volumes. Use e-pipettes programmable volume to investigate the limits of this project.

- How large a droplet can be held on to? (prelim: 8uL)
- How large (over above) can reliably self release (w/out touch down)
- How small a droplet can be dispensed (e-pipette has draw-back).

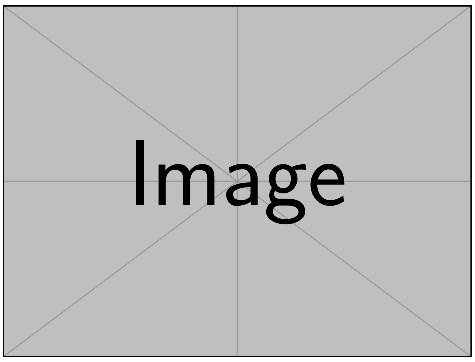
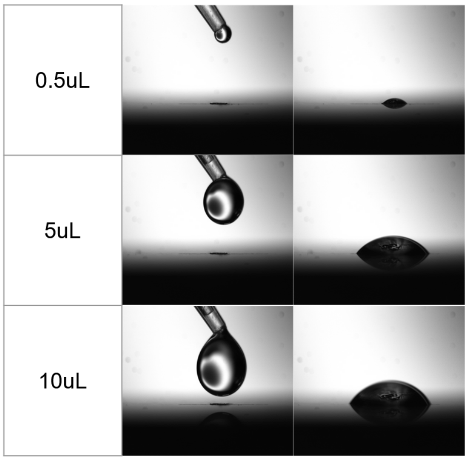


Figure 6.1: Left:



6.3 Repeatability and Reliability

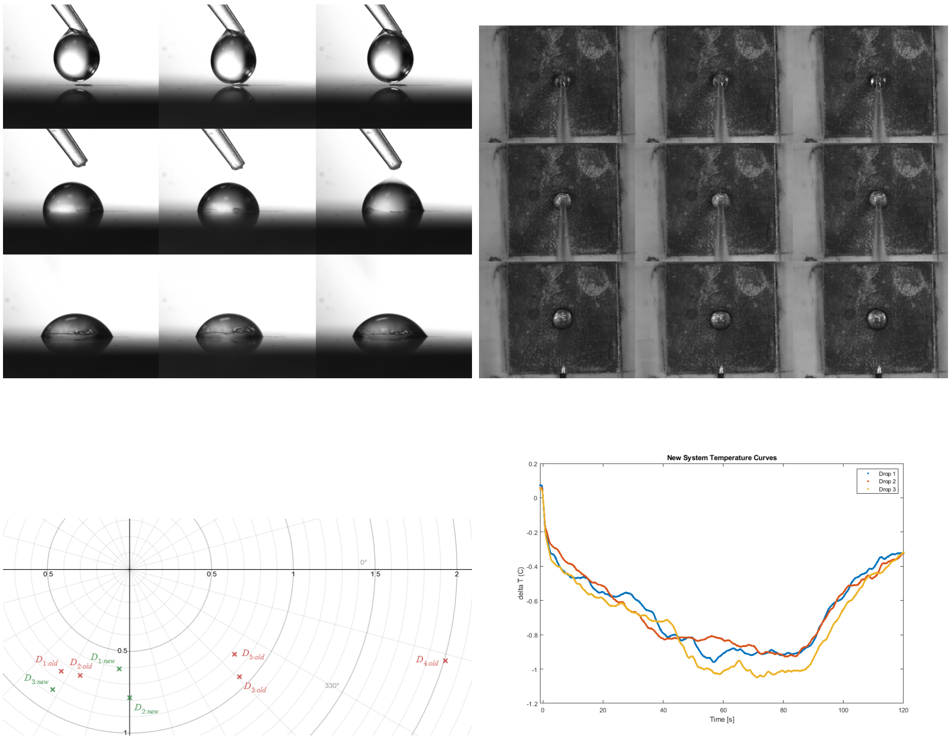
This section aims to produce the main set of comparable results for evaluating the projects produced system against the output of the previous setup. Thus justifying the success of one of main goals.

6.3.1 Procedure

- **Initial Setup:** Roughly Position substrate stage, reservoir platform and note angular positions as well as vertical clearance requirements.
- **Zero System:** Using overhead camera precisely position pipette tip above substrate centre
- **Data Acquisition:** Initialise cameras, collect pixel:mm calibration data for analysis, initial LabView temperature logger, and environmental monitor noted. Info: temperature data rate, camera frame rate
- **Automated Sequence:** Via the serial link, enter the procedures command sequence to represent $\rightarrow$ lower, draw up fluid, raise, position over substrate, dispense, lower, raise, clear camera view. With appropriate delays.
- **Capture:** Begin data collection and automated dispense.
- **Repeat:** Minimum of 5 times. Each time carefully cleaning substrate surface to minimised up measured factors.

6.3.2 Analysis and Results

To show the system successfully increases the consistency of droplet position and investigate whether this supports the hypothesis that this resulted in better temperature consistency.



Chapter 7: Conclusions and Future Work

7.1 Conclusion

7.2 Future Work

- User Friendly Graphical Control to interface with serial command controller
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