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Instrumentation System for Liquid Drop Impact and Evaporation

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Submitted in partial fulfilment of the requirements for
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

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, inkjet 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 is done with the intention to improve the reliability and usability of the collected data from the previous setup by better controlling for identified affecters, and introduce methods of automating the process.

1.2 Proposed Approach

This project proposes to build the next generation of this droplet instrumentation system, based on automation and motorisation with the express aim to improve repeatability, usability and reliability by controlling for variables that affects droplet position and morphology. More precisely the new system will use stepper motors and a serial control interface to automate the positioning of a droplet dispensing electronic pipette and electronically interface with it to enable remote droplet dispensing.

1.3 Goals

The goals of the experiment are to characterise the behaviour of a droplet impacting and evaporating from a given substrate. This forms the backbone for the goals of this project:

- Increased Repeatability and Reliability droplet position, volume and morphology with the intent that controlling these variables results in more consistent results.
- Increase speed and usability of the experimental process via automation to enable more data to be collected more easily and consistently.
- Produce an expandable platform that can be built upon beyond the scope of this project.

1.4 Evaluation

Evaluation of the success of this project is split in two:
Firstly, individual system components will be unit tested against their specifications and through the lens of improving system repeatability. I.e. Has the mechanical been designed to minimise vibration and resonance.
Secondly, as this project exists within the greater context of an existing experimental process, data from the initial system is used to form a baseline for a comparative evaluation of the project integrated system.

Chapter 2: Background and Related Work

2.1 Droplet Impact & Evaporation

Droplet Impact and Evaporation experiments have a consistent list of instrumentation requirements and variable considerations. At its core is the substrate upon which the droplet is deposited, this can be held at a variety of temperatures, have differencing surface and material properties that all affect the temperature evolution and physical interaction between the droplet and its surface. Secondly is the method of droplet dispensing or deposition, and third is the method through the which the experiment controls for, account for, or just records the variety of affecting factors.

2.1.1 Other Approaches

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 the single camera, has the separate uncontrolled rig for top view [6].

2.2 Background on Stepper motor control

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 starts 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.

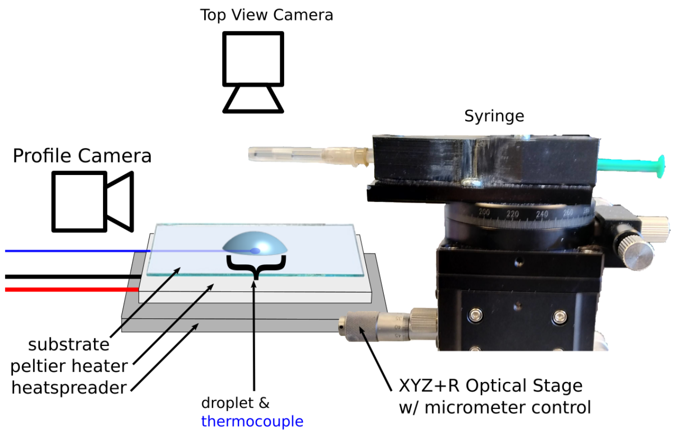


Figure 3.1: Initial Experimental Setup

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 an aluminium heat-spreader, Peltier heater, and metallic substrate (copper, stainless steel, etc) with an 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] 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 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 repeatability and reliability of the system and to compare the effect of the drop morphology and position with the resulting temperature evolution.
The first analysis is the image data. The substrate itself has a mark to represent the position of the thermocouple, this is used as 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

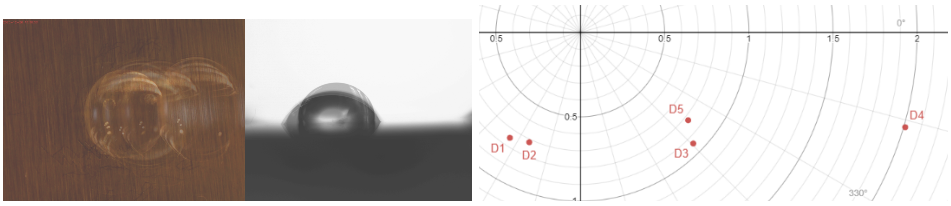


Figure 3.2: Droplet positional and shape variation; Left: Camera overlay, Right: Quantified Offsets [mm ∠ degrees]

and profile cameras respectively, and was used to measure the droplet centre offset and angle (from the reference point) as well as the height, width and contact angles of the droplet on the substrate.
As 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 3.1to compute it.

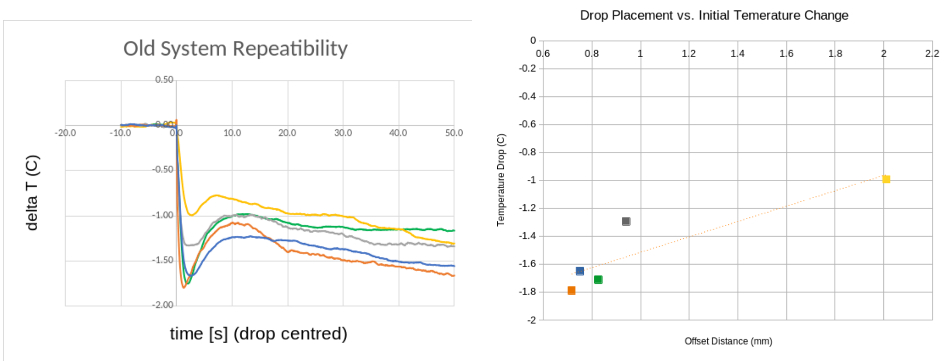


Figure 3.3: Left: Initial Systems temperature data showing large relative variation, Right: Drop offset magnitude (mm) against resulting measured temperature drop

By taking a series of consecutively collected temperature data using the initial system the observed variation can be quantified. As a pre-processing step a 1sec rolling average is applied to the collected vectors. They are then time aligned to zero at the point of droplet contact, indicated by a sudden temperature drop. This data is then transformed into a temperature delta relative to the temperature just before contact.
Observed is 0.112°C variance between the initial temperature drops between all runs and all runs are observed to evolve at differing rates, rebounding to drifting temperatures etc. This is the main justifying factor in perusing an improved instrumentation system.

3.3 Summary

Droplet	*Offset(mm)*	*Volume(uL)*	*delta T (c)*
1	0.7506	16.55	-1.649861
2	0.7164	17.91	-1.790142
3	0.9402	17.89	-1.294989
4	2.0104	17.57	-0.994441
5	0.8258	16.21	-1.712207
Variance	*0.2964*	*0.6288*	*0.1121527*

To summarise the results of this initial evaluation, a variance of the droplets morphology and resulting temperature measurement are taken and used as a guide for the projects specification and comparative evaluation.
To fully guide and justify the direction this project will take in attempting to improve this experiment it will consider and address a list of possible affecters on the experiment results.

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

**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*

Droplet position is a result of the method of dispensing and as seen in figure 3.3 correlates to variation in the observed temperature data collected via the substrates embedded thermocouple. Due to the manual method of dispensing, this variation is very likely to occur and is essentially uncontrolled in the initial experiment other than a reference point as a target. The volume and Contact angle of the droplet is more a result of procedural inconsistencies. The volume being a factor of the syringe and contact angle being very dependant of the surface finish/quality/cleaning of the substrate.
The environmental factors differ from these, as the experiment is carried out in a climate-controlled lab there are very few high-frequency changes but these factors can greatly affect the rate of evaporation of the droplet.
Given the above, this project will focus on the controlling the procedural affecters but will supply a method for collecting data on the environmental affecters for analysis.

Chapter 4: Design

4.1 Project Specifications and Justifications

Given the results of the initial evaluation, the project can now be constrained. Its 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 an extension.

4.2 Drop Dispensing and Volume Control

At the core of the system 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, an alternative solution is required to provide a core that allows the rest of the 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 a single channel electronic pipette from Labnet, P3600L-10.

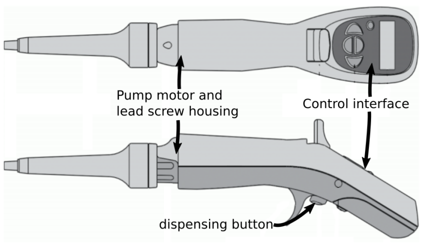


Figure 4.1: Labnet Excel P3600L-10

This product comes recalibrated and verified to dispense a droplet at a specified volume with an accuracy of $\pm 4.0 \rightarrow \pm 1.0\%/\mu L$ over 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 to 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 are 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 as to minimise backlash and prevent vibrations from propagating 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 the reservoir to substrate stack, the pipette needs to be held at a 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 for securely fastening the e-pipette at the correct angle.
- Laser Cut Mounting Tower: Sets pipette height and connects pipette to the 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 specifications are used to derive the full dimensions of the following assemblies.
The electronic pipette form-factor 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 distances 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.
To connect the tower assembly to the motor and optical stage. . .

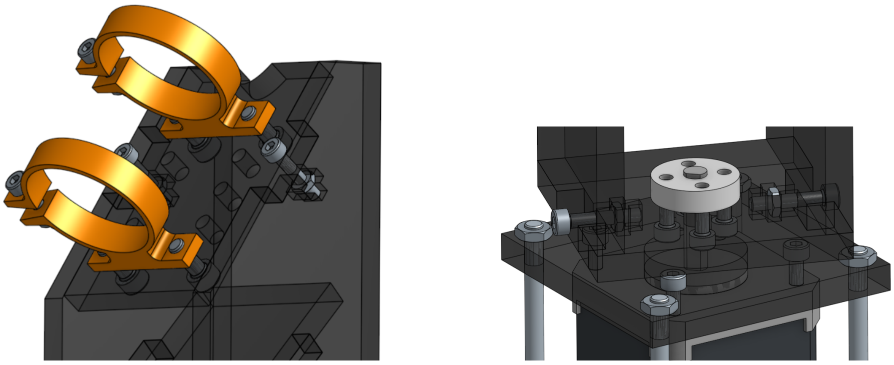


Figure 4.2: Left: Pipette Clamps and Tower, Right: Towers base mounting to the motor shaft

4.3.2 Z micrometer Control

In order to control the height of the pipette tip; to enable automated refilling and to place the dispensed droplet onto 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 presents 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.

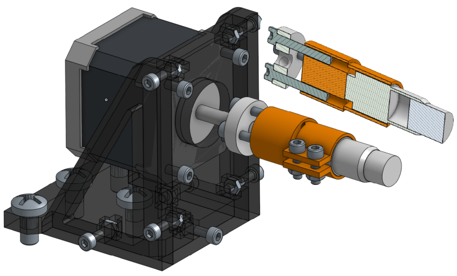


Figure 4.3: Z Driving Motor and Sliding Shaft Coupler

The figure above[5.2] 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 rotation of the motor 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 though 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 the 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 is 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 used, 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 provides 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 affecters [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 was 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 of implementation the microcontroller + display combo was chosen to be an Adafruit feather and OLED stack. specifically the RP2040 for its low power capabilities and JST LiPO battery connector.
Sensor options considered were the discrete LPS22/25 for pressure and DHT11/22 for humidity and temperature or the fully integrated BME280 for all measurements.

4.5 System Overview

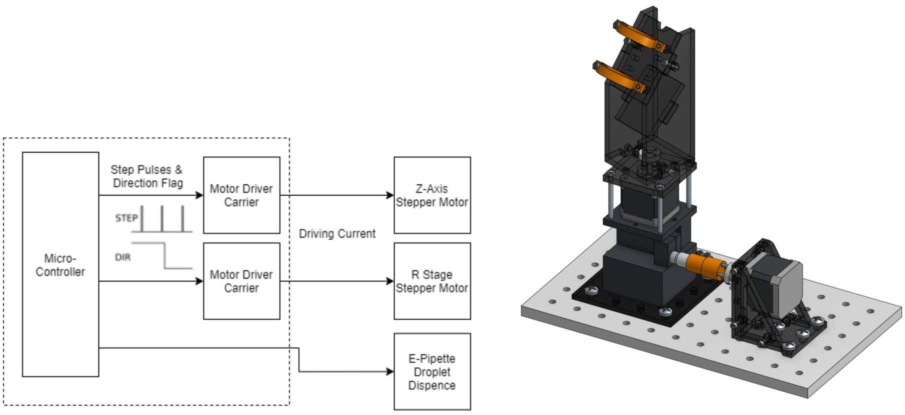


Figure 4.4: Left: Instrumentation Architecture, Right: Full CAD Design and Layout on optical breadboard

Chapter 5: Implementation

The implementation process took the planned designs and selected hardware and constructing an integrated system. This provided an opportunity to test, iterate finalise the designs and approaches of the project.

5.1 Mechanical Components

Implementing the mechanical components of the system covered the material choice, manufacture and adjustment of the motor mounting brackets, shaft couplers and interfacing and pipette mounting and supports. Considerations taken were speed of iterations. Flexibility in adapting specific dimensions to suit needs and to maximise reliability and stability.

5.1.1 Rotating Pipette Mount

The C-clamp's design did not fundamentally change from the initial design, and remained the duel clamping system with matched internal circumferences. They did however go through many smaller interactions to achieve the preferred performance. Firstly, obtaining the required internal circumference of the clamps from the asymmetric body of the pipette was taken using a length of string was used to at the points of intended fastening. The clamping pressure then deformed the initially circular parts to the ergonomic form of the pipette body.

This process, and the resulting measurements of 32mm and 36mm remained unchanged. However, the ring thickness was varied and tested. 3 options were 3D printed and trialled; 1mm, 1.5mm, and 2mm. This thickness affected the clamps ability to deform to the shape of the pipette, how rigid the mounting was and the strength at the clamping screw holes.

1mm was used for the longest initially, but had a noticeable woggle as well and resulting in the screw hole delaminating from the ring due to flexing in the plastic. After this failure, the 1.5 and 2mm versions were printed and trialled for a shorter period. The 2mm provided much better strength, showing no noticeable degradation at points of high-stress concentration. However where this thickness failed was in deforming, the added rigidity was just too inflexible to ever fully clamp and resulted in play/slippage. Given this, two 1.5mm version were printed to compromise and successfully deformed and remained intact over the remaining project time.

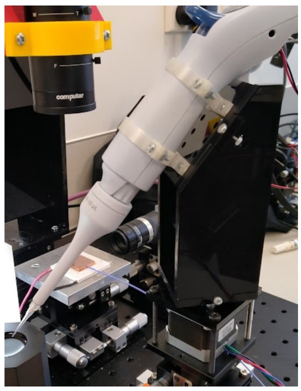


Figure 5.1: Final constructed Pipette stage mounting tower w/ clamps and motor

Another area of tweaking was the screw tolerance. These pieces were designed to take advantage of the plastics deformation to also allow for the screws to cut their own threads as provide a stronger grip. As the screw is initially inserted a too smaller hole can result in splitting delamination of the plastic layers, via experimentation, a +0.2mm diameter tolerance allowed for retaining that 'self-tapping' characteristic while maintaining structural integrity.

The tower itself was designed to be fully laser cut from acrylic to minimise [material] flexibility and to aid to modularity. This allowed the height to be adjustable by cutting different side pieces for example. This did not deviate from design, but initially, the tower was glued together to reduce weight but this was quickly scrapped for machine screw bolting, with the intention that any oscillations or resonance in the system would be tuned for on the motor driving side of the project.

5.1.2 Z micrometer Control

The Z height adjustment represents the most sensitive mechanical system and required careful measurements to axially align the micrometer knob and the shaft as well as matching the coupler length to accommodate the discrete fastening points of the optical breadboard.
The figure above 5.2shows the Z-motor statically mounted to the breadboard with a laser-cut bracket assembly. This, along with the aforementioned tight tolerance requires presented the first problem to overcome with mechanical performance.
The initial z-coupler was printed with a 1mm defect in it radius as too small M3 screw holes. This cause splitting under high load as well as large vibrations that propagated through the whole system as was causing premature droplet detachment.
After reprinting the coupler, these vibrations were greatly reduced by still present. To combat this, the motor driving parameters were adjusted, slowing the signal speed from 10 revolutions per second until it no longer resonated during the adjustment. Final parameters were 6 rev/s and 100 rev/s/s.

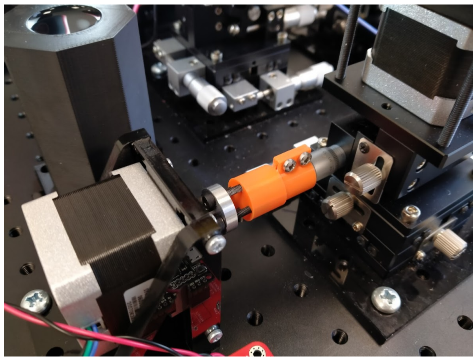


Figure 5.2: Constructed Motor mount and sliding coupler interfacing with the z-micrometer of the XYZ stage

5.2 Electronic Components

The aim of the electronics in this project is to provide an interface for the host computer to send commands with the controlling microcontroller and supply and support the stepper driving stages and their required current. The microcontroller receives command strings over serial USB and parsed them and executes them either at PWM control signals to the STEP inputs of the drivers or digital flag signals to the pipette. The driver requires a motor supply voltage of 8.2 – 45 V. This supply should have appropriate decoupling capacitors close to the board, and it should be capable of delivering the expected stepper motor current. These decoupling capacitors are to act as reservoirs for high loads and shield the onboard low-ESR ceramics from LC voltage spikes. These spikes can exceed the 45 V maximum voltage rating for the DRV8825 and permanently damage the board, even when the motor supply voltage is as low as 12 V. This was addressed with the addition of a pair of 100u electrolytic capacitors across the motor power rails right next to the carriers.
The figure5.3 shows the final electrical implementation and state the controller PCB (only partially populated due to COVID shipping delays). Note that this design included unfulfilled homing switch pads, as well as a 10 pin GPIO breakout for future expansion; i.e. external data acquisition syncing or other communication options.
The final consideration for this construction is whether the driver carriers require heatsinking or cooling. The DRV8825 driver IC has a maximum current rating of 2.5 A per coil, but the current sense resistors further limit the maximum current to 2.2 A, and the actual current you can deliver depends on how well you can keep the IC cool. The carrier's printed circuit board is designed to draw heat out of the IC, but to supply more than approximately 1.5

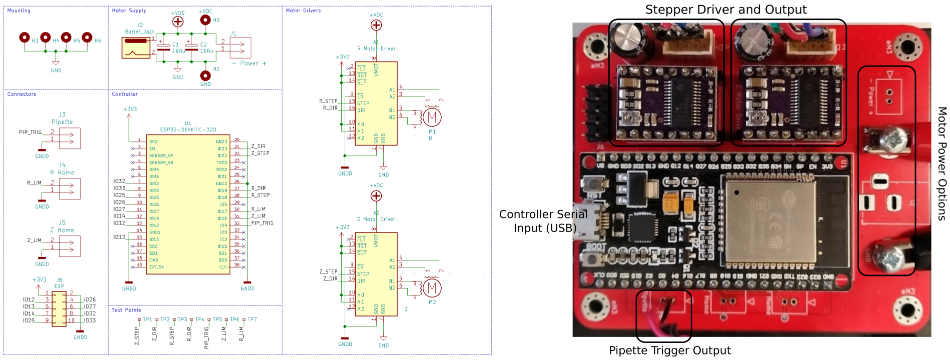


Figure 5.3: Left: Controller Schematic and Right: Constructed PCB

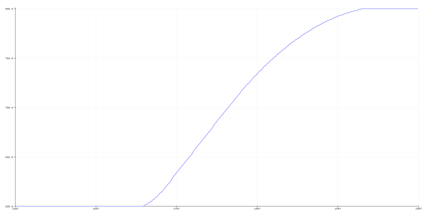
A per coil, a heat sink or other cooling method is required. To obtain the systems requirements, both motors were supplied with a 15V DC motor voltage and the total current draw was tested at holding and under load.
This resulted in a max single driver holding current of 0.41A and a peak load current of 0.58A. This is well below the uncooled limit so no cooling solution was supplied.

5.2.1 Motor Driving

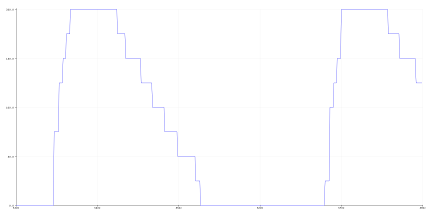
5.2.2 Setup and Requirements

To meet the driving requirements of the stepper motors outlined in this reports background [2], preventing stalling and minimising harsh start stop behaviour that could cause unwanted vibrations, the controller and driver must be verified to be able to supply the step pulse train with ramping speeds and characterise the motors to ensure no steps are skipped. If this occurs the open loops control scheme will mean that the systems positional accuracy will fail.
Test 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 of 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



(a) Pulse Count



(b) Pulses per Second

Figure 5.4

Figure 5.4: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 5.4:b showing the stepping change in pulses per second over the course of the pulse train.
Additionally, it was found that these motors experiences some resonance and began skipping step when in 1:1 driving mode at the specific frequencies of 90Hz, 100Hz and 180Hz. This was solved by enabling the driver carrier's 1:32 microstepping mode and modifying the firmware to match.

5.2.4 Pipette Triggering

The pipette draws and dispenses liquid be using an internal DC motor to drive a leadscrew pressure chamber. This is controlled via a multi-function switch on the DC input daughter board. This daughterboard was required to be removed to gauge the signal requirement needed to trigger this event.

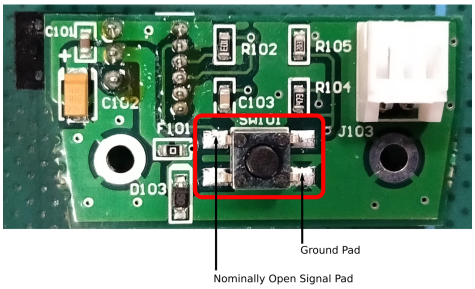


Figure 5.5: E-Pipette dispensing trigger switch daughter board with exposed pads

From this investigation, it was determined the internal GPIO was connected to the nominally open (unconnected) pin of the switch. When actuated this line is pulled down to ground indicating a button press. This triggers 1 of 2 actions; Pipette wake-up or toggle leadscrew position, either dispensing or refilling the reservoir tip.
To automate this process the nominally open pad was broken out to an output GPIO line on the controller and the ground was broken out and shared with the signal ground of the controller.

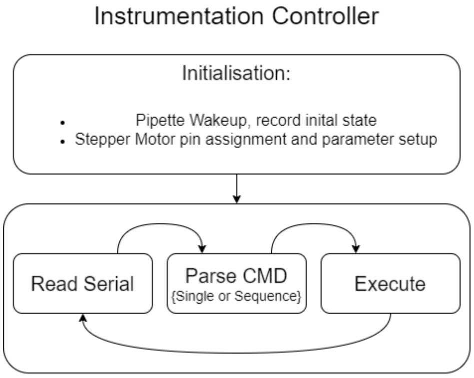
5.3 Software

5.3.1 Instrumentation Controller

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

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

The architectural approach for this controller is to provide an extendable and versatile command interface that allows for multiple input/control methods. For this reason, a continuous serial string input is polled for, parsed into internal library calls that control the motor driving signals and pipette actions. This allows the controller to be interfaced either directly with a text input serial command line, a LabView VISA serial control script or via a custom host side script.



`ADJ R or Z [n_steps]`	Debug command to allow individual stepping of motor
`R [n_revs]`	Primary Pipette rotation, in revolutions
`Z [n_mm]`	Primary Z height adjustment, in mm
`DEL [delay_time]`	Add time delay in ms
`PIP [UP|DOWN]`	Draw liquid (UP) or dispense (DOWN)

Upon boot, the firmware pings the pipette to wake it from sleep. Sets up symbolic motor objects to control signal generation with the correct micro steps, speed and acceleration terms. Then enters a command poll, parse and execute loop.
This command loop, translates real-world input units and translates them to the required step count. For example to rotate the pipette by half a revolution the command `R 0.5` is sent, and to raise the pipette by 5mm, `Z 5mm`. The full command list is as follows:
Internally the firmware keeps track of the last pipette action to ensure the user does not accidentally dispense or draw liquid.
To enable setup and tuning as well as full experiment automation there are two command input modes. Individual and Sequence. To enter a sequence, the special command `SEQ` is sent follows be semicolon-separated commands, `Z -5; PIP UP; Z 5; R 0.25; DEL 200; PIP DOWN; Z -4; Z 4; R -0.25; END;`.
This firmware produces two main parameters that are available for tuning when evaluating the performance of the integrated system: The step signals pulse speed, and its ramping acceleration.

5.4 Environmental Monitoring

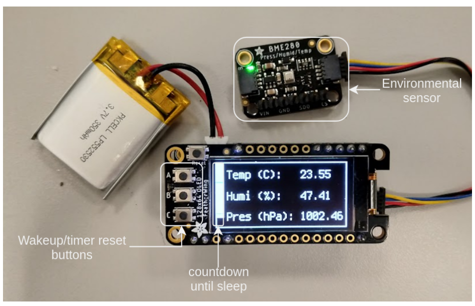


Figure 5.6: Implemented Environmental Monitor

The design values speed and quick integration, so assembly was plugin-play. The primary work down was the power management and data-collection software. The BME280 and

OLED screen are attached to the I2C bus with unique addresses. These are polled to retrieve prefiltered temperature, pressure and humidity data and pushed to the screen.

Low Power

As the system is portable and powered only by a single cell LiPO battery, long life is more of a requirement than continuous display, as the data is only needed to be noted at the beginning of an experiment. To achieve the firmware attaches button alarm interrupts to OLED screens buttons and counts downs an internal timer. Upon timeout this firmware clears the OLED, places the screen and BME in sleep mode. These will now draw $5\mu A$ and $2\mu A$ respectively. The RP2040 itself then enters deep sleep, clearing memory and shutting down most of its hardware, achieving $180\mu A$ of draw.

5.5 Full System

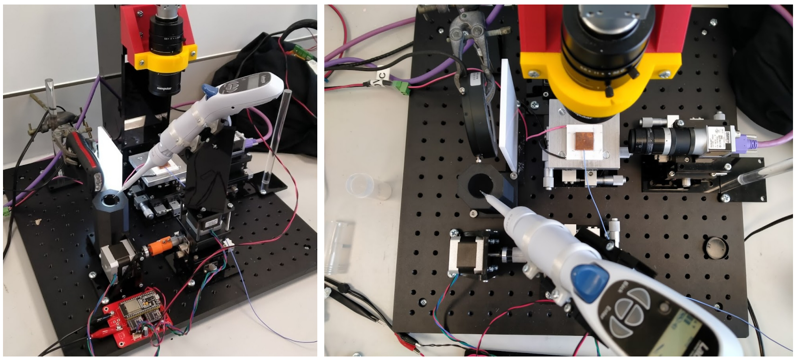


Figure 5.7: Full System

Fully integrated, this system is assembled on an optical breadboard with an assortment of adjustable XYZ micrometer stages; camera mounts, backlight and diffusers, a liquid reservoir and a central substrate stack. The procedure this instrumentation follows is: lower pipette tip into the static reservoir and draw pre-programmed volume into tip, raise pipette to the required height, rotate to depositing point, dispense droplet and pause, lower and raise pipette to deposit drop on substrate, rotate pipette clear of camera view.

Chapter 6: Evaluation

The aim of this project was to control for and improve the repeatability, and reliability of the position and volume of the dispensed droplets on a substrate with the informed hypothesis that these are major contributors to the observed high variation in resulting the temperature evolution during the droplet's evaporation. To show the success of the project this evaluation will investigating, quantify and compare the performance and positional repeatability of the new instrumentation as well begin to as investigate its effects on the temperature evolution of the droplet's evaporation.

6.1 Mechanical Stability

Given that the express goal of this project is to produce a more stable, repeatable system for depositing droplets of a set position the mechanical stability of the instrumentation is required to be accessed and tuned to minimise vibration and pipette tip oscillations (settling time and overshoot).
To evaluate the performance of the system, a parameter sweep of the pipettes R stage motor driving settings: speed and ramp acceleration.

6.1.1 Procedure

- Position tip at -1/4 revolution before zero point (proxy reservoir)
- Set Speed/acceleration values
- Swing to zero position
- Repeat for values across sweep: speed=1rev/s, acc=1/rev/s/s → 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

6.1.2 Results

By taking a 25 frames per second image sequence captured via the top camera of the same automated sequence performed at various parameters the pipette tip could be motion-tracked over time to extract its relative motion frame to frame quantitatively capture the settling behaviour of the pipette tip. Minimising ensured the best chance of avoiding prematurely detachment and precise positioning at the time of dispense.

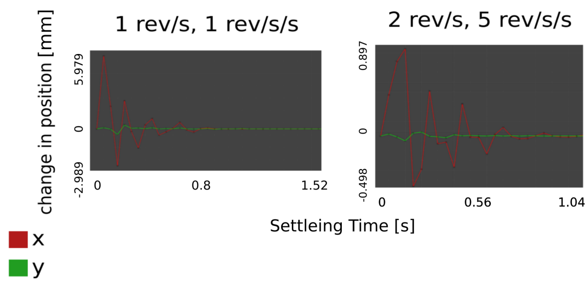


Figure 6.1: Worst (Left) and Best (Right) performing oscillations and settings

The figure [6.1] above shows this tip behaviour. This procedure and analysis helped determine a final parameter tuning for the R motor of 2 rev/s and 5 rev/s/s resulting in a maximum overshoot of 0.9mm and settling time of 1s. This can be used to inform the delay time require after tip positioning before dispensing the droplet.

6.2 Droplet Volume

Something the previous system could not achieve was accurately dispensing a variety of volumes.
The use of an e-pipette eliminates variation in absolute volume to a higher precision than what this project can evaluate but additionally the use of it programmable volume feature enables this. The instrumentation however may not be able to use the full volume range of $0.5\mu L$ to $10\mu L$.
The system had been observed previously to be unable to reliably dispense above $8\mu L$ without premature detachment. This was before the Z motor coupler was refined and the motors speed adjusted. We also had the hypothesis that variation in volume could have an effect on the y-position of the deposited droplet, via the mechanism of differing masses being affected more by surface tension with the tip.
The figure 6.2shows instrumentation successfully dispensing and depositing the full range of volumes, and confirms the systems ability to utilise the pipettes full functionality. Also of note that these results disprove the hypothesis of y-axis dependency, as after dispensing [if a delay of at least 500ms is allowed] all droplet volumes hang and settle with gravity.

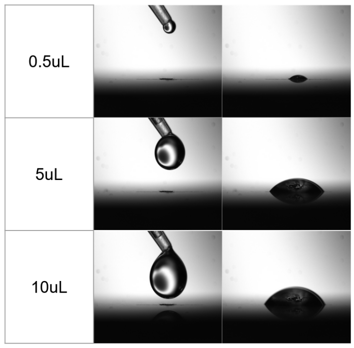


Figure 6.2: Successful droplet dispense and deposit of full volume range

To ensure consistent performance over the volume range the Z-height dip must be varied to successfully deposit the droplet on the substrate and prevent overly deforming it at high volume.

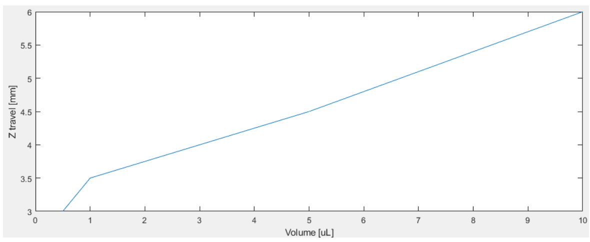


Figure 6.3: Drop Volume vs Required Z travel

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 the substrate, dispense, lower, raise, clear camera view. With appropriate delays.
- **Capture:** Begin data collection and automated dispense.
- **Repeat:** 3 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.

6.3.3 Position

The main bulk of the design and effort of this project were put towards ensuring consistent, accurate and repeatable pipette tip positioning with the intention of greatly decrease the run to run variance in droplet position. This was due to the static point temperature measurement being taken by a thermocouple and initial evaluation indicating a correlation between droplet offset from thermocouple position and temperature data variation.

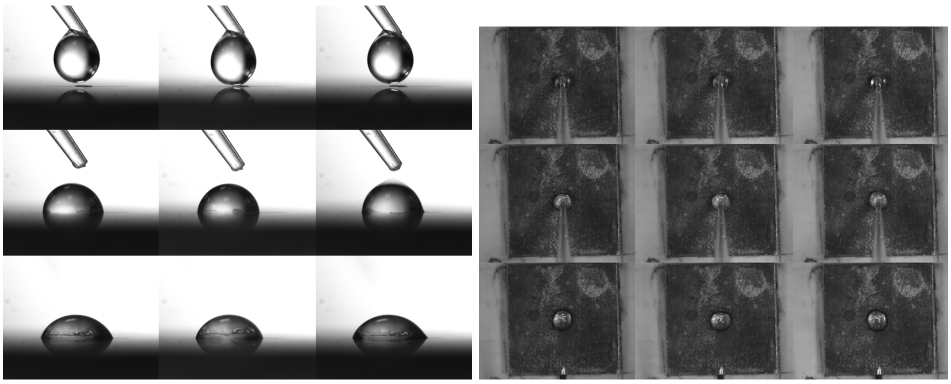


Figure 6.4: Visual results of consecutive experimental runs (Runs are column-wise)

Prior sections have covered to tuning and design decisions taken to produce consist pipette tip position but how does this translate to droplet variation. Figure 6.4shows the qualitative results of 3 consecutive 10 μL experiments. By observing these results, the pipette tip placement is indistinguishable between runs and hanging droplets before contact are also consistent. This image data formed the basis for further analysis to extract quantitative information.

Collected calibration reference images allows the translation of pixels to mm, and using an image processing and analysis tool droplet centre offset from substrate centre as well as surface contact area measured to quantify performance for comparison to initial system.

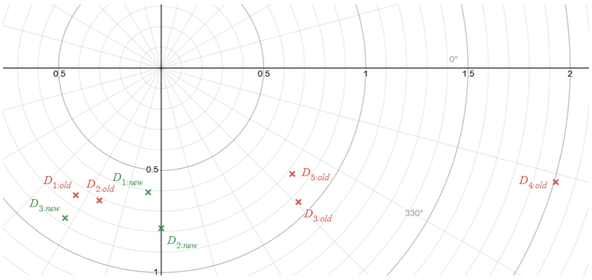


Figure 6.5: Caparison of old (red) and new (green) droplet positions

6.3.4 Temperature Evolution

The above droplet runs were also accompanied by the collection of substrate temperature data via the embedded thermocouple. The thermocouple was read at 30Hz, and MatLab was used to postprocess and analyse the data. As a pre-processing step a 1sec rolling average is applied to the collected vectors. They are then time aligned to zero at the point of droplet contact, indicated by sudden temperature drop. This The data is then transformed into a temperature delta relative to the temperature just before contact.

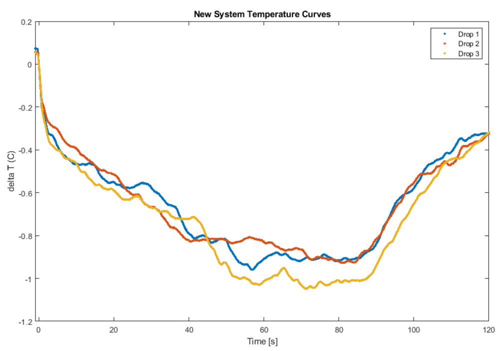


Figure 6.6: Captured Temperature Evolution of new drop tests

It is worth noting that this temperature data is in no way comprehensive, and differs from the initial data due to a difference in substrate material: stainless steel vs copper.

6.3.5 Summery

	Pos Offset [mm]	delta T [c]	contact area (mm^2)
Drop 1	0.6126	-0.9044	15.8928
Drop 2	0.7856	-0.9238	15.7082
Drop 3	0.8728	-1.009	15.0274
Variance	0.01753948	0.003096	0.20774716

Chapter 7: Conclusions and Future Work

7.1 Conclusions

The aims of this project were to control for variations in droplet morphology; droplet position and volume, providing an improvement over the previous system. Produce an extendable platform that enabled the experimental process to be automated/centrally controlled to speed up the procedure. Provide a data collection system for uncontrolled factors. These goals were chosen with the hypothesis that improving the system's performance in these aspects would carry through to an improvement in the inconsistent results observed in the previous iteration of the system.

To control for droplet volume and provide a method for variable volume, this project utilised a pre-calibrated electronic pipette as the central droplet dispensing tool that is interfaced with to provide remote GPIO control. Automation, user control and positional control was achieved via a serial command-driven stepper motor controller that drove the motion of a micrometer controlled XYZ stage mounted upon an optical breadboard.

Successes

The use of a pre-calibrated electronic pipette eliminates volume variation to a point beyond the scope of this projects ability to measure, but more importantly, the mechanical system was confirmed to be stable enough to support the full variable volume range from 0.5 to 10 microlitres.

The stepper motor driving system parameters were successfully tuned to reduced pipette tip settling oscillation below 1mm in 1s and achieves consistent and exact positioning. This precision in instrumentation control resulted in the reduction in droplet positional offset variance from 0.296mm to 0.018mm.

From initial analysis of the collected temperature profiles, this project can preliminarily confirm the hypothesis that improved positional and volume consistency will result in greater consistency in experimental results. Though more data is needed.

The firmware and controller implemented fully supports input of predefined command sequences that allows a user to quickly run the same complex experimental procedure much time, with the exact same instrumentation performance.

Drawbacks

Major drawbacks of the resulting design include the XY positional locking of the pipette stage due to static Z motor mounting on the breadboard. This results in any required adjustment to the camera, substrate and reservoir to be carried out to fit the pipette stage position.

This implementation lacks auto-homing to set zero position, and additionally due to the permanent magnetic pole of the stepper motor stator combined with the drivers micro steppers, the user can request an invalid holding position as home. This cannot be maintained due to current limits and will snap away from it. This should however be evident in the setup stage of the experiment.

7.2 Future Work

As stated this project produced an extendable platform from which a variety of features can be implemented.

- User-Friendly Graphical Control to interface with serial command controller. As of now, there exists a LabVIEW script that can interface with the serial input of the controller but more in-depth user-friendly version would be a great step up in the usability of the system.
- Due to the projects nature combined with an inopportune COVID19 lockdown the integration of homing switches to automate setup was planned but not implemented. This addition would increase setup speed and usability.
- Utilise included GPIO breakout header to synchronise external data acquisition
- Further investigate Temperature evolution with varied volume, substrates, cleaning techniques
- Add enclosure to isolate air currents and further control variables.

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