VICTORIA UNIVERSITY OF WELLINGTON
Te Whare Wānanga o te Ūpoko o te Ika a Māui

School of Engineering and Computer Science
Te Kura Mātai Pūkaha, Pūrorohiko

PO Box 600
Wellington
New Zealand

Tel: +64 4 463 5341
Fax: +64 4 463 5045
Internet: office@ecs.vuw.ac.nz

Instrumentation System for Liquid Drop Impact and Evaporation

Daniel Eisen

Supervisor: Gideon Gouws

Submitted in partial fulfilment of the requirements for
Bachelor of Engineering with Honours.

Abstract

Droplet impact and evaporation presents a complex physical process worth investigating not only from a fundamental research perspective but also in its potential for industrial application. However, in order to extract usable data from this small scale, fast phenomenon in the lab producing a droplet of repeatable volume and position as well as accucartly track and collect the data (temperature, impact, evaporation) is essential in order to extract reliable and study worthy results. This procedure form the basis of this project. This projects approach is to add motorised automation to droplet dispensing with aims to control for droplet volume, positional variation, contact angle and speed up the procedure and allow for greater flexibility in the experimental process.

Contents

Chapter 1: Introduction

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.

This preliminary report covers the key problem of the experimental setup that the project aims to improve, and identifying the main factors that can introduce variation into the results. It will also provide an overview and evaluation of the current and previous systems, and the variability of their results, including possible sources of these inconsistencies. It will briefly cover other similar systems in literature, and what they control and how. Then the report will redefine the project scope, its objectives, and what variables it aims to control and how. Finally, it will cover what work has been done and where the current progress and results stand, as well as detailing difficulties and decisions made along the way.

The Experiment

A droplet of liquid (concentrated milk, water, or similar) is deposited on a heated substrate (stainless steel, copper, or glass). The temperature of the substrate is monitored. The progression of the droplet's impact and evaporation is captured by two cameras; above and profile view. This produces a multidimensional perception of the developing behaviour and characteristics of the droplet over time. This usually takes between 1 and 2 minutes per droplet.

Problems

This experiment relies on the precise placement of a droplet above a temperature sensor, in a set focal plane, to measure the droplet as it progresses through it's evaporation. Therefore, it can be said there exists uncontrolled factors that can alter the results, affecting the final values and the repeatability of the experiment. These factors can be separated into environmental and procedural sources.

Environmental	Procedural
Humidity	Droplet Volume
Atmospheric Pressure	Droplet Position (Rel. to thermocouple)
Temperature	Contact Angle (contact surface area)

Chapter 2: Background

2.1 Current Experimental Setup

The instrumentation as exists is assembled with an optical breadboard and XYZ(R) stages with micrometre controls. A central stage holds the substrate with internally mounted thermocouple. Two manual focus cameras are positioned in profile and top down views, and the droplet is dispensed manually via a syringe mounted horizontally to a XYZ+R stage. The current procedure is a manual process. The syringe tip is rotated above a marked point on the substrate, and hand emptied and refilled. This results in volume and positional variation between runs. This procedural variance is the focus of this project.

	Distance from Mark	*Measured Temperature Drop*
Min Pos Offset	0.71mm	-1.7901°C
Max Pos Offset	2.01mm	-0.9944°C
	Volume	*Contact Angle*
Shape Variance	0.629mm^3	25.894 degrees †

Table 2.1: Variance in Setup

†This excluded an outlier of an almost spherical droplet with contact angles exceeding 95 degrees. This large variation is most likely due to inconsistency in surface chemisty from washing.

Data taken from a series of five droplet runs was analysed to extract the variety in droplets and its effect on the measure temperature profile.

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

2.3 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 energizing 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.

2.4 Revised Approach

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 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 preprogramed, 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 3: Work Completed

3.1 Substrate Mounting

The proposal initially outlined the design of a mount/fastener for the substrate stack, to integrate a heat spreader, and to better ensure centering and thermocouple placement. Initial meetings with the on-site workshop and design started early with rough sketch designs and discussions on material and manufacture. However, it was quickly decided that focus should be shifted elsewhere in the project and this be returned to at a later date if needed, as the substrate is a shared component of the two projects centred around this experimental setup, and the development new droplet dispensing was the true focus of this project.

3.2 Pipette and Mechanical Mounting

Given the decision for the new rig to be centred around an electronic pipette, as opposed to the manual syringe, a new mounting assembly was needed to secure the pipette to the XYZ stage, ensure there is minimal play and backlash, and position its tip above the substrate for droplet dispensing.

Requirements: The pipette had to be held at 150mm from the top of the optical stage, at 36 degrees. Finer adjustments to be made with the XYZ micrometre controls.

A tower [3.1] was designed as the mounting solution. It was constructed from laser cut 6mm acrylic as it had been successfully used in other parts of the existing rig, could be very quickly manufactured to allow rapid prototyping, and producing of a variety of mounting points and different plates. Assembly was left open to allow for access and modification. A taller than final tower design was cut to allow for the new procedure to be carried out before the motorised system was complete.

(a) Unassembled Tower (b) CAD Design (c) Tower Assembled

Figure 3.1: Pipette Tower

3.2.1 Interactions and Difficulties

The electronic pipette formfactor is very 'organic', so the clamping mechanism to fit it to the tower plate itself was challenging to design to successfully restrict its rotation and backlash. The base design used to accomplish this was a 3D-printed ring clamp [see 3.1:a] 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 I 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 to slot the pipettes support rest and a second ring clamp attached lower down of the body.

3.3 Electronic Design and Part Selection

The electronic design for this project is as follows: A microcontroller provides control signals to step/direction drivers for two stepper motors. One stepper motor controls the tower rotation and the other the optical stage z-axis. The controller also interfaces with the electronic pipette to trigger a droplet release.

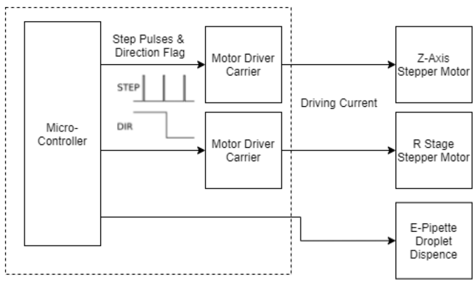


Figure 3.2: Block Diagram of Base Electronic Design

3.3.1 Motor

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.

3.3.2 Motor Drivers

The Requirements

To drive the selected stepper motors, I decided on discrete step/direction style micro stepping drivers. 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 3.1: 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.

3.3.3 Auxiliary Components

In addition to the above primary components lever-action limit switches were also selected if it were to be deemed necessary for the motor controller to have that kind of positional feedback for homing and the like. Shaft mounting hardware was also purchased.

3.4 Initial Driving Firmware Implementation

3.4.1 Setup and Requirements

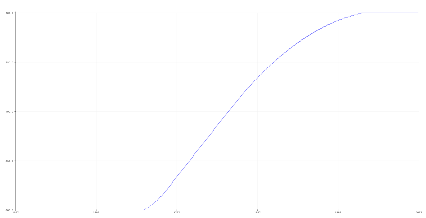
With the parts selected and ordered, I wrote test firmware on an ESP32 to validate its ability in producing the required pulse train step signal. The controller was required to produce N steps (pulses) at a set average speed, and ramp up and down that pulse speed at the head and tail of that signal.

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:

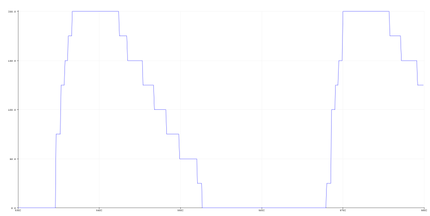
These pulses were captured on a second microcontroller listening for falling edges to trigger an interrupt routine to record and display that data.

3.4.2 Results

Figure 3.3: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 3.3:b showing the stepping change in pulses per second over the course of the pulse train.



(a) Pulse Count



(b) Pulses per Second

Figure 3.3

Upon the arrival of the motors themselves it will be determined what the exact requirements for this signal will be to prevent coil stalling and reduce vibrations in the system. It does however leave me with 3 main variables to tune this performance:

- Constant Step Count: What level of micro stepping can be achieved/whether it is required
- Step speed: Limits, usable speeds, stability
- Step Acceleration: Motor performance, stall avoidance, resonances

Chapter 4: Future Plan

Now that parts have arrived for a base deliverable prototype. Electronics can be assembled into rig, power and driving requirements can be properly determined and the new automated process can be tested and refined.

4.1 Work to be Completed

1. Assemble first motorised version (Immediately-2Wks)
   - Recut tower to new height
   - Mount R stage stepper to stage and tower
   - Design sliding shaft coupler for z stage micrometre
2. Integrate Firmware using test code a base to get things moving (1wk - 2wks)
   - Collect power requirement data
   - Evaluate performance in terms of vibration, backlash and stability
   - Begin running 'wet' runs with motorised droplet dispensing
3. Interface with electronic pipette to remotely trigger droplet dispense from controller (1wk - 2wks)
4. Running continuous testing run to optimise driving variables to minimising vibration and collect experimental data to compare to previous rigs performance (week 2 onwards)
5. Add environmental monitoring/data collection (end of prototyping, 5wks)
   - Bulk of redesigning and prototyping done during this storage
   - Informs the design of new parts, requirement for more components etc
6. Move electronic components "motherboard PCB" and finalise integrated rig design and automating procedure for final deliverable(Final 4 weeks)

Feedback

Evaluating the systems performance is now going to be two-fold. The first is as before, its performance as a new experimental rig. Does it produce more reliability and repeatability in its results, does its successfully control for the factors its has aim to control and this can be easily evaluated by comparison to the previous data collected on the old/current rig. But now I am aware the another goal of this project is the introduction of a level of automation that aim to increase the usability/flexibility of the instrumentation. What I am wondering is what would be an approach in evaluating the success of this aspect? Just that its successfully carries out a set of preprogramed motions and behaves as expects, the experiment is done etc?

Bibliography

[1] “Stepping motors and their microprocessor controls, second edition takashi kenjo & akira sugawara, 1994 oxford, oxford university press isbn 0 19 859385 6,” *European Journal of Engineering Education*, vol. 20, no. 3, pp. 386–386, 1995. [Online]. Available: https://doi.org/10.1080/03043799508928291

[2] E. Gatapova, A. Semenov, D. Zaitsev, and O. Kabov, “Evaporation of a sessile water drop on a heated surface with controlled wettability,” *Colloids and Surfaces A Physicochemical and Engineering Aspects*, vol. 441, pp. 776–785, 01 2014.

[3] J. H. Moon, D. Kim, and S. Lee, “Spreading and receding characteristics of a non-newtonian droplet impinging on a heated surface,” *Experimental Thermal and Fluid Science*, vol. 57, 09 2014.

[4] P. Hänichen, A. Bender, B. Voß, T. Gambaryan-Roisman, and P. Stephan, “Drop evaporation of hydrocarbon fluids with deposit formation,” *International Journal of Heat and Mass Transfer*, vol. 128, pp. 115–124, 01 2019.

[5] M. Frasão, A. Oliveira, and R. Gonçalves dos Santos, “Determination of nukiyama and leidenfrost temperatures for hydrocarbons using the droplet evaporation method,” 03 2018.

[6] S. David, K. Sefiane, and L. Tadrist, “Experimental investigation of the effect of thermal properties of the substrate in the wetting and evaporation of sessile drops,” *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 298, pp. 108–114, 04 2007.

[7] , “Implementing a step-direction interface-based stepper motor controller,” *Application Note AC413*, pp. 1–9, 2014.