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Instrumentation System for Liquid Drop Impact and Evaporation

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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 experimentation of interest and application to various industry. Such as milk powder spray drying, ink jet printing, and applications of evaporative cooling. This project will continue on from a previous instrumentation setup, evaluate its shortcomings, and design the next generation to improve the reliability and usability of the collected data and introduce methods of automating the process.

Report covers the key problem the experimental setup that the project aims to improve, and what are the main factors that can introduce variation into the results. An overview and evaluation of the current/previous system and the variability of its results and possible sources of that inconsistency. It was briefly cover other similar systems in literature can what they control/how. Then it will redefine the project scope, its objectives and what variables its aim to control and how. Finally it will cover what work has been down and where the current progress and results stand as well as detailing difficulties/decisions made along then way.

The Experiment

A droplet of liquid (concentrated milk, water, etc) is deposited on a heated substrate (stainless steel, copper, glass). The temperature of the substrate in monitored, along with the progression of the droplets impact and evaporation being captured with 2 cameras; above and profile. This produces a multidimensional perception of the developing behaviour and characteristics of the droplet over time. This usually take 1-2mins per droplet.

Problems

Such a process

Chapter 2: Background

2.1 Current Experimental Setup

The current procedure as of the project beginning is a manual process. There is currently no securing bracket of any kind for the substrate sample and heater stack, the cameras and other sensors are turned on one by one and most importantly the droplet is rotated above a mark in the substrate and dispensed via syringe by hand.

The droplet then falls onto the substrate, monitored by 2 high speed cameras (profile and overhead) and the temperature of the substrate is measured via an embedded thermocouple camera a time series waveform of the experiment.

We hypothesis that this method contributes a large amount of variation into the collected data that could be masking the parameter space of interest, and limiting the granularity at which conclusions can be drawn about the process of impact and evaporation.

Investigate how (a subset of affecting variables) the previous setup performs and its variability:

- note the drastic contact angle difference is a probable effect of the washing step

2.2 Existing Solutions

Brief discussion of other similar experiments and rig and what problems they solve with what methods

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 mean applicable to all driving and specific motor choices.

The stepper motors are provide precise positioning and are capable of moving their rotor to a specified position and holding that position irrespective of the load torque. This capability makes the stepper motors to be used 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 and direction signal, 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 [1].

Stepper motors typically have a step size specification (e.g. 1.8° or 200 steps per revolution), which applies to full steps. Step/Direction driver usually provide a 'microstepping' mode increases this resolutions by allowing intermediate step locations, which are achieved by energizing the coils with intermediate current levels [2].

The last major consideration in driving steppers is controlling the start-up and stopping speeds for the controllers 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 [2]. 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

What's the plan to solve what problems with what methods:

Focus on system automating the experimental process (motorised droplet position, dispensing and refilling), minimising variables that affect the repeatability of the experiment: Ie drop volume (pipette), drop position relative to substrate centre (programmed motor).

Chapter 3: Work Completed

3.1 Substrate Mounting

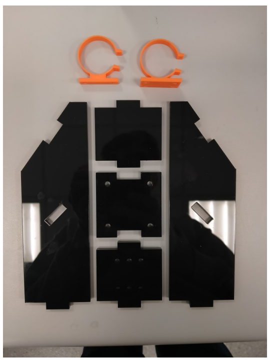
The proposal initially outlined the design mount/fastener for the substrate stack, to intergrade a heat spreader, better ensure cantering and thermocouple placement. Initial meetings (with workshop) and design started early with rough sketch designs and discussions on material and manufacture. However, 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 2 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

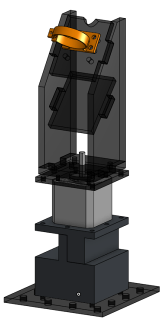
Given the decision for the new rig to be centred around an electronic (as apposed to the manual syringe) a new mounting assembly was needed to secure the pipette to the XYZ stage, ensure there is minimal play/backlash and position its tip above the substrate for droplet dispensing.

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.

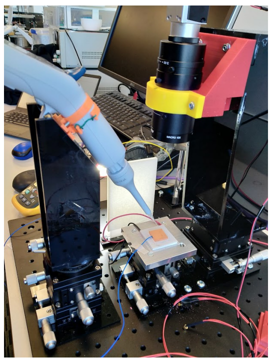
A tower [3.1] was designed as the mounting solution. It was constructed from laser cut 6mm acrylic as it had been successfully used in other parts of the existing rig, could be very quickly manufactured to allow rapid prototyping and producing a variety of mounting points and different plates. Assembly was left open to allow for access and modification. A taller than final 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 and 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 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/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 2 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.

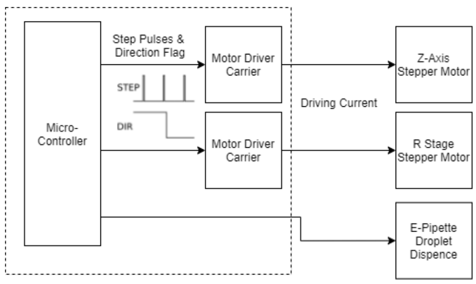


Figure 3.2: Block Diagram of Base Electronic Design

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 the from above the substrate to out of 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. When compared to standard brushed/brushless DC motors that require encoders for positional control or servos that can 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 pancake frame. Even through the pancake frame would reduce the overall height of the system the shaft length available for this motor are 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 it electronic placement to accommodate the experimental needs. Allows for a fairly agnostic choice for controller to supple 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 [2]
- 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 switch's 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

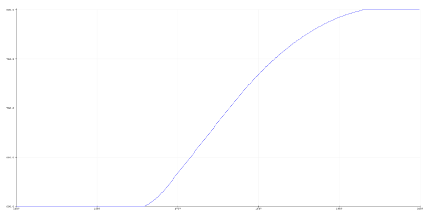
With the parts selected and ordered, I wrote test firmware on an ESP32 to validate its ability in producing the required pulse train step signal to control the motor drivers. This produced signal, required to produce N steps (pulses) at a set average speed and ramp up and down that pulse speed and the 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:

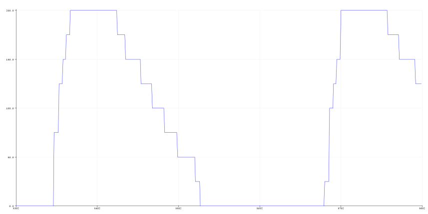
These pulses were captured on a second microcontroller listening for falling edges to trigger an interrupt routine to record and display that data.

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 bae 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)
   - Bulk of redesigning and prototyping done during this storage
   - Informs the design of new parts, requirement for more components etc
5. 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] , "Implementing a step-direction interface-based stepper motor controller," *Application Note AC413*, pp. 1–9, 2014.

[2] "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