**Chapter 1**

**Background**

In the last few decades, the world has seen a radical shift in the way that autonomous systems are utilised in the manufacturing industry. As factories and warehouses begin to become more reliant on robots performing repetitive tasks, there has been an upsurge in the number of other industries looking to enhance their everyday operations through the implementation of autonomous systems. Thanks to recent robotic developments in the areas of portability, safety, and ease of use, this new generation of collaborative robots has been designed to work alongside humans in the workplace. Collaborative robots have continued to push the bounds of what was previously seen as work that could only be performed by a human worker.

The use of robots in a lab environment is not a foreign concept, although now they are being considered for use in liquid handling and data collection roles. It is believed that collaborative robots have reached a level of technological advancement that they are able to overcome the challenges faced by typical robots of rigid movements and being less adaptable to changing conditions.

Likewise, the often-random nature of liquid makes it a difficult subject to integrate with autonomous data acquisition systems. There is often a large variability between different kinds of liquid each with their own mass, density, volume and viscosity, meaning that a system would have to account for all of these factors to accurate estimate its physical properties. Any system that can accomplish this task and be added to a lab would effectively help automate research and provide a cost-benefit to the organisations that utilise it.

In recent years there have been many attempts at developing a system that could perform these tasks to an acceptable degree. Methods such as the use of a camera to measure the changing height of a poured liquid, as presented in (Do & Burgard, 2018) and (Schenck & Fox, 2016), found that there were shortcomings with the use of transparent liquids such as oil. These methods were also susceptible to inaccurate data from their video data. Another intuitive method found was presented in (Liang, et al., 2020) and featured acquisition of liquid data based upon audio feedback of the pouring liquid. Like the previous methods this too was considered unsuitable due to erroneous data from the audio sensors and its incompatibility with highly viscous fluid.

The inspiration for this project was based upon the work presented in (Matl, et al., 2019). The method used in this paper was the use of a robotic arm with an accurate force/torque sensor. Based upon mechanical movements made by the arm and data readings for the mass and torque, it would be possible to accurately measure the properties of a liquid within a container such as mass, volume and viscosity. This method contained significant advantages over other papers such as having a wide range of liquids that could be accurately measured, regardless of viscosities or volume. Whereas other methods were centred around pouring of a liquid, this method was capable of measuring a liquid within an enclosed container. This project explores the use of this system design for the goal of autonomously measuring the physical properties of a liquid.

**Research Objectives**

The aim of this project is to develop a system that is capable of measuring the properties of a liquid through mechanical manipulation and data gathering via a robotic platform and mathematical models.

Specific objectives:

* Utilise the approach presented in (Matl, et al., 2019).
* Combine the above approach with a real autonomous system.
* Demonstrate the validity of this system as a solution to collecting physical properties of liquid samples.

**Report Organisation**

This report is organised as follows:

* Chapter 2 explores previous work that has been used to influence the project.
* Chapter 3 details the project approach and discusses the implementation of the chosen method.
* Chapter 4 presents the experimentation process and the project results gathered.
* Chapter 5 discusses the results and suggests project changes and potential future work that can be performed.
* Chapter 6 is the conclusions that were drawn from this research project.

**Chapter 2**

**Related Work**

**Liquid Mass Measurement**

Knowing the mass of a sample being manipulated by a collaborative robot has been a widely studied aspect of autonomous liquid handling systems. Due to the relative inaccuracy of visual data, liquid mass measurements are the prime method of calculating further physical properties of liquids such as volume from a known density, or density from a known volume. Solutions to the problem of collecting liquid mass data by autonomous systems has often been dependant on its final application. In the research papers (model based flow rate control) and (Outflow Liquid Falling Position) the solution to the problem of liquid mass measurement came from load-cell that were utilised during liquid pouring operations. Whereas this solution was adequate for the application of the systems described in the papers, it would be unsuitable for system applications involving careful handling of liquids.

This is in contrast to the method presented in (Matl, et al., 2019) where the liquid mass is based off of sensors readings from a force torque sensor. This is due to the project scope in (Matl, et al., 2019) being to design a system capable of measuring the physical properties of a liquid from within an enclosed container.

**Liquid Volume Measurement**

Correctly estimating the mass of a liquid within a container is a fundamental aspect of the goal set out to be achieved by this project. This topic has many extensively studied methods, with a majority of them involving the use of image data systems that often require further image processing and neural networks to adequate generate valid data (Schenck & Fox, 2016). Others have attempted to use audio feedback as a method of measuring volume, however this too incorporated a multitude of sensors and neural networks (Liang, et al., 2020). The method presented by (Matl, et al., 2019) showcases a way of using a physics-based model to generate equations for the volume of a liquid within an enclosed container based upon haptic feedback from a force torque sensor.

**Liquid Viscosity Measurement**

Due to the challenging nature of measuring liquid in motion, there have been many attempts to find a solution to this problem. Methods such as those presented in (Particle-Based Fluid Simulation for Interactive Applications) showcase a method of simulating liquid motion in a container. Other papers draw conclusions that such models can be equated to a much simpler multi-mass-spring-damper system (Point-to-point liquid container transfer via a PPR robot with sloshing suppression). Ultimately, the paper (Matl, et al., 2019) bases much of their mathematical models for calculation of liquid viscosity from (the new dynamic behavior of liquids in moving containers dodge) and they will be the methods I attempt to utilise in this project.

**Chapter 3**

**Overall Approach**

The goal of this capstone project was to investigate methods that could be incorporated with an autonomous system to measure the physical parameters of a liquid within an enclosed container. These methods were drawn from the research paper (Matl, et al., 2019) and were implemented based upon the resources that were available to conduct this project. The basis of this approach is the physical manipulation of a liquid within an enclosed container and gathering data via haptic feedback of internal fluid position and motion. The mathematical models used by (Matl, et al., 2019) to analyse this data into meaningful information provides equations to calculate the height and volume of a liquid within a container based upon its changing centre of mass. By analysing this data at discrete angular rotations an approximation for the internal volume of the liquid can be found. Likewise, the calculation of the liquid viscosity could be found through analysing the decaying oscillations of a sloshing liquid within a closed cylinder.

Implementation of these mathematical models required the development of an autonomous system that could collect and processing data effectively in a reasonable amount of time. This included managing the robotic hardware and software needed to adequately achieve the project objectives.

At the beginning of operation, the autonomous control code would zero the sensor readings coming from the force/torque sensor on the robot end effector. It would then allow a bottle to be placed in its gripper arm before recording the mass of the bottle and liquid and starting its pre-planned movements. These movements would take it through several discrete angular rotations, at each stage stopping to record torque readings generated by the liquid centre of mass. Once an adequate amount of data has been recorded the bottle is then rotated onto its side and rotated quickly back to an upright vertical position while torque data is continuously recorded as the liquid settles within the container. The data gathered by the system is then saved into files and analysed by the mathematical models discussed above.