Design of an Auto-Ratio Beverage Valve

University of Illinois at Urbana-Champaign

Spring 2019 ME 470 - Final Report

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Executive Summary

Cornelius is a global leader in the beverage dispensing industry. However, the flow control valves in the beverage dispensers produced by Cornelius have been manual for decades and have several disadvantages. Based on the needs of Cornelius, the UIUC Beverage Valve team has designed an automatic flow control system for Cornelius as a potential replacement of their manual flow control valve.

The automatic flow control system consists of a motorized ball valve, a volumetric flow rate sensor, and a microcontroller. A feedback proportional control law implemented in the microcontroller receives the signal from the flow meter and governs the behaviors of the motorized ball valve, which regulates the sensed volumetric flow rate to the set value while rejecting disturbances. The flow meter also provides real-time flow rate data for system monitoring. Meanwhile, the Beverage Valve team has conducted literature reviews regarding a steady-state ball valve volumetric flow rate prediction model and an advanced control design method based on system identification and the Simulink PID Tuner. The Beverage Valve team will deliver the results of these literature reviews to Cornelius as references for future work.

The automatic flow control system meets the primary design requirements from Cornelius, whereas space for improvement and future work exists and will be detailed in the conclusions and recommendations section.

The budget for this project was estimated to be $1030 at the planning stage. The final total cost of the deliverables was $870.68. The largest cost savings came from using an Arduino for data logging instead of the NI myRIO.

1. Introduction

1.1 Problem Statement

For decades, the flow control valves in the beverage dispensers produced by Cornelius have been purely mechanical. These flow control valves utilize a manually adjusted screw-spring-cylinder assembly to change the opening size of a set of orifices, which controls the volumetric flow rate of the fluid—syrup or carbonated water—in the dispensing line. These valves have several disadvantages:

1) The dispensing lines for different drinks require different tunings of the control screw due to the unique fluid properties of syrups of each brand.
2) Any environmentally induced fluid property change—such as temperature-induced viscosity change—requires a different tuning of the control screw.
3) End users of Cornelius beverage dispensers, such as restaurant owners, can adjust the control screw and decrease the proportion of syrup in a cup of drink dispensed to their economic advantage. Such behavior has been a source of complaint from the client syrup companies of Cornelius.

1.2 Project Objectives

The objective of the UIUC Beverage Valve team is to design an electromechanical flow control system for Cornelius that can automatically control the volumetric flow rate in the dispensing lines regardless of syrup brand or the environment and be immune to human intervention. Additionally, based on the operating conditions inside Cornelius' beverage dispensers and the expectations from the company, this new automatic flow control systems need to:

1) Have comparable dimensions with Cornelius' current flow control system.
2) Withstand a nominal inlet pressure of 40-110 psi.
3) Withstand a shock pressure of 550 psi without catastrophic failure in case of water hammer.

4) Allow a maximum volumetric flow rate of at least 3.55 L/min (dispense 1 cup of drink within 4 seconds).
5) Control the volumetric flow rate within 1% of the set value in the steady state.
6) Last for 7-10 years.

Due to the availability of testing equipment, a shock pressure of 550 psi could not be achieved, and a fatigue test on the material of the motorized ball valve could not be conducted. Hence, whether the system designed satisfies requirements 3) and 6) is unknown. Meanwhile, although the inner diameter of the motorized ball valve matches that of the dispensing lines in Cornelius' beverage dispensers, the total size of the system designed is larger than that of Cornelius' current flow control system. The system designed also requires software re-tuning whenever fluid property changes, failing to fulfill the adaptivity expectation from the sponsor.

2. Proposed Solution

The solution proposed by the UIUC Beverage Valve team is an automatic flow control system consisting of a motorized ball valve, flow meter, and microcontroller. The microcontroller implements a closed-loop feedback proportional control law based on a sampling period of 200 ms for the motorized ball valve and 1000 ms for the flow meter. The control law and converts the flow rate signal received from the flow meter to the voltage signal input to the motorized ball valve, eliminating the error between the sensed flow rate and the set flow rate. Meanwhile, the flow meter also outputs data for real-time system monitoring.

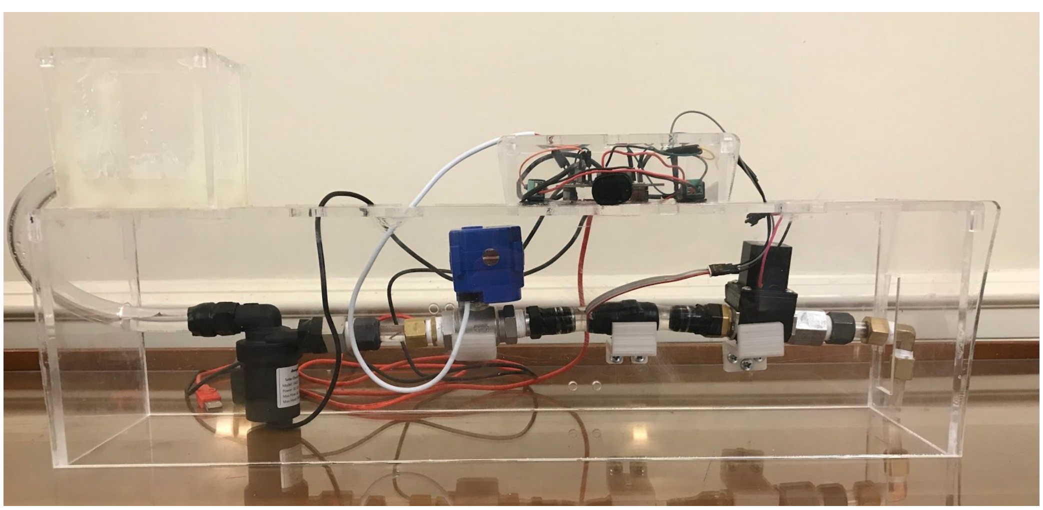

Figure 1. Final Prototype Design

2.1. Valve Design

2.1.1. Valve Literature Review

During the design process, the UIUC Beverage Valve team considered three types of valves: the butterfly valve, globe valve and ball valve. Each of these valves are known for their flow control capabilities while also having the ability to act as a shut-off valve as well. In both the butterfly and globe valves, there is a significant pressure drop between inlet and outlet orifices. This large pressure drop through the valve can increase the beverage carbonation since a large pressure reduction in a short amount of time will lead to greater bubble formation and a higher foam head [1]. This is because carbonation formation is dependent on three factors: temperature, surface contact and pressure [1]. In order for carbonation to occur, the temperature must be cold and there must be a large pressure drop. Since the amount of carbon dioxide gas dissolved into the fluid is proportional to the pressure, with a large pressure reduction, more bubbles are formed [1]. With more bubbles formed, the foam head on the dispensed beverage increases. The foam head is best kept to a minimum until the drink reaches the final nozzle.

The second consideration for the butterfly and globe valves is their creation of turbulent flow within the fluid as it passes through the valve. The flow is less turbulent in the ball valve. The turbulent flow created through the valve acts in very much the same way as the pressure drop by increasing the amount of bubbles formed and therefore increasing the foam head on the dispensed beverage [1].

Compared with ball valves, globe valves can achieve higher control accuracy while butterfly valves have simpler construction. However, the smallest globe valve and butterfly valve that the UIUC Beverage Valve team found on the market were two inches in inner diameter. Since the inner diameter of the dispensing lines in Cornelius' beverage dispensers is a 1/2", the UIUC Beverage Valve team discarded globe valves and butterfly valves for their bulkiness.

2.1.2. Flow Control Hardware

The valve system comprises of two components: the motorized ball valve and a solenoid on/off switch. Due to the usage of electromechanical components in the final system, motor wear was a large consideration in how the system will control the flow of the drink being dispensed. The team decided that having an all-in-one system where the valve opens to a certain angle for each beverage dispensed and then closes afterwards would increase the wear on the motor and the 7-10 year lifespan requirement. Instead, we designed a two component system. Prior to the end user's hours of operation, a calibration sequence will be done to set the ball valve to a certain angle correlating to a given flow rate. This calibration will be done for each syrup and water the valve will be used for. Once the calibration sequence is complete, the valve will remain in that position for the entirety of the day and the control system will work to ensure that the output flow rate remains within 1% of the desired flow rate. During the hours of operation, each time a beverage is dispensed the solenoid will be activated to allow the beverage to be dispensed. The system, Figure 2, reduces wear on the ball valve motor and ensures that the beverage valve will last the 7-10 year lifespan. Since the valve does not need to operate every time a drink is dispensed, it saves energy which positively impacts running costs to end user.

A B

Figure 2. (A) System's Motorized Ball Valve (B) System's Solenoid

2.1.3. Ball Valve Analysis

The team conducted testing on the motorized ball valve in order to understand how the valve works and how the flow is manipulated across the valve. From initial testing, the team was able to gain better insight into how the valve can be controlled. It was determined that the valve can be opened over a given range of time which is dependent on the power source to the system. The power input into the team's system is 12V and therefore the full time for valve opening is 4.5 seconds. Through testing, the team determined that the time of opening and angle of opening are proportional. Although the full time for valve opening is 4.5 seconds, the team determined that the angles of interest for controlling our system fall in the 30-60° range. All required flow rates can be achieved within this angle range and the relationship between them can be modeled linearly. With this range, the team was able to test the relationship between angle of opening and output flow rate (discussed in depth in the *Flow Analysis* section). It was determined that the relationship follows a sinusoidal curve over the entire range from 0-90° of opening. However, within our range of operation from 30-60°, the angle of opening and output flow rate approximate a linear relationship, Figure 3, allowing for our control system to be created with proportional control.

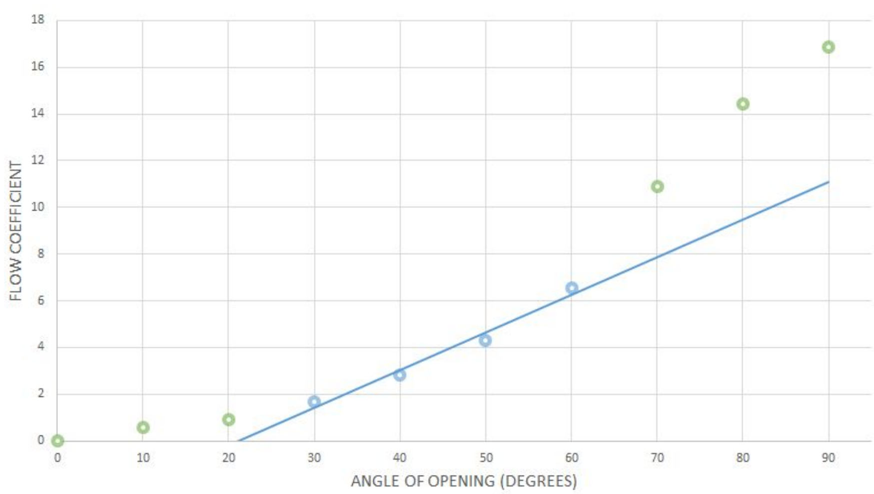

Figure 3. Output Flow Rate vs. Angle of Opening

The team also performed a fluid mechanic analysis on the motorized ball valve in order to determine the pressure drop across the valve's orifices. These calculations were created using our derived output function (discussed in depth in the *Flow Analysis* section). It was found that within our given range of operation, there is almost zero pressure drop across the valve, Figure 4. The overall behavior of the valve can be described as a decreasing pressure drop the more the valve opens with the largest pressure drop closest to being fully closed.

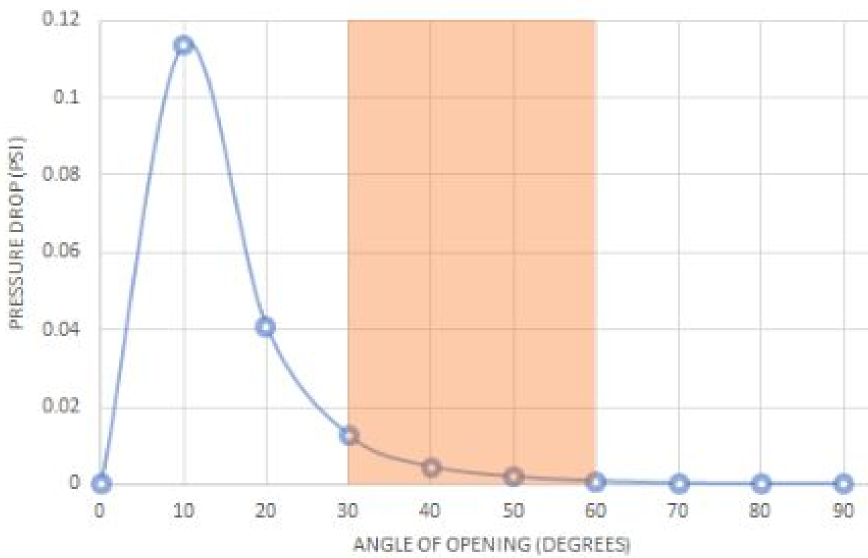

Figure 4. Pressure Drop vs. Angle of Opening

2.2 Flow Sensor

2.2.1. Sensor Literature Review

The repeatability and accuracy of a control system depends heavily on the sensors used to measure the state of the system. Accurate, real time volumetric flow rate measurements are necessary for dispensing drinks in consistent ratios.

Oval gear flow meters are displacement-type volume meters that transport defined incremental volumes in individual measuring chambers [2]. As shown in Figure 5, the measuring element consists of two oval-shaped gear, which are driven by the flow of the medium and mesh with each other. The number of rotation is a measure of the amount of fluid that has passed through the meter. The cost of oval gear flow meter is low compared to other sensor types.

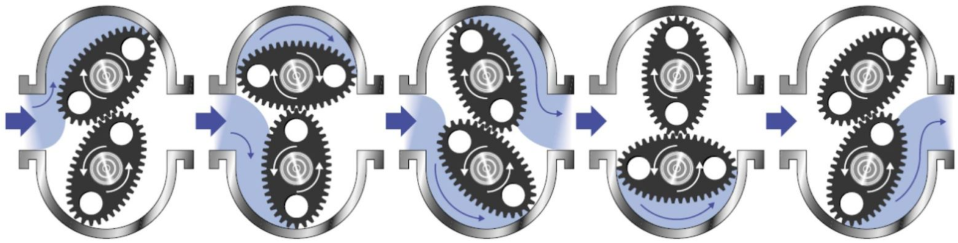

Figure 5. Oval gear sensor schematic

Ultrasonic flow meters work without direct contact with the fluid [3]. Both doppler shift flowmeters and transit time-based flowmeters make good candidates for detecting viscous fluid. As shown in Figure 6, doppler shift flowmeters use reflected ultrasonic sound to measure the fluid velocity in the piping. This sensor type works with a transducer acting as both transmitter and receiver of sound waves. The transducer emits the sound waves and upon receiving them back, look for changes in their frequency. The change in their frequency is caused by air particles or bubbles in the fluid since as the sound waves enter the bubbly fluid, they bounce off the particles and create change in frequency. The average cost of ultrasonic sensor is high above $40 budget limit.

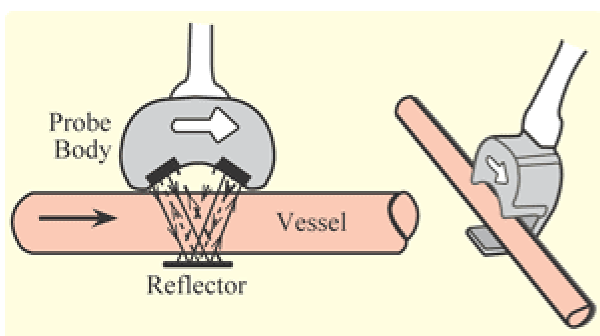

Figure 6. Ultrasonic flow meter schematic

Turbine flow meters consist of a fan or turbine in the path of flow as shown in Figure 7. The angular velocity of the turbine can then be correlated to the flow velocity and subsequently the flow rate. Turbine flow meters are economical but the contact between syrup and the turbine may lead to inaccuracies over long periods of time. A regular cleaning schedule may be able to mitigate this problem.

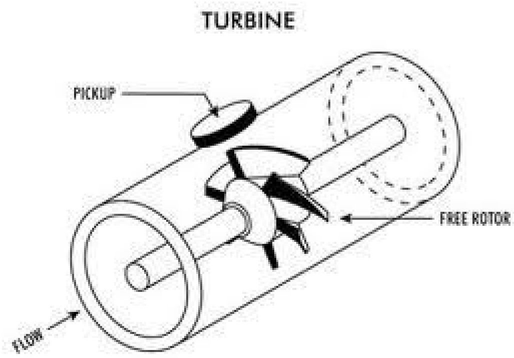

Figure 7. Turbine flow meter schematic

Vortex flow meters and temperature gradient flow meters proved to be unsuitable for our design. Vortex flow meters only work with turbulent flows, which should not be present in beverage dispensing valves.

Wedge flow meters utilize a wedge-shaped segment that protrudes into the flow path, producing a differential pressure that can be captured [4]. Wedge sensors are commonly used in industrial or energy applications for high viscous, contaminated fluids. Within the budget range, the corresponding wedge sensors cannot satisfy team's accuracy requirement.

Electromagnetic flow sensors detect flow by using Faraday's Law of Induction. The moving conductive liquids inside of a magnetic field generates an electromotive voltage which is proportional to average flow velocity [5]. As a result, this type of flow meter is unaffected by the temperature, pressure or viscosity of the liquid. Due to intricate design requirement, electromagnetic sensor is the most expensive of the other discussed sensors.

2.2.2. Sensor Selection Evaluation

As shown in Table 1, each type of sensor is assigned score based on four parameters: cost, accuracy, viscosity and flow rate type. Cost refers to whether the price range satisfies budget requirement. Accuracy refers to how close the sensor can reach the target 1% error range. Viscosity refers to the sensor's ability to detect high viscous liquids such as syrup. Lastly, volumetric flow rate refers to whether direct output of the sensor is volumetric or mass flow rate.

Volumetric flow rate is preferred because the changing viscosity no longer needs to be considered in the math model.

Table 1. Sensor Selection Evaluation

Type	Cost	Accuracy	Viscosity	Flow rate type
Weights	25%	15%	35%	25%
Oval Gear	5	4	5	5
Turbine Flow	3	4	1	5
Vortex	1	5	1	5
Ultrasonic	3	4	5	3
Wedge	3	3	5	3
Electromagnetic	1	4	5	3

Weights are applied to each ability based on the product specification importance as shown in Figure 8. In Figure 9, the weighted evaluation results shows oval gear sensor scores highest among a variety of sensors.

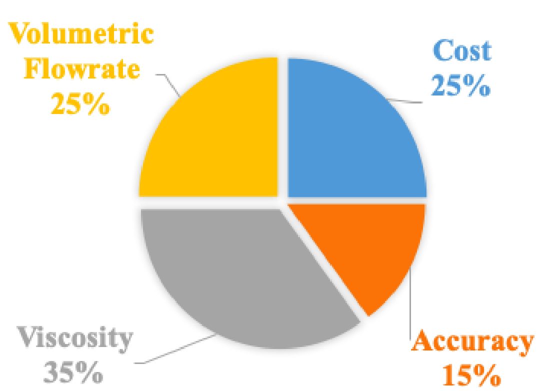

Figure 8. Evaluation weights

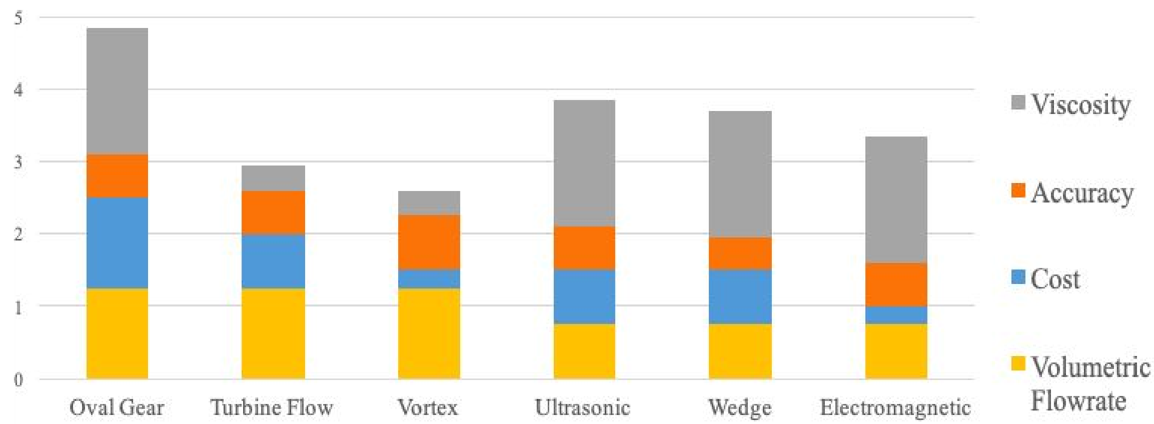

Figure 9. Weighted sensor evaluation

2.2.3. Prototype Sensor

Flow sensors for water and syrup are needed to measure the flow rate of the liquid dispensed. In order to avoid calculation transferring from mass to volume using the density of the fluid, volumetric flow sensors were chosen for both liquids to directly find the volume. An turbine-based flow meter (Swissflow, SF800) was supplied by Cornelius. The Swissflow meter, shown in Figure 10, is a turbine-based flow meter which calculates the flow rate based on the number of rotations of a rotor. This flow meter is not suitable for the syrup because the high viscosity of the syrup will accumulate on the bottom of the turbine and result in blocking the motion of turbine components.

Figure 10. Swissflow optical flow meter

An oval gear flow meter was used for the syrup. The oval gear flow meter (Aichi, OF05ZAT) shown in Figure 11, is a type of positive displacement flow meter that is suitable for high viscous and opaque flow. The cost of the oval gear flow meter is about $10 each. The detectable flow range is from 0.083 L/min to 10 L/min with an accuracy of 0.25% to 0.5%. With data sheet from Cornelius, optical flow meter (Swissflow, SF800) is used as a reference in calibration procedure for oval gear flow meter(Aichi, OF05ZAT) to obtain full operating data sheet.

Figure 11. Aichi oval gear flow meter

2.3. Flow Analysis

2.3.1. Theoretical Model

The team created a dynamics equation, Equation 1, expressing the output volumetric flow rate as a function of valve angle and pressure drop across the ball valve. This equation was used in calculating the pressure drop across the ball valve through the team's CFD simulations. This equation would also be used in calculating the output flow rate for a fluid running through our valve at a specified syrup:water ratio as well as at a specific temperature. Since the team's system uses a volumetric flow rate sensor, the output function is not needed to calculate the necessary output flow. Instead, the flow is independent of temperature. If the system would use a mass flow rate sensor, then the derived predictive model would be used to calculate the required output flow.

$$Q(\theta) = C_v(\theta)\sqrt{\frac{\Delta P}{S.G.}}$$

Equation 1. Derived Predictive Output Flow Rate Model

When using the model, the variable responsible for differentiating the fluid type and viscosity lies in the specific gravity. If the fluid of interest is syrup, the specific gravity value is can be looked up based on the syrup of interest.. If the fluid type is carbonated water, Equation 2 would be used to calculate the fluid density. Fluid density can be calculated from temperature and then plugged back into the specific gravity variable.

$$\rho_{fluid} = a_0 + a_1T + a_2(T - 87.4327)^2 + a_3(T - 87.4327)^3$$

Equation 2. Temperature Dependent Carbonated Water Density Formula

2.3.2. CFD Literature Review

Understanding the fluid mechanics across the ball valve was essential for the team to design a working system. This understanding began through a literature review of fluid flow across both butterfly and ball valves. The literature review was done on a thesis paper comparing the computational fluid dynamics applications for determining flow characteristics of valves [6]. Through this paper, the sinusoidal relationship between output flow rate and degrees of valve opening was discovered and is shown in Figure 12. From establishing this relationship, the team was able to narrow into the angle range of interest and establish a linear relationship between the volumetric flow rate and percentage of opening angle.

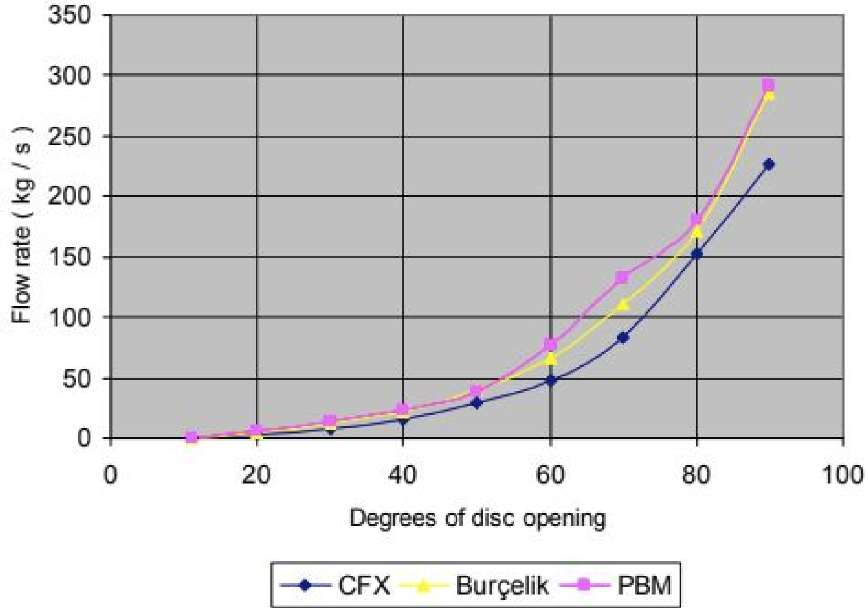

Figure 12. Literature Review CFD Output Flow Rate vs. Degrees of Openi

The paper also provided results for CFD modelling across the valves at different angles, Figure 13. The valve diameter for their modelling was 1" and the team's valve diameter is 0.5". Due to the differing valve diameters, the team wanted to ensure that the relationship results were scaleable to the system's valve diameter. In pursuing the validation of the relationship, the team performed CFD modeling on the valve system and planned to take these results to validate the literature review results. This process will be discussed in further sections, however, it was determined that the relationship did apply to the valve system. Additionally, the paper provided information regarding the flow coefficients of water across different valve diameters and at different angles of opening which was used to calculate the flow coefficients for flow across the team's valve system.

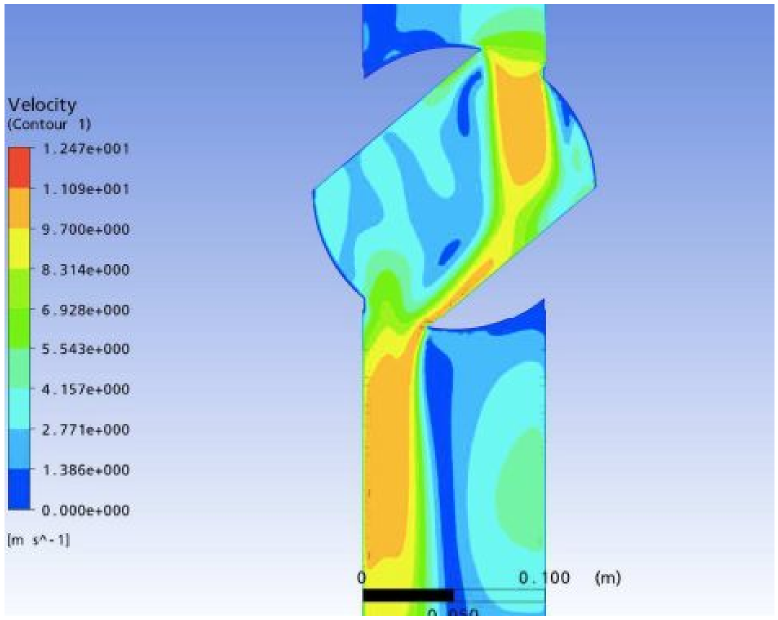

Figure 13. Literature Review CFD Contour Plot at 40 Degrees of Opening

2.3.3. CFD Construction

The team constructed a CFD model using prototype hardware dimensions. A ball valve CAD model was made with a diameter of 1/2in and placed in a 1.5in upstream and 2.0in downstream pipe, which matched team's prototype setup. Boundary conditions were set as pressure constraints. The inlet pressure could be changed due to pressure variation input and the outlet pressure was set to atmosphere. Simulation was conducted at different pressure at 90psi, 60psi and 20psi. The contour plots for 40 degree of opening at 90 psi inlet pressure is shown in Figure 14. As shown in Figure 15, at a constant inlet pressure, the flowrate response due to change of angle opening can be characterized with a second order polynomial. At the same valve position, flow rate increases as pressure difference increases. The obtained relation for flow rate and angle of opening has a similar trend as the results from literature CFD review [6]. For angles smaller than 70 degree, both show linear relation between volumetric flow rate and angle of opening.

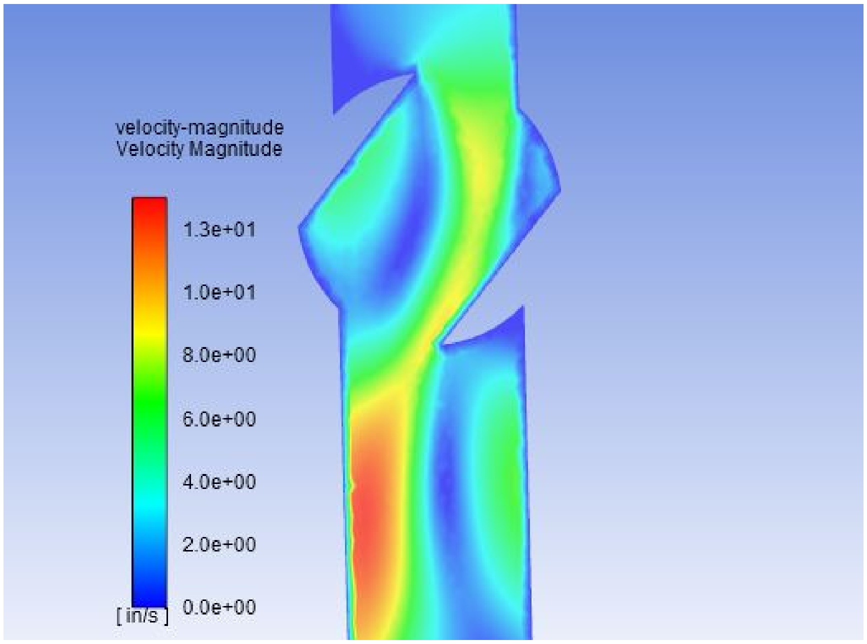

Figure 14. Team CFD Contour Plot at 40 Degrees of Opening

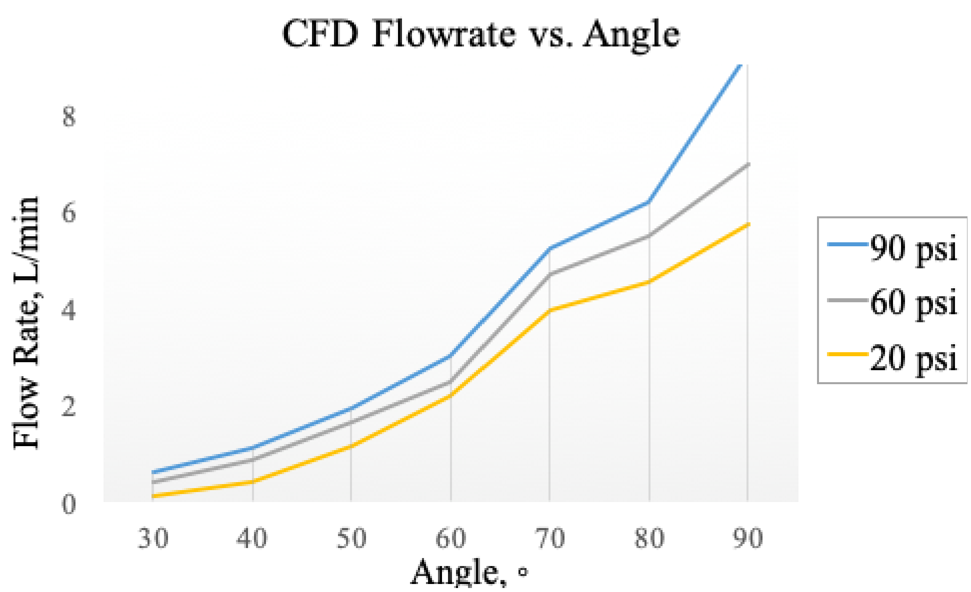

Figure 15. Team CFD results, CFD Flow Rate vs. Angle of Opening

2.3.4. Test Setup

The team's testing mainly focused around calibrating the sensors and understanding the flow across the valve. Figure 16 shows the open-loop testing setup for the sensors in order to properly calibrate them. The setup consists of the valve in fully opened position followed by both the Oval Gear and Swissflow sensors discussed in the previous sections. The calibration sequence consisted of pouring 100 mL of water in through the top of the ball valve and recording the measured values by the sensors. Both sensors are volumetric flow sensors and therefore output both the flow rate and quantity of fluid that passes through the sensor. The value of interest to the team was the quantity of fluid that passes through the sensor. Therefore, the team adjusted the calibration factors for both sensors until they both read the same quantity of fluid value of 100 mL since this is the volume of liquid inputted into the system.

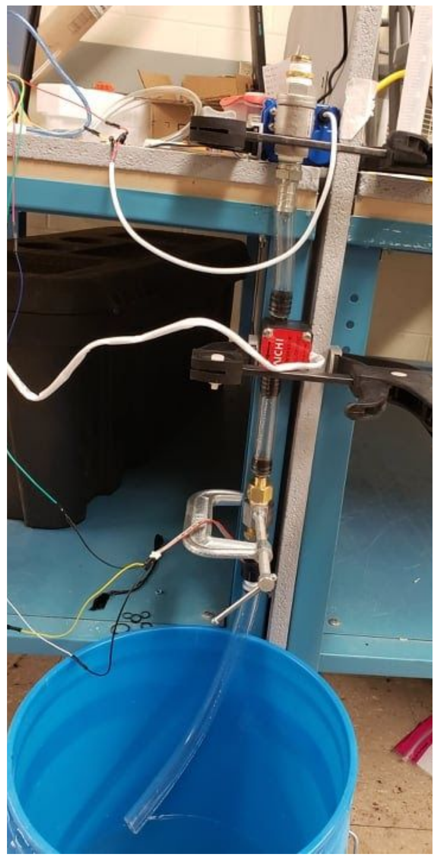

Figure 16. Sensor Testing Setup

The second set of testing centered around the control system and the motorized ball valve. The objective of these tests were to ensure the ball valve was correctly restricting the flow to our desired values as well as the control system being able to correctly keep the flow to within our desired output flow rate range. The setup for these tests are shown below in Figure 17. The setup comprises of all the components in our final system except with a larger inlet feed allowing for continuous flow through the system. This setup allows for steady state flow conditions to be met and accurate data to be collected. Therefore this setup is in closed-loop configuration.

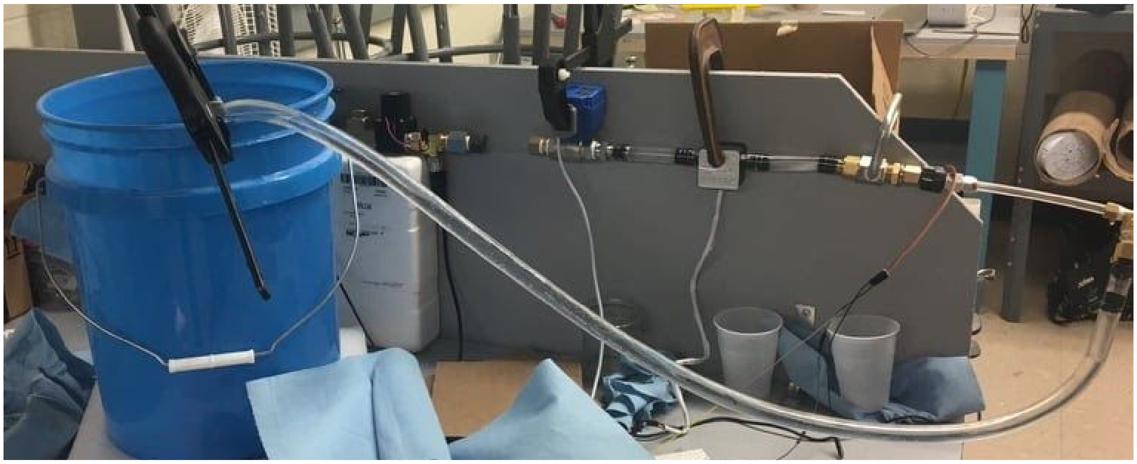

Figure 17. Valve Flow Rate Testing Setup

2.3.5. Test Data

The data acquisition time period is set to 150 ms due to the sensor frequency limitation. As shown in Figure 18, under testing input pressure, the flow rate increases as opening angle increases. A second order polynomial fits the data. After reaching 65% of opening, the flow rate increases slower. The minimum flow rate is around 0.2 L/min and the maximum flow rate is 3.6 L/min. The data ranging from 35 degree to 60 degree is sufficient to reach the desired flow rate, which follows a linear trend.

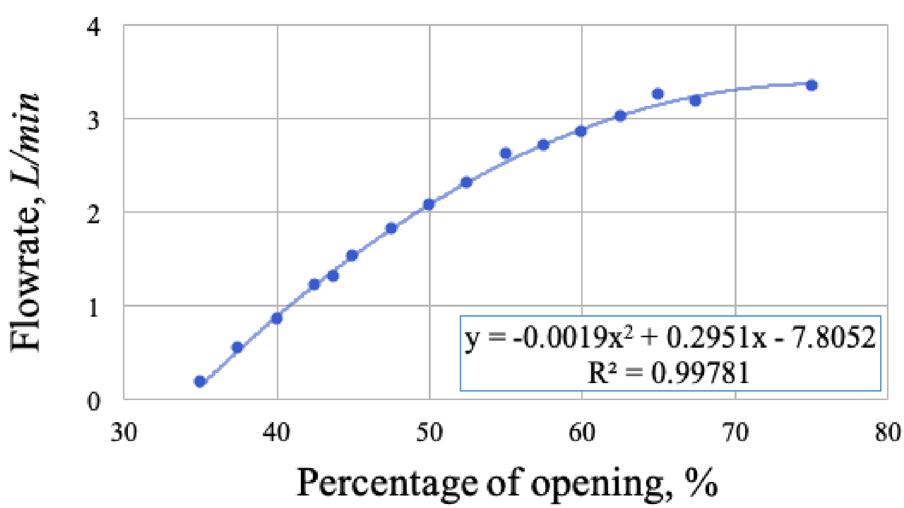

Figure 18. Test data for Flow Rate vs. Percentage of Opening

2.3.6. Test Data & CFD Model Discussion

Zooming in on the linear region between 33% and 67% opening percentage, both team CFD results and lab testing data can be fitted with a linear trend line. The fits lines for the CFD and the experimental results have slopes of 0.0975 and 0.0954, respectively. The percentage difference is 2.15%. The linear relation between flow rate and valve angle of opening is used in control algorithm.

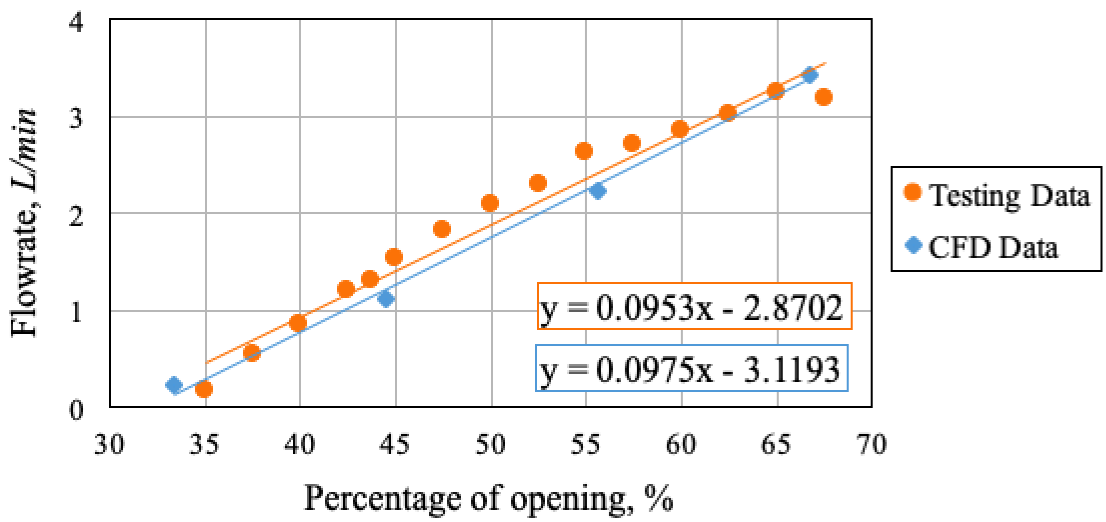

Figure 19. Testing Flowrate vs. Percentage of Opening Data Comparison

2.4. Control System

The complete test setup consists of a flow sensor, a reverse polarity ball valve, a pump, and a sinusoidal valve. To allow reverse polarity of the ball valve from Arduino, a h-bridge is added to control high and low voltage inputs. The h-bridge, flow sensor, and sinusoidal valve are connected to the 5V input from the USB port of the Arduino. The ball valve and all other components are connected to a 12V power supply.

The main goal of the control system is to regulate the current flow rate, the process variable (PV), at within the $\pm 1\%$ error range of the desired flow rate, or the set point (SP). With standard proportional control, this is easily achievable in the stable range of the valve opening but the present hardware limitation poses a challenge in the unstable range. The reading frequency of the flow sensor is too low to closely track the.oscillation of the PV near the SP, especially in the unstable range. At this range, the flow rate reacts more sensitively to even a small change in the valve opening angle and results in large oscillation. Since valve is receiving control signal based on the sensor data with high interval, it is not capable of settling down such high oscillation and continues to rotate back and forth at a small angle. A sensor with higher frequency can solve this issue by providing more frequent tracking data to the control signal and enabling more accurate control of the valve actuator.

To overcome this issue without changing the hardware, a control algorithm utilizing asynchronized communication is implemented. This means the sensor and the valve are activated in an alternating sequence and not simultaneously. In this design, the low frequency of the sensor is no longer a limiting factor since only the sensor is activated until the flow reaches steady state and corresponding reading data is gathered. Then the sensor is deactivated and the last data from the sensor is used to send a proportional control signal to the valve. Based on this signal, the valve is now separately activated to make the required change in angle and turns off after 0.5 seconds. The sensor is turned back on and the process is repeated until the error comes in within the desired range.

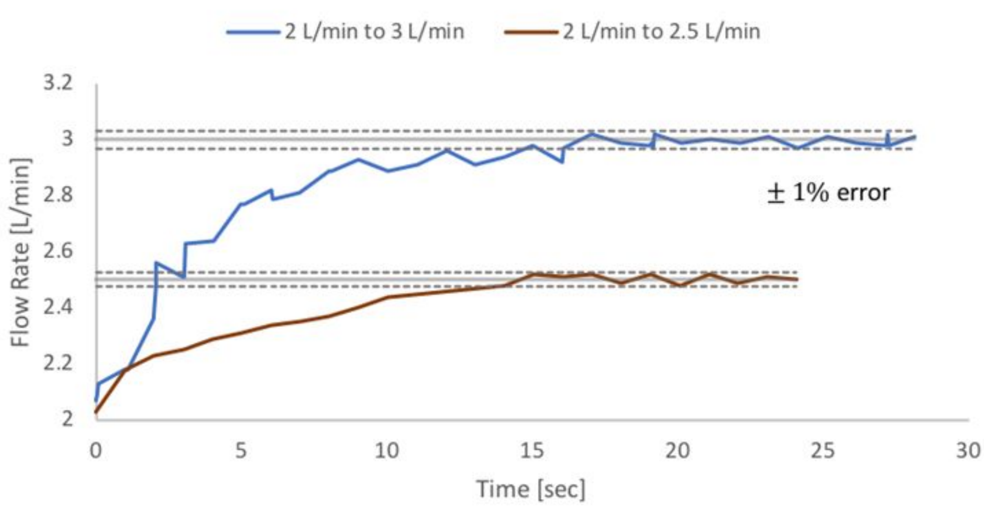

Figure 20. Flow Rate Adjustment with Asynchronized Communication

It is observed from the above figure that the asynchronized communication design successfully regulates the flow rate to the SP of 2.5 L/min as well as 3 L/min, clearly displaying its effectiveness in both the unstable and stable range. However, the design can only be implemented when time is not a critical issue as it takes about 15 to 18 seconds to finish the control depending on the status of PV and SP. Therefore, this control method is recommended for use in the calibration of the beverage dispensing system prior to the stores' opening hours. Although real-time control can not happen while customers are dispensing their beverage, a pre-calibrated setting is expected to be reliable for at least 24 hours, meaning that calibration conducted once everyday is sufficient. Only when the error is detected to be greater than 4%, the system will alert the user to re-calibrate the valve. During the store hours, the valve will be off and fixed at a set position and only the flow sensor will be on. This can also help save energy and provide real-time data collection for each beverage system in use.

3. Budget

The project was successfully finished under budget at $870.68. Two new cost categories that were added were travel and printing services from MechSE department. Major cost saving was achieved by using the Arduinos to log data from tests, thus eliminating the need for the $500 myRIO hardware. A detailed Bill of Materials and cost breakdown by category is given below.

Major reductions in cost were achieved by using Arduinos for data logging and by using technology loans from the MechSE department. The Arduino eliminated the need for the $500 myRIO hardware from National Instruments.

Table 2. Total Cost of the Beverage Valve Project

Item	Description	Quantity	Total Cost
Travel	Plant Visit Trip	1	$168.95
Valves	Motorized & Manual Ball	4	$87.19
Sensors	Temperature & Pressure	3	$64.56
Solenoid	On/off Flow Control	1	$18.95
Pump	Circulation Pump	1	$22.99
Piping/ Tubing	Fluid Flow & Circuit Creation	2	$19.11
Fittings	Component & Tubing Connectors	13	$207.89
Arduino	Control System Design	1	$20.00
H-Bridge IC	Control System Design	5	$66.76
Power Supply	Power for Circuit	1	$7.79
Silicone Fluid	Viscosity Fluid Testing	1	$146.49
3D Printing Services/ Acrylic	Final Prototype Stand	1	$40.00
			$870.68

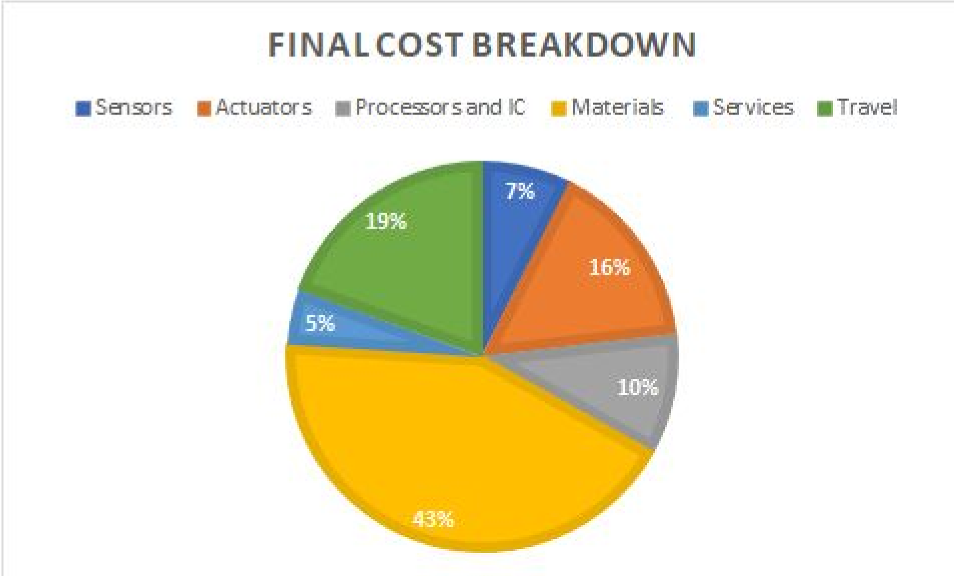

Figure 21. Final Cost Breakdown by Category

4. Conclusions & Recommendations

With the addition of automatic calibration function, the new beverage system takes a step towards digital data collection and control. Compared to the old purely mechanical model, the new model will be equipped with a microcontroller to enable several useful functions: automatic calibration of the valve with less labor, data accumulation, supervision and prevention of unethical system modification. The proposed design can regulate the flow rate and settle it to within $\pm 1\%$ error range of the target value in less than 20 seconds. In the future, with wireless connection to the microcontroller, this entire process can even be completed from long distance. Labor cost will be greatly saved since manual tuning of the screw is no longer required. Accurate consumer usage data can be accumulated from the sensors and used in business tactics. Syrup vendors can be reassured that the syrup ratio will be regulated at all times. The total hardware cost for manufacturing one syrup line is estimated to be within $100 and sensor and valve within $40. A syrup line represents one specific kind of drink that the system can dispense.

Although asynchronized communication design is the proposed solution using the provided hardware with limitations, a more ideal design can also be recommended. If Cornellius ends up acquiring a cost-effective control valve with much higher frequency in the future, a synchronized communication design can be easily implemented. Using the synchronized method where the sensor and valve are activated simultaneously the total time required to settle the flow rate to a set value can be reduced to around 0.15 to 0.3 seconds depending on the difference between initial and target flow rate. This is would be an improvement upon the current system In other words, the down time of the dispenser while adjusting to a new flow rate is short enough to allow a single valve to handle multiple syrups for different brands and real-time control can be achieved. This will not only reduce the physical dimensions of the beverage dispenser, but also eliminate the hardware cost for purchasing multiple valves.

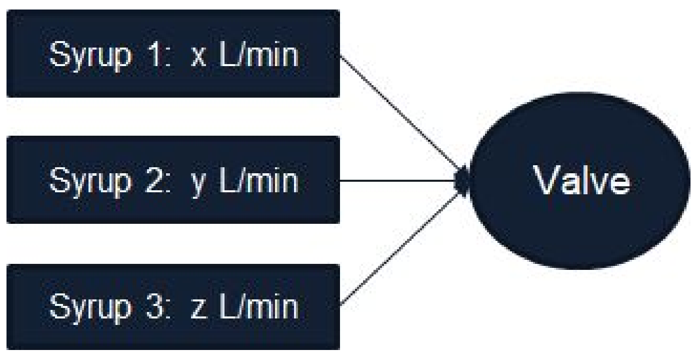

Figure 22. New Configuration of System with Synchronized Communication Control

To realize the above control design, it is crucial to understand the limitation of the current hardware. The current flow sensor has about 0.15 seconds of interval at maximum reading frequency, which is 3 times the optimal period of 0.05 seconds. Due to such low frequency, the flow sensor cannot track the change in flow rate with higher resolution and this becomes a significant issue when the flow rate is oscillating greatly near the set value in the unstable range. The oscillation is much larger at the 2L/min set point compared to the 3L/min set point as shown in figure 23. This results from the flow rate being highly sensitive to percent opening of the ball valve. Because current flow sensor cannot provide enough reading data at a faster rate, the ball valve continues to rotate back and forth and the large oscillation can never stabilize properly. All of this can be solved by using a sensor with higher frequency. Then the daily calibration process before store opening hours will not be necessary as real-time control will happen throughout the day. In this case, PI control can be added as well to minimize the total control time even further.

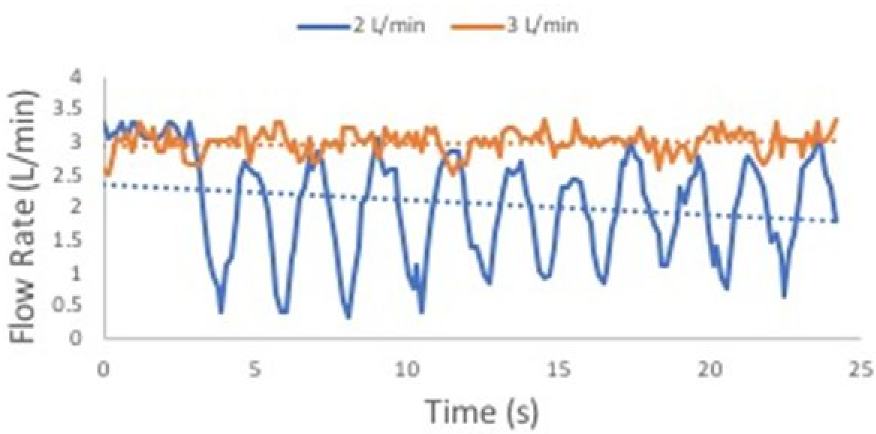

Figure 23. Flow Rate Adjustment with Synchronized Communication System

5. References

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6. Appendix

6.1. Sensor Calibration Sequence Standard Operating Procedure

All steps within procedure are assumed to take place using the provided prototype, components and code.

1. Pour a designated amount of water into the feed chamber located at the top left of the prototype.
2. Connect the Arduino into laptop or desktop with downloaded Arduino IDE program.
3. Open the Arduino IDE program and open the provided code for controlling the valve system.
4. Once code is open, compile and run the code.
5. Open the data tracker which outputs the sensor readings to the user's screen.
6. Plug the system's pump into the power source to turn on the system and push the fluid through the valve and sensors.
7. View the sensor data and ensure that the volume of fluid reading accurately matches the amount of fluid inputted to the system.
8. If the volume readings do not match the input fluid amount, modify the calibration factor in the provided code and re-run the previous steps until the sensors accurately record the correct volume through the system.

6.2. Team CFD Contour Plots

Figures a-b show contour plots at 30, 40, 50, 60, 70 degree of valve opening.

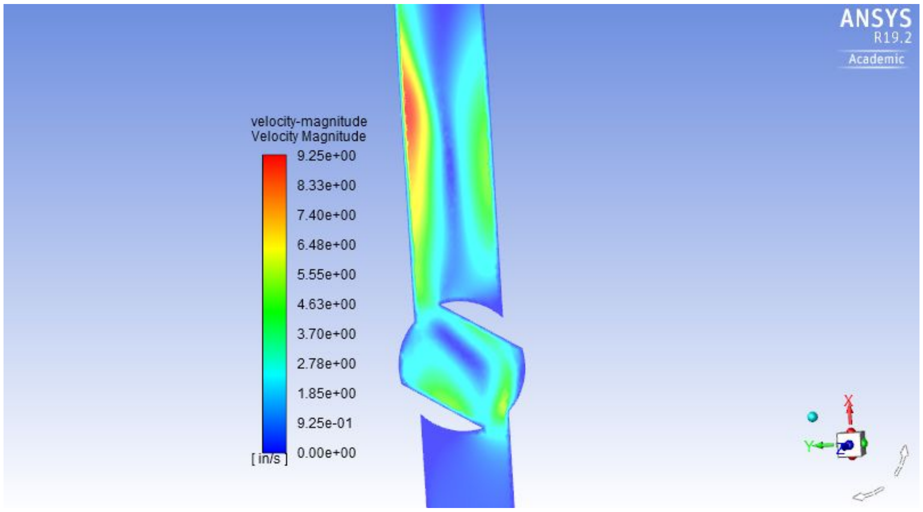


Figure 24. CFD contour plot at 30 degree of valve opening

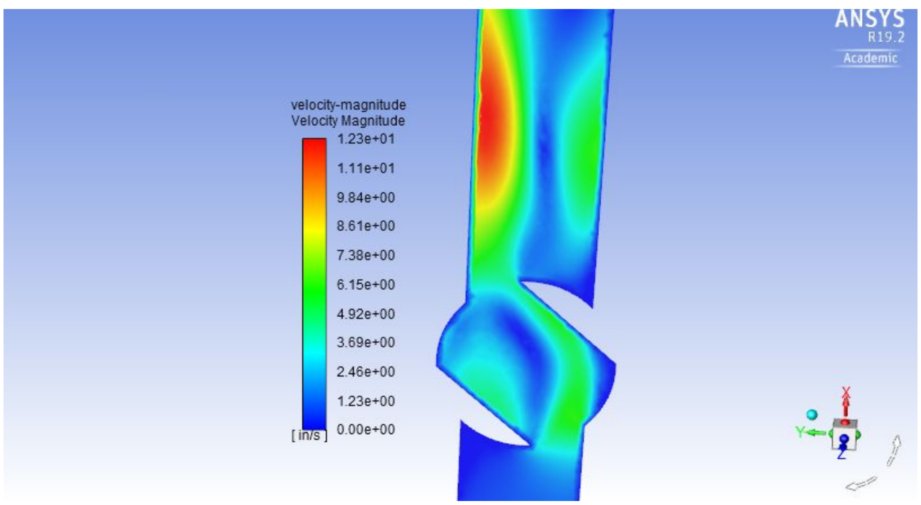


Figure 25. CFD contour plot at 40 degree of valve opening

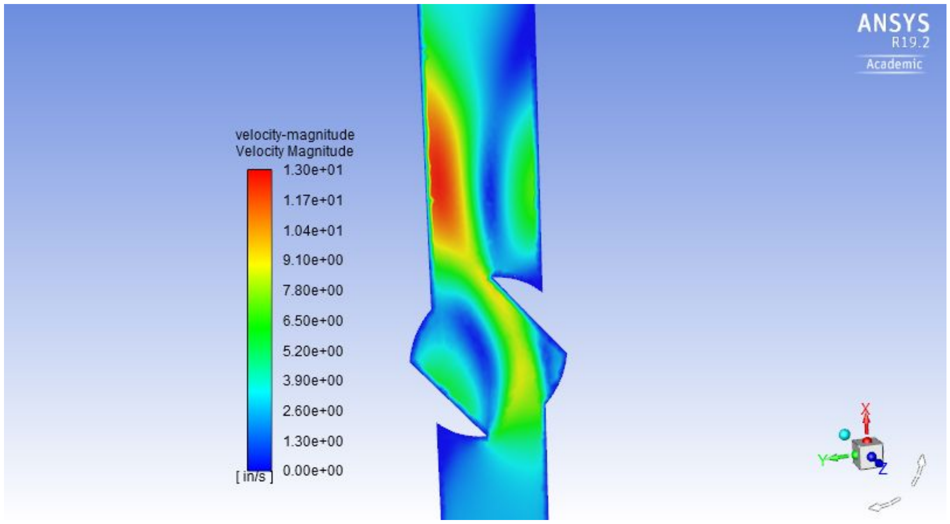


Figure 26. CFD contour plot at 50 degree of valve opening

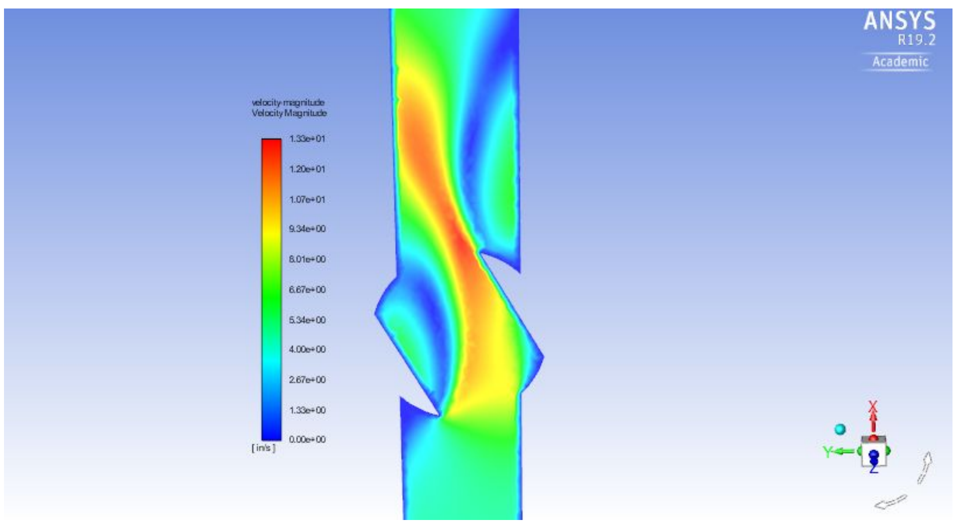


Figure 27. CFD contour plot at 60 degree of valve opening

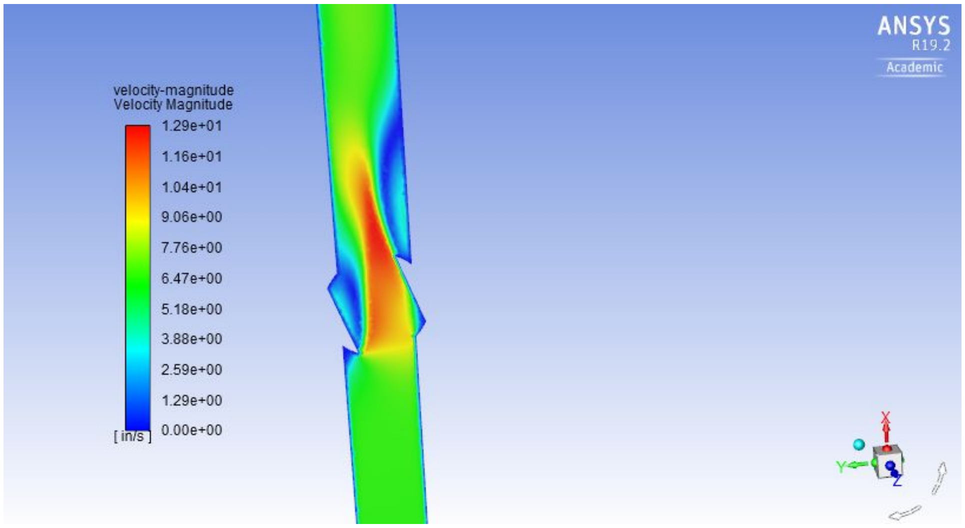


Figure 28. CFD contour plot at 70 degree of valve opening

6.3. Control System Code

Refer to Attachment.

6.4. Alternative Control System Design

The UIUC Beverage Valve team considered another control design method which could produce a more robust control algorithm with higher performances—control design in the Simulink PID Tuner. The prerequisite of control design in the Simulink PID Tuner is the plant transfer function—in this case, the open-loop transfer of the motorized ball valve—which, however, is unavailable. Theoretically, the plant transfer function can be constructed from system identification: a large number of tests of injecting sinusoidal control effort inputs of multiple frequencies or step control effort inputs—in this case, the valve angles—and collecting the outputs—in this case, the volumetric flow rates. The result of system identification is a set of Bode plots, from which the plant transfer function can be estimated. With the plant transfer function, the Simulink PID Tuner can enable the designer to set the response time and robustness of the controller as the designer desires, and release the corresponding gains, overshoot, rise time, settling time, gain margin, phase margin, unit step response plot, control effort plot, and disturbance rejection plot. However, three factors have rendered the approach described above unfeasible in this project:

1) The fact that the motorized ball valve has step motion responses instead of proportional motion responses to voltage changes, which means that sinusoidal control effort inputs are difficult to achieve without special circuitry and electrical manipulations.
2) The fact that the flow meter utilizes a sampling period of 1000 ms while the settling time of the system's step response is shorter than 600 ms.
3) Time constraints and the lack of equipment such as optical encoder and oscilloscope.

Because of the failure, the Beverage Valve team has decided to include the following example built in the MATLAB System Identification Toolbox to demonstrate the potential usefulness of system identification and control design in the Simulink PID Tuner for reference of future work.

1000 time-domain input-output samples based on a sampling period of 80 ms have been collected from experiments on a blow dryer. The input is a series of steps of input power to the blow dryer, and the output is the temperature of air from the blow dryer. The objective is to estimate an open-loop transfer function of the blow dryer relating input power to output air temperature, and to design a closed-loop PI controller for the blow dryer.

After being imported into the MATLAB System Identification Toolbox, the original time-domain input-output data has been divided into two halves: the first of 500 samples, represented by the red line, and the second 500 samples, represented by the mint line. The first half is used as the "Working Data" to estimate the transfer function, and the second half is used as the "Validation Data" to validate the estimated transfer function. As shown in Figure 32, the response from the estimated transfer function, represented by the green line, matches well with the response from the original data, represented by the black line. The MATLAB System Identification Toolbox can also export the estimated transfer function to the MATLAB workspace as a transfer function object, and explicitly shows the order and terms of the transfer function.

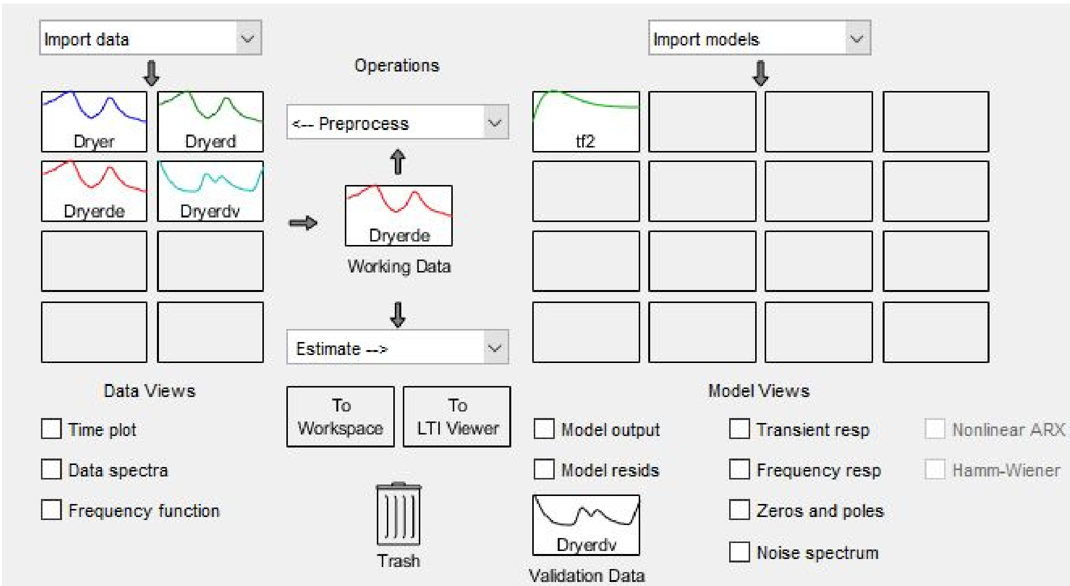


Figure 29. MATLAB System Identification Toolbox User Interface

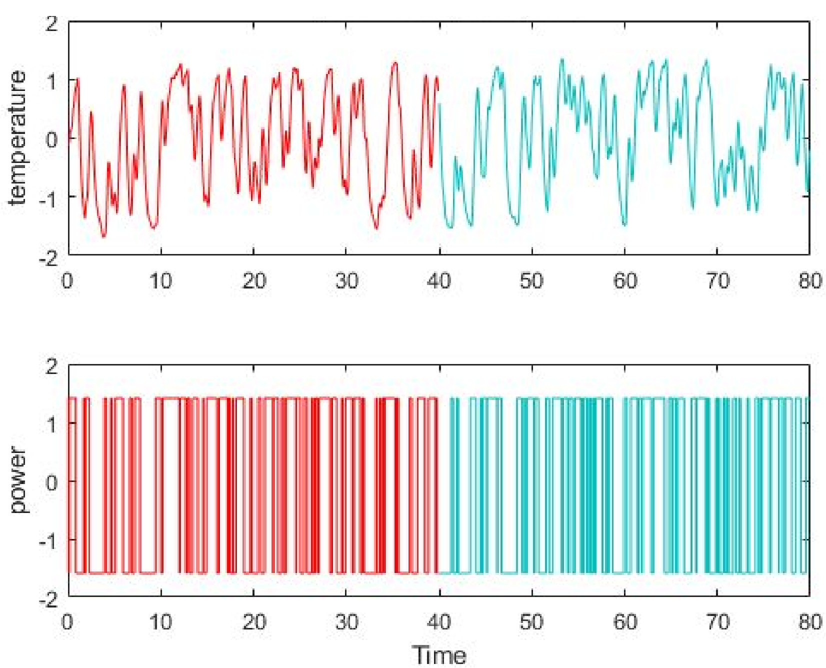


Figure 30. System Identification Original Input-Output Data

```
  From input "power" to output "temperature":
    -1.398 (+/- 0.09138) s + 13.97 (+/- 0.5289)
  ----------------------------------------------
  s^2 + 6.603 (+/- 0.2956) s + 15.58 (+/- 0.4455)

Name: tf2
Continuous-time identified transfer function.
```

Figure 31. Estimated Transfer Function from System Identification

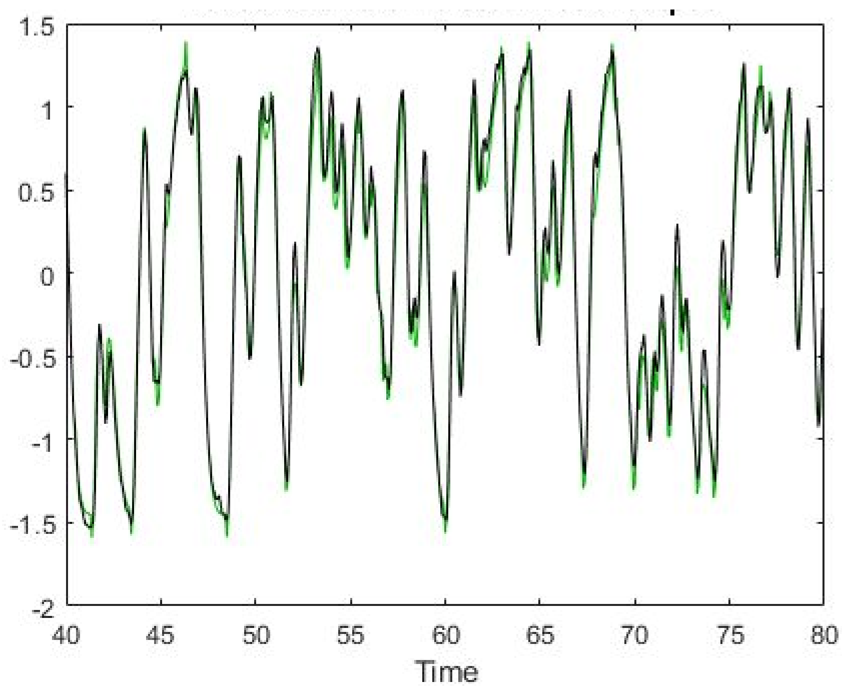


Figure 32. Validation of the Estimated Transfer Function

After system identification, the control designer can build a closed-loop control block diagram in Simulink using the PID Controller block, and manually enter the estimated transfer function to the Simulink transfer function block. Then, by clicking the “Tune” button in the user interface of the PID Controller block, the control designer can initiate the Simulink PID Tuner. Once the “PI” controller option is selected, the Simulink PID Tuner allows the control designer to tune the response time and robustness of the controller, and provides the control gains, overshoot, rise time, settling time, step response plot, control effort plot, disturbance rejection plot, etc., immediately after each tuning. The "Block Response" refers to the response based on the control gains currently in the PID Controller block, usually the previous control gains that the control designer intends to compare with the tuned values. With the MATLAB System Identification Toolbox and the Simulink PID Tuner, control designs with various requirements can be performed rapidly as long as input-output data of appropriate type—sinusoidal or step—is available.

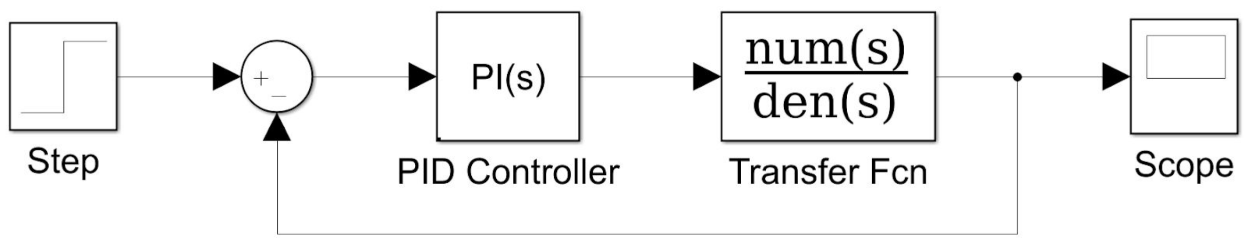
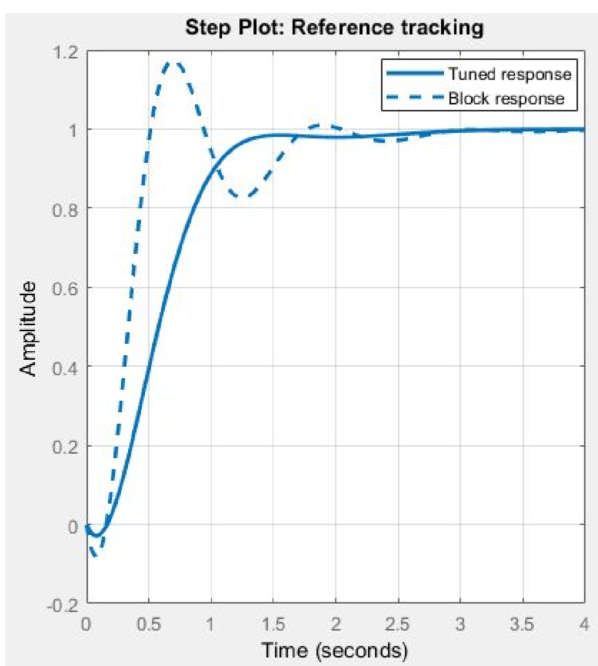


Figure 33. Simulink Closed-Loop PID Control Block Diagram



Controller Parameters

	Tuned	Block
P	0.5423	1.6223
I	1.5737	2.5564
D	n/a	n/a
N	n/a	n/a

Performance and Robustness

	Tuned	Block
Rise time	0.749 seconds	0.265 seconds
Settling time	1.37 seconds	2.62 seconds
Overshoot	0 %	17.4 %
Peak	1	1.17
Gain margin	14.9 dB @ 6.87 rad/s	7.74 dB @ 8.03 rad/s
Phase margin	69 deg @ 1.61 rad/s	46 deg @ 4 rad/s
Closed-loop stability	Stable	Stable

Figure 34. Step Responses and Controller Parameters from the Simulink PID Tuner

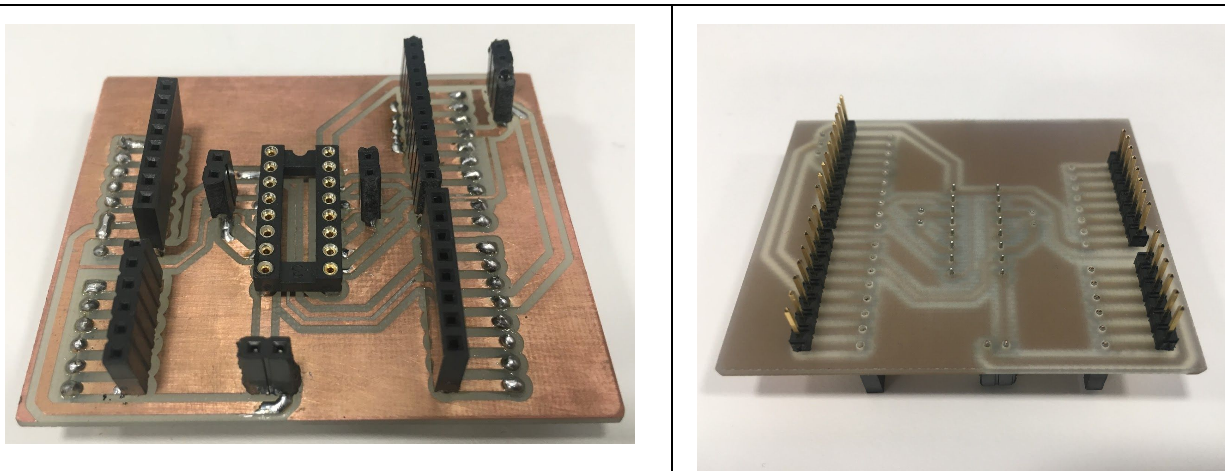
6.5. Printed Circuit Board Design

To simplify the wiring and save space on the prototype, the Beverage Valve team has designed and fabricated a printed circuit board for the L293D dual H-bridge integrated circuit and the SparkFun RedBoard microcontroller. The PCB was milled from a single-layer copper-coated plastic base, and has been designed to fit on top of the SparkFun RedBoard and to minimize wiring using embedded tracks. Embedded connections on the PCB include:

1) Equivalent pins of the SparkFun RedBoard that can be connected through the female sockets.
2) Power and digital common ground (pin 4, 5, 12, and 13 of the L293D).
3) 12 V power supply (pin 8 of the L293D).
4) Two motor drivers (pin 3, 6, 11, and 14 of the L293D).
5) Sensor power and H-bridge enabling (pin 1 and 16 of the L293D).
6) Sensor reading to digital pin 4 of the SparkFun RedBoard

It should be noted, however, that the 5V pin and the VIN pin of the SparkFun RedBoard are not connected through embedded track on the PCB. This connection is necessary for the sensor to function and should be achieved using an external wire and the female sockets on the PCB. Meanwhile, it should be noted that the PCB does not have vias, i.e., the top and bottom layers of the PCB are not electrically connected. The copper tracks on the top side of the PCB carry all electrical signals; therefore, waterproofing is critical for the PCB.

Pictures and the circuit design diagram of the PCB are shown below.



a. Top Side *b. Bottom Side*

Figure 35. Top and Bottom Sides of the Printed Circuit Board

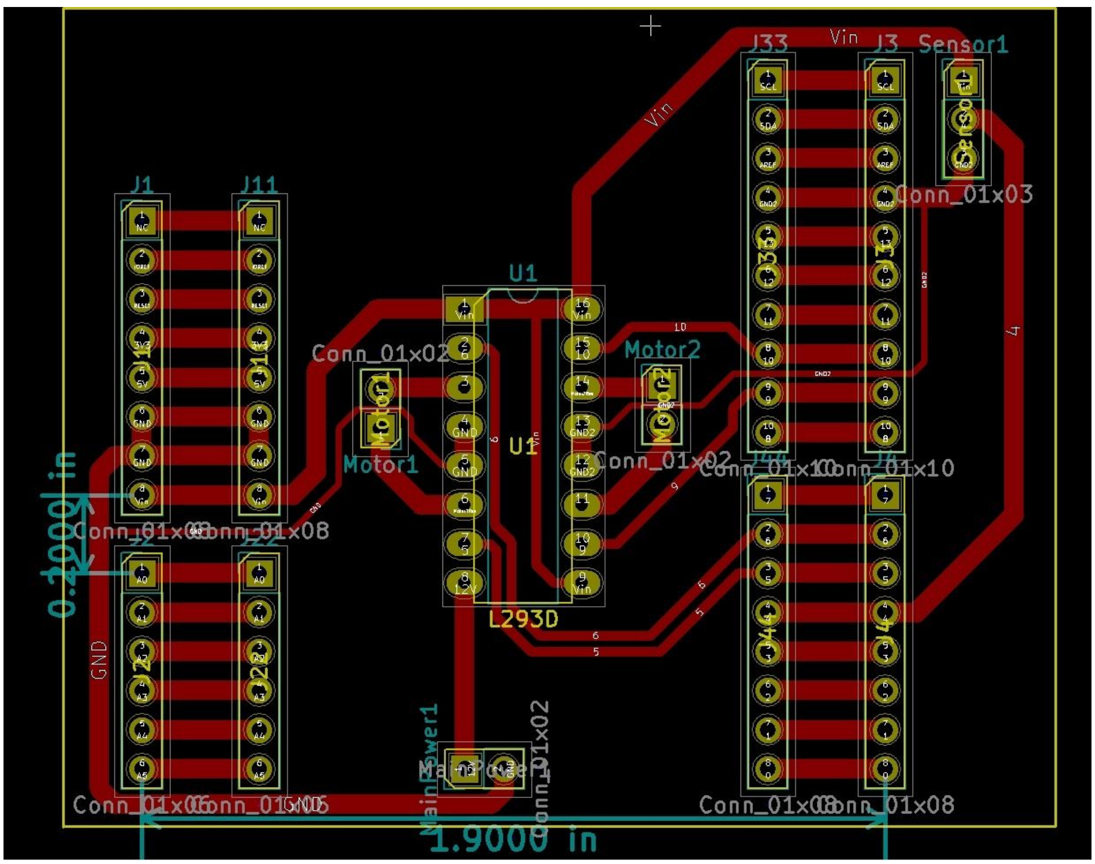


Figure 36. Circuit Design Diagram of the Printed Circuit Board