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Autonomous Bottling and Packaging System - Mechanical Bottling Portion

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Murray State University Honors College

HONORS THESIS

Certificate of Approval

Autonomous Bottling and Packaging System - Mechanical Bottling Portion

Kathryn (Katie) Gray
May 2024

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Autonomous Bottling and Packaging System - Mechanical Bottling Portion

Submitted in partial fulfillment

of the requirements

for the Murray State University Honors Diploma

Kathryn (Katie) Gray

May 2024

Abstract

This report details the complete mechanical design of an autonomous bottling automation system. This system is fully integrated with a bottling and packaging system. The scope of the full project is to successfully bottle and cap twelve small bottles (approximately 68 cm^3) in under three minutes and thirty seconds. The bottles shall be filled with an "electrolyte" and water mixture, and the mixture should be fully mixed. To complete this task, two tanks will dispense liquid (one electrolyte, and one water) into the bottles. Each tank shall have a measuring chamber, that will fill with the correct amount of volume for the corresponding liquid, and then dispense the liquid into the bottle. Then the bottle shall move via a conveyor belt to the capping station, where two pistons shall push a cap onto the bottle and firmly secure the cap. The entire system will be programmed with an Allen Bradley PLC, and use an HMI interface for future machinists.

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Nomenclature

V	Volume, mL
r	Radius, cm
h	Height, cm
h_f	Final Height, cm
h_i	Initial Height, cm
g	Gravity (Constant), 980 $\frac{cm}{s^2}$
v	Velocity, $\frac{cm}{s}$
ρ	Density, $\frac{g}{mL}$
m	Mass, g
N	Normal Force, N
μ	Coefficient of Friction

List of Figures, Tables, and Illustrations

Figure 1: 3 Ball Valve Measuring Chamber. Ball Valves are shown as closed and have solenoids attached. For scale, the length of the vertical tube is 15 cm.

Table 1: Cost Estimate for 3-way ball valve option

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Introduction

The purpose of this project is to extend an existing system that fills a small bottle to a set of water, adding a mixed electrolyte solution, as well as capping the small bottle to be ready for packaging. Each bottle is approximately 3.81 cm in diameter and 5.97 cm tall. The system shall first fill the bottle with electrolytes, then water, and finally cap the bottle before it is packaged. The group decided that the packaging is currently out of the scope of work for the project. The conveyor belt system will be programmed with an Allen Bradley Programmable Logic Controller (PLC), with an HMI interface available for the operator to overview the entire process. An enlarged CAD drawing of the entire system will be shown in Appendix A. The goal of the project is to successfully fill and cap twelve bottles in under three and a half minutes.

The report shall exclusively go over the design and design criteria of the bottling stations. The key constraints identified were ensuring that the bottles filled up with a correct amount of liquid every time, and did so in a timely manner. When reviewing the aspects of the project to keep safety in mind, the team determined that the most important risk to consider was keeping all of the electrical components up to code around water. Therefore, all electrical components will be kept as far away from the water as possible. Those that aren't able to maintain a safe distance, will be up to code 29 CFR 1910.303, which requires all pieces that could expose electrical components to water be liquid-tight. The equipment that is upstairs is already up to this code, and will be used again in the implementation of the bottling station. The next thing that was considered was the quality of materials that were being used on the system, specifically making sure that the components are food grade. This is because in an assembly for a water/electrolyte solution, these components would need to be food grade. However, after extensive research, it was determined that food-grade materials would not be feasible within the allotted budget.

Total System Design - General

To begin, a general overview of the total system working together is necessary for understanding the bottling station design. To start the system, the first bottle will be placed on the conveyor belt by a person. When the conveyor belt starts running, both three-way ball valves will open, going from the measuring chambers to the reservoirs, allowing for the measuring chambers to fill while the first bottle is moving. This first bottle will move on the conveyor belt until it is stopped by a bumper. In the original design, the bumpers had a limit switch that would be pressed to stop the conveyor belt. After testing, it was found that the bottles didn't have enough force to push the buttons. Therefore, the bumper design was altered so that the bottles would be guided to one side of the conveyor belt, and the conveyor belt will be stopped by a timer, programmed by the PLC. Once the conveyor belt is stopped, the 3-way ball valve on the electrolyte solution will close from the reservoir, and be open to the measuring chamber and vent. Then, the ball valve will open, allowing the electrolyte solution to be released. Once the liquid is dispensed, the ball valve will close and the 3-way valve will open from the reservoir to the measuring chamber, so that it may be ready for the second bottle.

When the first bottle is done at the electrolyte station, the bumpers will retract via a pneumatic piston, and allow the first bottle to move to the water filling station. When the bumper is retracted, the team member will put the second bottle on the station. This allows the bottles to be filled and capped at the same time. Each station is an equal distance from the next station so that the bottles will hit each station simultaneously. When the first bottle reaches the water filling station, the same mechanics as the electrolyte station will allow for the bottle to be filled with water. Simultaneously, the second bottle will be filled with electrolyte solution. When both ball valves are closed, the bumpers will be released and allow both bottles to move to the next station. The team member will place a third bottle on the conveyor belt. When the bottles reach their designated stations, the first bottle will be at the capping station. One pneumatic piston will push a cap out of the reservoir, and onto the bottle. A second pneumatic piston will push the cap onto the bottle, securing the cap. The other two bottles will be filled at their respective filling stations. Once this is completed, the bumpers will retract, the first bottle will move to the end of the conveyor belt and be unloaded by a team member. A new bottle will be placed onto the conveyor belt for filling and capping. This cycle will repeat until 12 bottles have been successfully filled and capped.

Description of Final Prototype Design - Bottling Station

There shall be two separate bottling stations. The first station will dispense the electrolyte solution, and the second will dispense the water. This will ensure that the electrolyte solution will properly mix into the water, and create the final product. Several alternate approaches will be considered in later sections, but this first section will outline in detail the plan to execute the dispensing of the liquids.

The major challenge that I deemed necessary to attack was dispensing a precise and accurate amount of liquid. To achieve this goal, I decided to use one three-way ball valve and one ball valve. Each container will need to be filled with approximately 13.4 mL of product, and approximately 25% (3.35 mL) of product will be electrolyte solution, and 75% will be water (10.05 mL). To achieve this goal, 3.5 cm. of 15 mm pipe will be in between the valves for the electrolyte solution, and 10.5 cm of 15 mm pipe will be in between the valves of the water.

To create the system, each reservoir will be set upright (as done in previous years). Starting with the electrolyte system, the reservoir will be 10.16 cm from the conveyor belt. Immediately following the reservoir will be a three-way, actuated, L-type ball valve. One side of the valve will be connected to the reservoir, one side will be connected to the vent, and the last side will be connected to the measuring chamber. The vent shall be a piece of pipe that creates an L shape so that the vertical piece will not hit the reservoir. The vertical piece of pipe shall be taller than the amount of water in the reservoir, to ensure that, in case of failure, water does not flow out of the vent. This is in line with code 29 CFR 1910.303. It is the intent of the group that the project will be as close to food-sanitary as possible, but with the scope of the project and budget, the group has elected to use coffee filters as the sanitary cap, following code 3A 63-04 of

3-A SSI Standards. The measuring chamber shall have the second actuated ball valve immediately attached on the other side since 3.5 cm is such a short length. It will be the length of the female connection points ball valve, with one male connector in between to attach. The process of loading and unloading the measuring chamber shall be:

1) Open 3-way ball valve to reservoir and measuring chamber. The timing shall be the downtime between receiving a new bottle to fill since overflow isn't a concern.
2) Move 3-way ball valve to be open to the measuring chamber and vent.
3) Open ball valve to dispense liquid.
4) Close ball valve.
5) Move 3-way ball valve to be open to the reservoir and measuring chamber. Repeat the process.

The water system shall be created in the same manner as the electrolyte system. The reservoir will be 10.16 cm from the conveyor belt. Based on the stability of the system a ring support may need to be 3D printed. Immediately following the reservoir will be a three-way, actuated, L-type ball valve. One side of the valve will be connected to the reservoir, one side will be connected to the vent, and the last side will be connected to the measuring chamber. The vent shall be a piece of pipe that creates an L shape, so that the vertical piece will not hit the reservoir. The vertical piece of pipe shall be taller than the amount of water in the reservoir, to ensure that, in case of failure, water does not flow out of the vent. It is the intent of the group that the project will be as close to food-sanitary as possible, but with the scope of project and budget, the group has elected to use coffee filters as the sanitary cap. The measuring chamber (10.5 cm of 15 mm tubing) shall have the second actuated ball valve attached on the other side. This will include the female connection points of the ball valves. The process of loading and unloading the measuring chamber will be carried out in the same manner as listed above.

Once I started looking at 3-way actuated ball valves to order, the issue arose that no approved vendor had the size of valve needed. With limited time between then and the paper being due, I came up with a second plan in case the 3-way ball valves couldn't be ordered. In this design, three 2-way ball valves will be used along with a wye-connection. The valves shown are actuated, and will work with a 24 V source with an open/close time of 5s. A model of the three 2-way ball valve system is shown in Fig. 1. Due to the unknowns of the other ball valve plan, I decided that this option is the best. Starting with the electrolyte solution, the reservoir will be 10.16 cm from the conveyor belt and be connected to an actuated ball valve. This ball valve will open and close to let water into the measuring chamber.

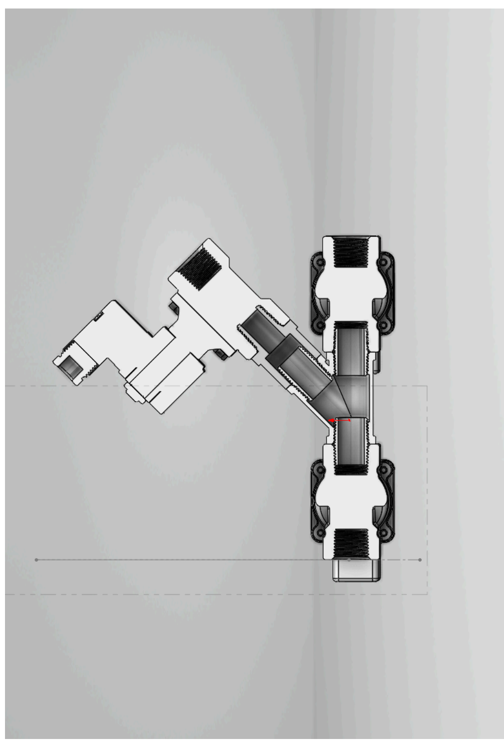


Figure 1: 3 Ball Valve Measuring Chamber. Ball Valves are shown as closed and have solenoids attached. For scale, the length of the vertical tube is 15 cm.

So that the measuring chamber can still have a vent to air, a Wye-connection will be installed, with a ball valve in the vent. This ball valve will be shut while the measuring chamber is filling, and open while the measuring chamber is dispensing. This way, part of the vent will be part of the measuring chamber, while allowing for a vent to increase flow during the dispensing process. The volume required for the electrolyte solution is still 3.5 mL, so 3.5 cm will be part of the measuring chamber, and only the connectors. The third ball valve will be on the other side of the t-connection, and will be used to dispense liquid. The following process will be shown in picture format in Appendix B. Due to the uncertainty of the 3-way ball valve's feasibility, I decided that this option was the best option to plan for.

The process of loading and unloading the measuring chamber is as follows:

1) Open ball valve to reservoir. Keep vent valve and discharge valve shut. The timing shall be the down time between receiving a new bottle to fill, since overflow isn't a concern.
2) Shut ball valve to reservoir. Open discharge valve, then open valve to vent slowly.
3) Once water has finished pouring shut discharge and vent valves. Then, open the ball valve to reservoir to repeat the process.

Moving to the water system, the reservoir will be 10.16 cm from the conveyor belt and be connected to an actuated ball valve. This ball valve will open and close to let water into the measuring chamber. So that the measuring chamber can still have a vent to air, a Wye-connection will be installed, with a ball valve in the vent. This ball valve will be shut while the measuring chamber is filling, and open while the measuring chamber is dispensing. This way, part of the vent will be part of the measuring chamber, while allowing for a vent to increase flow during the dispensing process. The volume required for the water solution is still 10.05 mL, so 7.62 cm will be part of the measuring chamber. The third ball valve will be on the other side of the t-connection, and will be used to dispense liquid. The process of loading and unloading the measuring chamber is the same as listed above.

Looking at the alternate approaches, the two options thatI decided between were opting for the two ball valve design versus a flow meter and single ball valve design. Starting with the pros of the two valve design, the ball valve design allows for minimal calibration for the PLC. Once the mechanical portion is complete, the programming should be much simpler. Also, since the design incorporates two separate reservoirs, no pump or mixing is required for simplicity. Moving to the pros of the flow meter and ball valve, the biggest pro is that all the components are already in the automation lab. Also, most of the design is already built by the previous group, so minimal work on the conveyor belt would need to be done. Instead, it would become more of a programming challenge, and likely add a packaging design to the scope of the project. Switching to the cons of the two-valve design, the 3-way actuated ball valves are expensive, and can be upwards of $600 a piece. This design also is the most mechanically difficult, not because the design itself is complex, but because it is completely different from what the Fall 2023 group did. Therefore, a complete disassembly and reassembly will be required. The biggest con of the flow meter design is that the flow meter would need to be calibrated. With the variable head pressure as bottles are being filled, I thought that it would be best to not do this calibration. In short, I valued getting a precise measurement the first time via mechanical means as more valuable than both the cost of the components and the time for assembly. A decision matrix can be found in Appendix C and shows all of the factors that went into determining the best design for the bottling stations and the outcome of the matrices.

Analytical Methods of Design

In designing the bottling stations, the calculations that were needed would be to determine the surface tension (in case of suction). I decided to do this by physical means of analysis (i.e. by using tubes already in the lab). While the water did come out of the tube while the top of the tube was sealed, the flow was nowhere near as fast as when the pipe was not sealed. It seemed to be a safer outlook to add the vent, so that any desired flow could be obtained. The next calculations were to find how large the measuring chamber needed to be, and how quickly the bottle would fill up. The following equations were used for the bottling and capping stations:

$$V = r^2 h \quad (1)$$

$$PE = m * g * (h_f - h_i) \quad (2)$$

$$KE = ½\, m * v^2 \quad (3)$$

$$m = \rho * V \quad (4)$$

First, the volume of each bottle was calculated using Eq. (1), where r = 1.97 cm, and h = 5.08 cm. While the bottle is taller than h, room needs to be left for the cap to fit nicely and not spill the mixture. This also allows for a small margin of error. Using Eq. (1), it is found that each bottle can hold 61.45 mL of product.

Next the length of the measuring chamber was calculated using Eq. 1, where r = 6.5 mm, V = 15.3625 cm^3 for the electrolyte solution, and V = 46.0875 cm^3 for the water. Solving for h, it's found that the length of the measuring chamber needs to be 11.6 cm for the electrolyte solution and 34.7 cm for the water. This assumes that the inner radius of the tube is accurate to 15 mm tubing.

Finally, the velocities of the solutions were calculated using the Law of Conservation of Energy, and Eq. (2), Eq. (3), and Eq. (4). Several assumptions were made during this process. The first assumption is that water could be assumed as a free-falling point mass, since the vent let out to atmospheric pressure. The initial height of the water was taken from the outlet of the dispensing ball valve to the conveyor belt. The final height of the water was taken from the outlet of the dispensing ball valve minus the height of the water in the bottle (5.08 cm). The second assumption is that the density of food coloring is about equal to the density of water (1 $\frac{g}{mL}$). Starting with the electrolyte solution, the density is 1 $\frac{g}{mL}$. The volume is V = 3.35 mL. Solving for Eq. (4), the mass of the water is 3.35 grams. The initial height is 5.97 cm. The final height is 10.16 cm. Then, using the Law of Conservation of Energy, Eq. (2), and Eq. (3) can be set equal to each other, where h_f = 10.16 cm, h_i = 5.97 cm, m = 3.35 g, and gravity is constant. The final velocity is 90.6 cm/s. Moving to the water, the density is 1 $\frac{g}{mL}$. The volume is V = 10.05 mL. Solving for Eq. (4), the mass of the water is 10.05 grams. Then, using the Law of Conservation of Energy, Eq. (2) and Eq. (3) can be set equal to each other, where h_f = 10.16 cm, h_i = 5.97 cm, m = 10.05 g, and gravity is constant. The final velocity is 90.6 cm/s. These calculations were used assuming that the 3-way actuated ball valve plan was used. If the 3 ball valve plan is used, then the velocity will be even greater, because the height will be greater, since some of the volume will sit in the vent, and the measuring chamber will be shorter.

Overall Cost Report (Initial)

Product	Individual Price	Quantity	Total Price
3-Way Actuated Ball Valve (Supplyhouse.com)	$119.67	2	$239.34
1/2" Nipples (Grainger)	$1.46	8	$11.68
Silicone Grease (Amazon)	$9.99	1	$9.99
Switches (VEX)	$14.49	2	$28.98
Tubing (Grainger)	$18.98	1	$18.98
Total			$308.97

Table 1: Cost Estimate for 3-way ball valve option

Product	Individual Price	Quantity	Total Price
Ball Valve (McMaster-Carr)	$140.97	4	$563.88
1/2" Nipples (Grainger)	$1.46	12	$17.52
Switches (VEX)	$14.49	2	$28.98
Silicone Grease (Amazon)	$9.99	1	$9.99
Tubing (Grainger)	$18.98	1	$18.98
Total			$639.35

Table 2: Cost Estimate for 3, 2-way ball valve option

Design Implementation and Changes

The total design of this project was completed in the Fall semester of 2023, while the implementation was completed in the Spring semester of 2024. While implementing this project, some changes were made that impacted the design and cost. This section will go over the problems that arose (specifically the bottling stations), the changes that were made, and how those changes impacted the project. This section will also go over the timeline of the project's completion.

As mentioned previously, two different designs were thought of for the bottling station (two, three-way ball valves vs. three, two-way ball valves). After discussing the possibility of getting the three-way ball valves from an unapproved vendor with School of Engineering personnel, the valves were deemed as attainable. During the month of January, I ordered these parts (and others) at the beginning of the semester. The team and I then began tearing apart the previous group's work. Once the station was clear, the group reattached the conveyor belts. When the actuators and valves came in, it was discovered that the shaft for the valve was not long enough to click in to the actuator motor. Therefore, the team had to do some quick problem-solving to come up with a solution. It was decided that the locking piece on the valve was too long in comparison to the shaft, so a new locking piece was dimensioned and 3-D printed. Several iterations of this locking piece were made, mainly due to the issue of slippage on the 3-D printer itself. During the month of February, the bumpers were put onto the conveyor belt, and the capping station was 3-D printed. I also cut the pipes for the measuring chambers.

In March, the team and I started putting the stations onto the conveyor belt station. I mounted the reservoirs while the team simultaneously mounted the capping station. During this time, the group began wiring the actuators. It was discovered that a relay is required to wire the actuators correctly. This oversight was a $100 mistake, but fortunately, the group had a significantly larger budget than the amount of components needing to be ordered. Therefore, this oversight was not critical. When the relays came in, the group immediately started wiring. When the team wired the first relay to the actuator, the actuator was not functioning properly. After consulting with a professional to make sure that the wiring was correctly done, the group tested with the second actuator. When the second actuator worked properly, it was determined that the first actuator must have come bad from the vendor. Therefore, I reordered the actuator, which delayed the project for about a week.

Once the actuators were correctly wired and programmed, it was discovered that when the valves turned from the initial position (reservoir and measuring chamber open) to the final position (measuring chamber and vent open), the hole that was moving from the reservoir to the vent would allow water to enter the vent. This meant that when dispensing, there was more water than anticipated. After much troubleshooting and consulting with the project mentor, I decided the best course of action would be to remove the three-way actuated ball valve from the scope and just time the two-way ball valve. To mitigate the risk of water spilling onto the conveyor belt, proximity sensors were added to both the electrolyte and water stations. These sensors don’t allow water to be dispensed when a bottle is missing from underneath the station.

Overall Cost Report (Final)

Description of Product	Vendor	Cost
Nipples & Tube	Grainger	$41.54
Grease	Amazon	$16.98
Valves & Actuator	Supplyhouse.com	$346.82
Nuts & Bolts	Lowes	$17.47
Pipes & Fittings	Lowes	$26.74
Plumbing and Zip Ties	Lowes	$22.40
SPDT	Grainger	$109.68
Another Actuator	Supplyhouse.com	$108.11
	Total	$689.74
	Amount Left	$810.26

Table 3: Final Cost Report

Testing

Since the factors of safety for the valves are so high in terms of the pressure ratings (a factor of safety of almost 10), the team decided that pressure tests would not be necessary. Typically, a manufacturer will test valves to the API 598 standard, which includes a visual examination, shell tests (pressure test), backseat test (leakage through stem or shaft test), and a closure test (leakage test during mechanism closure). Since these tests were completed by the manufacturer, the group decided that the only test that was truly pertinent was the closure test. Therefore, the group decided to do a smaller-scale test with water instead of air or inert gas as API 598 calls for. This is because closure leaks that would impact the success of the project would be at such small pressures in comparison to the valve's ratings, that just testing the opening and closing of the valve at with the small head pressure from the water seemed necessary. This test was completed by a member of the group filling a PVC pipe that was attached to the closed valve with water, holding the water for a few seconds to examine for drips, and then opening the valve. This test was successful, and also tested our electrical components. Since some of the valves were used in years prior, checking the electrical components was also of utmost importance for project success.

Prototype Demonstration

The prototype currently works to satisfy the requirements of the scope for my portion. However, in the event of a power outage, the program will continue to run when power resumes to the PLC. The prototype currently demonstrates the ability to properly fill and dispense twelve bottles in under two minutes, which is much quicker than the original goal. Appendix D shows that the bottles are being filled to the same amount, by means of weight. The prototype also demonstrates the ability to sense if a bottle is not at the necessary position for water to dispense into the bottle. In this event, no water or electrolytes will be allowed to dispense, which prevents catastrophic failure on the system. The system is set up so that future teams can add a packaging system to the current bottling system. All electrical components are stored safely away, so there is no risk of damage from water. The system is equipped with emergency stops, both as a mechanical button and a digital button on the HMI. The HMI shows what components of the system are currently in use, as well as counts the number of bottles that have been bottled and ready for packaging. Appendix E shows pictures of the completed system.

Design Changes for Consequent Prototype

At this stage, covers for all electrical components need to be added for project success. For a change in design, one thing that would have been more beneficial is to have a smaller actuator that was pneumatically driven instead of electrical. Typically, pneumatic actuators are faster-acting. This would allow for more bottles to come through the conveyor belt system over a shorter period of time. With this change, the electrical components would not have to be housed near the water sources either. This would make the entire system inherently safer in terms of electricity because all components would be controlled via pneumatics. However, pneumatically charged devices have their own safety considerations as well. Specifically, if the component turns on when it's not supposed to, causing damage to the system or a person. Adding nozzles to the dispensers would also mitigate any dripping.

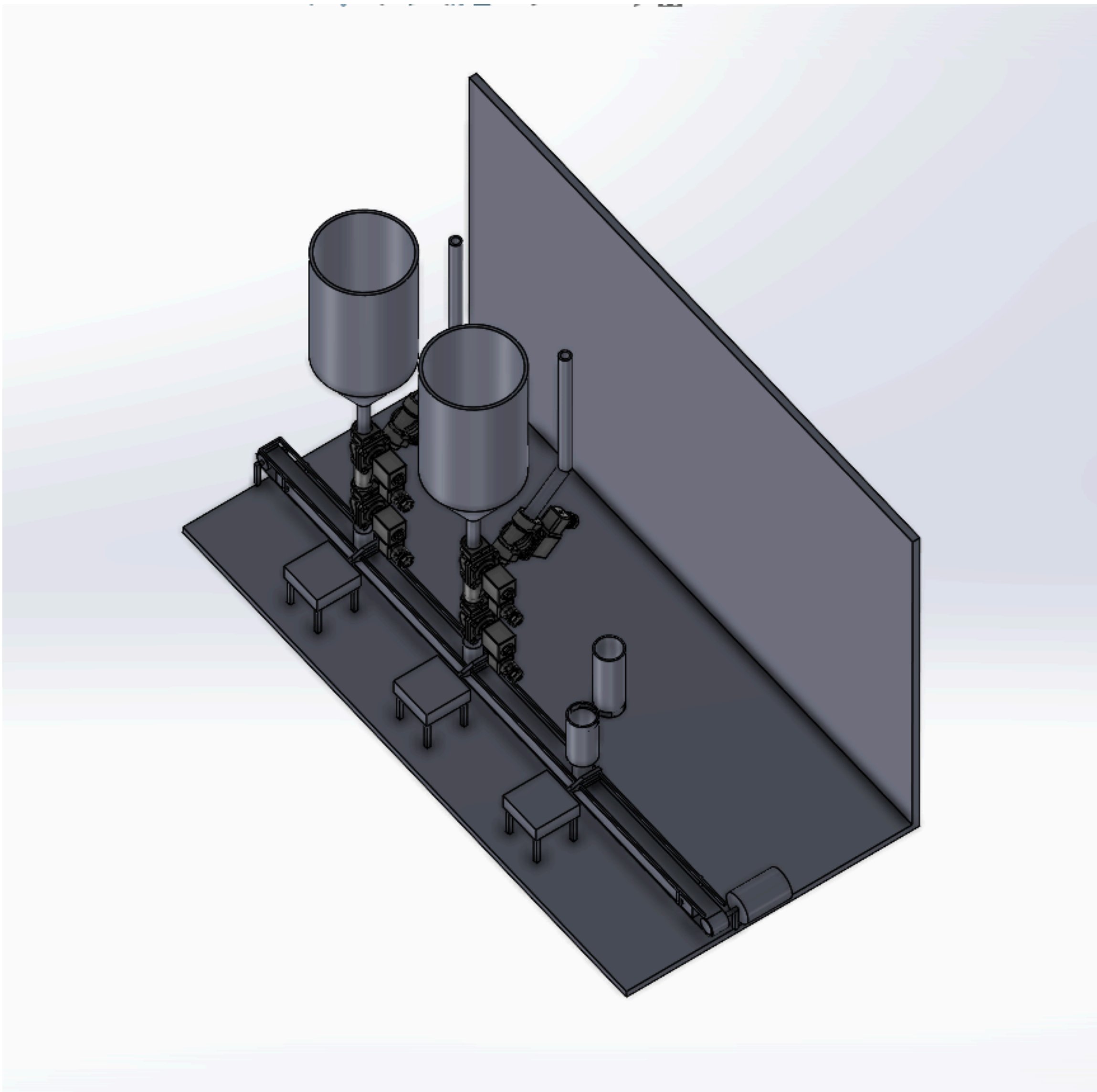
Another improvement would be to have the electrolyte solution and water mix and dispense in the same station. This would allow for the bottles to only stop at two locations instead of three. This would also cut down the time needed for a bottle to be filled and capped. However, a mixing design would be inherently more engineering. This would add sensors, valves, and overall more layers to this project. Since the team valued project success over a faster working project, this improvement was not feasible in the scope. However, this would be beneficial for further improvement.

Conclusion

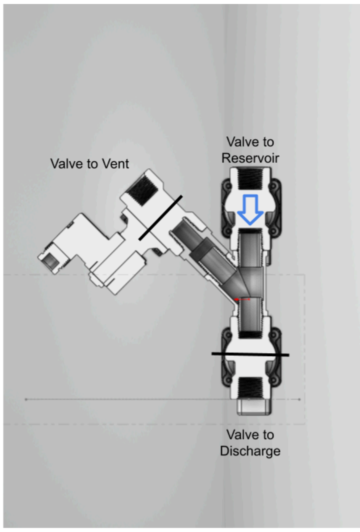
The goal of the design in to accurately dispense a set amount of liquid into bottles several times. To achieve this goal, the Allen Bradley PLC shall communicate with the ball valves to open and close in sequence, while also considering other pieces of the project for its full implementation. The bottling station shall start with the electrolyte solution first, then the water, so that the electrolytes can mix fully into the water, by just the water pouring into the bottle. Full safety considerations (including health and electrical codes) have been considered for this project, and safety remained priority throughout the process. These codes and standards were applied consistently throughout the project.

Appendices

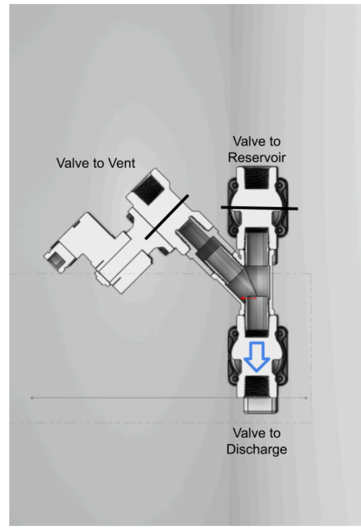
Appendix A: Enlarged Total CAD Drawing



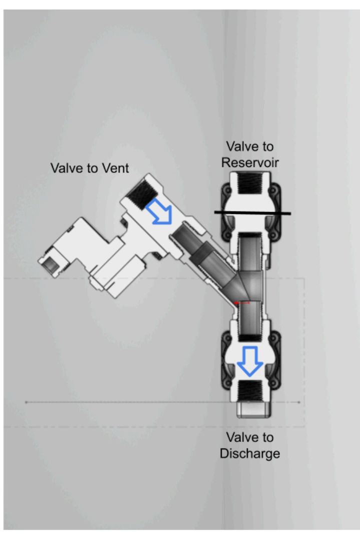
Appendix B: Three Ball Valve Option: Opening/Closing Sequence



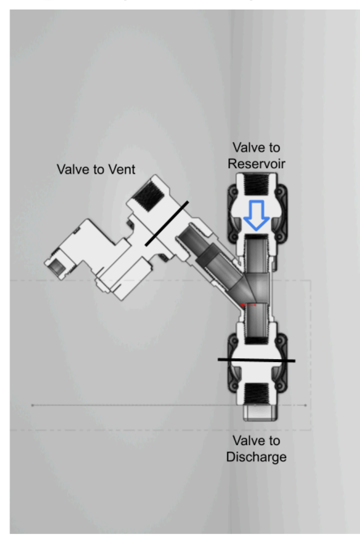
Step 1: Opening the Valve to Reservoir



Step 2: Closing the Valve to Reservoir. Opening Discharge Valve



Step 3: Opening the Valve to Vent



Step 4: Closing the Valve to Discharge and Valve to Vent. Opening the Valve to Reservoir, which repeats the process.

Appendix C: Decision Matrix Dispensers

Criteria	Flow Meter with Valve	Tee Ball Valve and Ball Valve
Cost	2	1
Installation	1	2
Accuracy	1	2
Sanitation	2	1
Programmability	1	2
Total	7	8

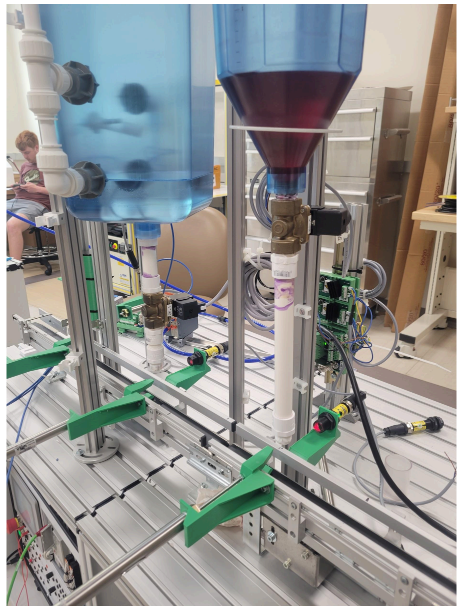
The decision matrix is based on a ranking system,with 1 being worse and 2 being desired. The greatest number is the best option. This decision matrix system doesn't allow for the factors to be weighted. The bullets below describe each factor:

- Cost - the total price of components needing to be ordered.
- Installation - Ease of deconstruction/installation of current and new systems.
- Accuracy - the ability to dispense the same amount of liquid every time.
- Sanitation - ability to clean the system thoroughly to prevent mold.
- Programmability - simplicity of the program, based on calibration and the programmer's prior experience.

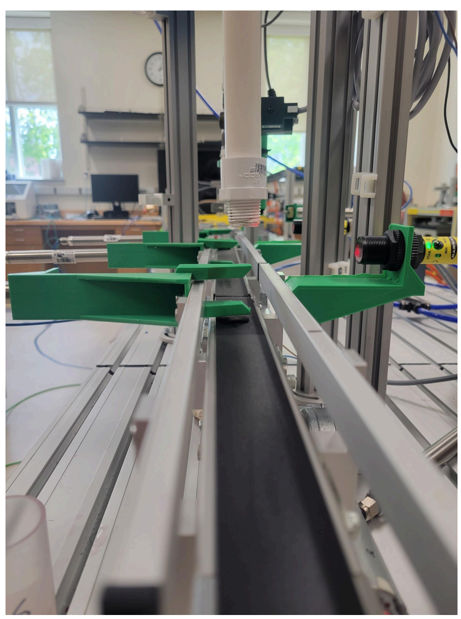
Appendix D: Bottles Weight Before vs. After Dispensing Liquid

Bottle Number	Empty Weight (g)	Full Weight (g)
1	17	57
2	17	61
3	16	59
4	16	59
5	17	58
6	17	59
7	17	61
8	17	57
9	17	60
10	17	60
11	17	59
12	16	59

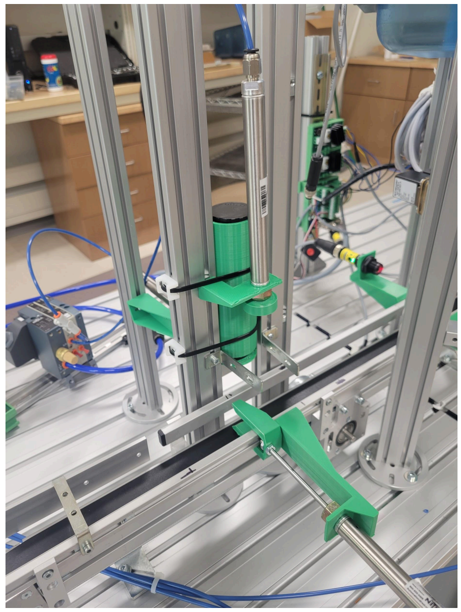
Appendix E: Complete Assembly



Electrolyte and Water Stations



Bumpers with Proximity Sensors



Capping Station

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