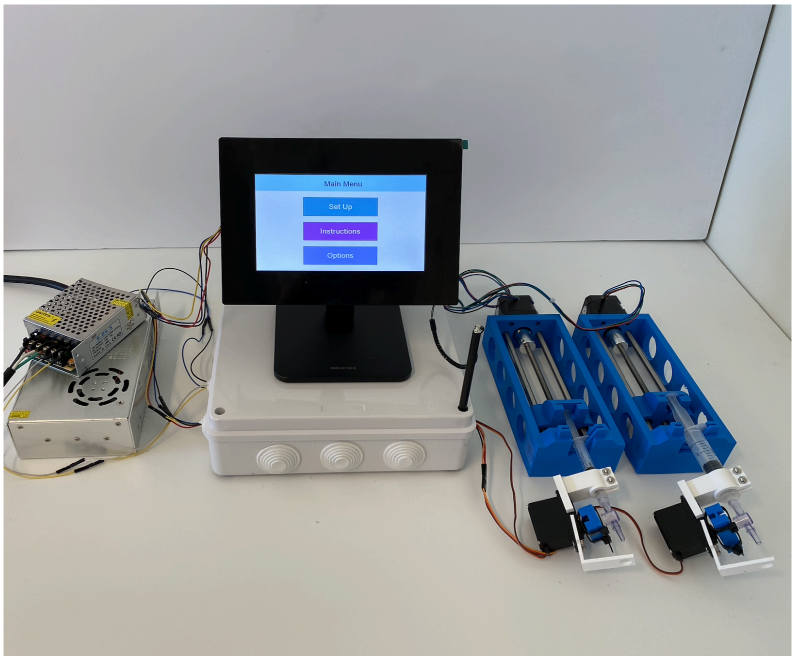
Designing a Flow System for Sustainable Chemistry



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Executive Summary

The practice of synthesizing chemicals has relied on low technology equipment such as glass flasks and pipettes for decades. Flow chemistry was invented in order to modernize and advance the practice of synthesizing chemicals in terms of both safety and efficiency. Flow chemistry consists of pumping reagents into converging tubing in which the reagents mix to form a product. Flow chemistry exhibits a number of benefits over traditional laboratory methods. Firstly, the safety of reactions is greatly enhanced due to the minimization of time spent handling flask continuing chemicals. Additionally, reactions occur with smaller volumes of the readgest at a single time, therefore greatly reducing the potential for a major explosion or mishap. Secondly, reactions are more efficient due to the high surface area to volume ratio of the reagents involved. Increasing this ratio increases the kinetics of the reactions resulting in greater yield. A third advantage of flow systems is the greater level of control that can be obtained in reactions. Due to the incremental nature of the reactions, the chemical can be closely monitored and maintained at specific temperatures and pressures before entering the reaction [1]. Despite its multiple advantages, flow chemistry systems come with one large downside. Commercially available systems cost upwards of $20,000. One of the reasons this system is so expensive is due to the low supply of these systems. The technology in these systems is rather complex, so it is difficult to manufacture many systems, leading to low supply and thus higher prices. In addition, these products are very accurate, so the price would make sense for that level of performance. However, this high price point makes this technology largely unavailable to academic laboratories and undergraduate students.

The sponsor of this project, Dr. Haim Weizman, a researcher and professor with the Department of Biochemistry and Chemistry, UCSD, hopes to make a chemistry flow system which is cost-effective and accessible to undergraduate laboratories. Various low-cost, DIY (Do It Yourself) flow chemistry systems have already been developed, however, these DIY systems have a number of shortcomings when it comes to ease of assembly and use. Dr. Weizman hopes to improve upon an existing DIY chemistry flow system by placing a greater emphasis on user-oriented design.

The specific flow system being improved upon is the Croatt Research Group's DIY flow system [2]. This system is open access and can be manufactured using only a 3D printer and parts ordered from Amazon for a cost of around $150 for a single pump. The system consists of a carriage which pushes a syringe from within the chassis as can be seen in Figure 1. The motion of the carriage is actuated by a stepper motor which is controlled by an Arduino. The system is commanded by the user who inputs a string of commands to the Serial Monitor of the Arduino.

Issues with this system include non-intuitive user input commands to the Arduino, corrosion of the threaded rod, syringe holders specific to the syringe size as opposed to a single design which can accommodate multiple syringe sizes, and disorganized cable routing and inadequate protection of the electronics in the system. Additionally, this system requires the user to fill the syringe by hand before performing the experiment. This is potentially dangerous when working with hazardous chemicals and can lead to serious accidents in the laboratory.

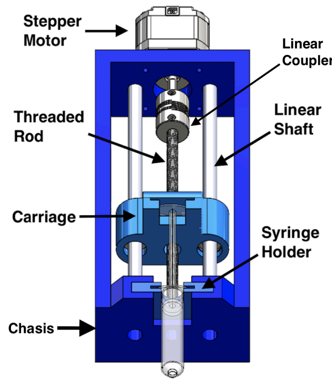


Figure 1. CAD model of Croatt Research Group's flow chemistry system

This project implemented additions and modifications to the Croatt Research Group's system in order to increase its functionality and usability. These additions include a Graphical User Interface (GUI), stainless steel hardware, a modular syringe holder, an electronics box and cable management strategy, as well as automated refill functionality. The GUI is intuitive and visually appealing as opposed to the previous commands entered into the Arduino's Serial Monitor. This reduces the resistance encountered by new users to learning how to use the system and decreases the potential of incorrect inputs being entered. The stainless steel hardware replaces the previous steel hardware which became susceptible to corrosion and limited the functionality of the syringe pump. The electronics box protects the electronics from any potential spillages on the lab bench and increases the visual appeal of the system. Furthermore, the automatic refill option greatly enhances the safety of the flow system and decreases the amount of labor needed to operate the system. The system exhibits below 10% error in the flow rate when operated below its maximum limits. Additionally, the stoichiometric ratios between two pumps track closely with the desired ratio, exhibiting less than 6% error. The system can be operated for extended periods of time to complete reactions requiring volumes of product. A complete system with four syringe pumps can be constructed for an estimated cost of $580.

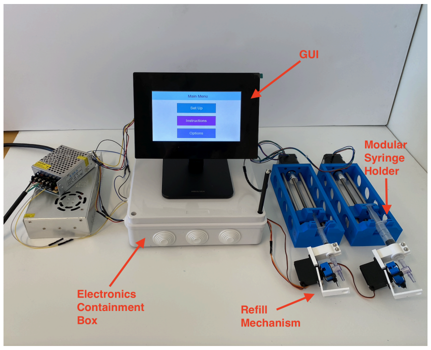


Figure 2. Final Design Solution

Abstract

This project, sponsored by Dr. Haim Weizman of the Department of Chemistry and Biochemistry at UCSD, focuses on the improvement of the Croatt Research Group's DIY (Do It Yourself) flow chemistry setup to enhance its usability. This project's motivation is to increase the prevalence of flow systems in undergraduate laboratories to grant students positive, hands-on experience with modern chemistry techniques. The Croatt system consists of a lead screw assembly that is coupled with a stepper motor which is able to translate the syringe plunger with each step of the motor. Major requirements for the system include a new user interface, non-corrosive components, a refill mechanism, a modular syringe holder, compact electronics containment and a user manual. The flow system consists of a Nextion graphical user interface, a servo motor refill mechanism, a modular syringe holder, an electronics containment box and corrosion resistant stainless steel rod components. The user interface was designed with the goal of making it intuitive. Prototypes for the refill mechanism and the modular syringe holder were tested.
The project resulted in a user interface that is capable of simultaneously controlling up to four syringe pumps and dispense fluid within a 10% error margin of the desired flow rate. A complete system with four pumps can be constructed for an estimated cost of $580.

Chapter 1: Project Description

Background

The practice of synthesizing chemicals has relied on low technology equipment such as glass flasks and pipettes for decades. However, these practices are outdated in a world of modern technology and leave a great deal to be desired in terms of both safety and efficiency. Flow chemistry was invented in order to modernize and advance the practice of synthesizing chemicals. In flow chemistry, reactions are conducted continuously as reagents are pumped through tubing and mix to form a product. Figure 3 presents a schematic diagram demonstrating the process of flow chemistry.

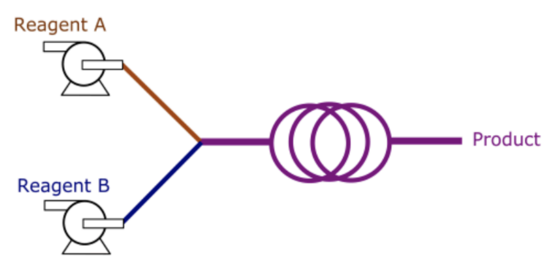


Figure 3. Flow chemistry schematic [1].

Flow chemistry exhibits numerous benefits over traditional laboratory techniques. Reactions are safer due to the smaller volume of hazardous materials reacting at once, are more efficient due to the high surface area to volume ratio which increases the kinetics of the reactions, and exhibit better control because reactors can be kept at specific temperatures and pressures [1]. Additionally, flow chemistry is more environmentally friendly and has generated new ways to manufacture sustainable materials. However, one large downside of flow chemistry is it's substantial price tag. Commercially available systems cost upwards of $20,000. Figure 4 displays a $20,000 chemistry flow system located in the Burkart Laboratory, UCSD. One of the reasons this system is so expensive is due to the low supply of these systems. The technology in these systems is rather complex, so it is difficult to manufacture many systems, leading to low supply and thus higher prices. In addition, these products are very accurate, so the price would make sense for that level of performance. This high price point makes it such that this technology is largely unavailable to academic laboratories and undergraduate students. These systems are also technologically complex that makes it difficult for students to set up themselves.

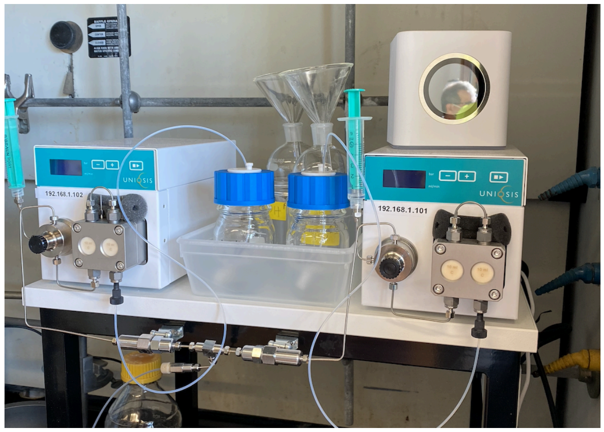


Figure 4. $20,000 flow chemistry system.

The sponsor of this project, Dr. Haim Weizman, a researcher and professor with the Department of Biochemistry and Chemistry, UCSD, has primary research interests of improving organic chemistry instruction at a college level and developing comprehensive laboratories to better train chemistry majors. Dr. Weizman hopes to use this flow system to advance these interests. By developing a chemistry flow system which is cost-effective, it will be more accessible to undergraduate laboratories. Although many universities are capable of securing high-end equipment for their laboratories, this equipment is often restricted for use by graduate students and professors. Therefore, undergraduates miss out on valuable learning opportunities due to the limited availability of high-end equipment, and due to the restrictions placed on its usage out of caution so that untrained students do not damage the costly equipment. However, with the introduction of low-cost flow systems, it will be easier for labs to acquire multiple systems for undergraduate students to use. Additionally, if an untrained student were to break the system, each component is low-cost, so that no major financial burden would be induced on the university or the student.

Dr. Weizman has also emphasized the importance of creating a flow system which is user-friendly to improve chemistry instruction. With chemistry being an already difficult major, Dr. Weizman wants to introduce no further obstacles in the path of student's completion of their education. The Croatt Research Group's system, as well as many other DIY flow systems, require users to input commands to the Arduino Serial Monitor. This may be out of the comfort range of many undergraduate chemistry students and add a level of complexity which may deter them from future chemistry labs. By creating a simple, aesthetic, and straightforward user interface, Dr. Weizman aims to remove any difficulties or mental blocks associated with the Arduino Serial Monitor chemistry flow system. With a pleasing and intuitive GUI design, students will hopefully be inspired to pursue chemistry as their major and future career path.

Review of Existing Design Solutions

Other researchers and professionals have likewise recognised the need for a cost-effective alternative to the costly commercially available flow systems. Therefore, various low-cost, DIY flow chemistry systems have been developed.

Croatt Research Group

The Croatt Research Group at UNC, Greensboro has developed a DIY flow system which is open access and can be manufactured using only a 3D printer and parts found on Amazon. This system costs around $150 total - roughly a 100th of the cost of commercial systems which can cost up to $20,000 for a high end system. The system consists of a syringe pump actuated by a stepper motor which is controlled with an Arduino. Commands must be sent to the Arduino through the Arduino Serial Monitor on a laptop or desktop computer. Figure 5 displays a model of the Croatt Research Group's syringe pump [2].

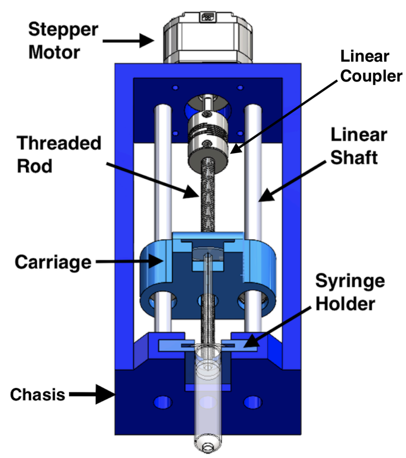


Figure 5. CAD model of Croatt Research Group's flow chemistry system.

The Croatt Research Group's system functions as a basic flow system, however, the overall user-friendliness of the system leaves something to be desired. A computer must be connected to the Arduino in order to control the system. Space is highly limited in many laboratories, so having a laptop connected to the system may pose an inconvenience. Additionally, this requires the user to bring a personal computer into the lab, unless a computer has been designated for use with the flow system. Either of these options may be undesirable as the first requires the user to use their personal possessions in the laboratory, and the second dramatically increases the cost of the system. Furthermore, it would be best to avoid having an expensive laptop in close proximity to the chemical workspace in the event of a spill on the workspace. Therefore, a stand-alone syringe pump system is more desirable in a lab environment.

An additional concern with the Croatt Research Group' system is the high learning curve associated with commanding the system. The user must input commands to the Arduino Serial Monitor. These commands consist of strings of numbers which require specific syntax in order to be properly read by the Arduino. Considering that chemistry students may likely have limited experience with coding, these commands may be daunting and deter students from using the system.

Furthermore, the Croatt Research Group's system offers little in terms of wire management. As can be seen in Figure 6, many wires are needed to connect the components of the system, resulting in a large nest of wires. Having exposed and mismanaged wires is inconvenient and unsafe to have in a chemistry laboratory.

Another issue with the system is that the steel threaded rod experiences corrosion after being left in the fume hood where reactions take place. This corrosion builds on the threaded rod and adds a significant amount of friction associated with the movement of the carriage. This negatively impacts the accuracy of the output flow rate.

Finally, the syringe holder within the chassis is specific to the size of syringe being used. There are separate syringe holders for syringes of size 1,3,5, and 10 mL. The syringe holder must be replaced when switching between syringe sizes. This is inefficient in terms of 3D printing filament used and time spent printing.

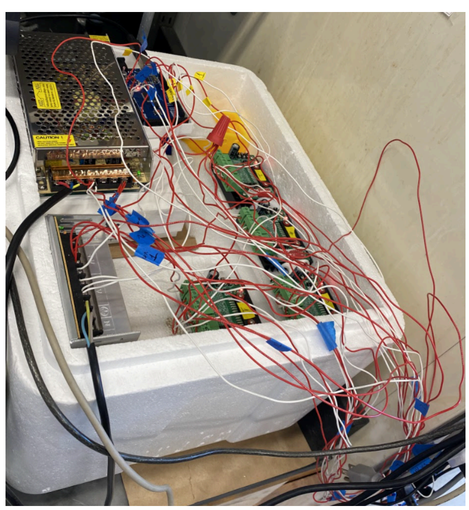


Figure 6. Arduinos and power supplies used to run four flow systems simultaneously [3].

Dr. D-Flo

A second cost-effective solution to flow chemistry was created by engineer David Florian and published on his website Dr. D-Flo [4]. This system is similarly open access, and can be created with a 3D printer and parts ordered from McMaster-Carr and Amazon for a total cost of $200. Also operated with a stepper motor and Arduino, the main difference between this system and the Croatt Research Group's is the use of an aluminum rail as opposed to a fully 3D printed chassis. It also does not account for the tubing and the refilling mechanism. Figure 7 displays David Florian's syringe pump design as manufactured by the Burkart Laboratory, UCSD.

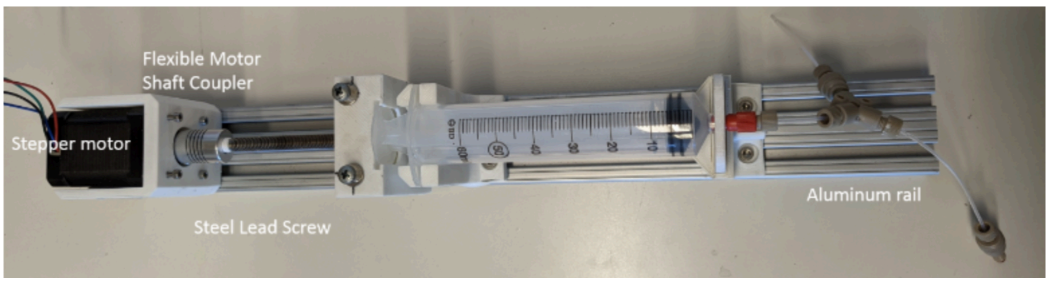


Figure 7. David Florian's syringe pump design.

This design presents the same issues as the Croatt Research Group's in terms of non-intuitive user-input commands, limited wire management solutions, and corrosion of the steel lead screw. Syringes of sizes ranging from 15 to 50 mL can be used with this system. However, changing the size of the syringe also requires modifying the 3D printed syringe holders.

PHD ULTRA™

A much more expensive syringe pump system that was found during the research process is the Standard Infusion Only PHD ULTRA™ Syringe Pumps. The cost of these systems ranges from $2,500 to $5,000 – five times the cost of the Croatt Research Group's System. This system uses a mechanical driving mechanism that resembles the Croatt Group's mechanism. It features a lead screw that, when rotated by a stepper motor, pushes a carriage which pushes the plunger of a syringe. This system also includes two low-friction guiding linear shafts for the carriage and a modular syringe holder design.

Figure 8. Standard Infusion Only PHD ULTRA™ Syringe Pump

Statement of Requirements and Deliverables

The objectives outlined by the sponsor of the project are as follows:

High Priority Objectives:

1. Implement an intuitive user-interface to control the system.
2. Design a modular syringe pump that can fit various sizes of syringes (1,3,5,10 mL).
3. Enhance resistance to corrosion of threaded rod.

Second Priority Objectives:

4. Provide an alternative design for refilling the syringe that doesn't rely on expensive check valves.

WOW Design Solution:

5. A system that can detect leaks and shut down the system when they occur.

Deliverables

1. Flow Chemistry System
    a. Two complete syringe pumps, including syringe holder and refill mechanism.
    b. GUI.
    c. GUI Holder.
    d. Electronics Containment Box.
2. Documentation
    a. User Manual

b. Manufacturing procedures
c. Instructional Videos
d. Code files
e. CAD (Computer Aided Design) and STL files
f. Bill of Materials

Chapter 2: Description of Final Solution

Functional Requirements

The chemistry flow system must have the following functional requirements:

- Conduct reactions in a continuous flow stream.
- Automatically refill syringes.
- Be completely controlled by the user interface.
- Control four syringe pumps simultaneously.
- Accurately dispense chemicals for flow rates from 0.5 to 8 mL/min.
- Match flow rates/stoichiometric ratios across all pumps.
- Accommodate syringe sizes of 1, 3, 5, and 10 mL.
- Be able to run for multiple hours at a time.

Design Solution

The final design solution is based on the Croatt Research Group's syringe pump design, with various additions and modifications made to enhance the usability and functionality of the system [2]. The improved system consists of up to four syringe pumps, a refill mechanism for each syringe pump, a GUI, electronics and associated coding, and an electronics containment box. When the system is in use, the GUI sends commands to the Arduino, which in turn controls the motors and functionality of the syringe pump. As the syringe pump is operating, the refill mechanism ensures that the flow of chemicals is in a singular direction. The electronics box provides water resistant packaging for the electronics. Figure 10. displays the final design solution for the improved flow system.

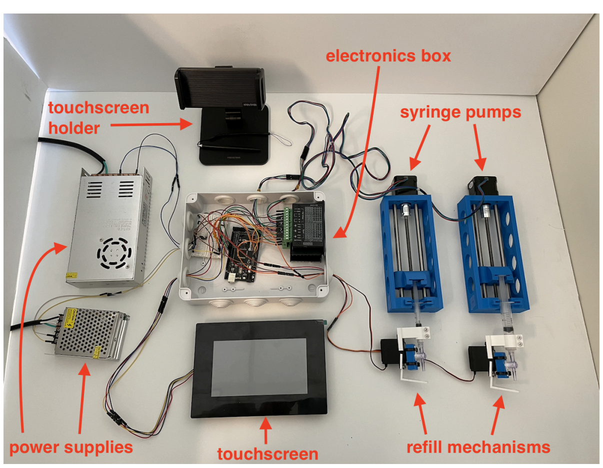


Figure 9. Disassembled Final System

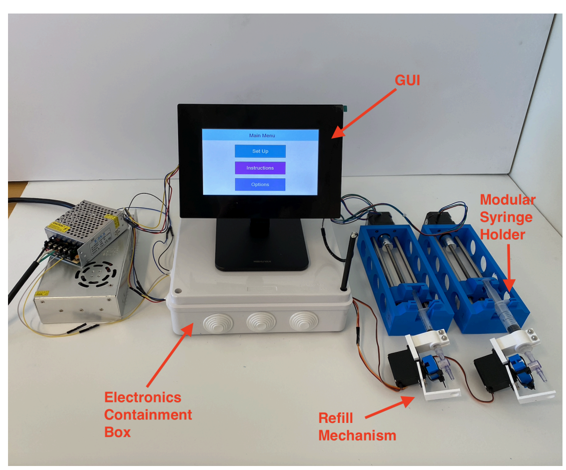


Figure 10. Assembled Final System

Syringe Pump

The syringe pump's main purpose is to retract and depress the plunger of the syringe so chemicals are drawn into and expelled from the syringe, respectively. The design of the syringe pump was heavily inspired by the Croatt Research Group's system due to its proven efficacy and simplicity of design. The Croatt Research Group's syringe pump consists of a 3D printed chassis, carriage, and syringe holder, as well as two linear rods, a threaded rod, a linear coupler, and a Nema 17 Stepper motor, as can be seen in Figure 11. The stepper motor is mounted on the back of the chassis and rotates the threaded rod as it turns. The stepper motor we used is a Hybrid stepper motor that provides a high torque. This torque enables the optimal rotation of the lead screw and assists in a smoother functioning of the syringe. A nut embedded in the carriage translates the rotational motion of the threaded rod into linear motion of the carriage. This motion is guided by the parallel linear rods. The flange of the syringe is held stationary in the syringe holder while the plunger of the syringe is held in a slot on the carriage. Advancement or retraction of the carriage results in motion of the plunger with respect to the syringe barrel so that chemicals are drawn into or expelled from the plunger. Figure 12 depicts the motion of the syringe pump.

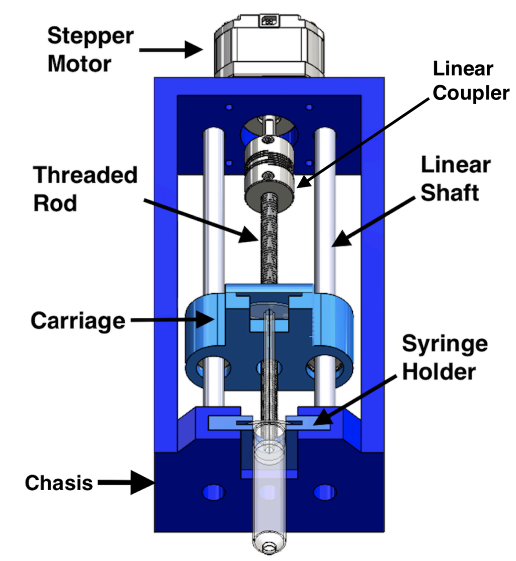


Figure 11. Croatt Research Group's Syringe Pump CAD

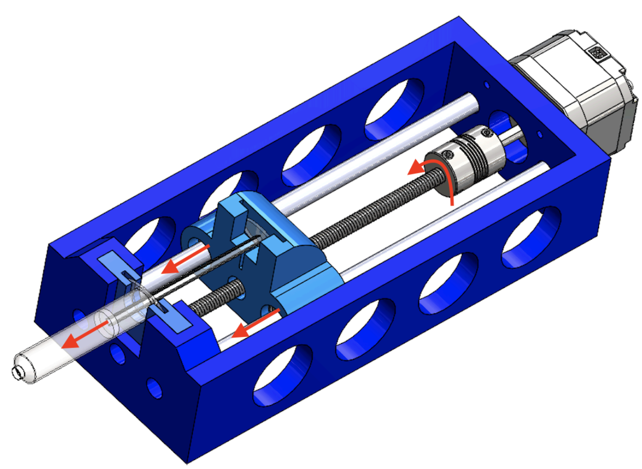


Figure 12. Syringe Pump Motion

In the final design, the main components and functionality of the syringe pump were left unchanged. However, modifications were made to increase convenience of use and corrosion resistance. These modifications include a modular syringe holder and carriage, as well as stainless steel hardware in place of steel. The final syringe pump design can be seen in Figure 13.

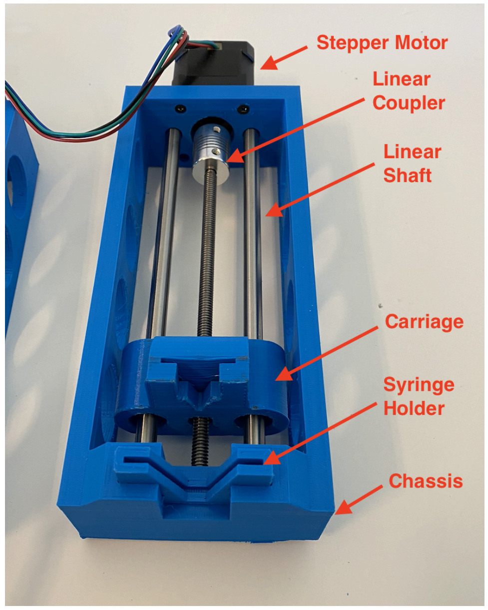


Figure 13. Final Design Syringe Pump

Refill Mechanism

The second major component of the flow system is the refill mechanism. This mechanism allows the syringe to be filled and dispensed autonomously and for the system to be run continuously. The Croatt Group's system does not have a refill mechanism and therefore requires the chemist to fill the syringe by hand. The refill mechanism eliminates the need for the user to handle the syringe when it has been filled with chemicals, and therefore greatly enhances the overall safety of the system.

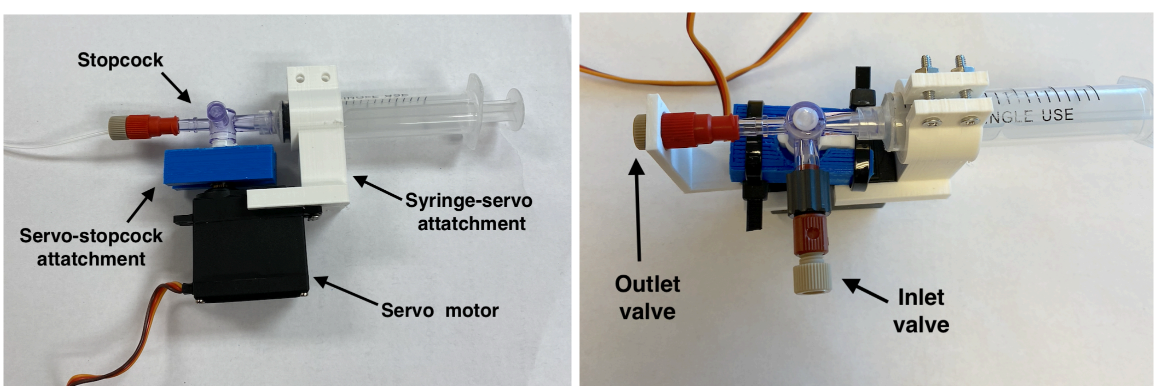


Figure 14. Servo motor-Syringe-Stopcock Connection.

The main components of this mechanism include a servo motor, three-way stopcock, and 3D printed components to attach the components and stabilize them with respect to the syringe as can be seen in Figure 14. The three-way stopcock is controlled by the servo motor. With the servo motor in its zero position, the stopcock is oriented such that the channel between the inlet and syringe is open. This allows for chemicals to be drawn in from the supply reservoir and for the syringe to be filled as can be seen in Figure 15. When the servo motor is rotated to be in a position 90 degrees from its zero position, the valve on the stopcock is rotated such that the channel between the syringe and the tubing exiting the reaction is open. In this position chemicals are expelled from the syringe as can be seen in Figure 16.

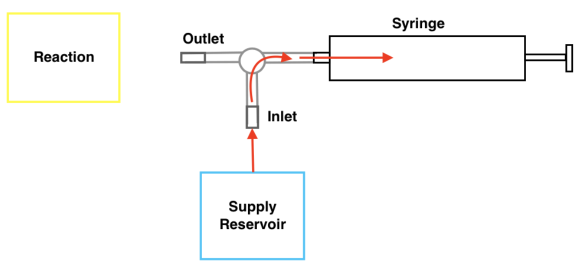


Figure 15. Refill Mechanism Filling Syringe

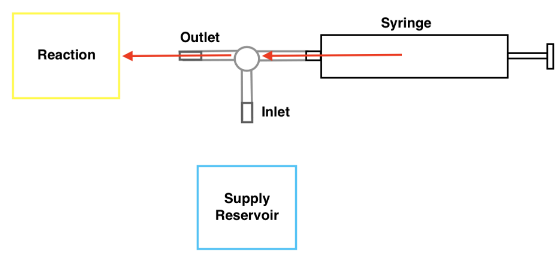


Figure 16. Refill Mechanism Dispensing from Syringe

The rotation of the servo motor is dictated by the direction set by the user. If the user indicates they wish to dispense chemicals from the syringe, the servo motor will rotate such that the stopcock is in the correct position to dispense. If the user indicates they wish to perform a cycle in which the syringe must fill and dispense multiple times, the servo motor will automatically change its position to coincide with the direction of travel of the syringe plunger.

The design of this refill mechanism was adapted from the Burkart Laboratory's flow system. While it was largely left unchanged, minor alterations such as heat set inserts and screw holes to increase the convenience of assembly were added.

Graphical User Interface (GUI)

The third major component is the GUI which controls all the syringe pumps. The user interface refers to both the hardware that displays the graphics and the software for designing the GUI. The key functionality of the GUI is that it has an intuitive layout where the user can easily set up one or more syringe pumps to perform flow chemistry experiments. The hardware selected for our user interface is the Nextion 7” Intelligent Series touchscreen display, as seen in Figure 17, because it includes easily programmable software for graphical user interface design and is compatible with Arduino. The Nextion Editor software used to create the GUI design is seen in Figure 18.

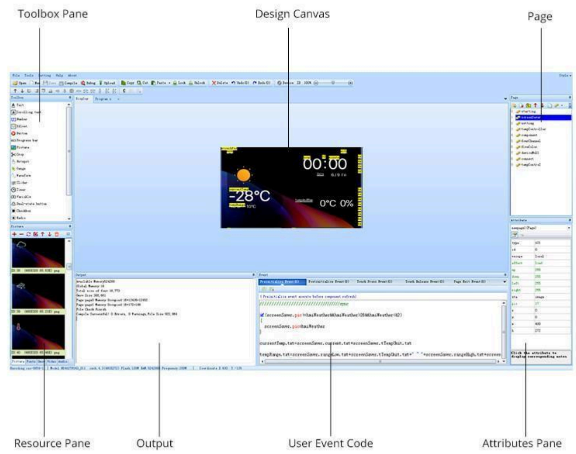


Figure 17. Nextion Intellegrent Series 7” Display

Figure 18. Nextion Editor Software

In order to control the syringe pumps, the GUI receives and collects user input. This user input includes mode of operation, syringe pump parameters, and desired flow rates as can be seen in Figure 19 and 20. There are five modes of operation that are programmed for the system. The first is the cycle mode. In this mode, a large target volume is selected for dispensing. If the target volume is too large for the syringe pump to completely pump out in one cycle, the syringe pump will continue to dispense and withdraw liquid until the total volume desired is met. The next mode is Continuous which is a time-based mode where the system would dispense and withdraw until paused. The Dispense only and the Withdraw only modes are used to dispense or withdraw particular volumes respectively. The maximum volume that can be dispensed and withdrawn depends on the current volume and maximum volume of the syringe. The Withdraw + Dispense mode allows the user to set the exact volume to withdraw and the exact volume to dispense after withdrawing. For each parameter that needs to be inputted, the user simply selects a text box in which they wish to input a parameter and types the desired value using the onscreen keypad.

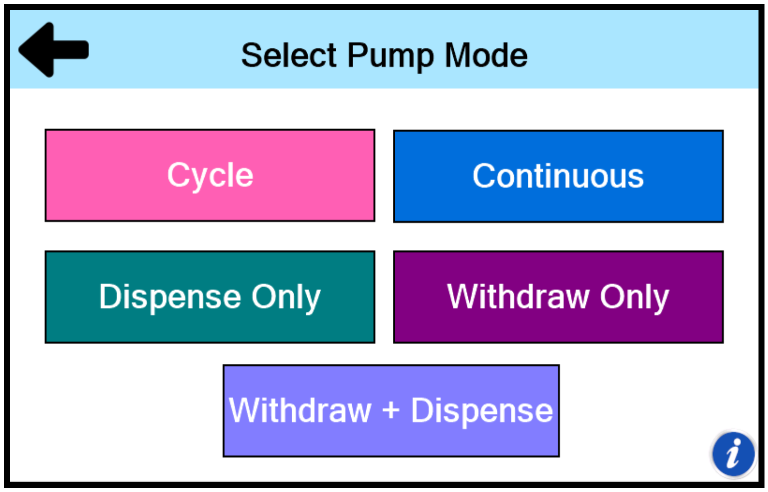


Figure 19. The *Select Pump Mode* page of the user interface.

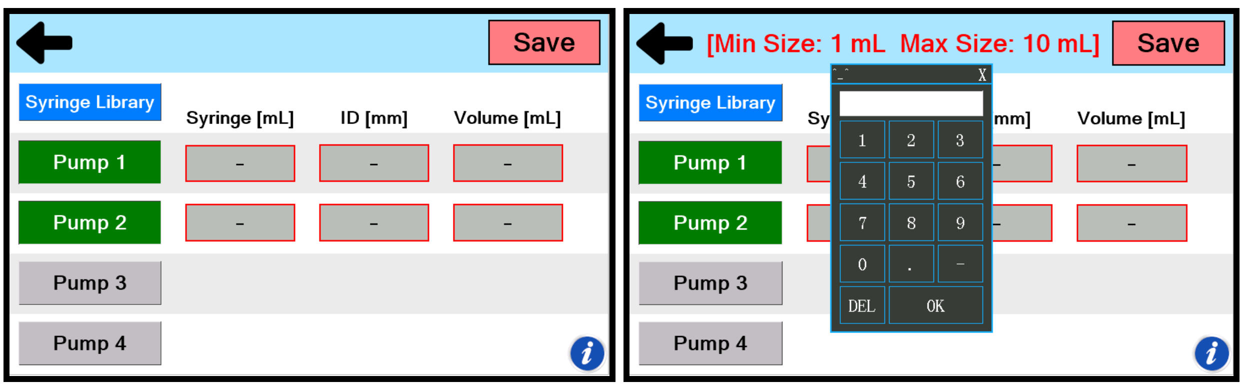


Figure 20. The *Syringe Parameters* page of the user interface.

Once the pump parameters are defined by the user, the pumps are able to be run using the user interface as well as be paused or resumed during the entirety of the operation. Its volume output progress is continuously tracked on the *Run Status* page of the display which can be seen in Figure 21. In order for this to occur, the Nextion display communicates with the Arduino. This communication entails sending data from the Nextion display to the Arduino Serial Monitor to set the syringe pump parameters and to start the operation. Data is also able to be sent from Arduino to the Nextion display in order to track the progress of the syringe pump. The Arduino Mega 2560 microcontroller board is used to control the syringe pump system directly and is a major element of the design solution, as described in the following section.

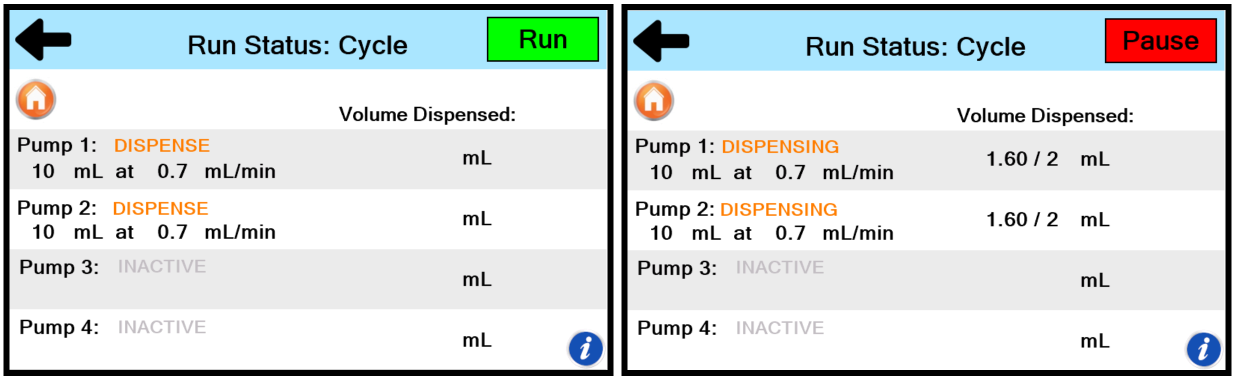


Figure 21. The *Run Status: Cycle* page of the user interface.

Electronics and Code

The electronics control the mechanical components of the system and are therefore essential to its functionality as a whole. The electronics feature an Arduino Mega 2560 along with one motor driver for every stepper motor in the system. Other electronics include the servo motors in the refill mechanism and the power supplies (5V and 12V) used to power the system.

The Arduino Mega 2560 provides the main means of control for the system and as such, the code to control the system was written using the Arduino software. The only external library used in the program is the AccelStepper library. Arduino program controls the stepper motors, and has the ability to control multiple stepper motors simultaneously. Serial communication is used for communication between the Arduino and Nextion touch screen. A schematic of the electronics wiring for the entire system can be seen in Figure 22.

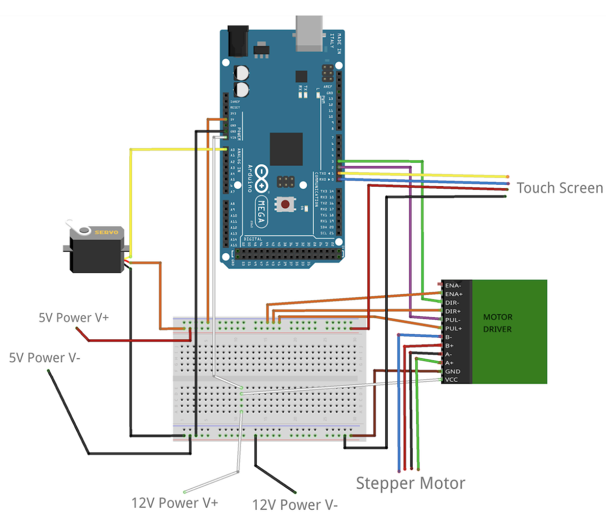


Figure 22. Electronics Schematic.

Electronics Box
The electronics box is necessary to contain the wires and electronics. The box selected creates a water resistant environment, which adds to the durability and safety of the overall design. Contained in the box are the Arduino, breadboard, and motor drivers. The power supplies are not currently kept inside the box due to heat generation concerns. The purchased electronics box as well as the internal electronics are seen in Figure 23 and 24, respectively.

Figure 23. Purchased Electronics Box

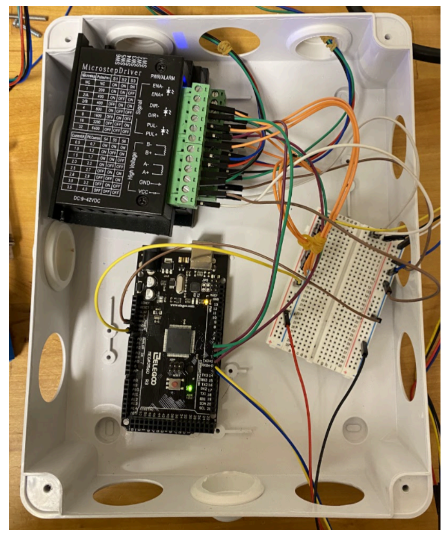


Figure 24. Internal Electronics

Performance Results

Upon completion and testing of the final design, various results regarding its performance were obtained. When operating below the maximum theoretical flow rates for each syringe size (as calculated in the Detailed Analysis section of the Appendix), the syringe pump exhibits under 10% error in the measured versus the desired flow rate. When operated above the maximum flow rate, this error grows. In terms of maintaining stoichiometric ratios between different syringe pumps, the system dispensed ratios with less than 6% error when compared to the desired output ratio. Furthermore, the system can run for multiple hours at a time without exhibiting any issues.

Additionally, the GUI in conjunction with the Arduino code controls the system as directed by the user and the automatic refill mechanism operates in sync with the syringe pump.

Chapter 3 : Design of Key Components

Major components:

- Syringe Pump
  - Modular Syringe Holder and Carriage
  - Corrosion Resistant Hardware
- Automatic Refill mechanism
- Graphical User Interface (GUI)
- Electronics
- Electronics Box

Syringe Pump

The syringe pump was modified based on the Croatt Research Group's original design. The three main components in need of modification were the syringe holder, the material of the hardware, and the lead screw mechanism.

Modular Syringe Holder

The modular syringe holder is one of the high priority objectives in the project proposal. The syringe holder is intended to be capable of holding syringes of 1, 3, 5 and 10 mL capacity without any alterations being made to the system. The Croatt Research Group's design required a different syringe holder for each syringe size. This was inefficient in terms of both material used and time spent setting up the system. Therefore, our sponsor is seeking a modular syringe holder which is compatible with all syringes ranging from 1mL to 10 mL.

Functional Requirements

The syringe holder must:

- Securely hold syringes of 1, 3, 5 and 10 mL capacity.

Comparison of Designs Considered

Designs Considered	Pros	Cons
V-shape with knob	• Provides vertical resistance which adds safety • Easy to assemble, minimal components	• Additional hardware • Increased cost • Additional manufacturing steps • Possibility of overtightening the knob leading to inaccurate volume/fracturing the

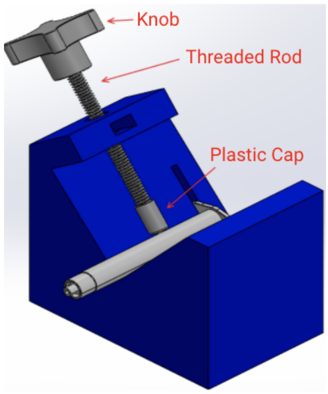
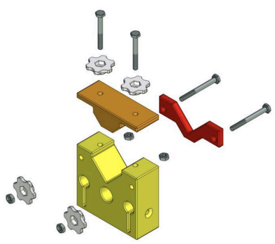
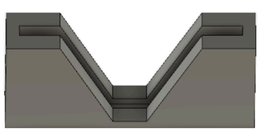
		barrel of the syringe ● No mechanism to prevent loosening of screw.
Mass Spectrometry Research Group, Open Source Syringe Pump [4] 	● Equal force applied along top of syringe	● Additional hardware ● Increased cost ● Additional manufacturing steps ● Possibility of overtightening the knob leading to inaccurate volume/fracturing the barrel of the syringe
3D printed v-shape 	● No additional hardware ● No additional assembly or manufacturing steps	● No additional securing mechanism ● Clamping force depends on the specific syringe dimensions which vary depending on syringe size and model ● Requires modular carriage design

Table 1. Comparison of Syringe Holder Design Considerations

Justification of Final Design Choice

The 3D printed v-shape design was selected as the final design for the syringe holder. This design has a number of advantages over the previous two designs, such as no additional hardware being needed. This decreases cost, complexity, and potential manufacturing errors. Another advantage of this design is its simplicity. With no additional manufacturing steps required, the assembly time and potential for manufacturing errors is significantly decreased. Additionally, the syringe holder can be inserted into the original chassis so that no extra filament or components are needed to create the design. Figure 25. displays the many syringe holders needed for the Croatt Group's system versus the single syringe holder needed in the improved flow system shown in Figure 26.

Figure 25. Croatt Research Group's Syringe Pumps

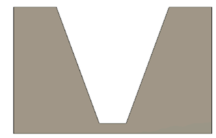


Figure 26. Final Syringe Pump

One notable feature of this design is that it allows syringes to sit at different heights within the holder. Syringes of smaller diameter will rest closer to the crux of the v-shape whereas the larger diameter syringes will be supported closer to the top of the v. In order to accommodate for the variance in height of each different syringe size, the carriage must also allow the syringe plunger to sit at different heights so that the syringe remains horizontal. The Croat Group's design included a single rectangular slot which didn't allow for the plungers to sit low enough to match the height that the smaller diameter syringes sit in the syringe holder as seen in Figure 27. Therefore, a simple modification to the carriage was made by adding a v-shaped cutout as can be seen in Figure 28. Similar to the syringe holder, this triangular geometry allows for the syringe to sit at varying heights depending on the syringe's diameter.

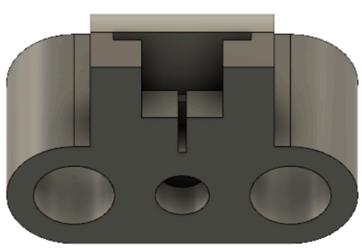


Figure 27. Croatt Research Group's Carriage

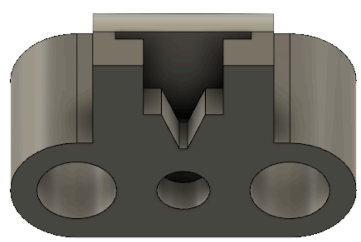
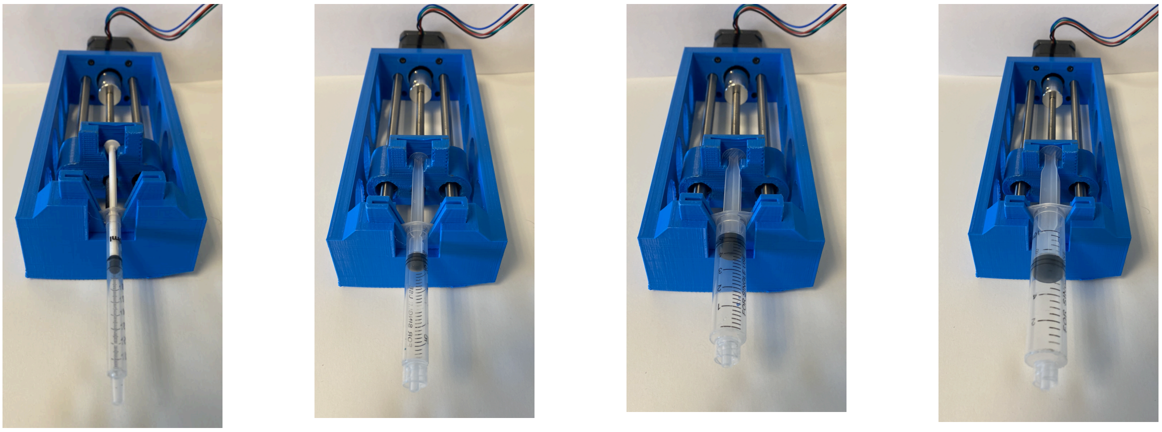


Figure 28. Modular Carriage

Figure 29. shows the successful implementation of the modular syringe holder and carriage. Syringes from 1-10mL can be held securely in the modular syringe holder and carriage combination.



1mL 3mL 5mL 10mL

Figure 29. Modular Syringe Holder and Chassis with 1-10mL syringes.

An additional feature of this design worth noting is the slot which holds the flange of the syringe. The flange of the syringe is meant to slide snugly within this slot to provide the most stability in the system. However, there is no universal standard for syringe dimensions, so syringes purchased from different manufacturers may fit more loosely or snugly within the slot. To account for this, modifiable CAD files have been added to the documentation of this project, and simple instructions have been provided for how to modify this file to best fit any syringe size. While this may appear to be a non-modular solution, it will only take a single modification to adjust for the type of syringe used by a particular lab. Once this modification has been made, the syringe holder will be able to accommodate syringes of varying size from that syringe brand.

It may also be noted that when the syringe holder is 3D printed laying down on its side as seen in Figure 30, post-processing is required to remove the remaining support materials from the interior slot. This was done using tools on hand such as pliers and a small screwdriver to scrape out remaining unwanted filament. Tweezers may also be useful for this task. However, the need for post processing can be eliminated if the syringe holder is printed upright rather than laying on its side as seen in Figure 31. With this print orientation, it is advisable to use a larger base layer so the syringe holder remains stable as it is being printed.

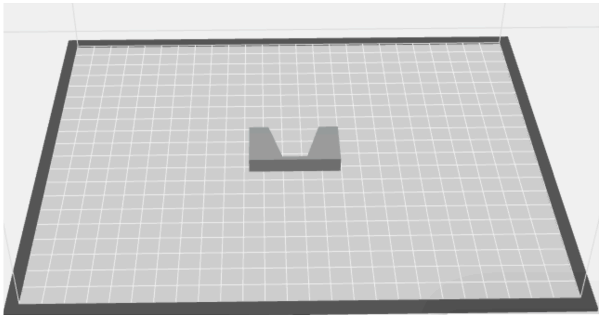


Figure 30. Side print orientation

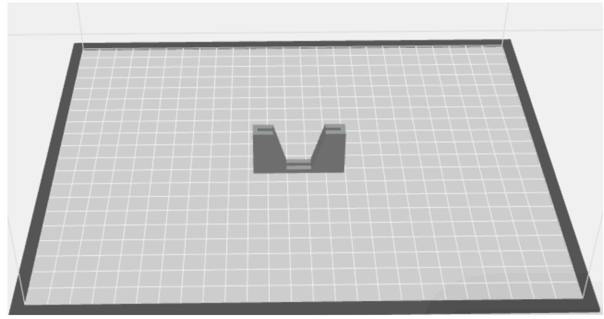


Figure 31. Upright print orientation

Corrosion Resistant Hardware

It is important to the functionality of the system that the hardware in the syringe pump be corrosion resistant. This requirement is specific to the hardware of the syringe pump because the pump is kept within the fume hood, while the other components in the system are kept outside the hood. Because the pump is in the fume hood, it is exposed to the gasses created as byproducts of reactions and any potential chemical spills or leaks within the fume hood. One particularly corrosive gas present in many chemical reactions is ozone. In the Croatt Research Group's and Burkart Lab's designs, the threaded rod, made from steel, experienced corrosion when it was exposed to the gasses within the fume hood. The threaded rod is essential to the motion of the carriage and the accuracy of the flow rate. It is therefore important that this component be corrosion resistant.

Functional Requirements

The hardware in the syringe pump must:

- Be corrosion resistant to common chemicals and gasses, particularly ozone.

Comparison of Designs Considered

Designs Considered	Pros	Cons	Cost
Stainless Steel 316	• Excellent resistance to chemicals, salt water, and ozone. • Easily accessible.	• May be slightly magnetic. • 4x the cost of medium strength steel.	1/4"-20: $8.03 / 3ft
Dry Moly Lubricant	• Corrosion resistant. • Decreased friction. • Resistant to dirt	• Requires reapplication.	$10.42/16 oz can

	and dust build up. • Requires less frequent application than other protective lubricants.		
Chemical Resistant PVC	• Satisfactory resistance to acids, alkalines, salt solutions, alcohol, ozone, and others. • Nonconductive and nonmagnetic.	• 7x the cost of medium strength steel. • Decreased strength may require an increased diameter, which increases the cost.	1/4"-20: $14.48 / 3 ft 5/16"-18: $16.20 / 3 ft 3/8"-16: $20.70 / 3 ft 1/2"-13: $24.42 / 3 ft

Table 2. Comparison of corrosion resistant hardware considerations

Justification of Final Choice

The final design decided upon was using a stainless steel threaded rod. This option is expected to provide the most corrosion resistance, especially when faced with ozone gas. Additionally, although the price is four times that of the steel threaded rod, it is comparable to the other options presented here. It also does not require further alterations to the system since it can be purchased with the same dimensions and threads per inch as the steel threaded rod in the Croatt Group's original design.

Graphical User Interface (GUI)

An important aspect of this system is having a suitable user interface that is easy to understand and use. The system is to be used by students and others looking to get into chemistry, and this audience might not have much experience handling electronics and programming. As such, it is essential to have an interface that can be operated by any inexperienced user.

Initially, there were a variety of different options that could be used for this interface. The existing design from the Croatt Research group utilized a bluetooth app as a way to control the syringe pump. While this is a valid solution, it requires an Android phone and users may be resistant to the idea of having an app for work or school installed on their personal devices. One could buy a low-cost Android phone specifically for the purpose of this system, but even the lowest prices range around $100. In addition, the app that the Croatt Research group developed was unavailable, so any app would have to be fabricated from scratch.

Another possibility was having an LCD screen with a physical control panel of knobs and sliders that can be used to adjust the settings of the syringe pump system. While it is feasible, a touchscreen interface is generally easier to work with and integrate into the system. The touchscreen greatly reduces the amount of wiring needed because it only requires a single cable connection, versus the multitude of connections needed to implement in a physical control panel. In addition, LCD displays generally come in smaller sizes, so to display all the wanted data, multiple screens or one large screen would be necessary. Though, with a larger screen, it is not much of a leap to simply go with a touchscreen LCD display, and any additional settings and options can be developed for the touchscreen device. Any such updates and changes to the UI to improve the function of the system would just need to be downloaded onto the device. With the non-touchscreen display and the control panel, more physical buttons and such would need to be bought and integrated into the control panel for any additional changes and options. In the end, under the guidance of this project's sponsor, a touchscreen device was chosen to be the user interface as it is very adaptable and is easy to use.

Functional Requirements

The user interface must be able to:

- Send commands to the microcontroller in order to control the servo and stepper motors.
- Receive data regarding the current position of the stepper motors from the microcontroller.
- Be operated when wearing a glove or with a stylus.
- Be big enough to display/read in all necessary parameters

Comparison of Designs Considered

	Nextion 7" Intelligent Display	Adafruit Touchscreen	Touchscreen with Arduino shield
Screen Dimensions	6" x 3.4"	4.7" x 3"	7" x 4"
Screen Type	Resistive	Resistive	Resistive
GUI Design Software	Nextion Editor	None, code from Arduino	None, code from Arduino
Cost	$90	$40	$70

Table 3. Comparison of GUI Design Considerations

Justification of Final Choice

The Nextion Intelligent HMI Display touchscreen was selected as the user interface in the final design. The Nextion touch screen has a lower learning curve when compared to other user interface software design due to its free Nextion Editor Software which features drag-and-drop components. This allows the user to visually create the GUI with minimal coding required for basic functionality. Additionally, the touchscreen is resistive as opposed to capacitive. Capacitive touchscreens rely on the conductive properties of the human body. These screens require the user to use their bare fingertips when using the touchscreen, which can be quite dangerous in a lab full of chemicals. Resistive touchscreens respond to any kind of pressure applied to the surface, so they can be operated by gloved hands or a stylus.

The Nextion touch screen is a bit more expensive than the other options considered, however, it includes software that allows developers to easily design a GUI by dragging in components such as buttons and sliders. ‘Touch events,’ i.e. what happens when a button is pressed by the user, can be coded in the software with simple commands and the Nextion can output data via serial communication, perfect for communicating with the Arduino. This saves a lot of time for developing the GUI as elements do not need to be coded in by hand.

Figure 32. Nextion Intelligent Series 7” touchscreen display with enclosure

Software and Programming

As mentioned above, the Nextion Editor Software allows buttons and text to be programmed according to one’s needs. It can also print information over Serial to a microcontroller. Essentially, this is the method of communication between the touch screen and Arduino. The two hardware components have their TX and RX pins connected (using jumper cables) to receive information from each other. Once the data is done printing over to the Arduino, it is just a simple matter of processing the string and changing the parameters of the system accordingly. This software provides a significant advantage as opposed to designing the user interface from scratch, and was therefore a key factor in the decision of the user interface selection.

Microcontroller

The Arduino Mega 2560 was chosen as the microcontroller to be used in the design. This particular Arduino meets all of the functional requirements listed below, and has a number of other positive attributes to be described below.

Functional Requirements

The microcontroller must have:

- Eight digital pins (two for each motor driver).
- Four analog pins (one for each servo motor).
- A TX pin and RX pin for serial communication.
- One 5V pin and one GND pin.
- Ability to connect to power supply or wall outlet or a Vin pin
- Ability to receive commands from the GUI over Serial and receive position data from the motor (from the AccelStepper Library).
- Sufficient memory to store the program

Comparison of Designs Considered

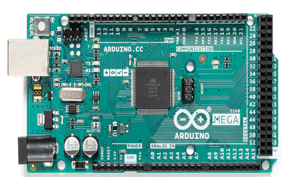
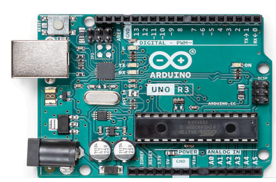
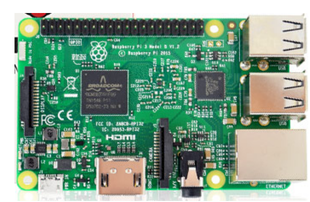
	Arduino Mega 2560 	Arduino Uno Rev3 	Raspberry Pi 3 Model B 
Operating Voltage	5V	5V	5V
Input Voltage (recommended)	7-12V	7-12V	4.75-5.25V
Input Voltage (limit)	6-20V	6-20V	4.75-5.25V
Digital I/O pins	54	14	26
Analog Input pins	16	6	14
Cost	$23	$23	$35

Table 4. Comparison of Microcontroller Design Considerations

Justification of Final Design Choice

The Arduino Mega 2560 was ultimately selected to be used in the final design. The choice of microcontroller was first narrowed down to an Arduino due to its compatibility with the code provided by both the Croatt Research Group as well as the Burkart Laboratory. The code used by these two groups requires the external AccelStepper library. This library has many useful built-in functions that work well with the system. The main functions used from this library are the functions that can receive the current motor position (counts), set the current motor position (counts), set the speed of the motor (in microsteps per second), run the motor at the set speed by telling it when to step. Naturally, with all of this available functionality, it would only make sense to continue with an Arduino as the microcontroller. Specifically, the Arduino Mega 2560 was selected because it has an abundant amount of memory and a greater number of digital I/O pins which will allow for additional syringe pumps to be added to the system if desired. However, any Arduino model with a sufficient amount of pins will suffice for this system.

Additionally, Arduino is an open-source hardware and software company. Arduino products are cost effective and may be interfaced to various other circuits and breadboards. Arduino is one of the most commonly used brands of microcontroller and can be purchased from a number of suppliers for low prices. Furthermore, no soldering is required to connect to the Arduino board. For a DIY system such as this one, this was considered to be a positive attribute because it makes it much easier for an inexperienced user to connect the electronics in the system by just plugging in jumper wires. Therefore, after comparing various Arduino and Raspberry Pi microcontrollers, the Arduino Mega 2560 was selected due to its compatibility and larger number of pins which will allow for any future additions to the system.

Electronics Containment Box

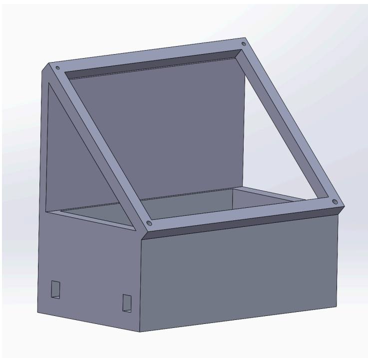
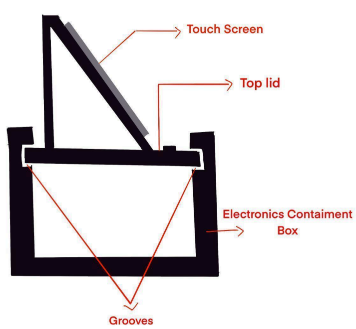
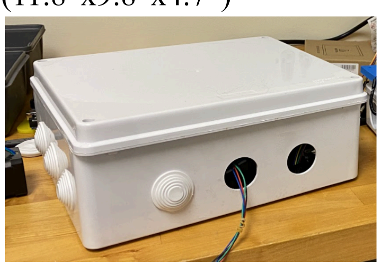
The electronics containment box is intended to house all of the electrical components excluding the power supplies. The mounting of the user interface was also considered in the design and selection of the electronics box.

Functional Requirements

The electronics containment box must:

- Fits four motor drivers, one Arduino Mega 2560, and one breadboard.
- Provide sufficient space for wiring so the flexibility of the wires is not exceeded.
- Provide easy access to all connections and electrical components.
- Prevent overheating of the internal components and allow for natural cooling.

Comparison of Designs Considered

Designs Considered	**Pros**	**Cons**	**Print Time/Cost**
Single 3D printed box 	• Customizable for internal electronics layout and hole spacing • Incorporated user interface holder	• Difficult to reach wires • Difficulties with 3D printing • Does not fit on 3D printer bed • Unprotected power supply	• 20+ hours
Two part 3D printed box 	• Ability to access electrical components with ease • Customizable for internal electronics layout and hole spacing • Incorporated user interface holder	• Unprotected power supply	• 18 hours+
Extra Large Electrical Box (11.8”x9.8”x4.7”) 	• No printing time needed • No manufacturing errors need to be considered • Increased waterproofing and protection of interior electronics, including power supply	• Less customizable • Internal heat generation of power supply • Non-incorporated user interface holder	• $24
Large Electrical Box (10”x7.9”x3.1”)	• No printing time needed • No manufacturing errors need to be	• Less customizable • Unprotected power supply • Non-incorporated	• $21

	considered • Increased waterproofing and protection of interior electronics, excluding power supply	user interface holder	

Table 5. Comparison of Electronics Box Considerations

Justification of Final Choice

The final design considered was a purchased electronics case. The main benefit in selecting a purchased box is the amount of time saved printing. Additally, with print durations over 18 hours, it is possible for the print to warp or shift, in which case the entire print may need to be remade, wasting additional hours. By selecting a pre-manufactured electronics box, the manufacturing and post processing time is entirely eliminated. Furthermore, the purchased box is only marginally more expensive than it would have been to 3D print the electronics box, accounting for the cost of filament used. PLA filament rolls for the MakerBot Replicator (the printer used to manufacture the 3D printed components in this design) cost $50.00. The electronics box designs used roughly a third of the filament spool, making them cost approximately $16.00.

The smaller option of the two purchased electronics boxes was ultimately decided upon due to concerns with respect to heat generation of the power supplies. It is unsafe to keep heat generating components with other electronics. Therefore, the smaller box was selected because it provided sufficient space for the Arduino, breadboard, and motor controllers, yet not the power supplies as can be seen in Figure 33.

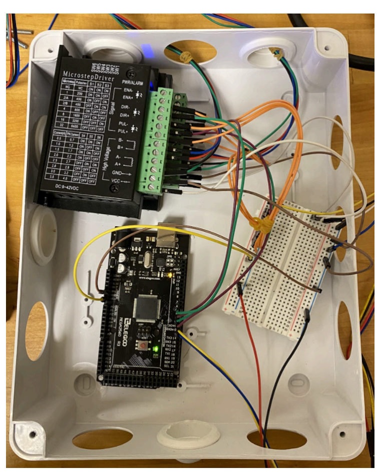


Figure 33. Internal Electronics Layout

User Interface Mounting Design

Earlier iterations of the electronics box included a user interface mount as well. However, as the decision was made to use a purchased electronics box as opposed to a 3D printed one, it was also decided that purchasing a stand was a better option to avoid any issues and delays with manufacturing. The stand selected is the Mibhuvan Tablet and Cell Phone Stand, which costs about $16. This stand securely holds the interface, allows the angle of the screen to be adjusted, and is compact. Figure 34. displays the user interface holder in use.

Figure 34. User Interface Holder

Chapter 4 : Prototype Performance

Theoretical Predictions

Theoretical predictions regarding the performance of the flow chemistry system were determined through experimentation as follows:

- The theoretical maximum pushing force that the motor is capable of producing was determined to be 593.3 N (or 133.3 lbf) and the analysis performed to get this value can be viewed in *Lead Screw Analysis* which is found in the appendix.
- The theoretical forces required to push syringes at a specific flow rate can be seen in the appendix under *Pushing Force Required Analysis*.
- The maximum flow rates that the syringe pump at which the syringe pump will be able to reliably operate for a variety of syringe sizes are listed in Table 6:

Syringe Size [mL]	Maximum Flow Rate [mL/min]	Step Resolution [μL/step]
1 mL	0.691	0.0057
3 mL	2.895	0.0241
5 mL	5.295	0.0440
10 mL	7.972	0.0663

Table 6: Maximum Flow Rates for given Syringe Sizes

- The calculations done to determine these flow rates can be found in the appendix under *Flow Rate Calculations*.

Test Conditions

Flow Rate Accuracy

The accuracy of the flow rate was determined for various syringe sizes and flow rates. The output flow rate in each setup was measured and compared with the commanded flow rate to determine a percent error between the expected and measured rates.

To measure the output flow rate, a scale and a stopwatch were used. For each experiment, the pump was set up with a specific syringe size and commanded to operate at a specific flow rate.

Once the ‘Run’ button was pushed, a stopwatch was started. All water dispensed from the syringe was collected. Once the syringe pump ceased running, the stopwatch was stopped and the collected water was weighed on a scale. The weight of the water was converted to mL according to the density of water ($1g_{H20} = 1mL_{H20}$). The flow rate was calculated by dividing the volume of water dispensed over the recorded time [mL/s].

The flow rates measured for each syringe size were scaled based on the maximum theoretical flow rate for the respective syringe size. An equally distributed range of rates up to the theoretical max were tested to assess the accuracy of the system when operating within recommended conditions. Each experiment was run five times in order to attain sufficient data. The data displayed in each table is the average of these five runs.

Maximum Flow Rate

The maximum flow rate that the syringe pump can operate at is determined by the maximum speed of the stepper motor. In order to verify the accuracy of the theoretical analysis performed, the syringe pump was commanded to operate above the theoretical maximum flow rate with respect to each syringe size. To verify whether these theoretical maximum flow rates were the maximum rates for which the system would remain accurate, the percent error of the flow rates above and below the theoretical maximum rate were compared. If the percent error increased significantly above the theoretical maximum rate, it was determined that this was in fact the maximum rate for which accurate flow rates can be expected.

Stoichiometric Ratios

The stoichiometric ratio refers to the ratio between the quantities of products being used in a chemical reaction. In the case of flow chemistry, this ratio is directly proportional to the ratio of the flow rates between the pumps (when using the same sized syringe in each pump). Therefore, in order to test how accurate the system was in maintaining the correct stoichiometric ratio, different flow rates were set on the pumps and the ratio between the two flow rates was calculated.

In the first experiment, a 1:1 ratio was used, so both pumps were set at a flow rate of 1mL/min. The ratio of the measured flow rates were calculated and compared with the theoretical 1:1 ratio. A similar procedure was followed for a 2:1 ratio, with one pump set to dispense at 2mL/min and the second set to dispense at 1mL/min.

Endurance

Over the course of all the other testing conditions, the pump was run nearly continuously for four hours, at various low and high speeds. There were no issues with the components overheating or otherwise malfunctioning in this extended period of time.

Results

Flow Rate Accuracy and Maximum Flow Rate

Commanded Flow Rate [mL/min]	Average Measured Flow Rate [mL/min]	Percent Error
0.5	0.515	3.03%
0.69*	0.711	3.07%
1	1.09	9.41%

Table 7. 1mL Syringe Flow Rate Testing
* maximum theoretical flow rate

Commanded Flow Rate [mL/min]	Average Measured Flow Rate [mL/min]	Percent Error
1	0.975	2.43%
2	2.120	6.00%
2.9*	2.688	7.32%
3	2.753	8.21%
4	3.451	13.73%

Table 8. 3mL Syringe Flow Rate Testing
* maximum theoretical flow rate

Commanded Flow Rate [mL/min]	Average Measured Flow Rate [mL/min]	Percent Error
1	0.988	1.13%
3	3.141	4.71%
5*	4.567	8.67%
7	6.375	8.92%

Table 9. 5mL Syringe Flow Rate Testing
* maximum theoretical flow rate

Commanded Flow Rate [mL/min]	Average Measured Flow Rate [mL/min]	Percent Error
1	0.910	9.04%
3	2.758	8.06%
5	4.460%	10.80%
8*	7.381	7.74%
10	8.834	11.66%
12	10.583	11.80%

Table 10. 10mL Syringe Flow Rate Testing
* maximum theoretical flow rate

Stoichiometric Ratios

Stoichiometric Ratio	Average Measured Ratio	Percent Error
1:1	1.05:1	5.67%
2:1	1.88:1	5.96%

Table 11. Stoichiometric Ratio Testing

Comparison of Results to Initial Performance Requirements

Qualitatively, the flow system meets its necessary functional requirements. It is able to expel chemicals at the desired flow rates, within an acceptable margin of error. Therefore, it is able to produce the chemical reaction that must take place. The modular syringe holder is capable of accomodating syringes of 1, 3, 5, and 10 mL. The automatic refill option is fully functional and allows the syringes to be repeatedly filled and dispensed without any intervention from the user. Additionally, the pumps can be controlled by the intuitive GUI. The system has the ability to run four syringe pumps simultaneously.

Quantitatively, the data obtained for the flow rate accuracy and maximum flow rate tests indicate useful trends. Firstly, it can be observed that smaller syringe sizes have higher accuracy. This may be useful to keep in mind when performing reactions which require high accuracy. Secondly, it can be observed that, in general, lower flow rates will lead to higher accuracy. This is due to the AccelStepper library having greater step resolution for the stepper motor at lower rates of rotation. Therefore, when operating at slower speeds, the flow rate will be the most accurate. While the error does increase with higher flow rates, it does not become a significant source of error until the maximum flow rate has been surpassed. The asterisks in the tables 7 through 10 indicate the maximum flow rate for each syringe size. For flow rates below this maximum flow rate, the percent error remains below 10%. Above this maximum flow rate, the percent error increases above 10% and therefore becomes a significant source of error. While commercial systems operate with high levels of accuracy, this is not necessary nor expected in this DIY system for use in undergraduate laboratories. Operating with an error less than 10% is acceptable for this system. Therefore, for flow rates below the theoretical maximum, the system maintains a suitable level of accuracy. It is recommended that the syringe pump be operated under the maximum flow rate in order to avoid inaccurate flow rates and overexertion of the stepper motors.

In terms of the stoichiometric ratios, the experiments resulted in errors of less than 6%. This is quite accurate considering the DIY nature of the system. This system will not be able to achieve the high precision which a $20,000 flow system can, yet it is suitable for undergraduate chemistry laboratories and general use.

It is of interest to note that these experiments were performed with two flow systems which were both manufactured with the same 3D printer (MakerBot Replicator 5th Gen). Therefore, these accuracy ranges unfortunately do not include the accuracy of systems manufactured with different printers. However, these measurements may provide a baseline to which flow rate deviations in other syringe pumps can be compared. Additionally, the accuracy of the flow rate will depend on the accuracy of the measurement of the inner diameter of the syringe. As can be seen in the *Flow Rate Calculations* section in the appendix, the inner diameter of the syringe is used in the calculation of the steps/mL value. This step/mL value essentially determines the rate at which the stepper motor rotates and therefore the flow rate extruded from the syringe.

Additional factors which may affect the accuracy of the system include both the physical components of the system and the coding used to control the pump. In terms of the physical components, a small gap between the carriage pusher block and the syringe plunger can lead to inaccuracies. This gap would result from the syringe not fitting tightly within the carriage. The code is written such that it assumes once the motor starts, the syringe plunger will be pushed or pulled at the first step the motor rotates. However, if there is a gap between the carriage and the plunger, then the motor will have to move a given amount of steps so that the carriage is contacting the syringe plunger and begin to push or pull the plunger. Therefore, the calculated volume dispensed will be inaccurate since it is assumed that the distance moved by the carriage is equal to the distance the syringe plunger travels. When the above tests were performed, it was ensured that the syringes fit tightly within the carriage in order to minimize these potential errors. Additionally, in order to prevent this error from occurring to those who make this system and operate it using a different brand of syringe, CAD files and simple modification instructions have been included in the user manual so that this issue can be fixed before it results in inaccurate flow rates.

Additionally, manufacturing errors may occur when inexperienced users assemble the system. These errors may introduce friction to the system in which case the output flow rate of the system would be lower than desired. It is therefore important to ensure that the carriage can slide easily along the linear rods and be rotated easily by hand when the stepper motors are disconnected from power.

Chapter 5 : Design Recommendations and Conclusions

Design Recommendations for the Future

Incorporate Real-time Flow Rate Sensing Capability

Due to the DIY nature of the project it is impossible to attain uniform results. Variations in the model of 3D printer used, 3D printing settings and conditions, tolerances of the hardware, as well as variations in the brand and model of syringes used all contribute to discrepancies between any two given systems. As such, the flow rate dispensed by each syringe pump may differ slightly from the programmed flow rate as well as from the other syringe pumps being used with the system. This is an issue due to the stoichiometric ratios not being maintained. Without proper stoichiometric ratios, reactions will not take place as intended and losses of supplies, time, and money may occur.

In order to avoid these discrepancies each syringe pump must be calibrated before usage. As the system currently stands, this calibration entails measuring the volume extruded from the syringe pump for a recorded amount of time, then manually calculating the flow rate from these results. Once the actual flow rate is known for a range of programmed flow rates, values can be entered to create equal flow between the syringe pumps to maintain proper stoichiometry.

This calibration process could be streamlined by implementing real-time flow rate sensing capabilities. By adding a flow-rate sensor to the output valve from each syringe pump and displaying the flow rates to the user interface, users would be able to see the flow rates in real-time. This would significantly reduce the effort required in the calibration process and make accurate, real-time adjustment of the flow rates possible.

Leak Detection System

Having the ability to detect any leaks was an objective for this project that unfortunately was not able to be met due to time constraints. This ability would be a safety precaution that would automatically shut down the system if any leaks were detected.

This device is currently not suitable for unsupervised use due to its lack of automated monitoring and emergency shut off controls. A chemist is needed to supervise the system in the case a blockage or leak in the system occurs. If such an issue occurs, the chemist supervising the experiment must detect the issue and manually shut off the system to avoid any accidents.

A solution for this problem is adding a pressure sensor that is connected via the tubing and which can detect if any leaks occur by continuously measuring the pressure of the fluid inside the tubing. Therefore, if a drop in pressure occurs during the operation of the pump then that would signify that a leak has occurred somewhere along the tubing and the system should be shut down.

Another solution is to ensure the implementation of real-time flow rate sensing as previously mentioned which would make autonomous detection of leaks or blockages in the system possible. If the flow rate is much higher than expected a leak may be present in the system. If the flow rate is lower than the expected, this would be an indication that there is a blockage obstructing the flow. Therefore, the ability to detect flow rates would allow for the implementation of an automatic shut off command which shuts off the system if the measured flow rate indicates that a leak or blockage has occurred.

The addition of an automatic shut off command would enhance the overall safety of the system and allow for a flow system that is safe to leave unattended for extended periods of time.

Position Updating

The GUI is programmed in such a way that all parameters displayed on the parameters page will be saved as the system's current parameters. This means that the displayed value for the current volume of the syringe will be the new position of the syringe once the parameters are saved. Unfortunately, the displayed position on this page does not currently update after an operation is completed, so the user will have to input the new position of the syringe every time the parameters page pops up. In future versions of the coding, it would be useful to implement a way to update the current volume of syringe between operations to make it easier on the user.

Servo Motor Mount

As of now, the servo motors are too tall to fit directly under the syringe so they sit at an angle. An issue with this is that if a spill occurs, the liquid may work its way inside the housing of the servo motor and damage the electronics. Another problem is that the weight of the servo motor refill mechanism causes the syringe plunger to dislodge from the carriage block slot as it tips down the syringe on one end. To prevent these problems, small stands have been 3D printed to support the servo motor in the vertical position. However, this is not an ideal solution as it requires additional external components. A number of solutions are available. One potential solution is integrating the servo holder into the chassis so that it is supported. Another solution would be to mount the chassis vertically on the back wall of the fume hood. This would prevent the servo motor from deflecting the syringe downwards.

Lead Screw Mechanism

A threaded rod with different screw dimensions could be used which would have an impact on performance of the syringe pump system. The reason is that the lead of a screw, the linear distance a nut on a screw moves per rotation, depends on the dimensions of the screw. A screw with a large lead would be able to travel farther and faster than a one with a smaller lead. This relates to the syringe pump system as the screw lead determines flow rate and step resolution. Therefore, one needs to pick the correct threaded rod depending on their application and what performance goals they have for their system.

Safety Considerations

Safety considerations for this project relate to the use of chemicals within the flow system, electrical wiring, and 3D printing protocols.

When designing the system, care was taken to account for the safety of the individuals operating the system. Therefore, an automated refill option has been included to minimize the handling of chemicals by allowing users to command the system to refill the syringes using the user interface. Without this option, the syringes must be detached from the system, refilled by hand, and repositioned within the syringe pump. This process may lead to accidental chemical spills and the chance of chemicals coming into contact with the operator's skin.

When dealing with chemicals proper laboratory protocols should be followed at all times. Experiments should be conducted with the flow pump system within a closed fume hood. If a leak or blockage is detected the system should be shut off immediately. As the design currently stands, the flow system should never be left unattended.

With respect to the electrical components in the system, it is important that the wiring diagrams be followed and that there are no loose wires hanging out to avoid the possibility of having a short circuit. A short circuit may produce sparks, smoke, or fire. This may result in personal injury, as well as permanent damage to the electrical components in the system. Meanwhile, if there is an incorrect connection where too much power is provided to a component, the component may become permanently damaged from burning out and heating up.

Operation of the 3D printer is another area of potential risk. To mitigate this risk, it is important to follow the operating instructions of the specific 3D printer being used. 3D printers are generally safe machines, although care must be taken to avoid touching the heated components of the printer. The nozzle of the printer is generally heated to 210 - 250ºC and the bed to 60 - 110ºC. If contact with the skin occurs, a burn may result. Additionally, when removing supports from the finished 3D printed components, care must be taken to not to scratch oneself on the jagged support material.

Although this flow system does not require syringe needles, these needles are sometimes included when ordering syringes. These needles pose a safety hazard and must be disposed of properly. The California Department of Social Services has guidelines regarding proper disposal of syringe needles [6]. It is currently illegal to dispose of syringes in trash, recycling, or composting bins. To properly dispose of needles they must be discarded in an approved disposal container and later disposed of at a proper disposal facility.

Since chemicals could accidentally come in contact with the screen, a stylus is included in the final design.

Engineering Standards

Restriction of Hazardous Substances (RoHS)

The Restriction of Hazardous Substances (RoHS) Directive (2002/95/EC) regulates the use of hazardous substances in electronic devices [7]. The RoHS Directive was adopted by the European Union in 2003. California adopted the directive in 2003 as well but under a limited scope. The hazardous substances limited by California Senate Bills 20 and 50 include four of the ten substances limited by the RoHS Directive, those being lead, mercury, cadmium, and hexavalent chromium. Another directive which sets standards for electronic equipment is the Electromagnetic Directive (EMC) (2014/30/EU). A device is EMC compatible if it is able to function acceptably in its electromagnetic environment. This includes limiting the unintentional generation, propagation and reception of electromagnetic energy, all of which may cause unwanted effects such as electromagnetic interference (EMI) or physical damage in operational equipment [8]. The electronics in this design were selected to be compliant with the RoHS and EMC directives. Specifically, the Nextion 7" Basic Series Display and Arduino Mega 2560 are both RoHS and EMC compliant.

ASME Y14.5 Dimensioning and Tolerancing

The ASME Y14.5 Dimensioning and Tolerancing standard is applicable to this project due to the use of CAD files in order to design the 3D printed components. This standard creates a common technical drawing language for standardized drawing practices and has been revised over the years to be compatible with electronic systems, such as Computer Aided Design (CAD). This standard was therefore applied when creating the CAD files for the 3D printed components of the system.

ANSI Internal and External Thread Classes

ANSI Internal and External Thread Classes is a widely adopted standard for thread screw classes which specifies the degree of tightness between threaded components [9]. Thread screw classes specified in the ANSI Thread Classes represent manufacturing tolerances that specify minimum and maximum pitch diameters for both internal and external threads. The stainless steel threaded rod used as the linear actuator in the syringe pump system is sized with ANSI class 2A external threads. This class is intended to maximize the strength of the threads, and is therefore an advisable choice for this design since the threaded rod and nut are used to translate rotational force to linear force acting on the syringe. The tolerance allowed for a class 2A lead screw is a minimum pitch diameter of 0.2127 inches and a maximum pitch diameter of 0.2164 inches. The threaded rod in the system is paired with an ANSI class 2B steel hex nut which has an allowed pitch diameter ranging from a minimum of 0.2175 inches to a maximum diameter of 0.2248 inches.

Chemical Hazards and Toxic Substances

OSHA (Occupational Safety and Health Information) has standards regarding Chemical Hazards and Toxic Substances. Controlling Exposure is a section of these standards which includes controls such as Elimination/Substitution, Engineering Controls, Administrative and Work Practice Controls, as well as Personal Protective Equipment. The Engineering Controls involve implementing physical change to the work environment which reduces or eliminates the hazard on the job. Examples of such controls include changing processes to minimize contact with hazardous chemicals, isolating or enclosing the process, use of wet methods to reduce generation of dust or other particles, general dilution ventilation, and the use of fume hoods [10]. This flow system has been designed to adhere to these standards. Specifically, the automatic refill option was designed to minimize contact with hazardous materials. In the Croatt Research Group's original design, the chemist is required to fill a syringe by hand, install it in the syringe pump, and refill the syringe when necessary. With the automatic refill, the need for contact with and transportation of a syringe full of hazardous materials is eliminated by automating the process once the syringe has already been placed in the syringe pump. Additionally, the design of this flow system was made to control exposure by accommodating the use of fume hoods. Extended wires between the syringe pump and the GUI allow for the syringe pump to be placed in an enclosed fume hood while the GUI and electronics sit on a nearby surface. Therefore, the portion of the system in contact with chemicals and hazardous substances can be enclosed in a fume hood while the electronics remain operable at a safe distance away. These design choices have been made to act in accordance with OSHA's Chemical Hazards and Toxic Substances standards.

Impact on Society

Green chemistry (or sustainable chemistry) refers to the development of efficient chemical processes that reduce or eliminate the generation of hazardous substances [11]. It takes into consideration the environmental impact of every step in the process of chemical synthesis, from the waste created during the reaction to the lasting effects that the chemicals created will have on the environment. It also concerns safety, aiming to minimize potential hazards to laboratory personnel. As environmental concerns have come to a head over the past half-century, government, academia, and industry alike have begun to look towards green chemistry as a necessary scientific advancement in order to promote a more sustainable civilization [12].

Flow chemistry has made valuable contributions towards the practice of green chemistry. By allowing for strict control of reaction parameters, the efficiency of reactions is increased, waste is reduced, and safety is enhanced. However, one important consideration when it comes to green chemistry initiatives is the economic impact of the processes being implemented. Governments, industries, and research institutions desire both environmental and economic sustainability. Practices must therefore be cost effective in order to gain acceptance and widespread use. Currently, chemistry flow systems are prohibitively expensive and therefore largely impractical for large-scale implementation. By greatly reducing the price of flow systems, use of these systems will become more commonplace as institutions no longer have to choose between environmental and economic sustainability. This creates opportunity for a larger portion of chemical synthesis to be conducted in a sustainable manner.

This design will have valuable social implications in addition to its environmental ones. Cost-effective, DIY flow systems have already been developed, however these systems are non-intuitive and not user friendly. The user-friendly nature of this flow system will allow for increased prevalence of flow systems in undergraduate laboratories because students will not require significant training and expertise to operate the system. Therefore, a greater number of students will have the opportunity to conduct experiments using this equipment, leading to a workforce of adept chemists. Furthermore, by removing unnecessary obstacles associated with operating the system, students will be inspired rather than discouraged when using this flow system. This inspiration will encourage students to persevere through difficult courses, and enhance the retention of students from underrepresented groups in STEM fields.

Professional Responsibility

While the use of this design advances sustainable chemistry initiatives and therefore addresses environmental concerns, the environmental implications of the production of this system must also be taken into consideration. The majority of the design is 3D printed, and is therefore not intended for long-term use. Replication of this design will therefore lead to the creation of plastic waste once the system has reached the end of its lifespan. Most common types of 3D printing filament are classified as Type 7, or “Other” by the ASTM International Resin Identifier Codes [13]. Type 7 plastics are not recycled by most curbside municipal recycling programs and consequently often end up in landfills. However, independent plastic recycling and processing companies exist which process plastics not typically handled by municipal recycling programs. It is also possible to melt down old 3D printed components and re-extrude them as usbale filament [13]. Additionally, PLA (Polylactic Acid), one of the most commonly used 3D printing filaments, is a biodegradable material which means that it can be broken down over time. As 3D printing gains popularity, there is discussion regarding the introduction of more comprehensive recycling codes in order to include common 3D printing filament polymers [14]. Therefore, there are options for recycling the 3D printed components created for the purpose of this flow chemistry system.

Lessoned Learned

A number of valuable lessons were learned over the course of this project. Firstly, it was learned that just because something can be 3D printed, this does not mean that it should be. This lesson was learned through the design process for the electronics box and touchscreen holder. 3D printing was initially chosen due to the customizability of designs that can be printed, as well as its relatively low cost. However, major downsides associated with 3D printing include inaccuracies due to shifting and warping, as well as extremely long print times. While 3D printing did prove useful for manufacturing the smaller, unique components of the syringe pump, it was not the best method to use for the larger electronics box and touchscreen holder. 3D printing these designs took 18-28 hours per print, imposed design constraints due to the size of the 3D print bed, and led to warping and shifting of the prints. It was therefore decided upon by the team and sponsor that the customizability that comes with 3D printing was not worth the effort, especially with numerous low cost, satisfactory solutions ready to be ordered on Amazon. This was a valuable lesson learned about the importance of considering all options before deciding on a solution.

A second lesson learned was the importance of robust design when creating a user interface. Since human behavior can not be controlled nor predicted, it is important to include responses and safeguards against improper user inputs in the design process. For the final GUI in this project, these safeguards block the system from operating when an improper value has been input by the user. The importance of these fail-safes was brought to light after allowing the system to be operated by inexperienced users. Since the system is ultimately for use in undergraduate laboratories, it can not be assumed that students have sufficient knowledge about the system and the chemistry at hand to always put in the correct values. Therefore, these fail-safes are an important part of the final solution, and provide a valuable lesson for the team about the importance of a robust design.

Finally, the importance of teamwork and communication was learned. In a project with many interconnecting components, it is vital that all team members be on the same page. Lack of communication between teammates ultimately results in wasted time and energy since one team member may be headed down a path which is not in line with the entire team’s perspective, which may result in twice the amount of work being done to get back on course. Additionally, it was learned that it is important to communicate the vision for the project clearly with the sponsor early on, and to attain approval or make necessary adjustments before significant design work has been done. This will save time and energy, and create a trusting and harmonious relationship between the sponsor and the team.

Conclusion

Improvements made to the Croatt Research Group's flow chemistry system were successful as they increased the ease of usability as well as functionality of the system and added safety considerations to the original design. These improvements include: a touch screen GUI, a modular syringe holder, an automatic refill mechanism, an electronics containment box, and non-corrosive hardware made out of stainless steel. The results of the project are two working syringe pumps which can be easily controlled by the Nextion GUI. A user manual containing all the relevant information, from how to assemble the system to how to control it with the new graphical user interface, was created to accompany the system.

The pumps in this system operate within a 10% error of the target flow rate, assuming the target flow rate is below the maximum flow rate specified for each syringe size. Additionally, the two pumps operate within 6% error of the desired stoichiometric ratio, which is important to maintain the desired chemical reactions.

A complete system with four syringe pumps can be assembled for an estimated cost of $580. While this is significantly more than the $150 cost to assemble the Croatt Research Group's system, it is important to note that this price was calculated for a system with only one pump. Therefore, assembling four pumps using the Croatt Research Group's design may amount to $350-$400. Additionally, the Croatt Research Group's system did not include an automatic refill option. Taking these two factors into consideration, the price of the improved system is not significantly higher than the price of the DIY Croatt Research Group's system. Additionally, the enhanced functionality, ease of use, and safety precautions incorporated into the improved design provide significant justification for the increased price. Furthermore, this DIY system is still significantly more cost effective than commercial flow systems, which range from $2000 to 50,000.

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Appendix

DIY Syringe Pump System Data Sheet

Technical Specifications:

Mode: Dispense and Withdraw

Accuracy: Flow rates are within 10% of the expected value when the system is operated below its maximum flow rate conditions.

Syringe Size (Min/Max): 1 mL to 10 mL

Syringe Type: Plastic

Minimum Flow Rate: 0.5 mL/min (with 1mL syringe)

Maximum Flow Rate: 8 mL/min (with 10 mL syringe)

Maximum Linear Force (Theoretical): 593.3 N (133.3 lbf)

Display: Nextion 7" Intelligent Series Display (Enclosed)

Connectivity: Arduino

Power: 12V 30A DC (Stepper Motors) and 5V 5A DC (Servo Motors)

Motor Drive: 1.8° Nema-17 Stepper Motor with Micro-stepping

Step Resolution: 0.396 µm/step

User Manual

https://docs.google.com/document/d/1YDq3oy2axuiYRWvt7MsWcyNP4qZTGKJB/edit?usp=sharing&ouid=104276304895776553823&rtpof=true&sd=true

Drawings/Layouts/Parts Listing

(All dimensions are in millimeters as mentioned in the drawings)

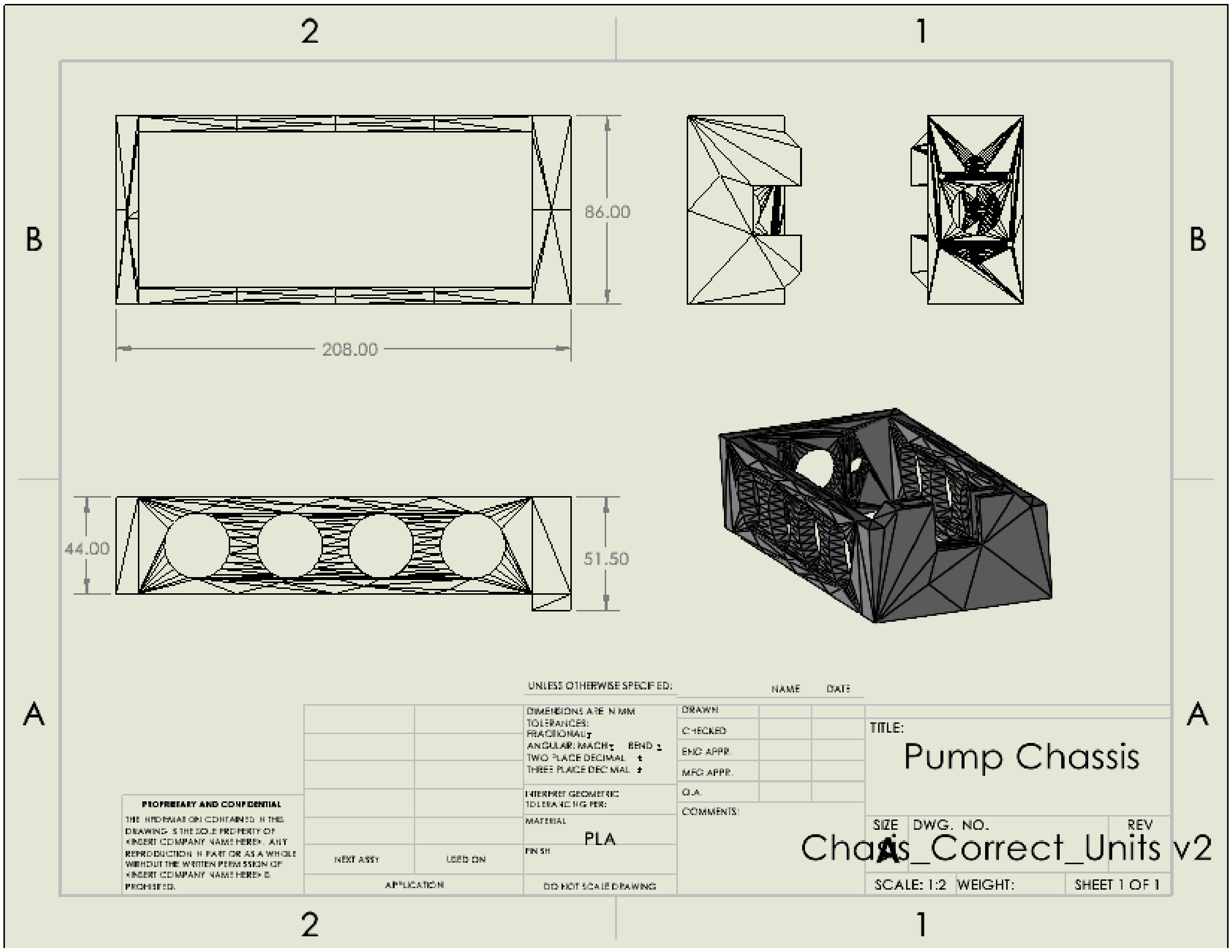

Figure 35. Chassis CAD Drawing

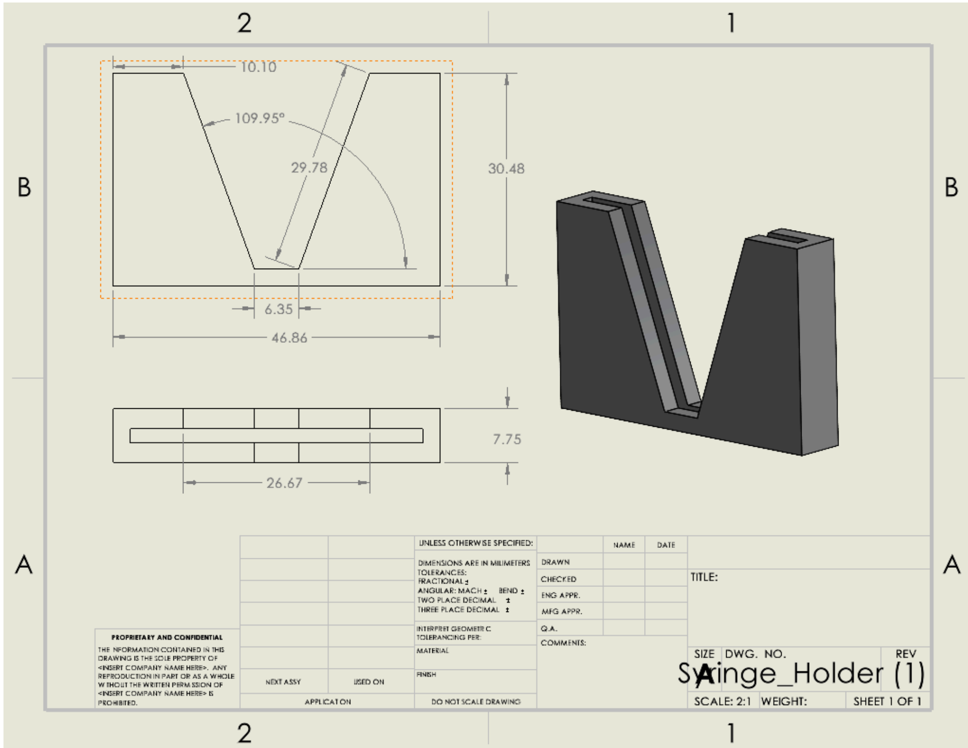

Figure 36. Syringe Holder

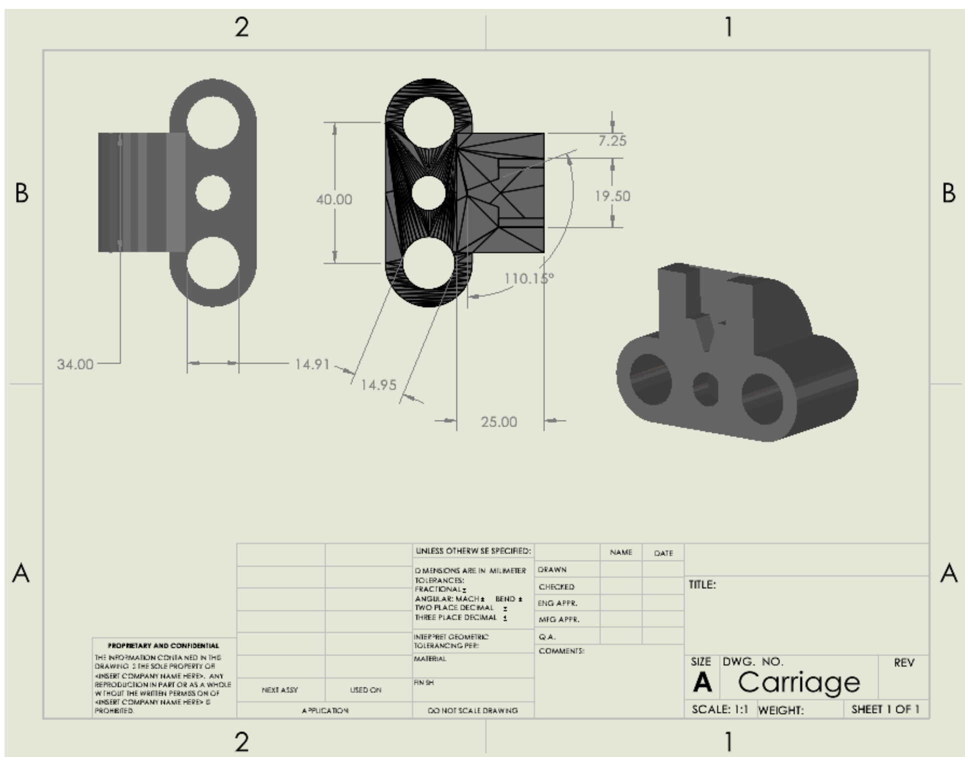

Figure 37. Carriage CAD Drawing

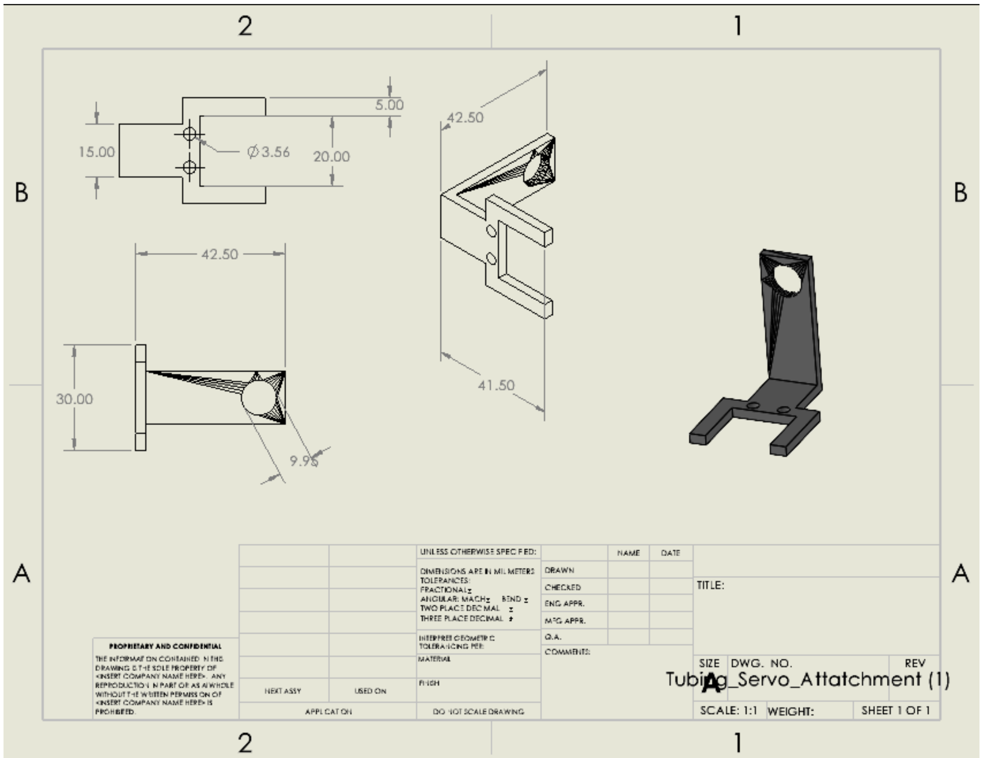

Figure 38. Servo Tubing Attachment

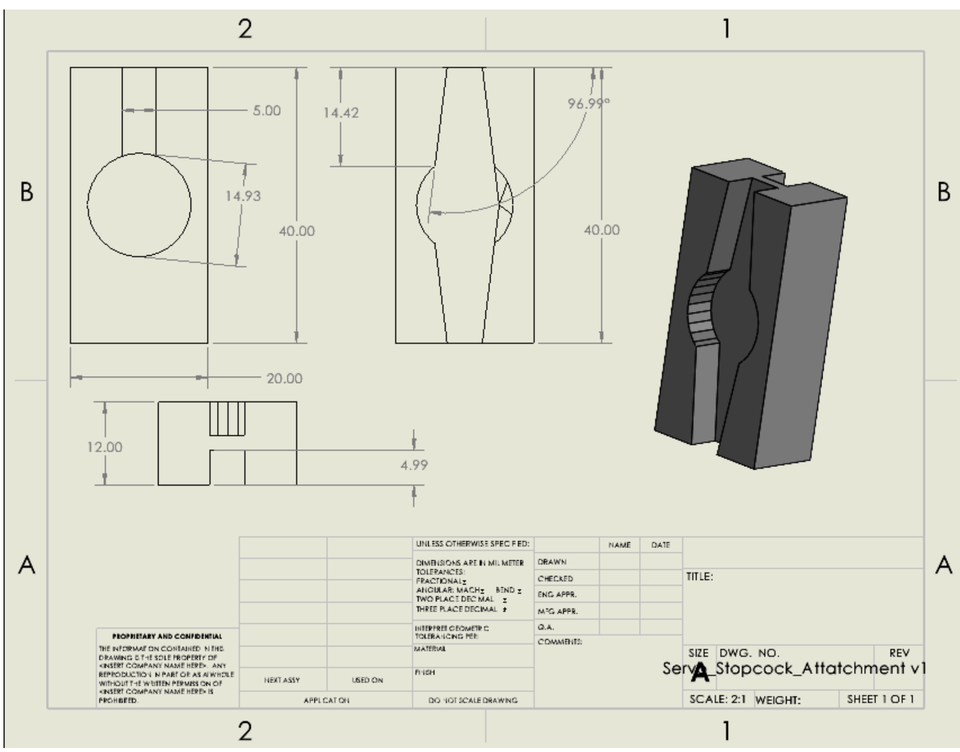

Figure 39. Servo Stopcock Attachment

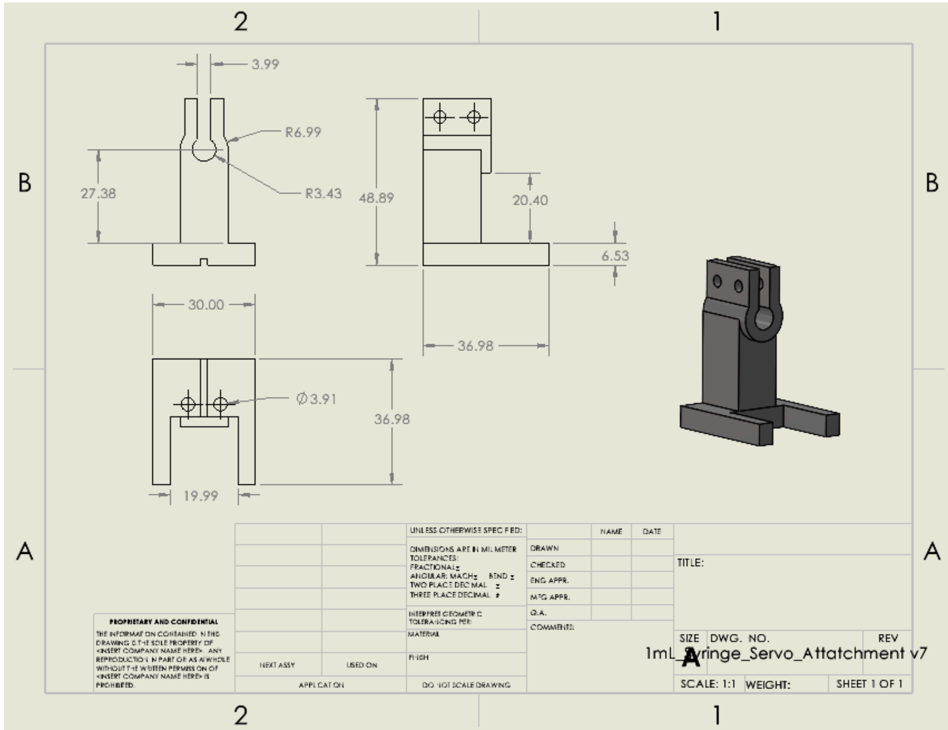

Figure 40. 1mL Syringe Servo Attachment CAD Drawing

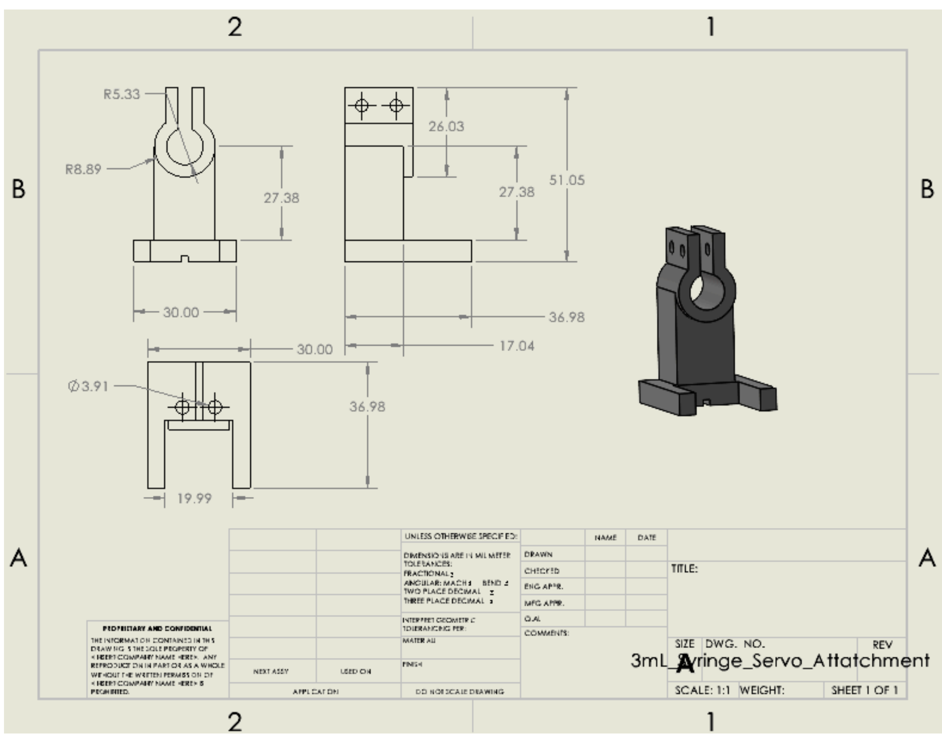

Figure 41. 3mL Syringe Servo Attachment CAD Drawing

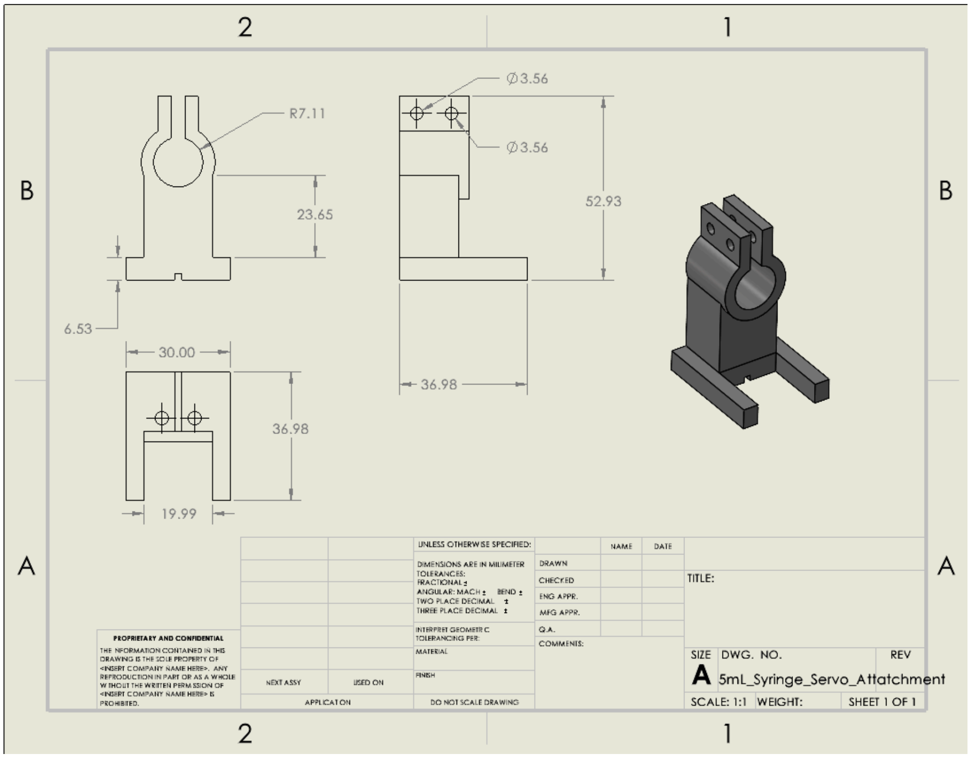

Figure 42. 5mL Syringe Servo Attachment CAD Drawing

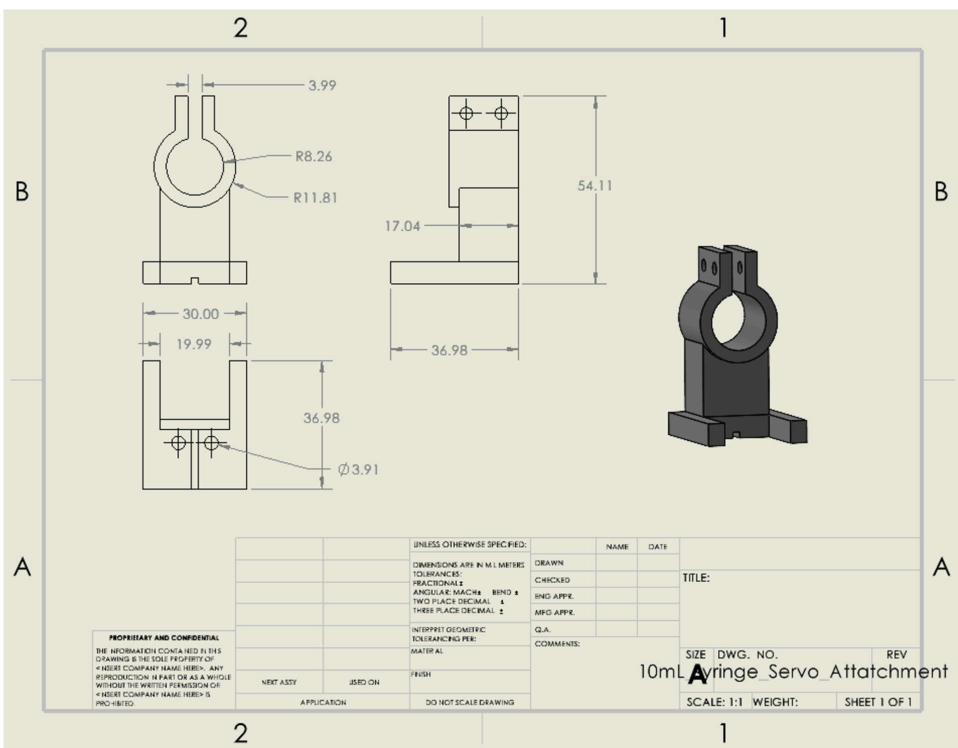

Figure 43. 10mL Syringe Servo Attachment CAD Drawing

Bill of Materials

Item	Quantity (single pump system)
Linear Ball Bearings (8mm bore, 15mm OD, 24mm length)	2
Linear Rods (8mm x 200mm)	2
Fully threaded rod (¼”-20, 7.1”)	1
Linear Coupler (5mm to 5mm)	1
¼”-20 Stainless Steel Hex Nut	1
Nema-17 Stepper Motor (40mm 64oz.in (45Ncm) 2A 4 Lead)	1
M3, 0.5 x 14 mm screws	4
Heat Set Insert (4-40, 0.135”)	2
4-40 ⅜” screws	2
4-40 ¾” screws	2
4-40 nuts	4
MakerHawk MG995 Metal Gear Waterproof Servo Motor	1
Arduino Mega 2560	1
12V 30APower Supply	1
5V 5A Power Supply	1
400 Point Solderless Breadboard	1
Stepper Motor Driver	1
3 Wire Power Cord	2

Nextion Intelligent Series 7” Resistive Touch Display	1
Stylus Pen	1
Breadboard Jumper wires	1
Electronics Box	1
Zip ties	2
Tablet Stand Holder	1
Cord Protector (¼”, 10ft)	1

Table 12. Bill of Materials

Specification Sheets for Parts Purchased

Product	**Seamuing Micro Servo Motor, MG995 RC Servo**
Product Dimensions	1.6” x 0.78” x 1.69”
Item Weight	7.8 Ounces
Item Model Number	0510U1J2GPSINM3091A89
Purchasing Link	Amazon.com: Seamuing Micro Servo Motor, MG995 RC Servo, 20kg Metal Gear Servo for RC Robot Arm Helicopter Airplane Remote Control (4PCS) : Toys & Games

Table 13. Seamuing Micro Servo Motor, MG995 RC Servo, 20kg Metal Gear Servo for RC Robot Arm Helicopter Airplane Remote Control Product Information.

Product	**NX8048P070-011R-Y (7.0 inch resistive touchscreen with enclosure)**
Layout Size	218.1mm(L)×150mm(W)×22.5mm(H)
Active Area	164.90mm(L)×100.00mm(W)
Visual Area	154.08mm(L)×85.92mm(W)
Resolution	800×480 pixel

Touchtype	Resistive
Weight	445g
Link to Datasheets	https://nextion.tech/datasheets/NX8048P070-011R-Y/

Table 14. Nextion Intelligent Series 7" Touch Display Specifications

Product	**Nema 17 Stepper Motor**
Step Angle	1.8º
Positional Accuracy	±5%
Number of Phase	2
Holding Torque (2 phases on)	0.45 Nm
Rated current/Phase	2.0 Amps DC
Rated Voltage/Phase	2.2 V DC
Purchasing Link	https://www.amazon.com/Stepper-Motor-Bipolar-64oz-Printer/dp/B00PNEQI7W#HLCXComparisonWidget_feature_div

Table 15. Nema 17 Stepper Motor Specifications

Product	**Usongshine Stepper Motor Driver**
Rated Output	3.5 A
Output Current	4.0 A (peak, in 100 ms)
Input Port internal pull down resistor	100 K
Purchasing Link	https://www.amazon.com/UsongShine-Stepper-Controller-Arduino-Printer/dp/B07HHS14VQ?th=1

Table 16. Usongshine Stepper Motor Driver Specifications

Product	**ALITOVE AC 110V/220V to DC 12V 30A 360W Universal**

	Regulated Switching Power Supply
Input	AC 110V/220V 50/60 Hz
Output Voltage	DC 12V
Output Current	30A max
Output Wattage	360W max
Working temperature	-10 to 50 ºC
Storage temperature	-20 to 60 ºC
Purchasing Link	https://www.amazon.com/ALITOVE-Universal-Regulated-Switching-Transformer/dp/B06XJVYDDW/ref=sr_1_3?keywords=12v%2Bpower%2Bsupply&qid=1637114650&sr=8-3&th=1

Table 17. ALITOVE AC 110V/220V to DC 12V 30A 360W Universal Regulated Switching Power Supply Product Specifications

Links to the other products purchased are included in the full Bill of Materials.

Detailed Analysis

Syringe Pump Maximum Flow Rate:

The purpose of these calculations is to determine the maximum theoretical flow rates as well as the dispensing resolution for syringe sizes: 1 mL, 3 mL, 5 mL, and 10 mL. The maximum flow rate was calculated by using the maximum speed that the stepper motor was limited to in the Arduino code, which is 2000 steps per second (600 RPM). Also used for this calculation is the lead of the screw, the linear distance that the carriage would move per revolution of the motor. The threads per inch (TPI) is used to calculate the screw pitch by taking the inverse of TPI. The screw used in this project has single start threads which means that the screw pitch is equal to the lead of the screw. Therefore, the TPI of the threaded rod is used to calculate the lead of the screw.

$$Lead = \frac{1}{TPI} = \frac{1}{20} = 0.05[in] = 1.27[mm]$$

The stepper motor is set to microstep at 3200 microsteps per revolution. The step resolution [mm/μsteps] of the motor is calculated as follows.

$$\frac{Lead}{Revolution} \times \frac{Revolution}{Steps} \times \frac{Steps}{Microsteps} = \frac{Lead}{Microsteps} = \frac{1.27[mm]}{3200[\mu steps]} = 0.000396[mm/\mu step]$$

The volume that is dispensed from the syringe per microstep of the motor, also known as the dispense-step resolution, is calculated. The equation for the volume of a cylinder is used to calculate the dispensed volume of a syringe and is based on the linear distance that the plunger travels. As mentioned before, the distance that the nut moves per rotation of the screw, lead, is equal to the distance that the syringe plunger moves.

$$V = \pi r^2 h$$

r: inner radius of the syringe

h: distance traveled by the plunger

For example, here is the dispense-step resolution calculation for a 10 mL syringe with a measured inner diameter of 14.6 mm.

$$V = \pi r^2 h = \pi \times (\frac{14.6[mm]}{2})^2 \times (0.000396[mm/\mu step]) = 0.0663[\mu L/\mu step]$$

The maximum flow rate is calculated by multiplying the dispense-step resolution by the maximum speed of the motor which is given as 2000 steps per second.

$$Q_{max} = V \times w_{max}$$

The maximum flow rate for a 10 mL syringe is calculated as follows.

$$Q_{max} = V \times w_{max} = (0.0663[\mu L/\mu step] \times (2000[steps/second]) = 132.6[\mu L/second] = 7.972[mL/min]$$

The results for the rest of the syringe sizes can be seen in the table below.

Syringe Size [mL]	**Maximum Flow Rate [mL/min]**	**Dispense-Step Resolution [μL/step]**
1	0.6912	0.0057
3	2.895	0.0241
5	5.295	0.0440

10	7.956	0.0663

Table 18. Theoretical maximum flow rates and step resolution for the syringe pump.

Syringe Size [mL]	Maximum Flow Rate [mL/min]
1	0.7
3	2.9
5	5.3
10	8

Table 19. Recommended maximum flow rates for each syringe size.

These results are significant because they help define the flow rate limits of the syringe pump system as well as the dispense-step resolution. As a result, one can determine based on these pump specifications if these maximum flow rates meet their requirements and choose whether or not to use this system based on them.

Lead Screw Analysis

The purpose of this static analysis was to characterize the maximum linear force that the stepper motor coupled with the lead screw could produce. An assumption that was made to make this analysis possible was that the maximum torque of the Nema-17 motor, based on the specification sheet, was 0.45 Nm (Table 15). Another assumption that was made was that the dry friction coefficient between the external threads of the screw and the internal threads of the hex nut is 0.20 [15]. Based on these assumptions the motion of the lead screw is modeled using static analysis techniques.

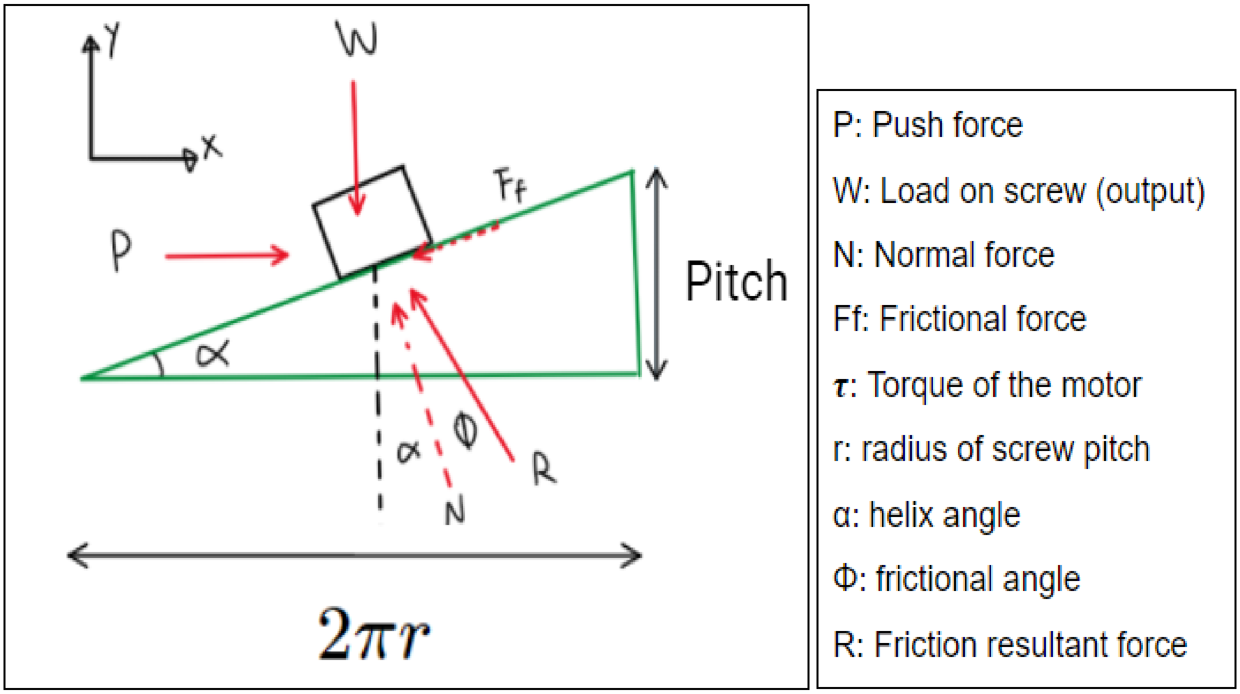

Figure 44. Free body diagram of a linear load (W) on the external threads of a screw at the moment of impending motion [16].

The motion is modeled as the external threads of the lead screw are supporting a linear load, W, which for this case is the hex nut embedded in the carriage block that provides the linear force to displace the syringe plunger. The 2D free body diagram seen in Figure 35 models the impending motion of the screw as it is supporting a load.

The green slope represents the external threads of the screw and the outlined black square represents the internal threads of the hex nut. The external threads of the screw are unwrapped to allow them to be modeled in two-dimensions. As a result, the base length of the slope represents the circumference of the screw and the height represents the screw pitch, the distance between threads. The screw lead which is equal to the screw pitch has been calculated in the previous section. The pitch diameter to calculate the circumference of the screw, is found using a reference table [17] since all screws manufactured are standardardized. With all of this information available the sum of the forces for the free body diagram is solved and the maximum linear force produced by the lead screw mechanism is calculated.

Calculations:

The forces along the x-axis direction are summed to get the equilibrium equation below.

$$\Sigma F_x = 0 \longrightarrow P - Rsin(\alpha + \phi) = 0$$

Pushing force, P, is the force produced by the motor and is equal to the torque of the motor over the pitch radius of the screw.

$$P = \frac{\tau_m}{r_{pitch}}$$

Substituting for P, the new equilibrium equation along the x-direction can be found.

$$\frac{\tau_m}{r_{pitch}} - Rsin(\alpha + \phi) = 0$$

The friction resultant force is solved for.

$$R = \frac{\tau_m}{r_{pitch} \times sin(\alpha + \phi)}$$

From the summation of the forces along the y-axis the equation below is the result.

$$\Sigma F_y = 0 \longrightarrow -W + Rcos(\alpha + \phi) = 0$$

Solving for R here results in the second equation for the friction resultant force.

$$R = \frac{W}{cos(\alpha + \phi)}$$

The two equations for R that are found from each of the summation of forces are then equal to each other.

$$\frac{\tau_m}{r_{pitch} \times sin(\alpha + \phi)} = \frac{W}{cos(\alpha + \phi)}$$

Finally, the linear load force, W, can be solved for and the resulting equation is shown below.

$$W = \frac{\tau_m}{r_{pitch} \times tan(\alpha + \phi)}$$

The results found from the lead screw analysis is that the maximum linear force, W, provided by the lead screw mechanism is 593.3 N (or 133.3 lbf). This result is important because it gives a maximum baseline for the linear force produced by the linear actuator. Also, the result is significant because it shows that the motor is more than capable of producing the required linear force to push or pull any syringe size from 1 to 10 mL. The analysis for the forces required to operate the syringe pump for this range of syringe sizes can be found in the next section, *Pushing Force Required Analysis*.

Pushing Force Required Analysis

The goal of this analysis is to characterize the force required to push the syringe plunger during the operation of the syringe pump system when it is used with different syringe sizes. This analysis is done using Poiseuille's Law for Laminar Flow which states that the driving force for the flow of a liquid inside of a tube is the pressure difference between each end of a tube [18].

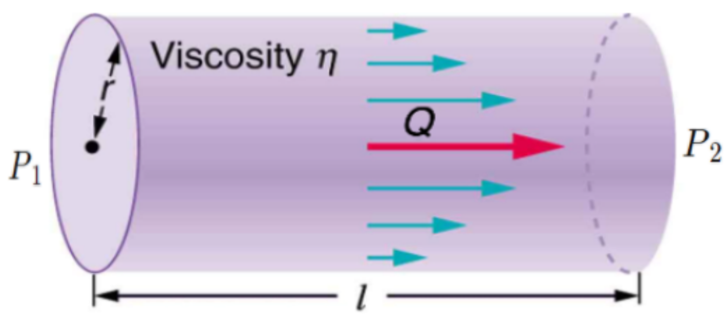

Figure 45. Poiseuille's Law applied to a tube [18].

Assumptions that are made include assuming the flow inside the syringe is completely laminar, the friction inside of the syringe due to the rubber tip of the plunger sliding along the plastic barrel is negligible and the pressure at the tip of the syringe was at atmospheric pressure. The analysis takes a look at water at 20 celsius which is used to determine the value of viscosity and a flow rate that is set to 2 mL/min. The inner diameter and length of tube of the syringe is known from taking measurements with digital calipers.

Calculations:

Poiseuille's Law for Laminar Flow Equation

$$Q = \frac{P_2 \ - P_1 \, \pi r^4}{8 \eta l}$$

Q: Flow Rate

P_2: Pressure at outlet

P_1: Pressure at syringe plunger

r: inner radius of syringe

n: viscosity of the liquid

The linear force, F, pushes the plunger of the syringe and creates a pressure, P_1, on the surface of the water where the plastic tip of the syringe plunger contacts it.

$$P_1 = \frac{Force}{Area}$$

All the variables from Poiseuille's Law for Laminar Flow Equation are known except the force which creates P_1. Therefore, the force is solved for each syringe size. The results achieved from this analysis can be seen in the table below.

Syringe Size [mL]	Force Required [N]
1	1.47
3	6.16
5	12.0
10	16.9

Table 20. Pushing forces that are required on the syringe plunger to get a flow rate of 2 mL/min.

These results are significant because they give a range of forces that would be required to operate the syringe pump for a given flow rate. The results also show that the mot or used for the system will be more than adequate to drive the syringe plunger for these specific syringe sizes. A greater flow rate could be used for this analysis, but the force required would still be in the same range as the one calculated for 2 mL/min.

Individual Component Analysis

Anti-Corrosive Material Selection

The threaded rod used in the Croatt Research Group's Design is made of standard steel and experiences corrosion when kept under a chemistry fume hood with a mix of gasses (the most corrosive being ozone) and sustained moisture. This corrosion inhibits the ability of the threaded rod to advance the carriage as intended. Therefore, additional consideration is needed to determine an alternative threaded rod which eliminates corrosion.

Research Process:
By searching the Thomas Register using key words “threaded rod” and “lead screw,” a large number of manufacturers and distributors resulted. This list was narrowed down by excluding custom manufacturers due to their higher price points and limited accessibility. From the remaining results, companies specializing in lead screws could be identified, such as Thomson and Helix Linear Technologies.

Helix Linear Technologies supplies lead screws, however, they are mainly restricted to series 300 stainless steel. While this was not very helpful in the search for various material options, Helix also provides anti-backlash lead screw nuts as well as accompanying design guides. When testing the flow chemistry system, we noticed significant backlash after the stepper motor reversed its direction. Therefore, information regarding anti-backlash lead screw nuts will be useful in future design considerations for the flow chemistry system.

Similar to Helix, Thomson does not offer a wide range of materials. However, their website includes design guides for lead screw usage. From these design guides, useful information was gathered such as the use of PTFE coatings in order to increase resistance to corrosion and decrease friction. With this new knowledge of PTFE coatings, companies/suppliers specializing in lubricants and coatings could be identified using the Thomas Register. After identifying CRC industries as a supplier of coatings and lubricants, contacting an application engineer revealed that PTFE coatings are best suited for plastic adhesion rather than metal. This engineer then suggested CRC’s Dry Mold Lube in order to provide superior corrosion resistance, decreased friction, and better results when adhering to a metal lead screw.

An additional company found using the Thomas Register was Paramount Fasteners. While this company primarily specializes in fasteners, they also offer lead screws made from a range of materials. In order to get an expert’s opinion on the most suitable material options to resist corrosion, an application engineer from this company was contacted. This conversation revealed stainless steel 316 to be the superior grade of stainless steel when it comes to resisting corrosion. For plastic options, he advised against nylon and suggested looking into PVC. After discussing pricing and shipping options, it became apparent that this company did not align with our project objective to build a low cost and accessible system.

Due to our project's budget and accessibility requirements, it is clear that specialty suppliers and manufacturers are not the best option. However, they were useful in providing engineering specific information and design guides. The products suggested and discovered throughout this research process were cross-referenced with products available from well known, highly accessible, and well priced suppliers such as Amazon and McMaster to ensure the components meet both the functional requirements and the overall project objectives.

1. Functional Requirements

1. Corrosion resistant to fumes (specifically ozone) and moisture present in fume hood. Fumes will vary according to the chemical reaction taking place.
2. Must transform rotary motion from the stepper motor into linear movement of the carriage.
3. Low Cost.
4. Easily Accessible.

2. Description of component options

1. 316 Grade Stainless Steel Threaded Rod.

   316 Grade Stainless Steel is significantly more corrosion resistant than the standard steel threaded rod currently in use, and superior to 18-8 and 410 grade stainless steel rods in its resistance to corrosion. It has excellent resistance to chemicals and salt water. Additionally, it displays excellent resistance to corrosion resulting from ozone, which is a main factor causing corrosion in these chemistry flow systems. It can be noted that 316 stainless steel has paramagnetic properties. This is only an area of concern if there is an externally applied magnetic field in the vicinity of the flow system, and if the stepper motor relies on a magnetic encoder rather than an optical one. In this case, the externally applied magnetic field or the magnetic field induced in the rod may interfere with the encoder counts.

2. Solid-film Lubricant.

   A solid-film lubricant can add a layer of corrosion resistance to existing hardware. Specifically, the Dry Moly Lube (Molybdenum Disulfide), from CRC Industries is well suited for use on metal lead screws, will increase resistance to corrosion, and reduce friction. The frequency of reapplication depends on the tolerances between the lead screw and the nut, the amount of friction in the system, and the frequency and duration of use. This product is intended to withstand sufficient use before reapplication is required, and it is possible to go months without needing to reapply, depending on the system. An additional advantage of this product is its resistance to dirt and dust build up, which will keep the carriage running smoothly along the lead screw.

3. Polyvinyl Chloride (PVC) Threaded Rod.

Another option when it comes to enhancing resistance to corrosion is PVC plastic. PVC is a plastic which is largely resistant to corrosion. PVC exhibits satisfactory resistance to ozone and many other common gasses and chemicals found in chemistry experiments. Additionally, PVC has a friction coefficient comparable to that of 316 stainless steel. However, rigid PVC has a tensile strength of 32-64 MPa whereas stainless steel has a tensile strength of 480 MPz. In order to increase the strength of the PVC threaded rod, a thicker diameter may be required. The necessary diameter can be calculated using the column strength equation for a lead screw in compression. A thicker diameter will not be an issue design-wise, however, the cost of the threaded rod increases with diameter.

3. Summary table comparing the pros and cons of the different components found.

Options	Pros	Cons	Cost
1. Stainless steel 316	- Excellent resistance to chemicals, salt water, and ozone. - Easily accessible.	- May be slightly magnetic. - 4x the cost of medium strength steel.	McMaster 1/4"-20: $8.03 / 3ft
2. Dry Moly Lubricant	- Corrosion resistant. - Decreased friction. - Resistant to dirt and dust build up. - Requires less frequent application than other protective lubricants.	- Requires reapplication.	Amazon $10.42

3. Chemical Resistant PVC	- Satisfactory resistance to acids, alkalines, salt solutions, alcohol, ozone, and others. - Nonconductive and nonmagnetic.	- 7x the cost of medium strength steel. - Decreased strength may require an increased diameter, which increases the cost.	McMaster 1/4"-20: $14.48 / 3 ft 5/16”-18: $16.20 / 3 ft 3/8"-16: $20.70 / 3 ft 1/2"-13: $24.42 / 3 ft

Table 21. Comparison of corrosion resistant hardware considerations

Conclusion:

316 Stainless Steel is the best option due to its excellent resistance to corrosion, affordable price, and wide availability.

4. List of References Used.

Databases: The Thomas Register, Google Scholar.

Key words: “threaded rod”, “lead screw”, “corrosion resistant”

Contacts:

- Application Engineer from Paramount Fasteners, Roy Hurst. (562) 903-7610.
- Application Engineer from CRC Industries, Ben (did not offer last name). (800) 521-3168.
-

Stepper Motor Selection

The system works with a stepped motor that is connected to a threaded rod. As the motor rotates the rod screws through the mount attached to the syringe, pushing the syringe down. The rate at which the stepper motor rotates and the torque it exerts determines the flow rate at which the chemicals are deposited.

Main Requirement

- The optimal stepper motor would be one that would provide maximum torque.

Component Description and Analysis

A stepper motor is a brushless, synchronous electric motor that converts digital pulses into mechanical shaft rotation.

There are three main types of stepper motors.

- Permanent magnetic Stepper
- Variable Reluctance Stepper
- Hybrid Synchronous Stepper

Operating Modes of Stepper Motors

Stepper motors have three operating modes, the Full Step, Half Step and the Micro Step. The full step takes 200 steps and has an angle of 1.8 degrees, the half step has 400 steps and a 0.9 degree step angle and the micro step has 51,200 distinctive steps and has an angle of 0.007 degrees.

Summary Table

Type of Stepper Motor	Resolution Angle	Torque
P.M Stepper	Low	Low
V.R Stepper	High	Low
Hybrid Stepper	High	High

Table 22. Stepper Motor Types

From this table we can conclude that the optimal stepper motor to be used would be a Hybrid Stepper motor. However, further research would determine whether it is the most cost effective and sustainable choice.

Operation Mode of the Stepper Motor	Torque and resolution output summary
Full Step	Exists in two models namely Single and Dual. Single phase provides less torque and control and is good as replacement use whereas Dual phase provides good torque but uses more power.
Half Step	Alternates single and dual phase operation. Compared with the full step drive, the motor's step angle resolution is doubled, and the motor runs more smoothly and quietly.
Micro Step	The microsteps are produced by proportioning the current in the two windings according to

	sine and cosine functions. This mode is only used where smoother motion or more resolution is required.

Table 23. Stepper Motor Operation Modes

Conclusion

From these tables we can tentatively conclude that the most optimal stepper motor for the risk reduction and testing stage would be to use the Hybrid Motor run on a Full step with a dual phase setup. However, as it uses more power and is not the smoothest option, the Hybrid stepper motor ran on a Half step operating mode would be the most efficient step as the motor would run more smoothly with the resolution angles and also provide sufficient torque inorder to push the syringes at the respective flow rates requires.

References

[19], [20], [21]

User Interface Selection

An important component of the flow chemistry syringe pump system is a suitable user interface. As the system is to be used by students and even hobbyists, they do not necessarily have technical experience in electronics. As such, it is important for the system to have a user-friendly interface that is non-intimidating, especially for those only just getting into flow chemistry as their focus is to learn chemistry, not to learn about electronics and programming.

Functional Requirements

This user interface is only meant to control the syringe pumps, so there are not that many functional requirements for its operation. Essentially, it just needs to reliably send and receive information to and from the system's microcontroller. There will need to be inputs for which pumps are on/off, the syringe size, the flow rate, and a start/stop input. Of course, the controls on the interface should be very user friendly.

User Interface Options

There are three general interface options for this system. The first would be a touchscreen display that connects to the microcontroller. Second, the system could just be hooked up to a switchboard with knobs, switches, and sliders to control the various inputs necessary to control the syringe pumps. There would be an LCD display here for the user to keep track of what their inputs were and what the system is currently outputting. Finally, the original flow chemistry system designed by the Croatt Research Group had an Android app for controlling the syringe pump (with a bluetooth dongle on the microcontroller to receive information from the app). The sponsor of this project would prefer to steer away from this control scheme as it is exclusive to only Android phone users and some people would not like having stuff pertaining to business on their personal phone. However, this is still an option, and to accommodate this, an inexpensive Android phone can be purchased and hooked up to the system.

Touch Screen Interface

Two of the most common types of touchscreen technologies are resistive and capacitive touch screens. With resistive touch screens, there are two layers of material separated by a tiny gap. The resistance between the two sheets of material is measured at different points. "Pressing down upon the top sheet will change that resistance, and by comparing the measurement points it can be determined where the screen was pressed" [22]. These resistive touch screens are generally less expensive and can be operated with any touch input whether it be from finger, stylus, or while wearing gloves. However, they are more susceptible to scratches on the display. The display is also a bit dimmer due to the resistive overlay. Alternatively, there are capacitive touch screens that use the conductivity of the human body. When the glass is pressed with one's finger/body, the current changes and sensors can then tell where the screen was pressed [22]. As this sort of touchscreen depends on the conductivity of the body, it is not possible to operate with gloves or a stylus. They are more durable and brighter than resistive touchscreens, and allow for multi-touch sensing. However, they are not as precise and are more vulnerable to accidental touches.

Based on where this flow chemistry system is expected to be used, there will likely be gloves involved since chemists may deal with some dangerous chemicals. Thus, it would be a better idea to go with resistive touchscreens as they are operable while wearing gloves. Their display may be a little duller, but that is not much of a concern as the purpose of this touchscreen is just to send commands to the microcontroller. The touch screen is more susceptible to scratch damage, but if that ever happens, it can simply be replaced.

Display with Switchboard

Instead of a touch screen, one can use a switchboard with knobs, switches, and sliders to control the inputs of the system. Switches can turn pumps on and off, sliders can control the syringe size, and knobs can increment the flow rate. The display screen or another sort of screen display can display the current inputs and flow rate. There may be up to six pumps that can be controlled by an Arduino, so there may be six pump settings, but only three are shown here for the mockup.

Generally, display screens are pretty cheap, but they often come in small sizes. Common LCD displays for the Arduino come in sizes of 16 x 2, 16 x 4 and 20 x 4 characters [23]. However, the display may need to be bigger to accommodate all the information. Perhaps a solution here would be to buy multiple display screens to display all the information.

Bluetooth App

Finally, the other option would be to have a bluetooth app that controls the microcontroller. There was an app developed by the Croatt Research Group, but the link on their website no longer works, so it is necessary to contact the group for further information about it. Alternatively, a new app can be created with compatibility for more mobile devices. The app from the Croatt Research Group only works for Android, but this can be remedied with the development of a new mobile app.

Summary

	Pros	Cons	Estimated Cost
Touch Screen	- intuitive -easy to use -can operate with gloves	-costly -susceptible to scratches -harder to troubleshoot -potential programming issues	\$40-\$90
Display + Switchboard	-easy to use -generally inexpensive -easy to troubleshoot -replaceable parts if one breaks	-lots of different parts -displays generally come in small sizes -knobs and such might break	\$10-\$30 (for display screen only)
Bluetooth App	-easy to use -intuitive	-very costly -potential programming issues -harder to troubleshoot -likely cannot operate with gloves (phones usually have capacitive touch screens)	\$90-\$180 for Android phone

Table 24. User Interface Selection Considerations

Other Considerations

Some of the other considerations that came up while researching about the user interfaces was the possibility of using a Raspberry Pi instead of an Arduino to control the syringe pump. While this is not the interface that the user will be interacting with, it may be worthwhile looking at the advantages of using a Raspberry Pi as opposed to an Arduino. Another consideration is all of the wirings that go in between all of the electronics. An inexperienced user would be at a loss at how this connects to that and so on. Perhaps there is a wireless solution to this problem? Maybe the signals that the microcontroller sends can be wirelessly transmitted to a receiver where the stepper motor is to do away with all the convoluted cable connections.

Check Valves

The component chosen to research is the check valve, which is essential for controlling the flow of liquids or gasses in flow chemistry setups. Check valves are used in systems that require one-way flow such as continuous flow systems. The functional requirements of the system are that the check valve should protect the system from backflow, provide pressure relief, allow a constant flow rate, and prevent contamination from backflow.

Some secondary considerations were that the check valve should allow the syringes to be refilled, contain wetted materials that are non-corrosive to a wide range of chemicals, and offer low maintenance requirements.

The tubing used for the flow system will dictate which size check-valve will be used. Furthermore, the chemistry itself will influence what tubing size will be utilized. A tubing size of 1/16" outer diameter and 0.02-0.04" inner diameter is recommended for our application.

After browsing through catalogs from suppliers these are three check valves that meet the requirements:

- Check Valve Inline Non-Metallic 1/4-28
- Masterflex Inert Inline Inlet Check Valve
- Slim-Line In-Line Check Valve w/ 1/16" Ball Cartridge

Here is more information gathered from the webpage of each check valve option:

1) Check Valve Inline Non-Metallic 1/4-28
   This check valve is made of polyetheretherketone (PEEK) and perfluoroelastomer. It has a cracking pressure of 1 psi and a maximum pressure rating of 2000 psi.
2) Masterflex Inert Inline Outlet Check Valve
   The wetted materials in this check valve are PEEK and ethylene propylene diene monomer rubber (EPDM). It has a cracking pressure of 0.99 psi and a maximum pressure of 100 psi.

3) Slim-Line Inline Check Valve w/ 1/16" Ball Cartridge
   The wetted materials are 316 stainless steel, PEEK and ruby ball/sapphire seat. It has a cracking pressure of 1 psi and a maximum operating pressure of 18,000 psi.

Check Valve	Pros	Cons
Check Valve Inline	• PEEK and Perfluoroelastomer:	• Expensive ($117.80) • Requires additional components

Non-Metallic 1/4-28	Made of chemical resistant materials ● Rated for up to 2000 psi ● Compatible w/ other PEEK tubing components	for the 1/16 outer diameter tubing
Masterflex Inert Inline Outlet Check Valve	● Inert flow path which minimizes turbulence ● No metal components ● No maintenance required ● Lower cost ($59) ● Made of PEEK which is a corrosive resistant material	● Requires additional components which adds to its cost ● Only rated for up to 100 psi
Slim-Line Inline Check Valve w/ 1/16" Ball Cartridge	● Ruby and Sapphire Ball and Seat ● Ultra low internal volume ● Low resistance to flow ● Operates independent of gravity ● Rated for up to 18000 psi	● Expensive - $126.50 (or $168.30 with complete assembly) ● Also needs additional check valve for inlet

Table 25. Summary of Check Valve Options

Conclusion

All these check valve options are for high precision flow chemistry operations and the chosen check valve to use will be reliant on the type of chemistry done. For our choice we want to go with the industry standard Check Valve Inline Non-metallic 1/4 - 28 because the PEEK material makes this excellent in terms of chemical resistance and its higher pressure rating of 2000 psi allows for use in chemical reactions which require high temperatures and pressure. Also, another reason for choosing this check valve specifically is that it is compatible with the tubing connectors and joint components, most of which are also made out of PEEK.

Summary

Keywords - Check valve 1/16" tubing, High-performance liquid chromatography (HPLC) check valve, PEEK inline check valve

References

[24], [25], [26]

Budget

Name	Quantity	Cost (per quantity)	Cost ($)
Stepper Motor	2	12.99	25.98
Linear Coupler (4 pc)	2	6.66	13.32
Ball Bearing Bushings (4 pc)	2	4.245	8.49
8 mm Linear Rods (2 pc)	1	10.89	10.89
Fully Threaded Rod	1	13.76	13.76
Stepper Motor Driver	2	8.79	17.58
Bluetooth Transiever	1	8.39	8.39
M3 0.5x14mm Flathead Screws (	1	4.57	4.57
Nextion Touchscreen	1	112.3	112.3
12V 30A Power Supply	1	27.99	27.99
3 Wire power cord	1	17.25	17.25
File	1	6.45	6.45
8 mm Linear Rods (2 pc)	2	8.99	17.98
Fully Threaded Rod	1	12.98	12.98
Servo Motor (4 pc)	1	23.69	23.69
5V 5A Power Supply	1	10.76	10.76
3 Wire power cord	1	11.31	11.31
Digital Caliper	1	10.99	10.99
Stylus Pen	1	8.81	8.81
Electronics Box (Size Large)	1	17.99	17.99
Zip Ties	1	5.29	5.29
4-40 Phillips Screws-Hex Nuts As	1	15.07	15.07
6-32 Phillips Machine Screws	1	8.37	8.37
4-40 Threaded Heat-Set Inserts	1	11.95	11.95
Nextion Intelligent Series Touchs	1	120.81	120.81
6-32 Phillips Machine Screws 2-1	1	10.13	10.13
6-32 Phillips Machine Screws 3/4	1	8.49	8.49
Tablet Stand Holder	1	18.29	18.29
Breadboard Jumper Wires	1	21.52	21.52
Silicone Tubing	1	9.69	9.69
Electronics Box (Extra Large)	1	23.69	23.69
Arduino Mega 2560	1	20.99	20.99
Total Spent			634.78
Remaining			365.22

Table 26. Budget

Project Management

Task Distribution

Sponsor
Haim Weizman, PhD.
Senior Lecturer
Department of Chemistry and Biochemistry
University of California, San Diego

Sponsor Liaison, GUI Design and Analysis
Zaivy Gonzalez-Valencia

Safety Manager, Syringe Holder and Servo-attachment Design
Eden Detmer

Financial Manager, Electrical Containment and GUI Holder Design, 3D Printing
Shravan Suresh

Website Manager, GUI Design and Programming
Nhat Tang

Intermediate Milestones

Milestone 1: Assemble and test the unmodified Croatt Research Group's chemistry flow system (Risk Reduction).

Milestone 2: Assemble two unmodified Croatt Research Group's chemistry flow systems for future testing.

Milestone 3: Syringe holder design decision.

Milestone 4: Establish communication between the GUI and Arduino.

Milestone 5: Fully functional automated refill option.

Milestone 6: Electronics casing design decision.

Milestone 7: Implement real-time updated syringe position displayed on GUI.

Milestone 8: Implement dispense/withdraw only and continuous output options.

Milestone 8: Finalized GUI layout and design.

Milestone 9: Finalized flow system, including two assembled syringe pumps.

Risk Reduction Efforts

The risk reduction consisted of assembling and testing the unmodified Croatt Research Group's chemistry flow system. This was chosen as the risk reduction effort due to the team's need to be familiar with the existing design in order to make improvements upon it. Through building and testing the flow system, a foundational knowledge of the system was built which allowed for informed decision making going forward. Furthermore, a functional prototype was built which allowed for testing of new modifications to the design and additions to the Arduino code.

Additionally, performing this risk reduction made the team aware of the impacts that increased friction has on the measured flow rate. When assembling the initial system, the wrong diameter or linear rod was delivered. The delivered rod had a 10mm diameter in comparison to the desired 8mm diameter. Due to the time constraints, it was not possible to obtain a replacement for the rods. Therefore, in order to still complete the risk reduction, modifications were made to the 3D printed parts and to the assembly. The holes which the rods fit into were drilled out in order to fit the larger diameter. Additionally, teflon sleeves were used in place of the 8mm inner diameter linear bearings to allow the charriage to glide along the rods. While these changes allowed for a complete syringe pump to be produced and tested, a number of issues resulted from them. The largest issue encountered was excessive amounts of friction introduced by misalignment of the rods due to non-concentric drilling of the holes. With this misalignment of the rods, the carriage was unable to slide along them without significant resistance. This resistance was too much for the stepper motor to overcome and led to inaccurate flow rate measurements upon testing. Once the correct diameter rods were delivered and a new syringe pump assembly was built, these issues were resolved and made no impact on the performance of the system. However, it was useful to be able to observe these effects in order to identify any future problems due to friction.

Code Written

Arduino code:
https://drive.google.com/file/d/13izrdC9j5wuCZtK5Y7hM9LnQ8QrbMQze/view?usp=sharing

TFT file for Nextion Touch Screen:
https://drive.google.com/file/d/1xIcZnFLgrDMyTa6UvCiiy7ntjbgDRl2_/view?usp=sharing