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PRELIMINARY DESIGN REVIEW UPDATE AND FINAL PROTOTYPE DESCRIPTION

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Table of Contents

Project Background **5**
Literature Search 5
Relevant Terminology (AS) 5
Electrospinning Process (AR) 6
Syringe Pump (AR) 7
Syringe Pump Effects on Fibers (AR) 8
Users and Stakeholders (AR) 9
Patents (JM) 10
US7635349B2: Smiths Medical International 10
US7311879B2: Steve Hodson 11
US10391241B2: Deka Products LP 12
Current Products (SJ) 13
KD Scientific Syringe Pumps 13
Harvard Apparatus Syringe Pumps 13
New Era Instruments Syringe Pumps 14
Problem Statement (AS) **16**
Requirements (SG) **17**
Conceptual Design (AS) **21**
Concept 1 21
Concept 2 21
Concept 3 22
Concept Down-Selection (SG, JM, AR) **23**
Weighted Matrix (SG) 23
Pugh Matrix (SG) 25
Final Design Description **27**
Selection Criteria (SJ, AR) 28
Modifications (AS) 29
User Input (SG, AR) 29
Syringe Pump Mechanics (JM) 30
Circuitry (AR) 31
Task Distribution (SJ) 31
Functional Diagram (SJ, AS) **32**
Circuit Design (AR) **33**
Pseudocode Diagram (SG) **34**
References (AS, AR) **35**

List of Figures

Figure 1: Electrospinning setup with three major components. 6
Figure 2: Polymer solution (PEO in water) drop 7
Figure 3: KD Scientific 100 Legacy Syringe Pump 8
Figure 4: Jet Behavior 8
Figure 5: Effect of Flow Rate on Initiating Drop 9
Figure 6: Smith's Medical International Patent Design 11
Figure 7: Hodson's Patent Design 12
Figure 8: Deka Products LP Patent Design 13
Figure 9: Standard Infuse/Withdraw Pump 11 Elite Programmable Syringe Pump 14
Figure 10: NE-300 Just Infusion™ Syringe Pump 15
Figure 11: Concept 1 Diagram 21
Figure 12: Concept 2 Diagram 22
Figure 13: Concept 3 Diagram 22
Figure 14: Final Prototype Diagram 27
Figure 15: Final Prototype CAD Model 28
Figure 16: Ball Screw Mechanism 29
Figure 17: Calculations for Program 30
Figure 18: Functional Diagram for Final Prototype 32
Figure 19: Syringe Pump Circuit Schematic 33
Figure 20: Pseudocode Diagram for Final Prototype 34

List of Tables

Table 1. List of Requirements.. 17
Table 2. Weighted Matrix... 24
Table 3. Pugh Matrix 25

Project Background

Literature Search

Relevant Terminology (AS)

1. Syringe pump: A motor-driven precision pump that can use one or more syringes to deliver precise and accurate amounts of fluid [1].
2. Spinneret: A metal plate consisting of numerous small holes used to extrude polymer solution to form fibers. Streams of polymer are injected through the openings to produce filaments from polymer solution [1].
3. Collector: The conductive substrate that collects the charged fibers during the electrospinning process. The deposited fibers are conducted to ground which affects the amount of that are collected [1].
4. High voltage power supply: A direct current power supply that can be adjusted from 5 kV to 50 kV. The high voltage allows the repulsive force within the charged solution to become larger than its surface tension and a jet erupts from the tip of the spinneret [1].
5. Electric field: The physical field that surrounds electrically charged particles and exerts force on all other charged particles in the field. The applied voltage and working distance affect the extent of the electric field in the electrospinning process [2].
6. Electrode: The terminal through which electric current passes between metallic and nonmetallic parts of an electrical circuit. The spinneret nozzle acts as an electrode where a high electric field is applied.
7. Electrostatic force: Charges that are non-contact forces that move from one surface to another [2].
8. Surface tension: The tension of the surface film of a liquid caused by the inherent attraction of the particles in the surface layer. Reduced surface tension allows for the formation of smooth fibers.
9. Polymer: Any class of natural or synthetic substances composed of large molecules that are multiples of simpler chemical units called monomers, or molecules that can be bonded to other identical molecules.
10. Capillary tube: A tube with a calibrated diameter and length made up of thin, rigid materials where a liquid flows up into the tubes against gravity in a process called capillary action.
11. Taylor cone: A cone shaped deformation of the drops of polymer solution caused by the jet emerging from the needle of the spinneret. [3]
12. Nanofibers: Fibers that contain a large surface area to volume ratio and form due to the uniaxial stretching of the polymer solution in the nanometer range. They are used in the following products due to their unique physical properties: scaffolds, sensors, filters, membranes, batteries, protective clothing, and wound dressing [4].

Electrospinning Process (AR)

Electrospinning is an electrostatic fiber fabrication technique that creates nanoscale fibers by applying a strong electric field on a polymeric solution [5]. An electrospinning setup consists of three main components: a high voltage power supply, a spinneret, and a collector as shown in **Figure 1.**

The voltage source is used to create an electric field between a drop of polymer solution at the syringe tip and the collector. One electrode is placed in the solution and the other electrode is placed on the collector creating an electrostatic force. The polymer solution is led through the tube to the needle by the syringe pump [5]. The polymer solution is held in a capillary tube and subjected to an electric field to create a charged solution. When the applied voltage is increased, the electric field reaches a critical value and the repulsive forces created in the solution will overcome the surface tension holding the polymer solution together. A drop of the solution then emerges from the tip of the syringe as a Taylor cone at the tip of the spinneret as shown in **Figure 2.** The charged jet rapidly whips which aids in evaporating the solvent from the polymeric solution and travels towards the oppositely charged collector to creates fibers [6].

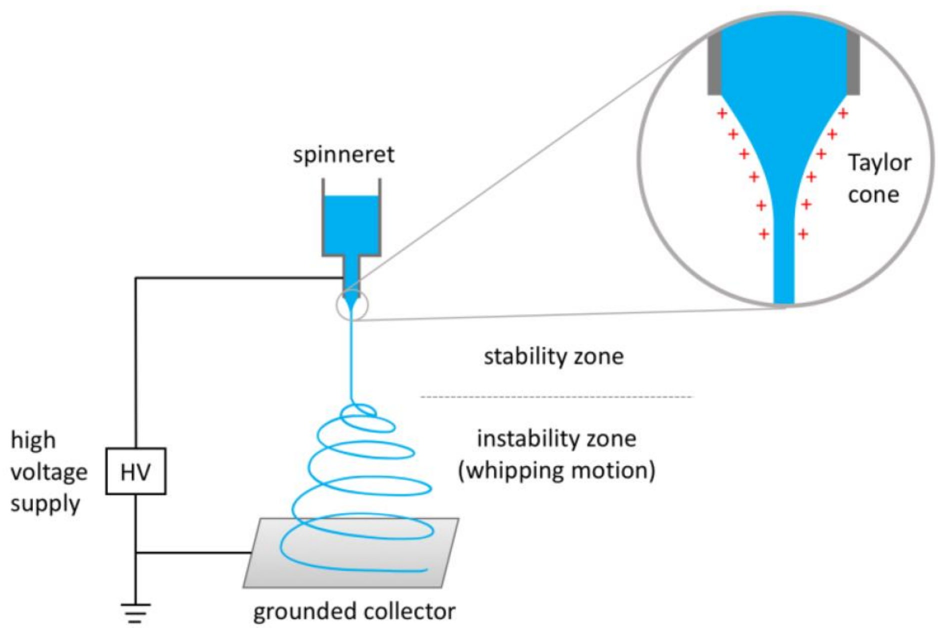

Figure 1: Electrospinning setup with three major components.
Positively charged polymeric solution is shown at the tip of the needle forming a Taylor cone [7].

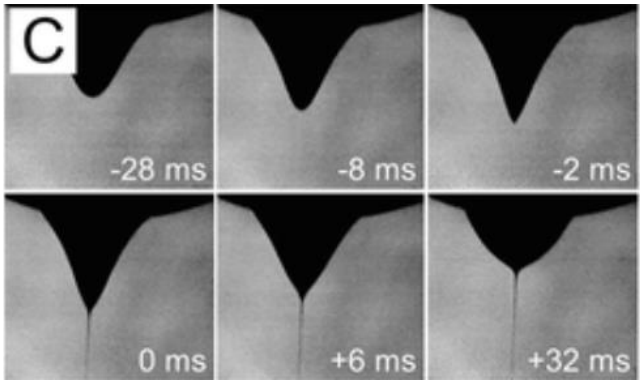

Figure 2: Polymer solution (PEO in water) drop changing to conical shape, followed by jet formation [8].

Syringe Pump (AR)

A syringe-pump is “a motor-driven precision pump that uses one or more syringes to deliver precise and accurate amounts of fluid [9]”. Syringe pumps used in laboratory or industrial applications are built to handle smaller volumes and very accurate fluid deliveries. There are different types of syringe pumps including: OEM module syringe pump, multi-syringe syringe pump, and high-pressure syringe pump [9].

In simple electrospinning setups, a high-pressure programmable syringe pump is used to push the solution at the desired rate [10]. **Figure 3** details the KD Scientific 100 Legacy Syringe Pump which can drive a single 10μL to 60 mL syringe [11]. The syringe pump retails for $1,267.41 and takes input for various parameters such as syringe size, volume dispensed, and flow rate [12]. The KD scientific syringe pump has accuracy within a .05% margin and can exert a linear force of 20lb [11]. Researchers do not necessarily need all the features incorporated into expensive and highly accurate syringe pumps. With limited funding and many projects, research facilities aim to reduce costs – one way is to provide a more cost-effective syringe pump for electrospinning setups.

Figure 3: KD Scientific 100 Legacy Syringe Pump

Syringe Pump Effects on Fibers (AR)

The syringe pump is used to control the flow rate, which is the volume dispensed per unit time. Control of the flow rate affects the deposition area, the fiber morphology, and jet initiation. As the flow rate increases, the area covered by the nanofibers (called deposition area) increases because there is more splitting in the initialing jet as shown in **Figure 4.C** [13]. The fiber diameter also increases when flow rate increases.

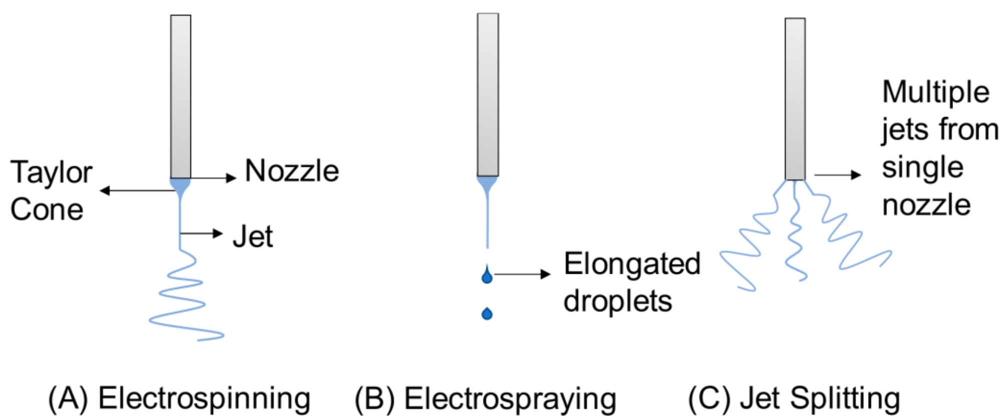

Figure 4: Jet Behavior

(A) Normal electrospinning: occurs at ideal flow rate
(B) Electrospraying: occurs at increased flow rate
(C) Jet Splitting: occurs at increased flow rate and when there is a high voltage: flow rate ratio

Citation:

When the flow rate is increased, different fiber morphologies can result due to the voltage to flow rate ratio. A low voltage to flow rate ratio causes the polymeric solution to be pushed out faster than the voltage can pull it causing beading or dripping. Beading or dripping is when the solution is ejected but all the solvent has not evaporated because of the high flow rate. Unspun droplets also occur at higher flow rates when the solution is ejected from the needle without being stretched to create a fiber. On the contrary, if there is a high voltage to flow rate ratio, the polymeric solution is pulled by the voltage faster than it is being pushed out by the syringe pump causing branched, splitting fibers.

Additionally, an increased flow rate can create different initiating droplets and shapes. In this study, the ideal flow rate was 0.5 mL/hr. In **Figure 5.A**, the flow rate was increased to 1.0 mL/hr and the droplets take on a more spherical shape and more droplets are unspun. In **Figure 5.B**, the flow rate was increased further to 1.5 mL/hr causing drops to accumulate and create an elongated shape and unspun droplets [14].

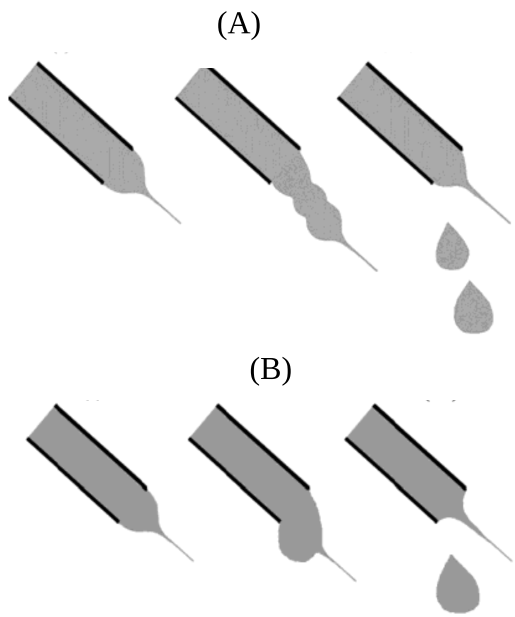

Figure 5: Effect of Flow Rate on Initiating Drop

Users and Stakeholders (AR)

Users:

- Companies producing any products with electrospun components use syringe pumps in their electrospinning setups to make their product.
    - This includes products such as scaffolds, sensors, filters, membranes, protective clothing, wound dressing, and catalyst [4].
- Research facilities and universities use syringe pumps in electrospinning setups to research various topics including drug delivery, tissue engineering, and protective clothing [15, 16].

- Syringe pumps are utilized by patients and healthcare providers for micro dialysis, organ/tissue perfusion, and fluid circulation [17].

Stakeholders:

- Manufacturers that make syringe pumps.
- Manufacturers that create components used to make syringe pumps.
- Consumers of any of the mentioned products.
- Patients receiving tissue engineered treatments using electrospun scaffolds or wound healing using electrospun fibers.
- Transport companies that will move the syringe pump.
- Engineering companies that design syringe pumps.

Patents (JM)

US7635349B2: Smiths Medical International

Smiths Medical International filed a patent on their syringe pump design that specifically focuses on their force sensor's ability to detect occlusions and the motor response to that occlusion. Another aspect of the invention is that the motor response to the occlusion is conducted by reversing the drive on the plunger to reduce excess pressure on the medication. An occlusion sensor typically detects the occlusion in the tube attached to the syringe tip. If excess force is detected, an alarm is generated, and the motor is reversed to reduce the force to about 10%. The claims in this patent include: the ability to receive a syringe, the application of force to drive the plunger, the detection of the force on the plunger, the response of excess force, and the use of an occlusion detector [18].

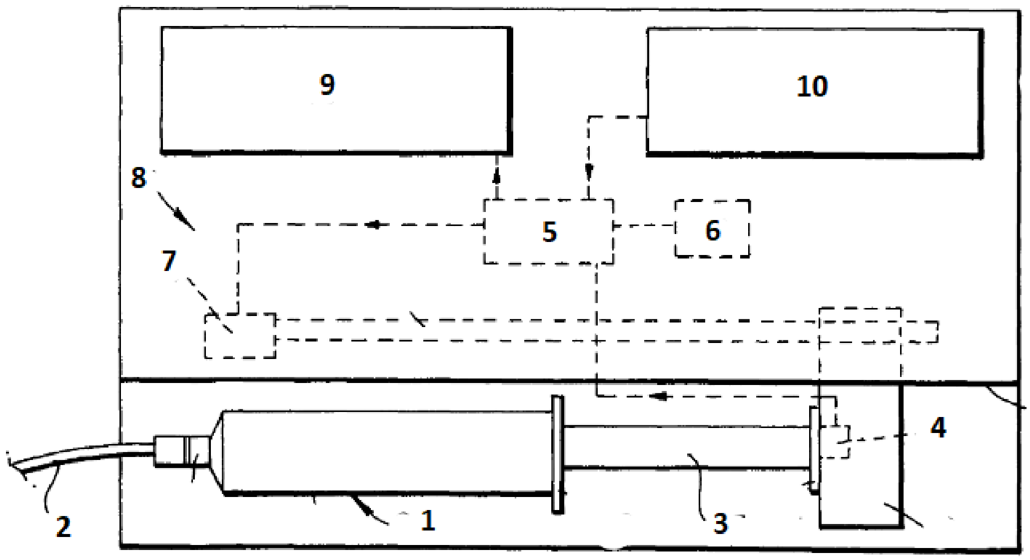

Figure 6: Smith's Medical International Patent Design

(1) Syringe, (2) Infusion Line, (3) Plunger, (4) Sensor, (5) Control Unit, (6) Memory, (7) Motor, (8) Driver Mechanism, (9) Display Panel, (10) Keypad

US7311879B2: Steve Hodson

Hodson filed a patent on his syringe pump design that focuses on the automation of the syringe pump to dispense the reagent based on changes in physical properties of the reaction mixture such as temperature or ion content. The design aims to reduce human monitoring when delivering reagents to a chemical mixture and create a closed-loop feedback system for the syringe to control the reagent dispensing. The claims in this patent include: a syringe driving mechanism, a logic control circuit to program the parameters of the pump dispensing, a barrel clamp for security, and at least one input jack for a probe to measure the physical properties of the reagent and send the required input signals to the logic control circuit for specifications on how much to dispense [19].

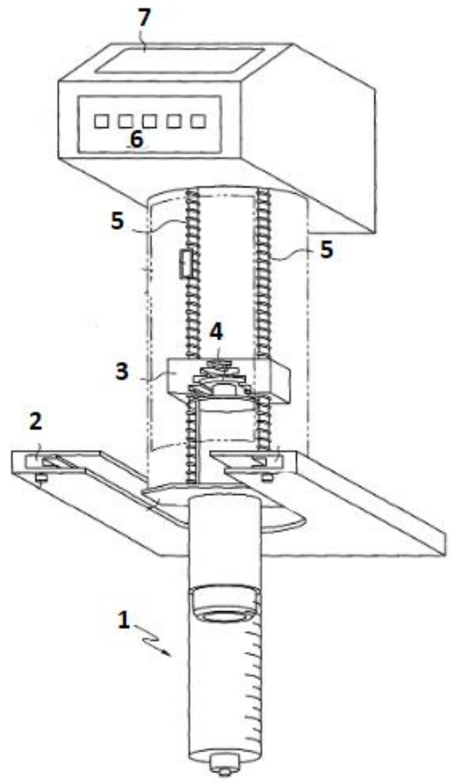

Figure 7: Hodson's Patent Design

(1) Syringe, (2) Barrel Clamps, (3) Drive Block, (4) Plunger, (5) Drive Shafts, (6) Keypad, (7) Display

US10391241B2: Deka Products LP

Deka Products filed a patent on their design of a syringe pump having a pressure sensor assembly. The design is made for hospital environments when using a syringe pump to deliver medications to patients. The syringe pump design includes a syringe pump actuator, a memory, and a processor. The design also uses an occlusion sensor and uses it as a constraint to test before the different phases in using the syringe pump. This is iterated through many syringe pumps as the model is designed to hold several syringes. The claims in the patent include a pressure sensor assembly that uses pressure sensors adjacent to the sensing surfaces of the plunger. The pressure sensors are used to estimate the fluid pressure within the syringe to mitigate any future occlusions based off whether the fluid pressure goes past the set threshold of the syringe [20].

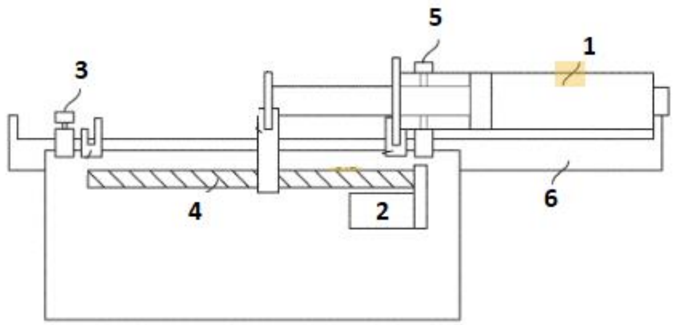

Figure 8: Deka Products LP Patent Design

(1) Syringe, (2) Motor, (3) Syringe Diameter Sensor, (4) Threaded Shaft, (5) Syringe Internal Diameter Sensor, (6) Syringe Holder

Current Products (SJ)

KD Scientific Syringe Pumps

KD Scientific has a wide range of different syringe pumps for various needs. They all feature a menu with an alphanumeric display to control the infusion/withdrawal rate and volume of fluid dispensed. The pumps automatically shut off when the set dispensed volume has been reached. The dispensed volume is also tracked and displayed during dispensation. The pumps can also be controlled externally through USB, TTL, or RS232C. Most KD Scientific syringe pumps can accommodate .5 µl to 60 ml syringes. The maximum linear force that the pump can exert is 13.6 kg. These pumps can operate with a flow rate of 1.28 pl/min to 88.28 mL/min. The prices of the syringe pumps vary based on the features they include. The programmable syringe pumps range from $4,500 to $9,500, depending on how new of a model it is. The infusion-only syringe pumps are cheaper, but their prices still range from $3,500 to $5,000. The KD Scientific 100 Legacy Infusion Syringe Pump is the cheapest option which costs around $1,300 (**Figure 3**). However, this model cannot be programmed [21].

Harvard Apparatus Syringe Pumps

The Pump 11 Elite Series from Harvard Apparatus includes single and dual syringe options that are programmable (**Figure 9**). They include a high-resolution touchscreen that allows for a friendly user interface. The single-syringe models can accommodate .5 µl to 60 ml syringes. These pumps can be externally controlled by USB and RS-485. These pumps also allow you to create, save, and run complex methods without needing external control. The flow rates that these models can pump are 1.28 pl/min to 88.28 ml/min. The average linear force for these pumps is 16 kg, but this force is adjustable by the user. A Pump Elite 11 syringe pump can cost up to $6,000. These pumps are much more advanced with many features that can be discarded when creating a cheaper alternative [22].

Figure 9: Standard Infuse/Withdraw Pump 11 Elite Programmable Syringe Pump

New Era Instruments Syringe Pumps

The SyringeONE syringe pump models from New Era Instruments is an economical single-syringe programmable pump. It features a keypad interface and can operate stand-alone or from a computer. This model can accommodate .5 µL to 60 mL syringes. The pump can operate with a flow rate of .73 µL/hr to 2100 mL/hr. The single-syringe model with infusion/withdrawal can cost from $800 to $1000. The infusion-only model only costs $325 (**Figure 10**), but it is not fully automated. The SyringeONE series include some of the most cost-friendly models that can be currently found on the market that maintains many features such as full programmability and inputting dispensed volume and flow rate. The display on this device is of lower quality, but it does not take away from the main functions of the device [23].

Figure 10: NE-300 Just Infusion™ Syringe Pump

Problem Statement (AS)

Electrospinning is a process used by researchers to create nanofibers for scaffolds. A key component of electrospinning is the syringe pump. Researchers at universities need syringe pumps to dispense polymer solution in a precise and controlled manner for electrospinning applications. Syringe pumps offer significant advantages over manual administration of polymer solutions and fluids, such as defined volumes of fluid, delivery of fluids at accurate speeds, and controlled fluid pressure. Inadequacies in flow rate and volume of dispensed fluid can cause inaccurate fiber morphology. However, the high cost of manufacturing a syringe pump limits the use of this device, especially for researchers that have limited funding for projects. A cost-effective syringe pump design is needed for promoting expansion of this technology.

Requirements (SG)

Table 1 displays the requirements for the new design of the syringe pump distinguished by their level of importance, with 1 being the most important.

Table 1. List of Requirements

Number	Requirement Name	Description	Justification	Importance (1-5)	Date Created	Verified?
1.0	**Cost**	The syringe pump must be less than $300.	The high cost of the current pump in use has been a severe limitation for the client's research.	1	3/7/2023	N
2.0	**Indication of Operation**	The syringe pump must have some sort of indication that it is being operated.	An indication of operation can provide added safety for the user by displaying that the pump is currently in use.	1	3/7/2023	N
3.0	**Stop Feature**	The syringe pump must have a way to stop the device within 3 seconds.	A stop feature would enhance the safety for the user and minimize the waste of polymer solution or the risk of creating the wrong fiber mat.	1	3/7/2023	N
4.0	**Start Feature**	The syringe pump must have a way to start the device.	The syringe pump must have a way to start the device because the current syringe pump can also be manually operated at times.	1	3/7/2023	N

Number	Requirement Name	Description	Justification	Importance (1-5)	Date Created	Verified?
5.0	**Compatibility with Syringe Material**	The syringe pump must be compatible with a 30 mL single use plastic syringe.	The current syringe pump is compatible with a single use plastic syringe. The client has specified the need for compatibility with this syringe type, as it is what is being used currently.	3	3/7/2023	N
6.0	**Number of Syringes During Operation**	The syringe pump must be able to function with at least one syringe during operation.	The client has mentioned that a dual-syringe pump is not necessary. Therefore, the newly designed pump must be able to operate with one syringe.	1	3/7/2023	N
7.0	**Level of Precision**	The syringe pump must have a level of precision of 2 significant figures in mL/hr.	To obtain the desired flow rate to produce higher quality fibers, a level of precision up to 2 significant figures is desirable.	1	3/7/2023	N
8.0	**Range of Flow Rates**	The syringe pump must operate under flow rates ranging from 0.3 mL/hr – 2.0 mlL/hr.	The typical flow rate range syringe pumps operate over is 0.3 mL/hr – 2.0 mlL/hr. The new design of the syringe pump must also be able to	2	3/7/2023	N

Number	Requirement Name	Description	Justification	Importance (1-5)	Date Created	Verified?
			operate under this range of flow rates to produce the desired fibers.			
9.0	**Flow Rate Control**	The syringe pump must be able to control the flow rate.	The current syringe pump in use can control the flow rate. In this same way, the new design of the pump must also have a way to control the flow rate.	2	3/7/2023	N
10.0	**Dimensions**	The syringe pump should be similar in dimensions to that of the current pump in use (9 x 6 x 5 in).	The current syringe pump in use can be easily transported and does not take up much room in the laboratory. Creating a device similar in size would enhance the user experience and make setting up the electrospinning process more convenient.	5	3/7/2023	N
11.0	**User Input**	The syringe pump must have a way for the user to input information.	The current syringe pump enables the user to input information on the device itself. The newly designed pump must also have this feature to enhance the	1	3/7/2023	N

Number	Requirement Name	Description	Justification	Importance (1-5)	Date Created	Verified?
			functionality of the syringe pump.			
12.0	**Unobstructed Syringe Holder**	The syringe holder must be constructed in a way so that the syringe pump is not obstructed or leaky.	Constructing the syringe holder in this way would allow for the syringe to be stabilized as it is being pushed. Volatile movements could potentially alter the set flow rate.	1	3/29/2023	N
13.0	**Computer Control**	The syringe pump must be computer controlled.	Computer control would allow for control of the device outside of the electrospinning box.	1	3/29/2023	N
14.0	**Smooth Moving Mechanism**	The syringe pump must not exhibit jerky movements.	Volatile movement could alter the set flow rate.	1	3/29/2023	N

Conceptual Design (AS)

Concept 1

Figure 11 displays the diagram of Concept 1 in a side view, top view, and frontal view. This design uses a lead screw actuator for the movement of the syringe pump, and contains a digital display, flow rate, volume, and precision buttons, guide rails, a pusher block, a power switch, and a USB-B connection port for the Arduino Uno. This design also has a button that can be used to start, stop, and pause the release of fluid, as well as incremental and decremental buttons that can be used to control flow rate and volume. The lead screw actuator is a desirable component of the design due to its low cost of around $96, ensuring the cost of the syringe pump is below $300 when factoring in the cost of the other components. An advantage of the lead screw actuator is its linear motion.

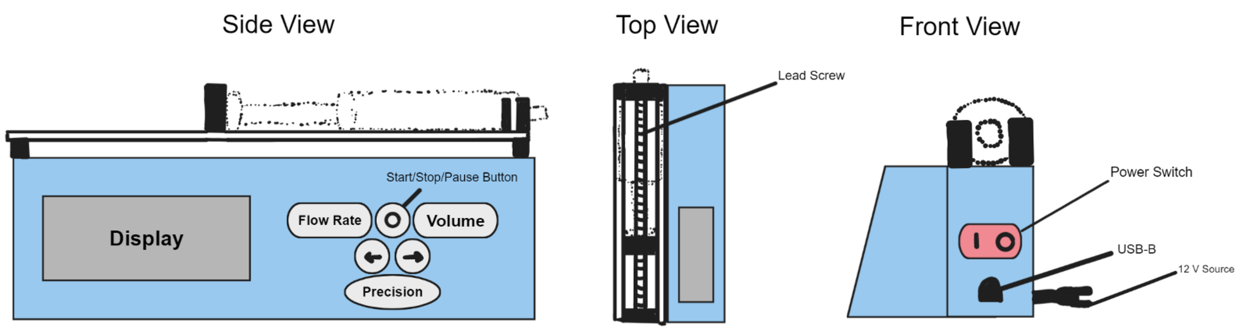

Figure 11: Concept 1 Diagram

Concept 2

Figure 12 displays the diagram of Concept 2 in a side view, top view, and frontal view. This design utilizes a rack and pinion actuator for the movement of the syringe pump, and like Concept 1, consists of a digital display, various buttons for controlling flow rate and volume, an LED indicator, pusher block, syringe holder, guide rails, a power switch, and a USB-B connection port. The LED indicator serves to give indication of when the pump is in use and the syringe holder helps stabilize the syringe for efficient fluid dispensing. An advantage of the rack and pinion actuator is its precise motion and low friction movement. The rack and pinion actuator is viable due to its low cost of $64, ensuring the cost of the syringe pump system is below $300.

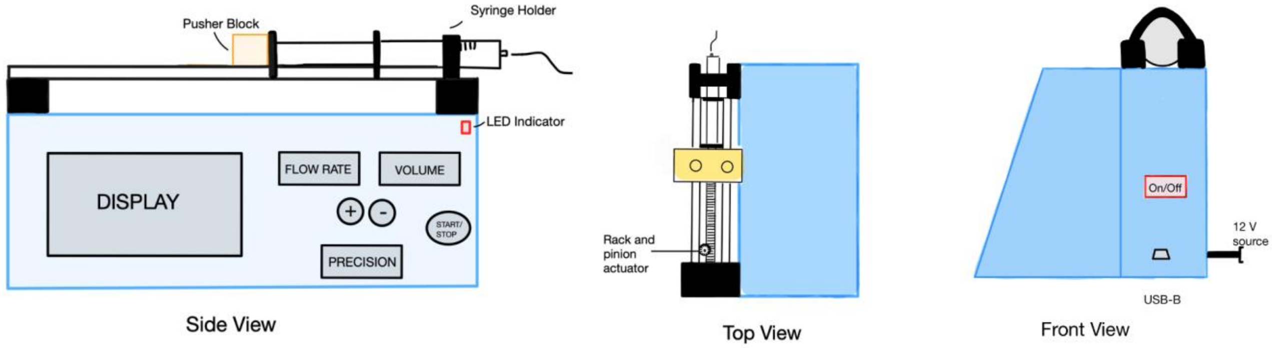

Figure 12: Concept 2 Diagram

Concept 3

Figure 13 displays the diagram of Concept 3 in a side view, top view, and frontal view. This design consists of a computer-controlled user interface, where the desired flow rate and volume can be entered. Concept 3 employs a ball screw actuator for movement of the syringe pump. The design also contains an LED indicator, pusher block, syringe holder, guide rails, a power switch, and a USB-B connection port. A significant advantage of the ball screw actuator is its low friction and efficiency, making it a preferable choice for the syringe pump system as it is cost effective and productive. The ball screw actuator is desirable due to its low cost of $79, ensuring the syringe pump system total cost is below $300.

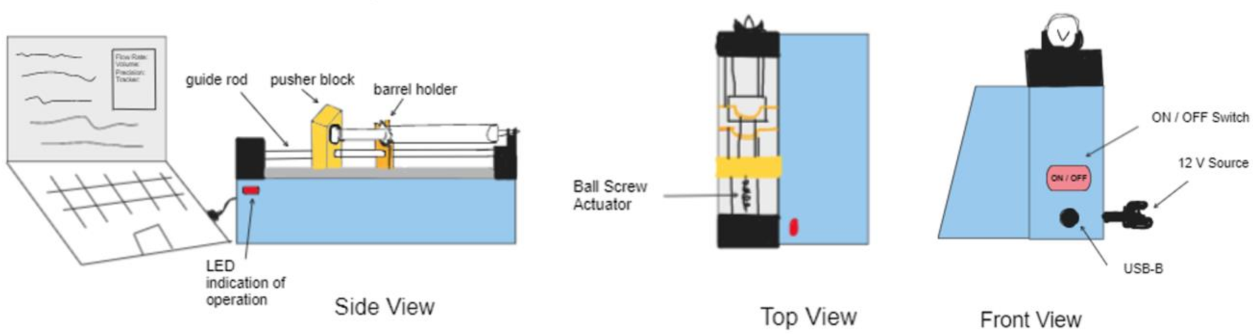

Figure 13: Concept 3 Diagram

Concept Down-Selection (SG, JM, AR)

To begin the down-selection process, our team decided to evaluate all the conceptual designs based on the stop/start functionality, user-input, constructed syringe holder, and moving mechanism. These specific requirements were chosen because we thought they would be the most impactful for the functionality of the syringe pump. The stop and start functions of the syringe pump hold great value because it provides a means for the user to control the device from starting or stopping abruptly. In addition to this, user-input is also an important requirement that adds to the functionality of the syringe pump. The conceptual designs showed different ways of inputting information such as through pressing buttons or typing a command through a keyboard. When evaluating the designs for this requirement, our team kept in mind the needed flexibility and usability for the syringe pump. The syringe holder is also an important aspect of the design of the pump because it provides the needed stability for the syringe to output the desired volumetric flow rate. The three conceptual designs were evaluated based off what could provide the most stability to the syringe to prevent volatile movements. The last requirement that the conceptual design of the syringe pumps was evaluated on was their moving mechanism. It is crucial for the syringe pump to have a smooth moving mechanism to ensure that the desired volumetric flow rate can be executed, and the fibers created are uniform in nature. The moving mechanism was evaluated based on the type of movement created, friction generated, and efficiency for moving the syringe. The ball screw was chosen for its efficiency, low friction, and smooth movement.

Weighted Matrix (SG)

Table 2 displays the weighted matrix used for down-selection of the three conceptual ideas our team came up with. A weighted matrix was used by evaluating the different designs against specific requirements, shown below on the table. A "weight" was then assigned to each requirement based on its level of importance. For this matrix, a scale of 1-3 was utilized, with 1 being the worst, and 3 being the best. The team then evaluated how well the different conceptual designs met each requirement. This concept score was then multiplied by the requirement weight and totaled for each design.

Table 2. Weighted Matrix

Scale: 1 = Worst, 3 = Best

Requirement	Weight	Concept 1	Concept 2	Concept 3
Stop / Start Function	3	3	3	2
User-Input	3	1	1	3
Syringe Holder	2	1	2	3
Moving Mechanism	3	2	1	3
Totals		**20**	**19**	**30**

Concept 1 consisted of buttons to control the stop and start functions, as well as user input. The team concluded that the buttons were an easy way for the user to control when to start and stop the device in comparison to a user having to know what commands to type on a keyboard to achieve the same function. However, the buttons acted as an obstacle when inputting other information such as volumetric flow rate. It would take the user much longer to input the same information through buttons than it would for the user to type the information. In addition to this, if one digit was inputted incorrectly, the user would have to start inputting information again from the beginning. The syringe holder of this device acts more to prevent the syringe from sliding off the top of the device, however, it does not help prevent jerky movements that could occur from the pusher block pushing it. Lastly, concept 1 utilizes a lead screw, which consists of a screw shaft and a nut with threads on it. A lead screw allows for linear motion and has a low cost. However, it is not an efficient option for a continuous application because as the threads move against each other, there is significant friction and energy loss.

Similarly to Concept 1, Concept 2 also implemented buttons for both user-control and the stop and start functions. The syringe holder for this device had a hook feature that went across the top of the syringe. A concern for this concept was its ability to prevent the syringe from sliding out from the front as the pusher block pushed the syringe forward. However, the device also contained a barrel holder which helped stabilize the syringe. This concept design incorporated a rack and pinion for its moving mechanism. The pinion is a round gear and the rack is a straight piece. The teeth of the pinion fit into the rack, allowing for the rack to move linearly when the pinion rotates. Although the rack and pinion provide precise motion in unlimited length, smooth, low-friction movement, and is long lasting, it has limited mounting options and can take up too much space on the device. In addition to this, although the teeth mesh together, there is a small gap where they fit together, causing a loss of energy.

Lastly, Concept 3 differed from the previous two conceptual designs because it did not implement buttons to control any aspect of the device. Instead, this design utilized a computer to control user-input and the stop/start functions. As mentioned before, user input on a keyboard provides a better user-experience, however, it could serve as a limitation for starting and stopping the device. The team decided that user-input control on things such as volumetric flow rate and volume held a greater importance than a stop or start button. In addition to this, the syringe holder on this device has a piece that holds the tip of the syringe in place. The syringe is also stabilized with a barrel holder that keeps the barrel flange secured on the device. This conceptual design utilized a ball screw. A ball screw is similar to a lead screw because it also consists of a screw shaft and a nut. However, there are balls that roll between the matching grooves within the nut, minimizing the friction experienced by the system.

Pugh Matrix (SG)

Table 3 displays the Pugh Matrix generated from the three conceptual designs. This was the second down-selection tool that our team utilized to pick a final concept to proceed with. A Pugh Matrix is similar to a Weighted Matrix, but it also allows for the comparison of ideas against a "benchmark" or reference concept. Each concept is then compared to the benchmark design for every requirement. The benchmark design is denoted by "D." If a solution is better than the benchmark solution, it is marked with "+." Alternatively, if a solution is worse than the benchmark solution, it is marked with a "-."

Table 3. Pugh Matrix

Scale: (+) = Better, (-) = Worse

Requirement	Design 1	Design 2	Design 3
Stop / Start Function	+	+	D
User-Input	-	-	D
Syringe Holder	-	-	D
Moving Mechanism	-	-	D
Totals	**-2**	**-2**	**D**

From **Table 2**, our team found that Concept 3 had the highest weighted total. Using this information, we approached the Pugh Matrix by setting Concept 3 as the benchmark solution. When comparing the stop and start function of Concept 1 and 2, which both utilized buttons, to the benchmark solution, the team agreed that buttons for this function made the device easier to use for a user. Conversely, the team agreed that user-input with buttons was more tedious than through a keyboard, seen on Concept 3. The syringe holders of both Concept 1 and Concept 2 had a negative aspect which did not successfully stabilize the syringe in place as well as Concept 3.

Lastly, the ball screw actuator seen on Concept 3 was the best option when compared to the lead screw and pinion and rack actuators due to the system's low friction and reasonable cost.

Utilizing the Weighted Matrix and Pugh Matrix allowed our team to easily see that Concept 3 would be the best design to use for the rest of the engineering design process with. The down-selection methods chosen helped clearly define crucial requirements that could impact the functionality of the device, as well as pick the most versatile device that could satisfy these requirements.

Final Design Description

Figure 14 details the final prototype diagram in a side view, top view, and frontal view. The components of the syringe pump system are labeled and further defined in the *Syringe Pump Mechanics* section. **Figure 15** displays the syringe pump prototype as a computer-aided design (CAD), which shows the design as a 3D model.

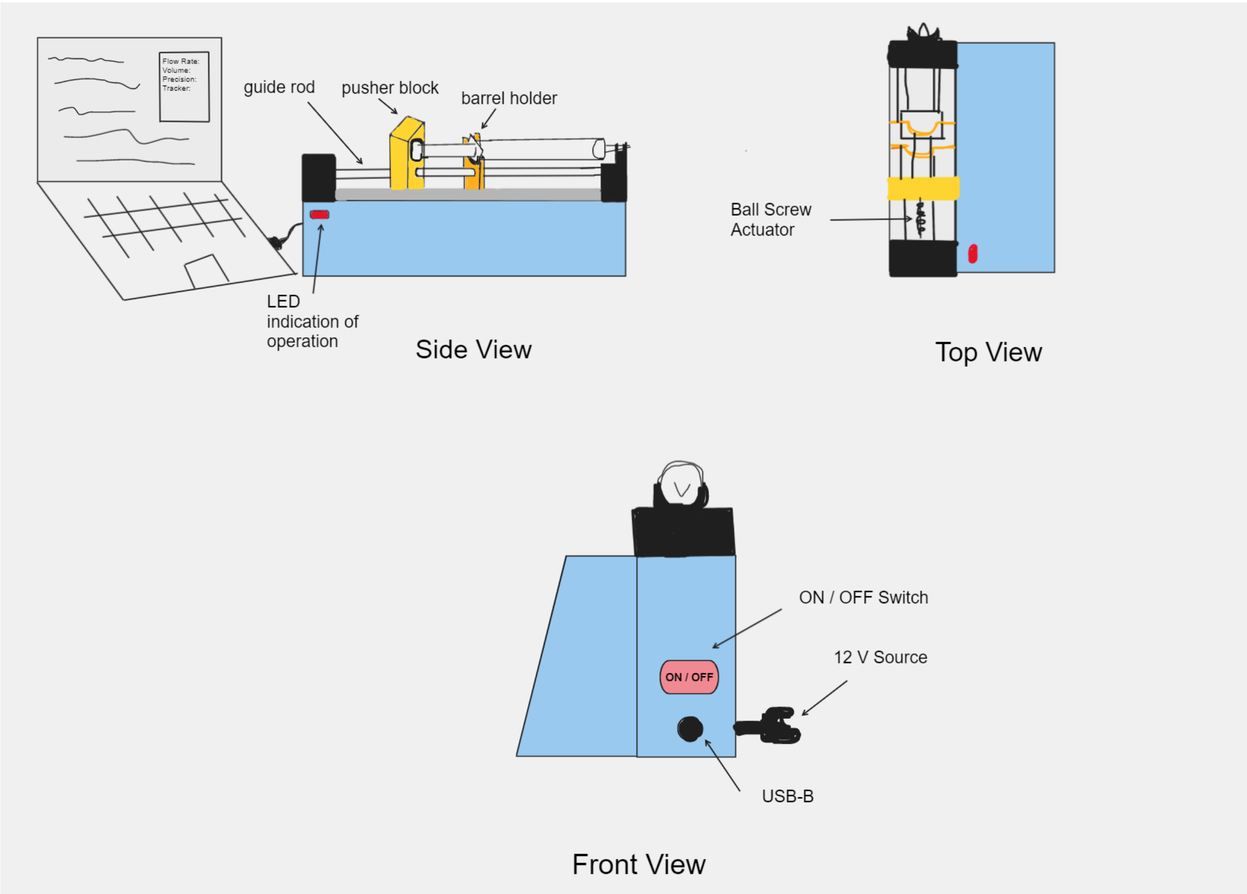

Figure 14: Final Prototype Diagram

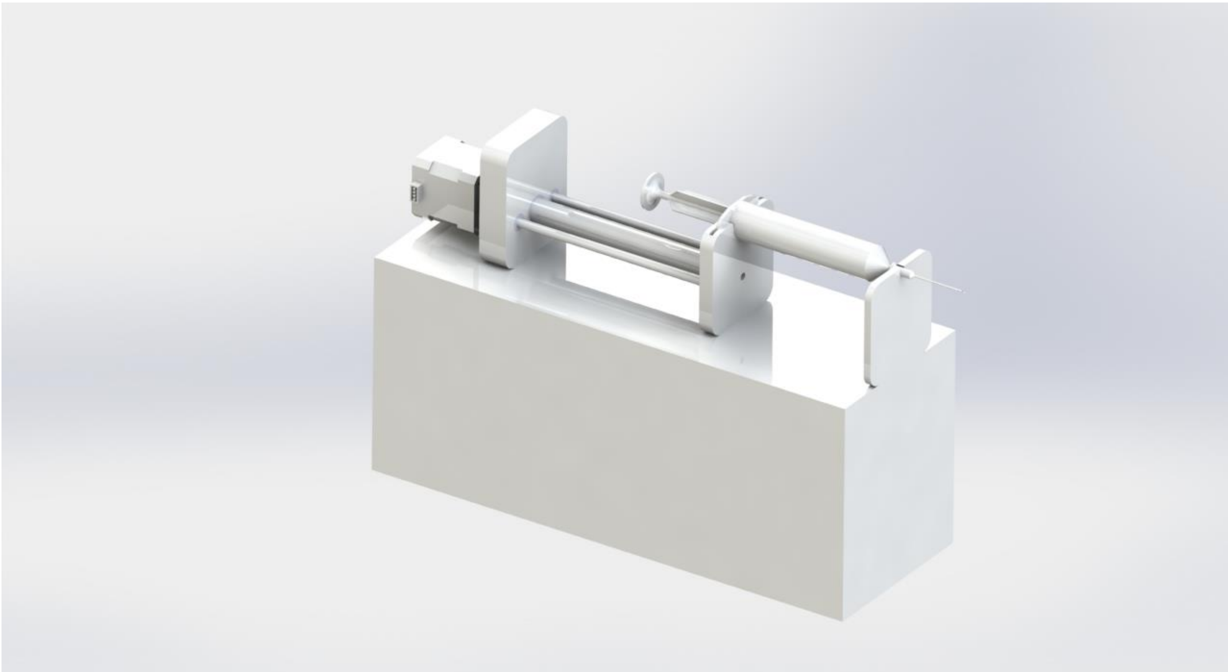

Figure 15: Final Prototype CAD Model

Selection Criteria (SJ, AR)

There are several key reasons why we chose Design 3 over the other two designs. Design 3 utilizes the pressing of a key on a keyboard to start and stop the device entailing a small inconvenience. Our other design ideas use a push button on the device to start and stop the device. Although this design was deemed more difficult for the user to start and stop the device, it did not prove to be a major inconvenience to type in a single character for start and stop of the device. It was also agreed that it would be more difficult to implement a start/stop mechanism on the frame of the device compared to just controlling this function on the computer.

Design 3 was determined to have the easiest method of inputting the flow rate and dispensed volume. The user can type their values directly into the interface associated with the computer-controlled syringe pump. In the other two designs, one would have to use left and right keys to cycle through digits until the correct value is observed on the display.

Design 3 also had the best method of holding the syringe in place. It has a piece that holds the flange of the syringe in place as well as a piece that holds the tip of the syringe up. This appeared to be the easiest to build and the most secure method of holding the syringe. Design 2's syringe holder did not prevent the syringe from sliding off the device when the plunger is being pushed. Design 1 had a simple way of holding the front face of the syringe, but it was agreed that the syringe had too much freedom to move in this design.

Finally, Design 3 had the best actuator utilized in its design, the ball screw, which is the most efficient in linear motion when compared to a lead screw or rack and pinion actuator which are used in the other designs. Although a ball screw actuator is slightly more expensive, it is more durable and efficient because of its minimized friction of the ball nut against the screw. The ball screw has ball bearings inside the nut that roll inside the grooves of the screw as shown in **Figure 16**. The ball screw provides a smooth, precise, and reliable movement attributed to the ball bearings. Additionally, ball screws have a high load capacity [24].

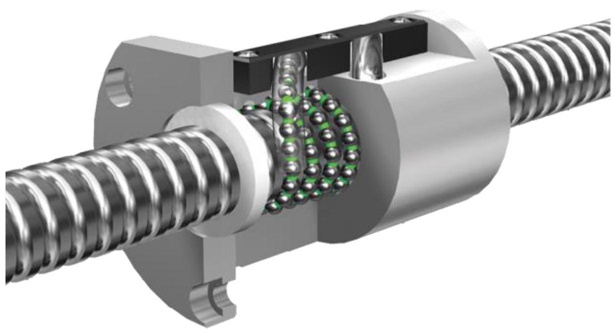

Figure 16: Ball Screw Mechanism

Cross section shows nut containing small ball bearings inside

Modifications (AS)

The initial model consisted of a syringe tip holder that would stabilize the syringe tip from underneath the tip. After further consideration, the syringe tip will be held in place by using a plexiglass plate with a hole drilled into it that matches the size of the syringe tip. This ensures the syringe tip is stabilized and held in place on all sides, rather than just the bottom.

User Input (SG, AR)

To create a highly functional syringe pump, an efficient means of getting user input is necessary. The interface asks the user to input a volumetric flow rate in units of mL/hr which is a top requirement for the client. The program then converts the flow rate (mL/hr) to rotations per minute (rpm) using the calculations shown in **Figure 17**.

$$\dot{V} = VA$$

$$V = \frac{\dot{V}}{A}$$

$$\dot{V} = flow\ rate\ \left(\frac{m^3}{s}\right)$$

$$V = velocity\ (\frac{m}{s})$$

$$A = area\ (m^2)$$

$$\frac{m}{s} \cdot \frac{1\ turn}{5 \times 10^{-3} m} \cdot \frac{60s}{1\ min} = rpm$$

Figure 17: Calculations for Program

After inputting the flow rate, the user can control when the syringe pump turns on and starts dispensing the polymeric solution at the decided flow rate. Additionally, the user can control when the pump turns off if needed. Otherwise, the device will automatically stop dispensing once the solution runs out.

In addition to the volumetric flow rate, the program also asks the user to input the desired volume to be dispensed. This allows the program to automatically stop dispensing the solution. The time, in hours, is calculated by dividing the volume by the volumetric flow rate. The time in hours is then converted to milliseconds. A delay is then implemented which allows the pump to run for a set amount of time before the pump stops.

Syringe Pump Mechanics (JM)

In designing the syringe pump, we had to make sure that the model that we are creating would be feasible for the scope of this project. We were given a NEMA 17 stepper motor, a 5 mm coupler, ball bearings and metal rods for the railing. We ended up ordering a ball screw and an additional coupler to adapt the screw that came with the ball screw set and with our stepper motor. We first set the stepper motor to the leftmost side of the syringe pump. We attach its axle with the 5 mm end of the coupler and attach the main screw to the other end of the coupler. We created three plexiglass blocks that will be used in the syringe pump. The first block is the push block, and it will function as the pushing mechanism of the syringe's plunger. There are three holes drilled at the bottom with two small holes for the guide rods and one bigger hole in the middle for the ball screw. When drilling the two holes for the guide rods, we had to also account for the thickness of the ball bearings that will also be attached to the push block. They are used to decrease any friction between the holes of the push block and the guide rods when the push block goes through linear motion. The ball screw and ball bearings will be attached to the push block throughout the syringe pump process. The second block is for holding the syringe flange by creating a slit between two blocks of plexiglass. There will also be three drilled holes at the bottom of the syringe holder. However, the dimensions will be smaller in comparison to the push block because the holes are for the guide rods and the main screw only. The height of the syringe holder will also be smaller to properly stabilize the syringe flange. The last block is the syringe tip holder. This block is about the same height as the syringe holder block and only has a semicircle indent at the top to hold the syringe tip.

Circuitry (AR)

The final design uses an Arduino Uno, Arduino Motor Shield Rev3, 9V battery, LED, resistor, and NEMA 17 stepper motor. The stepper motor is used to actuate the ball screw which converts rotational motion to linear motion. Stepper motors are effective in controlling speed precisely as the programmer can dictate the number of steps per revolution of the motor. Additionally, the programmer can control the number of steps or the angle through which the motor rotates. To program the motor, the design uses an Arduino Uno as the microcontroller to control the motor speed, the duration the motor runs, and when the motor stops. Additionally, using a microcontroller allows the user to have control over the motor as mentioned in the user input section. The motor shield is used to amplify the Arduino's amperage and voltage to sufficiently power the motor. The 9V battery is necessary for the circuit to operate. The LED needs a resistor and is used to indicate if the syringe is operating.

Task Distribution (SJ)

Sonali and Aiman are creating the software and circuitry for our device. They are programming the Arduino Uno to be able to receive input and rotate the motor at the desired speed. Joseph, Akhila, and Siddarth are working on the hardware for the design. This includes the construction of circuitry housing, the syringe holder, and the assembly of the pusher block with the actuator using plexiglass, metal railings, and a ball screw system. After measuring the parts, Akhila and Siddarth focused on cutting and gluing the parts together while Joseph worked on creating the CAD model of the components. Once the software, circuitry, CAD modeling, and the housing of the syringe and circuitry is finished, Joseph, Sonali, and Aiman will join Akhila and Siddarth in the assembly of the final product. The group will work collectively on the assembly of the actuator with the pusher block, as well as the full integration of the software and hardware components of the device. We will test the device multiple times and collaborate as a group to fix issues that arrive in preliminary testing.

Functional Diagram (SJ, AS)

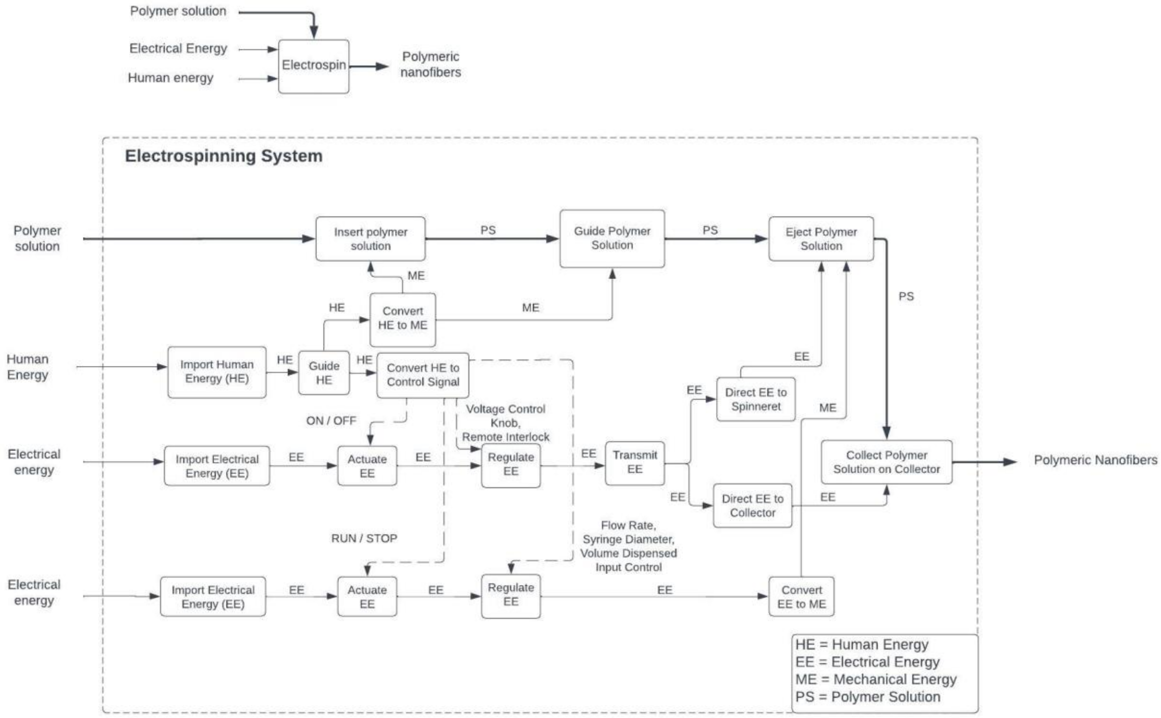

Figure 18: Functional Diagram for Final Prototype

Circuit Design (AR)

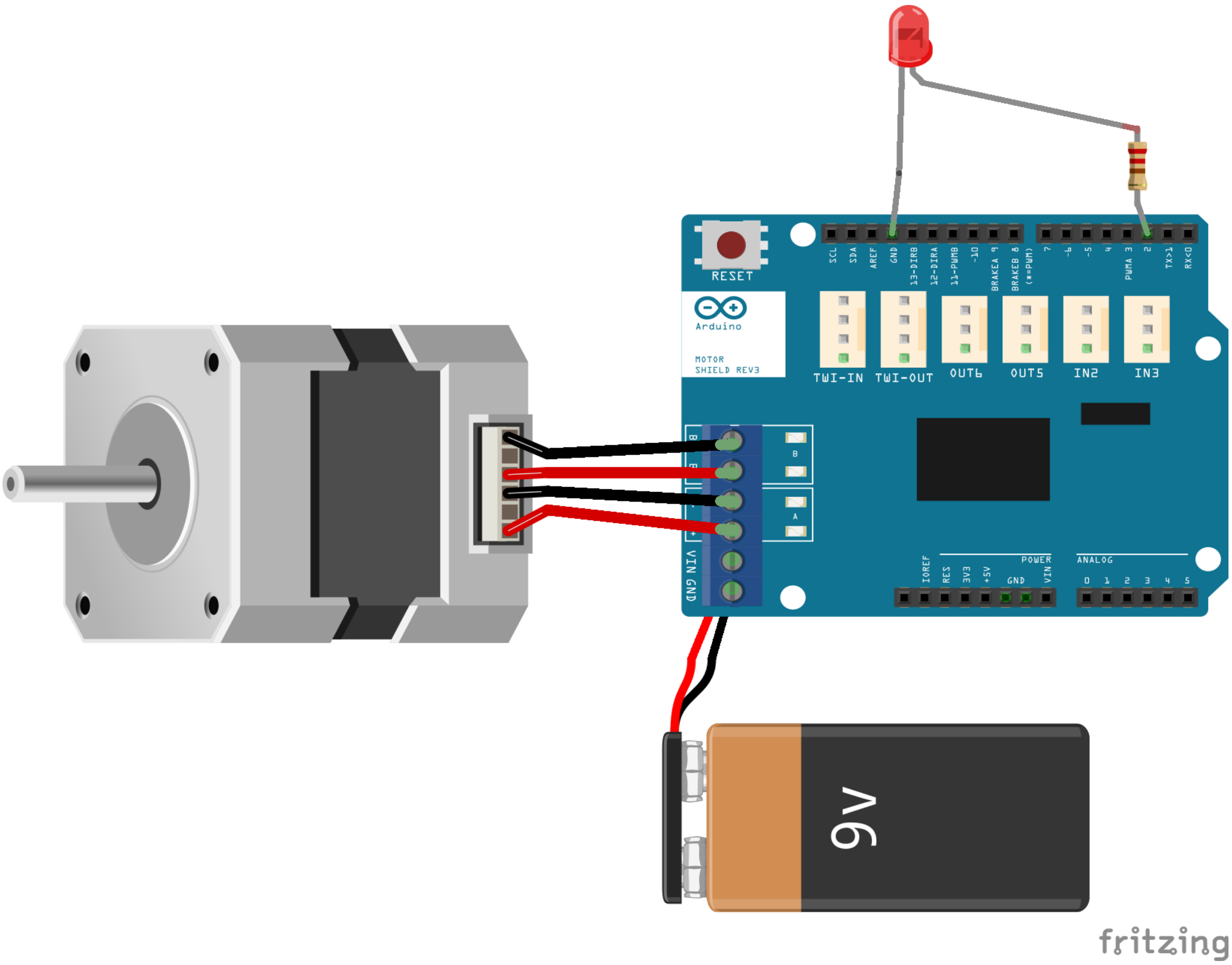

Figure 19: Syringe Pump Circuit Schematic

The motor shield is directly connected to the Arduino Uno (not shown).

Pseudocode Diagram (SG)

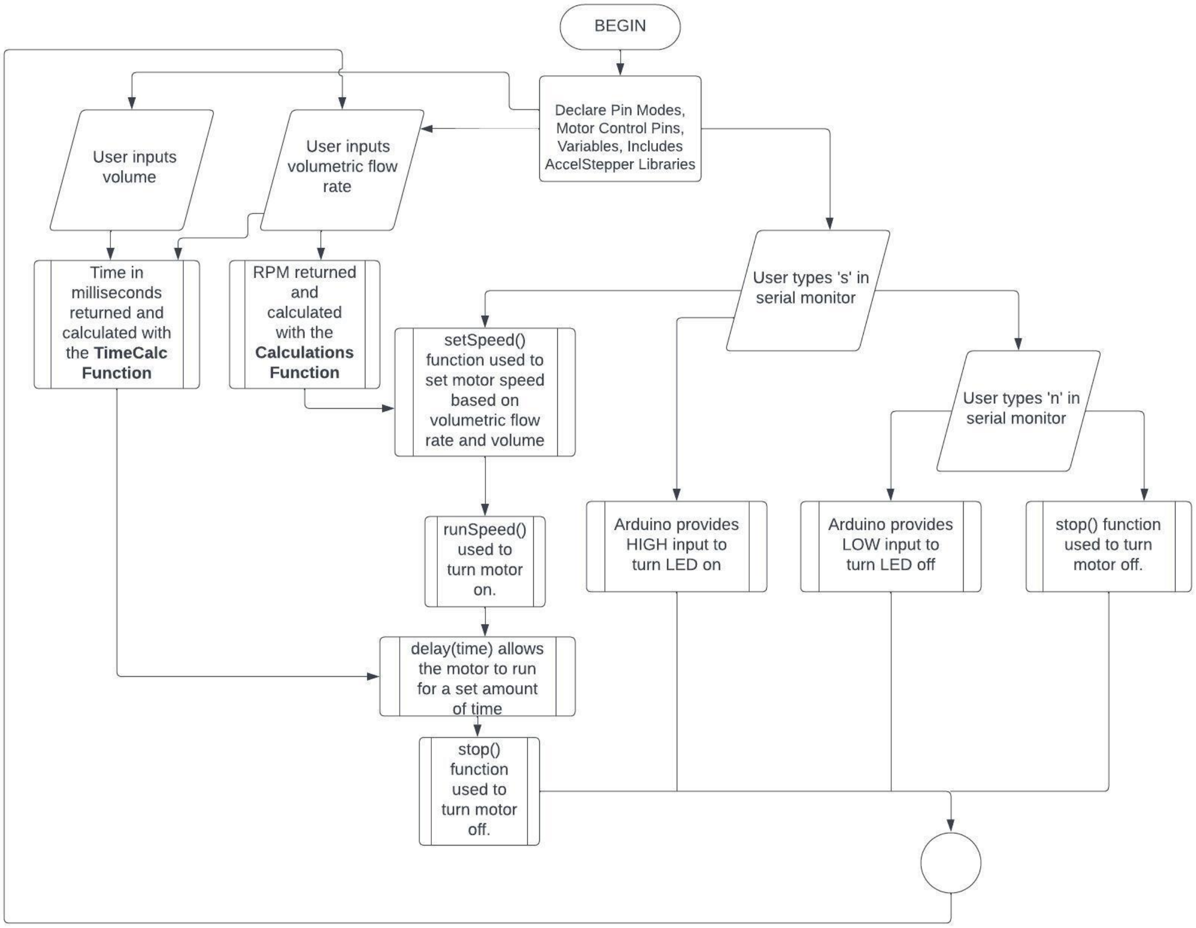

Figure 20: Pseudocode Diagram for Final Prototype

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