12T: Automated Sample Dispenser Final Design Proposal

Team 126
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The Faculty of Engineering and Applied Science
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Executive Summary

The following report displays the design process of an automated fluid dispenser (AFD). An AFD is a device that is integral in the pharmaceutical industry; it can formulate specifically concentrated solutions used in medical practices. The design we have created is built primarily out of acrylic and 3D-printed plastic and will function without human aid almost entirely – apart from the start button. It will dispense different amounts of powder and liquid to create solutions with different concentrations with precision.

The major constraint defining this project depends on its ability to run without human interaction. The design uses an Arduino to rotate the device that is responsible for dispensing finite amounts of powder, a motor with specific gear ratios to rotate the turn table, and a pump to accurately dispense the necessary values of water into the test tube. The design must take extra precautions from a safety perspective, as many of the subfunctions require complex electronics to run and the exposed wires must be protected from all water sources. Another important constraint is the cost of materials and the limitations on the parameters of the design. The design cannot be over 200x200x210mm and must be created using a limited number of resources: groups may only use 30 000mm^3 3D printer filament with a printing time of less than 120 mins, and less than 600cm^2 acrylic. This proved difficult as the design required cutouts in the parts to meet the acrylic requirement; however, it was eventually a challenge conquered through careful editing of the original parts.

The design process began with reviewing the necessary components of the system, and how the individual parts must work to properly create a successful design. It was then important to discuss all the possible designs for each of the subfunctions to be certain the selected designs were optimal. The final design decided upon is comprised of 5 main subfunctions: a turntable that allows the test tube rack to rotate, a powder dispenser that accurately dispenses specific amounts of powder, a water pump that dispenses accurate amounts of water without impacting the electronics, a stand for the device that supports the machinery effectively while being efficient with both material and cost factors, and a gear ratio box that allows for the turn table to spin at the desired rate for the design.

The project then entered the testing phase of the process, in which the machine was built, involving changes to the design to accommodate the real-world design flaws that were not visible in SolidWorks during the theoretical creation stage. This involved small detail changes; namely, designing new holes in the pieces for them to fit together properly. While the physical design was being crafted, the code to allow the entire process to run was being written to include a method for dispensing each quantity precisely, a device that allows the turntable to stop, and the performance of the start and emergency stop buttons. After these changes were made, the design was functioning properly within the constraints and was ready for the evaluation process.

The testing evaluation consisted of four major tests: the performance of the entire design, the accuracy of the powder dispensing, the accuracy of the water dispensing, and the usage of the emergency stop button. The design met all the requirements required to pass the testing examination, having a fully functioning complete design and a working emergency stop button.

Overall, the final design was optimal for the constraints put in place for this project. It met all the requirements integral to its functionality and did so within the bounds of the safety and material requirements. In order to make this design optimal for a hospital setting, there would be many revisions important to have a perfectly accurate design. However, through the lens of the APSC 101 course, this final design was well crafted.

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Problem Description and Definition

The overall goal of this term-length construction project was to create a working prototype of an automated fluid dispenser that will be used to respond to the needs of HumanEng Inc. By having the ability to dispense powder and saline without human contamination, a solution of aqueous naloxone hydrochloride dihydrate will be accessible for its use in the treatment of opioid drug usage, which is a leading cause of death worldwide [1]. The system must also be able to operate autonomously, such as to ensure workers are not exposed to the API in either the solid or solution form [1]. The primary client is HumanEng Inc., a fictitious university spinoff focused on socially conscious product development. The end-users, in this case, are researchers and pharmaceutical professionals involved in Phase III clinical trials for naloxone hydrochloride. The stakeholders include regulatory bodies overseeing drug development and, indirectly, the broader public affected by the opioid epidemic. One crucial facet involves the role of government in controlling safe drug usage. This extends to considerations about how such initiatives may affect individuals in lower-income situations or those lacking access to healthcare. The potential benefits of a large-scale project addressing drug use issues could have a cascading effect on the welfare of marginalized populations. In other words, access to healthcare emerges as a key focal point of this project.

Sustainability considerations are addressed using 3D printing and laser cutting technologies for production, emphasizing scalability, and minimizing environmental impact through reduced amounts of waste and energy consumption of alternative options such as polymer injection moulding [2]. To ensure compatibility with pharmaceutical standards and Health Canada safety regulations [3], the device must also adhere to strict guidelines. A complete set of detailed requirements for this system is seen on the *Design Checklist* page of the project instructions.

The project presented in APSC 101 demonstrated what types of challenges engineers encounter when solving problems and creating designs. Also teaching useful workforce skills such as communication, collaboration, and the construction of unique solutions for problems that are encountered. There are several larger challenges in this project which include creating the design of accurate powder dispensing, the turntable rotation, the gearbox and determining the location of the vital electronics.

The challenge of accurate powder dispensing required a deep understanding of the properties of powder behavior, as well as precision in the automated dispensing mechanism to ensure reproducibility of concentrations. The turntable rotation presented challenges in terms of mechanical design to guarantee consistent positioning and thorough mixing of the solutions in each test tube. The gearbox design required careful consideration to ensure smooth and reliable rotation without compromising accuracy or space. Determining the optimal location for vital electronics involved balancing accessibility for maintenance with the need for protection from spills through sealed electronics.

Moreover, as detailed in the fictitious requests outlined in week six, it is important to consider not only theoretical functionality, but also the potential for human error, the importance of aesthetics, the accessibility for incoming personnel who require training, and the value in easy transportation. The optimal theoretical design does not just encompass functionality, but also user-friendly subfunctions, and general accessibility to those who will be using it. It is important to value the audience, not just the product from the eyes of an engineer.

Prototype and Testing

Many decisions made throughout the course of the design process were very important to the success of the final prototype. One of the most drastic changes made was the design of the powder dispenser - its role vital in the overall functionality of the AFD. There were many designs for the powder dispenser, one of which is shown in Figure 1. These were the best two designs that were created and the key decision that led to the final design was the possible issue with overhanging components in Figure 1. This proved to be a problem as well with the friction that would be created while the servo would move the platform to both holes. These realizations led to the final design which limited both the friction and the overhanging components. After the completion of the final powder dispenser design, the prototypes for the rest of the subfunctions were created smoothly. The turntable went through processes of trial and error in order to minimize friction. As well, the final design implemented BB balls used in a baring to allow the base of the test tube holder to rotate freely sitting on top of the base that is connected to the peg board. The limit switch was placed on the base holding the test tube rack since its placement would be stable enough to be reliable. As both the powder and turntable subfunctions were being finalized, the designs of the mast and liquid dispenser had to go through necessary changes to account for the overall material usage. The original design for the water dispenser can be seen in Figure 2. However, this design proved unnecessary, and a water reservoir was created using alternate resources to preserve materials. Moreover, the pieces of acrylic used throughout the design had intentional cutouts created to maximize the area of acrylic given for the project. When each of the subfunctions was finalized, the design was fit together to create a completed prototype, all of the functions working together efficiently.

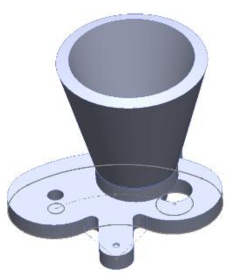

Figure 1: Original powder dispenser proposal viewed in SolidWorks.

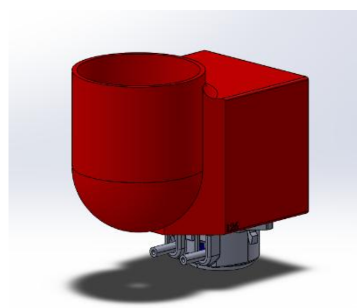

Figure 2: Original water dispenser proposal viewed in SolidWorks.

The final design is shown in Figure 3 and Figure 4, Figure 3 displaying the design built in SolidWorks, and Figure 4 shows the design built with the actual materials. The powder dispenser is shown in Figure 5, which includes the servo and the powder dispenser that was printed.

The final powder dispenser design had two main pieces. As seen in Figure 9, a small funnel built into a hollow, horizontal cylinder shape, with the hole in the bottom of the funnel lining up with a hole through the side of the horizontal cylinder. In Figure 10, the second piece is a smaller, solid cylinder fed through the tubular center of the funnel apparatus. The solid cylinder has an incomplete hole resembling a scoop, and it holds exactly one gram of powder. The secondary cylinder attaches to the servo, rotating the scoop holding the powder 180 degrees to dispense the finite amount of powder out of the bottom of the primary hollow cylinder. This process is repeated until the full dispensing is complete, in increments of 1g.

The turntable, shown in has the test tubes held in place by holders in the bottom and in the middle. The base of the turntable is comprised of two key pieces: the first is a solid base printed using 3D materials, with supports at each quarter of the circle including pegs to attach it to the pegboard and hold the entire design in place, and an inner ring made out of thin plastic, designed to be smaller than the base but large enough to hold the BB's in place to create a baring for the turntable to rotate on top of. Through the sturdy base, there is an axel-sized hole directly in the middle, designed to connect the gear placed below the peg board to the turntable itself, via an axel inserted through the bottom of the peg board. The gear connected to the base was the last gear in our gearbox, connecting the full turntable design to the gear system. The gear system was entirely placed below the pegboard and connected to the motor which sat on top of the pegboard via axle.

The final design for the mast and water dispenser is shown in Figure 7. This shows the place for the water tank and pump, the water tank being a small plastic water bottle. This also shows the Arduino which was placed above all the water and possible hazards. Finally, the gearbox is shown in Figure 8. The gearbox is similar to the original design and has a gear ratio of 1:600. The gearbox is attached below the peg board using the supports seen on the side. Most of the prototype was created using the parts provided, by 3D printing or using acrylic.

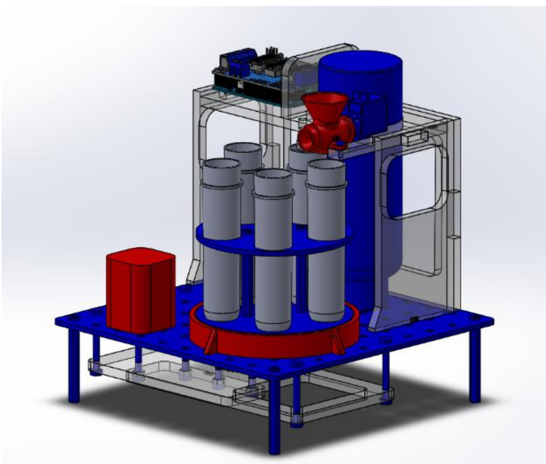

Figure 3: Entire system proposal viewed in SolidWorks.

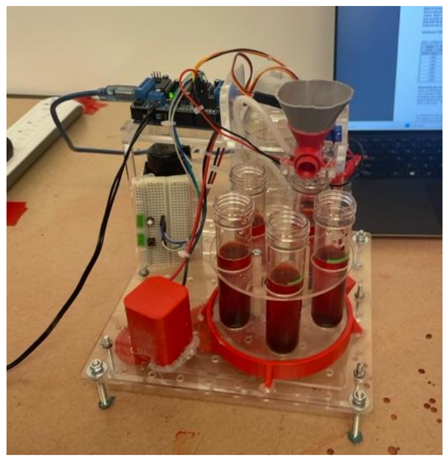

Figure 4: Final liquid and powder dispenser prototype during testing.

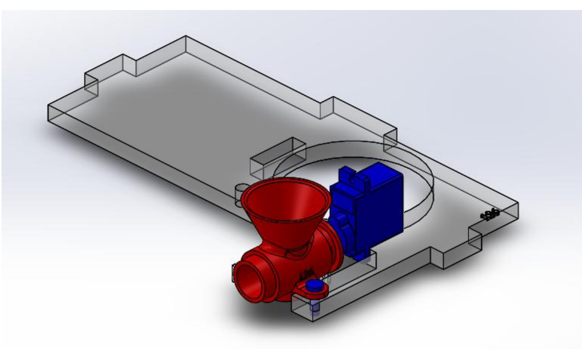

Figure 5: Powder dispenser and servo proposal viewed in SolidWorks.

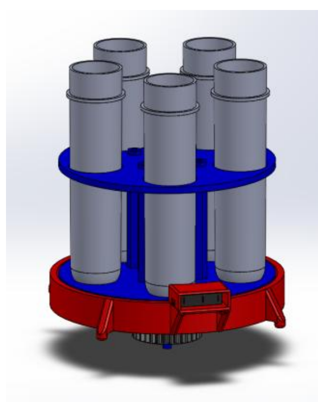

Figure 6: Test tube rotating rack system viewed in SolidWorks.

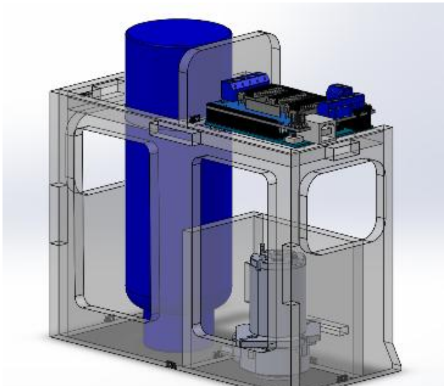

Figure 7: Liquid dispensing system and liquid storage container viewed in SolidWorks.

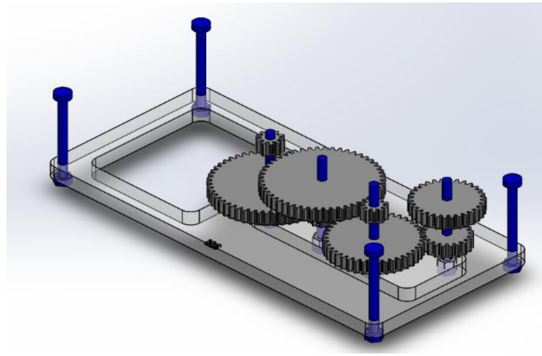

Figure 8: Gearbox system and casing viewed in SolidWorks.

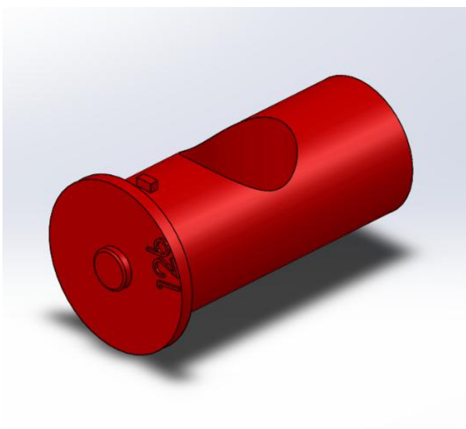

Figure 9: Inner cylinder of final powder distributing system made from PLA plastic viewed in SolidWorks.

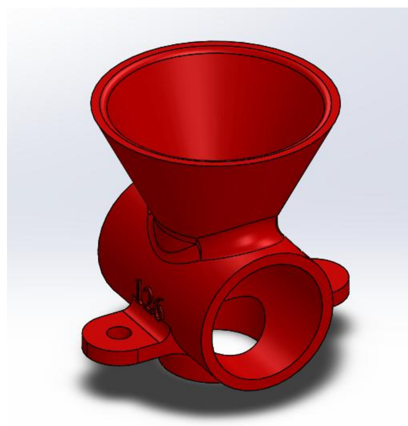

Figure 10: Outer cylinder and lower funnel of final powder distributing system made from PLA plastic viewed in SolidWorks.

There were five tests conducted on the prototype: one to test the accuracy of the powder and water dispensers, one to test the accuracy of the emergency stop button, one to test the structural integrity of the full design, and one to test the entire design for a demonstration, filling each test tube with predetermined amounts of powder and water. The final design passed each of the five tests, withstanding 5N of force without compromising the structure or safety of the design, stopping immediately with the push of the emergency stop button, dispensing 20mL of water within $\pm$ 1ml of error and roughly 1g of powder, and completing a full rotation of the design with no inaccuracy or safety concerns.

Equations 1, 2 and 3 model the gear ratio, R, using the number of teeth in the gears, N, the torque, τ [mNm] and, the angular velocity, ω [rev/min]. The equations rely on the assumption that all friction is accounted for with the efficiency to the power of the number of gear pairs and that the motor runs constantly at its maximum efficiency.

$$R = \frac{N_2}{N_1} \tag{1}$$

$$R = \frac{40 \times 40 \times 50 \times 50 \times 30}{10 \times 20 \times 10 \times 10 \times 10}$$

$$R = 600$$

$$R = \frac{\tau_2 \times Efficiency^{\ Gear\ Pairs}}{\tau_1} \tag{2}$$

$$\tau_2 = R \times \tau_1 \times Efficiency^{\ Gear\ Pairs}$$

$$\tau_2 = 600 \times 4.5 \times 0.9^5$$

$$\tau_2 = 1594.3\ mNm$$

$$R = \frac{\omega_1 \times Efficiency^{\ Gear\ Pairs}}{\omega_2} \tag{3}$$

$$\omega_2 = \frac{\omega_1 \times Efficiency^{\ Gear\ Pairs}}{R}$$

$$\omega_2 = \frac{12530 \times 0.9^5}{600}$$

$$\omega_2 = 12.3\frac{rev}{min} = 0.2\frac{rev}{s}$$

Testing the prototype of automated fluid dispenser reveals that the mathematical models for the gearbox accurately predict its angular velocity and correctly determined sufficient final torque, however, friction being accounted for by the efficiency to the power of the number of gear pairs greatly oversimplifies the resistive forces acting on the gearbox. This oversimplification can potentially cause error in the predictions for torque and angular velocity as the efficiency does not take material the axle spins on or the load on the gearbox into consideration.

Equations 4 and 5 are used to calculate the maximum deflection of the mast, δ_{max} [mm], using the second moment of area, I_x $[mm^4]$, the thickness, b [m], the width, h [m], the length, L [mm], elastic modulus, E [MPa] and the applied force, F [N]. These calculations rely on assumptions such as, the beam profile being simplified, perpendicular beams will not impact the deflection and the applied force is evenly distributed throughout the mast.

$$I_x = \frac{bh^3}{12} \tag{4}$$

$$I_{x,A} = \frac{4 \times 6 \times 5^3}{12} \qquad I_{x,B} = \frac{2 \times 6 \times 65^3}{12}$$

$$I_{x,A} = 250mm^4 \qquad I_{x,B} = 274625mm^4$$

$$\delta_{max} = \frac{FL^3}{3EI_x} \tag{5}$$

$$\delta_{max,A} = \frac{5 \times 126^3}{3 \times 3200 \times 250} \qquad \delta_{max,B} = \frac{5 \times 126^3}{3 \times 3200 \times 274625}$$

$$\delta_{max,A} = 4.17mm \qquad \delta_{max,B} = 0.002mm$$

The mathematical models predict a deflection between 4.17 mm and 0.002 mm, however, experimentation using the prototype indicates that the mathematical models used to determine deflection are inaccurate. The experimentally determined deflection is significantly less than the model predicts, this error in the mathematical model can be attributed to the assumption that perpendicular beams do not impact the deflection. The beams connecting the two parallel beams (the back and top mast pieces) greatly reduces the deflection of the mast to near zero.

As detailed in the problem definition, the goals for this project through the scope of 101 were to create an automated fluid dispenser that functioned at a precise level and was entirely autonomous outside of the initial push of the start button. The final design created meets each of the detailed criteria and does so safely and efficiently. However, changes would need to be made to the design to allow it to function at the level necessary for implementation in real world situations. The prototype described in this report would not be valuable in a hospital setting, as it's subfunctions are not up to par with the precision necessary to create treatments for real world applications.

When referencing the fictitious responses from pharmaceutical technicians provided in week six, it is noteworthy that an ideal design would not only be functional but also aesthetically pleasing. If this design were to undergo changes with access to better resources, the look of each of the pieces would be cleaned up and run with less friction and noise emitted. Another key change made to the design would be the easy disassembly of each of the parts – this design relied partially on glue to solidify its structural integrity. The user-friendly aspect of this design would also need to be revaluated in order to meet our project goals, as its code is understandable to those who can read it, but its accessibility to new hires would be a difficult skill to train.

This design is optimal when looking at the necessities provided in the requirements outlined by the APSC 101 course. It would require significantly more work, and higher quality resources in order to be considered ready for treatment in a pharmaceutical setting.

Final Design

The final design of our real-world system is seen in Figure 11: Front view of final AFD prototype., Figure 12, Figure , and Figure 14. It resembles the intended prototype quite closely as little changes were made to the system. Additionally, the design constraints were followed through size limitations, the use of provided materials, and electronics placement among others.

The prototype's iterations were modified on a test-to-test basis, where the critical subfunctions that required tuning or fixing were identified by simulating real-world applications. In other words, by filling up all five test tubes with random amounts of water and Kool-Aid and analyzing where faults originated. Through multiple days of tampering the overall prototype did end up working at full function and was able to fill up all five test tubes perfectly under supervision during the scheduled testing time.

Figure 11: Front view of final AFD prototype.

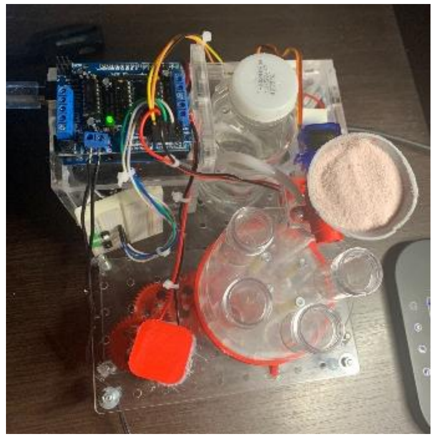

Figure 12:Top view of final AFD prototype.

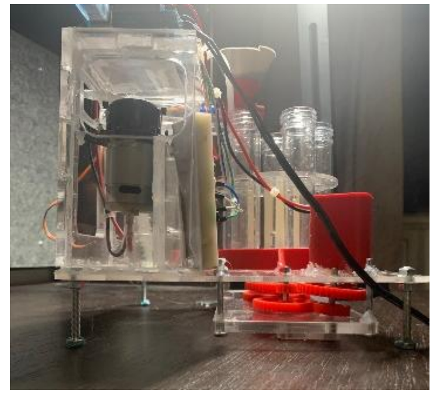

Figure 13: Left side view of final AFD prototype.

Figure 14: Right side view of final AFD prototype showing limit switch.

When comparing the virtual SolidWorks version of our prototype in Figure 3 to the final built system in the four figures above, the only modification brought to the system was the rearrangement of the limit switch. As its original positioning seen in Figure 6 would displace the test tubes out of position rather than engage the limit switch arm. To ensure less torque is delivered onto the test tubes by the limit switch arm, the latter was raised closer to their point of rotation on the upper turntable as seen in Figure 14.

The testing of the prototype was overall successful, as it was able to meet all the criteria of dispensing the water and powder. However, there are many aspects of the design that can be improved to increase efficiency and allow it to be implemented in hospitals. As of now, many of these things are missing due to the limited resources available to develop the prototype thus, only the main functions are prioritized in the current design. A major area where there would be lots of improvements would be the safety aspect. This mainly includes making a boxed area around the AFD made of acrylic, plastic, metal, or some other strong material. This will prevent anyone from putting their hands into the machine and stop contaminants from reaching the test tubes as well as keeping harmful substances from the AFD from leaking into the surroundings. The protection of electronics used is also a very important integration that needs to be considered. Essentially to protect electronics from potential spills or leakages. Using acrylic, covers can be designed to cover the electronics and have areas where they can still be accessed for maintenance.

The prototype was able to do all the required tasks within the given time frame, however it can still be improved to further increase time efficiency and accuracy. First, with the powder dispenser, it faced a lot of friction when turning to dump to powder into the test tubes. This was mainly fixed by sanding the PLA material down to make the surface smoother. This was effective at allowing it to move more freely which could be seen during the testing phase, but there was still some friction which could hinder the dispense if it was to be used more offend and at a faster rate. A way to fix this problem would be to use a different material that has less of a rough surface. Other aspects of the protype include the Arduino code seen in Appendix III, which could execute all required elements successfully in one loop thanks to arrays that store powder and liquid amounts. The code's only limitation stems from the fact that the emergency stop function is repeated inside every nested loop to be operatable. To simplify and increase code execution speed, a solution would be to find a way to have one stop button command work for all the actions to make the code run faster.

Accessibility is a vital aspect of design a device to be used on a larger scale. This is mainly due to most people that will be operating the device will not have much experience with the device due to it being used by doctors in hospitals. The prototype is accessible but a lot of the finer details like adjust water and powder dispensing must be done by changing the variables within the code. With no material constraints, a touchscreen can be attached to the outside of the AFD and allow the operator to adjust the dispensing amount without having to adjust the system's software, increasing usability and accessibility. The screen can also serve as a monitor for the reservoir that notifies the operator when the reservoirs are low. Another important element that was hindered by design constraints was the start and emergency stop buttons. The button had to be attached to the side of the AFD by the water pump due to resource and size constraints. For the final design, the emergency stop button would be on the outside casing to allow the operator to stop the device without having to be in proximity to the AFD in case of emergency. The start button would also be attached to the casing near the stop button or integrated into the touchscreen if one was implemented.

The design and implementation of a consistent powder dispenser proved to be the hardest subsystem. Our powder dispenser seen in Figure 14 works on a gravity-fed basis, meaning that grains of powder would jam the rotating inside cylinder to a point where the servo could no longer rotate. As such, the two circular surfaces had to be sanded down and regularly lubricated to allow servo movement. In addition, the indent on the inner cylinder meant to 'scoop' the powder from the fed funnel was designed with a volume of 1x1x1 cm^3, which translates to a mass of 1 g. In other words, the code is implemented to rotate the servo 180˚per gram of powder that is needed to be dispensed in the specific test tube. In addition, the code is implemented to rotate 1˚/10ms while distributing the powder to provide the necessary torque. As well as rotate by 1˚/ms while initializing back to the powder feeding opening at the top, as less torque is required due to the lack of powder grains, thus optimizing time spent dispensing. To implement this prototype on a real-life basis, the material consisting of both components would have to be precision cut to a low uncertainty measure. Essentially creating a seal between the two escapes and protects the rotating surfaces from grains and debris. This added weight and friction would also require a servo capable of providing additional torque.

A big design criterion was having the AFD structurally sound and portable while making sure it didn't go over the PLA and acrylic limit. This resulted in the use of screws to keep the main platform up and allowed the gearbox to rest under the platform. This made the AFD stable enough, but it would be ineffective to have screws standing the final design up. Instead, stands would be made using acrylic or metal to provide more stability and it is much easier to make portable. The design also used a considerable amount of glue to provide further reinforcement to the structure of the AFD and to prevent certain parts such as screws from shifting or loosening after use. This implementation would affect the prototype's portability, however, which was one of the stakeholder's desires. An iteration that can be used would be to make the parts interlocking and have bolts that secure them together. This will make it easier to disassemble and move around when needed. Another iteration that will be added to the final design would be spots for wirings to run through. With the prototype, the wires connecting all the parts were all unorganized. This was due to the constraint on PLA and acrylic as well as the lack of long wires given to properly make the wiring efficient and well-ordered. The final design will have longer wired which will allow for better manipulation of the wiring paths. There will also be spots in the main structure that will house and protect the wires.

An important part of the prototype that worked up to expectations was the gearbox and turntable. The gearbox provided enough torque to turn the turntable at the required speed using plastic bb's as a ball bearing. The prototype was very loud during testing which was the result of the gears rubbing against the platform and the plastic bb's. The final design will use stainless steel ball bearings which will create less noise and alongside that, less friction. The gearbox issue was mainly due to the gearbox being compressed to fit under the platform and remain under the height limit. The final design will have the platform higher which will give the gearbox more room and allow for the gears to move without touching the platform.

Below are the drawings of the final design with the interactions discussed above:

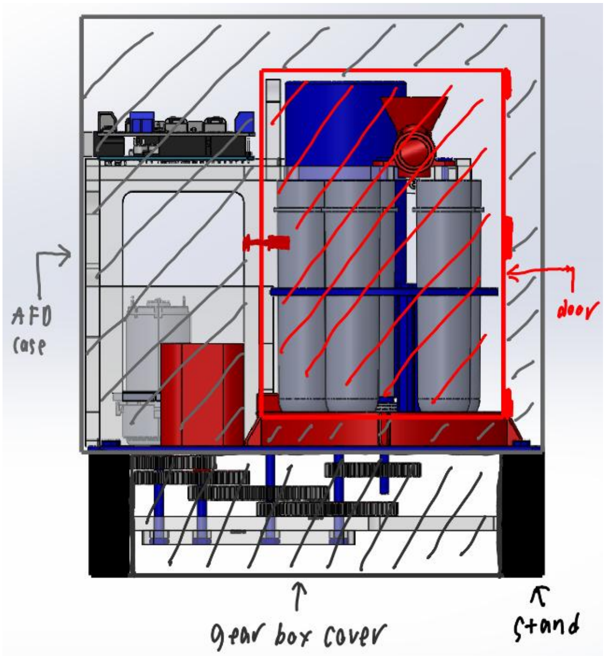

Figure 15: Front view of the final design with the changes that came for testing the protype.

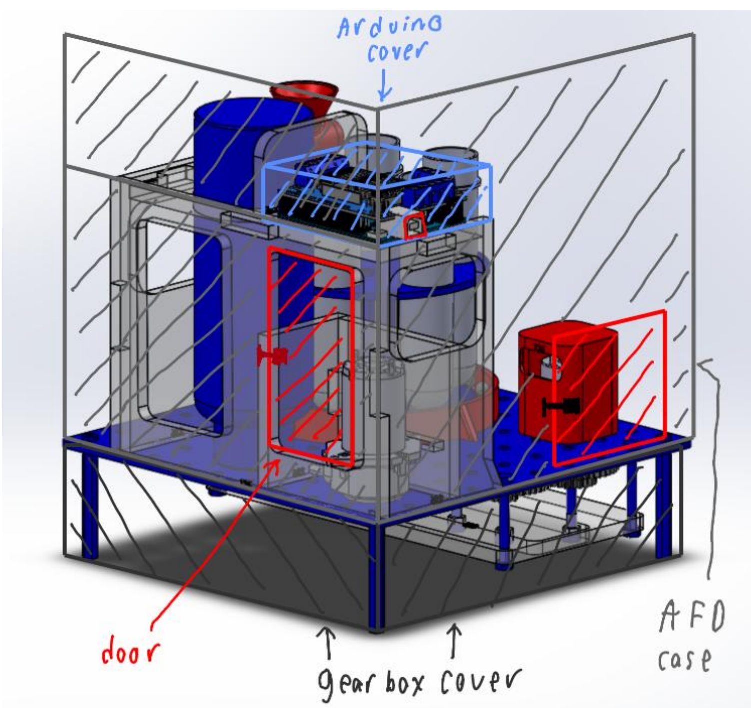

Figure 16: Back and Side view of the final design with the changes that came for testing the protype.

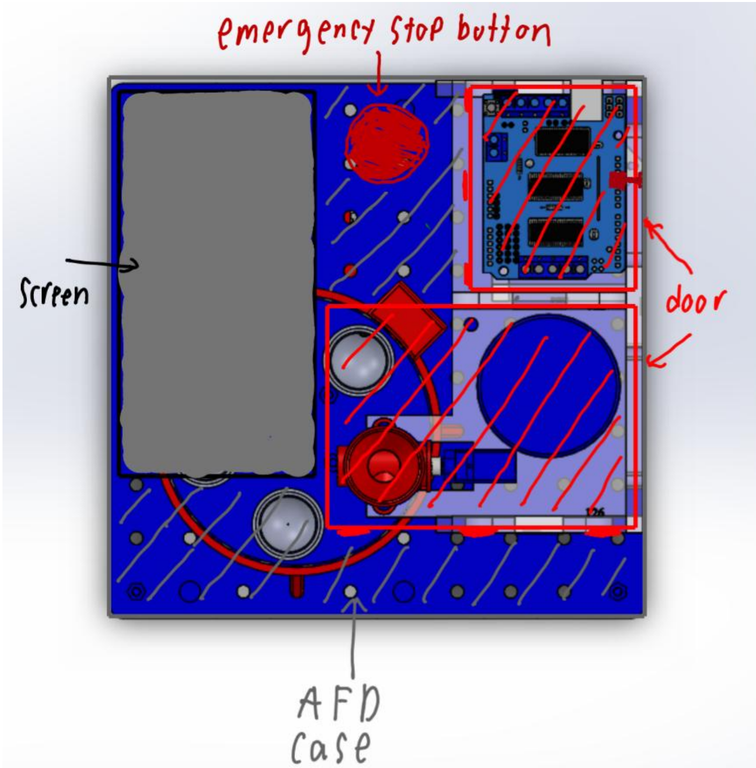

Figure 17: Top view of the final design with the changes that came for testing the protype.

References

[1] Drugs.com. (2023). Naloxone. [Online]. https://www.drugs.com/naloxone.html. [Accessed December 2nd 2023].

[2] Rodon Group. (2019, May 22). Injection Molding vs. 3D Printing: What's the Difference? [Online]. https://www.rodongroup.com/blog/injection-molding-vs-3d-printing. [Accessed December 2nd 2023].

[3] CADTH. (2017, March). Automated Medication Dispensing Systems: A Review of Worldwide Technologies and Research. [Online]. https://www.cadth.ca/sites/default/files/pdf/htis/2017/RB1134%20Automated%20Medication%20Dispensing%20Systems%20Final.pdf. [Accessed December 2nd 2023].

Appendix I – Work distribution

Tasks	Activity Duration (h)	Individual responsible
Title page	0.25	XXXX
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Final design	10	XXXX, Julien
References	0.5	Julien
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Appendix II	4	XXXX
Appendix III	10	Julien

Appendix II – Team Performance Assessment

Our team grew a lot throughout the term. We learned how to efficiently communicate what work needed to be done, and what people would be best suited to each of the necessary components of each week. As we got to know each person's strengths and weaknesses, we were able to tailor the tasks to each individual and this ultimately helped us get work done effectively.

The design process was a large learning curve, as most of us had not had experience with this type of hands-on learning before, however it was a difficult challenge we conquered through supporting one another and allowing each person to participate in a way they felt was valuable. Moreover, the writing component of this course was one of our initial weaknesses, our internal deadlines not useful to the process. As the weeks went on, we were able to understand what acceptable draft deadlines looked like and how these could be implemented to keep us on task without being overwhelming. For 12T, we set multiple internal deadlines with small tasks associated to make sure the little tasks were being completed on time and properly, allowing us a large amount of time for flow and conciseness edits. This was imperative to the writing process, and a skill we learned throughout the weeks.

For the next design project, we are presented, we will make sure to use the skills we have learned throughout this term. These skills do not end at internal deadlines and finding peoples individual strengths – we are also more confident in effective communication with other group members, appropriate use of the valuable functions in word and the structure of reports in general.

Rubric for 12T: Final project report

For required team sections

	7-8 Outstanding	6 Expectation	5 Minimum competency	4 Developing	0-3 Not Demonstrated
Executive summary (CO-Written)	Clearly organized, precise and concise non-technical summary fitted to audience needs.	Organized and mostly audience-appropriate non-technical writing with few grammatical errors, designed for non-technical audience	Loosely organized with minor grammatical errors, somewhat supported message, some verbosity, not fitted to audience needs.	Verbose, disorganized and difficult to understand writing and graphics poorly directed at the audience with many grammatical errors.	Unclear and unstructured document with many errors that doesn't follow guidelines.
Problem Definition and Context (DE-Define)	Meets expectations and: Provides detailed context supported by quality information that inform process, model, and conclusions.	Clearly defines the problem and described necessary information informed by quality information sources	Problem definition is clear but missing some elements.	Problem definition misses important elements; important information missed, or trivial/incorrect information included.	Problem not defined, little useful information, or information directly copied.
Testing/evaluation of prototype (DE-Assess)	Meets Expectations (next column) and describes how prototype would be tested for real application.	Describes testing procedure and subsystem/prototype operation, comparing test results to requirements and modeling, referencing uncertainties and safety.	Description of procedure, results, and comparison with predictions is reasonably complete but leaves some uncertainty about prototype performance.	Description of testing and results misses some required elements from instructions and leaves some uncertainty about prototype performances.	Description of testing and results does not allow reader to draw meaningful conclusions.
Model evaluation (PA-Formulate)	Accuracy of mathematical model compared to testing, identifying reasons for differences and improved approach that describes better the physical system	Evaluates accuracy of mathematical model compared to testing, identifying reasons for differences	Evaluates accuracy of mathematical model compared to testing, with possible but unsupported reasons for differences	Some gaps in evaluating accuracy of mathematical model compared to testing	No meaningful analysis of mathematical model compared to testing results
Final design (DE-Solutions)	Clearly describes exceptional quality design that meets all requirements for project and for an identified client.	Clearly describes final design appropriate to the problem that meets almost all design requirements, with clear explanation for all major design decisions.	Describes design with explanation for most design decisions.	Design description is not well supported.	Design description is superficial.
Safety (PR-Safety)	Thoughtful approach to incorporating safety, supported by outside material, incorporated	Incorporates safety, into problem definition and final recommendation	Some gaps in incorporating safety into problem definition and final recommendation	Safety mentioned but doesn't inform final recommendation	No consideration of safety

	into problem definition and final recommendation				
Equity (PR-Equity)	Thoughtful approach to considering equity, supported by outside material, incorporated into problem definition and final recommendation	Principles of equity and fairness incorporated into problem definition and final recommendation	Some gaps in incorporating equity and fairness into problem definition and final recommendation	Equity considered but doesn't inform final recommendation	No consideration of equity or fairness
Sustainability (PR-Sustainability)	Thoughtful approach to considering sustainability, supported by outside material, incorporated into problem definition and final recommendation	Principles of sustainability incorporated into problem definition and final recommendation	Some gaps in incorporating principles of sustainability into problem definition and final recommendation	Sustainability considered but doesn't inform final recommendation	No sustainability principles mentioned
Standards (PR-Standards)	Highly relevant independently identified standards/ codes/ regulations used to define problem and inform final recommendation	Standards/codes/ regulations used to define problem and inform final recommendation	Standards/codes/ regulations used inconsistently to define problem and inform final recommendation	Standards/codes/ regulations mentioned but not informing final recommendation	No standards/ codes/ regulations used
Information literacy (LL-Information)	Uses a range of high-quality information sources to support the definition and design.	Uses appropriate information sources to support the definition and design.	Uses appropriate information sources to support some aspects of the project.	Uses little or marginally useful information sources to support some aspects of the project.	No meaningful information sources uses.
Team performance assessment (LL-Reflection)	Comprehensive description, analysis, and evaluation of team performance showing feedback and self-reflection used consistently and providing insightful proposals for improvement.	Describes, analyzes, and evaluates team performance showing some feedback used and with proposals for improvement.	Describes, analyzes, and evaluates individual and team performance, with some superficial analysis not directly related to the team's actions.	Describes, analyzes, and evaluates individual and team performance, with some significant gaps.	Superficial analysis, or only generic description not directly related to the project or team.
Organization (CO-Written)	Writing is clearly organized into logical paragraphs and sections including smooth transitions and clear links between sections.	Writing is mostly organized at the document-level, however loosely organized at the sentence level.	Disordered document-level organization and loose sentence-level organization.	Writing is disorganized and challenging to follow.	Writing is disorganized with little to no discernible structure at any level.

Reasoning (CO-Written)	Statements are well supported by evidence synthesized from quality sources/analysis, and consider how limitations and uncertainties affect conclusions	Statements are supported by evidence of varying quality. Limitations and uncertainties may not be included.	Message is presented, however not entirely supported; citations not the best quality, often from popular literature.	Primary message has not been supported by evidence presented, or scope oversimplified.	No clear supported message.
Vocabulary (CO-Written)	Precise and/or concise use of technical vocabulary, appropriate to the audience.	Word choice partly appropriate for audience, with emerging technical vocabulary but some unnecessary words/colloquial language.	Some writing is verbose and/or not directed to audience with frequent use of colloquial language.	Writing shows little sense of audience, is vague, unnecessarily verbose, colloquial, and/or contains frequent vocabulary errors.	Careless or inaccurate word choice and/or vocabulary errors which obscure meaning.
Graphical elements (CO-Graphical)	Graphical elements are all carefully designed and support the main purpose.	Graphical elements are used to support the main purpose.	Graphical elements used appropriately but not consistently referenced in text and/or do not directly relate to purpose.	Some graphical elements not discussed and/or do not contribute to the report.	Graphical elements not understandable, not related to text.

Appendix III – Arduino Code

```
#include <AFMotor.h>
#include <Servo.h>

AF_DCMotor motor(3);  // Motor on M3
AF_DCMotor pump(4);   // Pump on M4
Servo servo;           // Servo on A0

const int limitSwitchPin = A1; //Limit Switch on A1
const int buttonPin = A2; //Start button on A2
const int emergencyButtonPin = A3; //Emergency stop button on A3

const int numFunnels = 5;
const int waterAmounts[numFunnels] = {20, 20, 20, 20, 20}; // mL
const int powderAmounts[numFunnels] = {1, 1, 1, 1, 2}; // mL

const int waterPumpTime = 5200;  // 5.2 seconds for 5mL
const float waterPumpTimePerML = 930; // 0.93 seconds per additional mL
int servo_pos = 0; //Initialize servo value at 0

void setup() {
  //Setting up all motors and electronics
  servo.attach(A0);
  pinMode(limitSwitchPin, INPUT_PULLUP);
  pinMode(buttonPin, INPUT_PULLUP);
  pinMode(emergencyButtonPin, INPUT_PULLUP);
  digitalWrite(limitSwitchPin, HIGH);
  servo.write(0);
  motor.setSpeed(180); //Set motor speed to comfortable speed for gearbox
  pump.setSpeed(255); //Set water pump speed to as fast as possible (255)
}

void loop() {
  if (digitalRead(buttonPin) == LOW) { //If Start button is pressed
    for (int funnel = 0; funnel < numFunnels; funnel++) { //FOR loop that is
executed once for every test tube
      while (digitalRead(limitSwitchPin) == HIGH) {   // Spin the DC motor
until the limit switch is hit.
        if (digitalRead(emergencyButtonPin) == LOW) { // Check emergency stop
button
          motor.run(RELEASE);
          pump.run(RELEASE);
          servo.write(0);
          return;  // Exit the loop and stop execution
```

```
        }
        motor.run(FORWARD); //Motor forward while limit switch is not pressed
      }
      delay(75); //Delay 0.075s to let test tube release limit switch
      motor.run(RELEASE); //Stop motor

      for(int x=1; x<= powderAmounts[funnel]; x++){ //Spin servo for the
respective powder amount
        for (servo_pos = 0; servo_pos <= 180; servo_pos += 1){ //FOR loop
that adds onto servo position with delay every degree to slow movement down
and increase torque
          servo.write(servo_pos);
          delay(10);

          if (digitalRead(emergencyButtonPin) == LOW) { //Check for emergency
button press
          servo.write(0);
          motor.run(RELEASE);
          pump.run(RELEASE);
          return;
        }
        }
        delay(20000); //Delay to let powder fall into test tube

        for (servo_pos = 180; servo_pos >= 0; servo_pos -= 1){ //FOR loop
that adds onto servo position with delay every degree to slow movement down
and increase torque
          servo.write(servo_pos);
          delay(1);

          if (digitalRead(emergencyButtonPin) == LOW) { //Check for emergency
button press
          motor.run(RELEASE);
          pump.run(RELEASE);
          servo.write(0);
          return;  // Exit the loop and stop execution
        }
        }
      }

      // Dispense water with the pump.
      int requiredWater = waterAmounts[funnel]; //Integer for required water
amount
      //5.2s to pump intial 5mL, then 0.93s for every additional mL
```

```
      int pumpTime = waterPumpTime + ((requiredWater - 5) *
waterPumpTimePerML); //Formula to determine pump time
      pump.run(FORWARD);

      while (pumpTime >= 0) {  //WHILE loop executed while pump time is
greater than 0
        if (digitalRead(emergencyButtonPin) == LOW) { // Check emergency stop
button during pump operation
          pump.run(RELEASE);
          motor.run(RELEASE);
          servo.write(0);
          return;  // Exit the loop and stop execution
        }
        delay(10);  // Check every 0.001s
        pumpTime -= 10; //Reduce pump time by 0.001s until it reaches 0s
      }

      pump.run(RELEASE); //Stop pump
      delay(25); //Delay 0.025s to let water fall into test tube
    }

    motor.run(RELEASE); //All 5 test tubes are filled, stop motor
  }
}
```