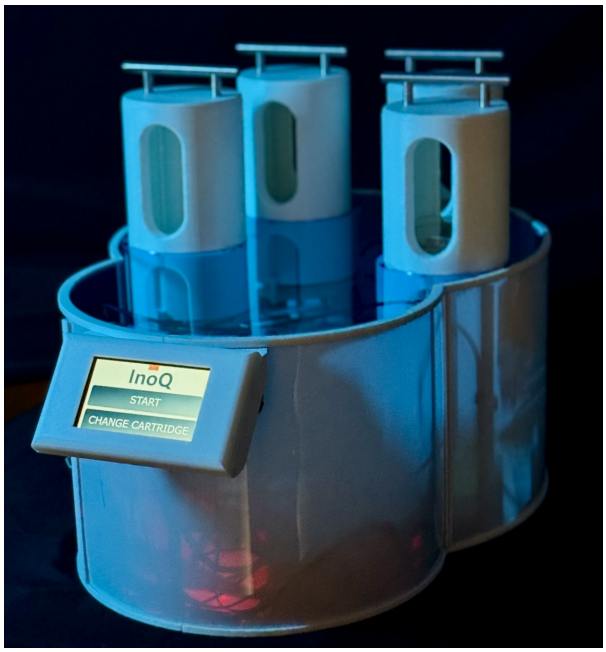


InoQ
Automating Lab Work One Dish at a Time

Mechanical Engineering 310 Spring Design Document

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1 Executive Summary

In the world of diagnostics, time is often the difference between proactive care and delayed treatment. While human healthcare systems benefit from large-scale laboratories equipped with cutting-edge automation, veterinary labs operate under vastly different constraints. On average, human healthcare sees a per-capita annual expenditure of $14,570, while animal healthcare receives only about $243 per patient. This stark disparity results in veterinary labs being comparatively under-resourced, often characterized by limited physical space, lower sample throughput, and minimal funding for advanced automation.

Veterinarians face significant diagnostic delays, particularly in identifying bacterial infections, where time-sensitive decisions rely heavily on lab results. The manual workflow of bacterial culturing—receiving the sample, inoculating it on a Petri dish using streaking patterns, and preparing it for incubation—consumes valuable technician time and introduces inconsistencies due to human variability. In high-pressure clinical settings, this not only adds to the workload but can also impact diagnostic accuracy and the speed at which treatment is initiated.

Sponsored by Hamilton Company, a leader in laboratory automation, our team was tasked with exploring innovative solutions in the veterinary diagnostics space. Through rigorous needfinding conducted at Stanford's Veterinary Service Center and AniCura Byåsen Dyrehospital in Norway, we discovered that Petri dish inoculation was a bottleneck common across labs of all scales. Technicians routinely repeated tasks such as lid removal, swabbing, streaking, and relidding, with little automation support available due to budget and space limitations.

While several human-lab-grade solutions exist that automate the streaking process, they often come with six-figure price tags and require significant laboratory real estate—making them unsuitable for veterinary clinics that might only process 10 to 30 samples a day. This created a clear design opportunity: to create a system that is **affordable**, **compact**, and **intelligently simple**—without compromising core functionality.

Enter **InoQ**, our solution to this challenge. InoQ is a semi-automated Petri dish streaking device designed specifically for small- to mid-scale veterinary labs. Built with a total budget of under **$2,000** and occupying only **0.2 square meters** of lab space, InoQ brings the power of automation to settings previously excluded by cost and size barriers. With just **three user touches on the touchscreen interface**, the technician can initiate a complete streaking cycle: the system handles dish loading, lid removal, sample inoculation via user-defined streaking patterns, sterilization, and dish restacking.

The mechanical and electrical systems of InoQ were designed to be modular, enabling rapid iteration and ease of future upgrades. The compact frame was tailored to fit on standard benchtops, and our team incorporated cost-effective components like 3D-printed fixtures, a minimalistic GUI, and smart motor control strategies. Importantly, the system supports multiple streaking patterns and allows users to adjust parameters depending on the bacterial culturing requirements, bringing flexibility usually reserved for higher-end devices.

The InoQ project brought together a multidisciplinary team of engineers and designers from Stanford and our international partner institutions. Through careful backward planning, iterative prototyping, and close collaboration with veterinary professionals, we developed a device that satisfies both technical constraints and end-user needs.

What began as a challenging technical prompt transformed into a deeply impactful design. InoQ

stands not only as a testament to frugal innovation but also as a symbol of our commitment to closing the automation gap in animal healthcare. By equipping veterinary labs with a tool that enhances efficiency, standardization, and speed, we aim to contribute meaningfully to the future of veterinary diagnostics—where timely care and quality testing are available to every animal, everywhere.

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Glossary

Aliquoting The process of dividing a larger sample into smaller, measured portions for storage or analysis.

Agar A gel-like substance from red algae, used to grow microorganisms. In vet labs, common types include blood agar (for detecting bacteria that break down red blood cells) and chocolate agar (for growing fastidious organisms).

Bacteria Culture The controlled growth of bacteria in a nutrient medium for study or testing.

Biosafety The handling of potentially hazardous biological materials with safe working practices.

Cartridge Cartridge: A replaceable container holding Petri dishes.

CEP Otherwise known as a Critical Experience Prototype. A prototype designed to test an experience-based idea in order to receive user feedback.

CFP Otherwise known as a Critical Function Prototype, this is a prototype built to test a concept that is critical to addressing the problem statement.

Cross-contamination The transfer of harmful contaminants, such as pathogens or bacteria, from one object to another, with dangerous effect.

Funky Prototype A rough prototype designed to test creative ideas in early-stage development.

Functional Prototype A working model of a design that demonstrates its key features and intended operation.

Human bio-lab A Human bio-lab is a laboratory dedicated to analyzing biological samples from humans for research, diagnostics, and clinical applications.

Incubation The process of maintaining optimal conditions (eg., temperature) to promote the growth of bacteria cultures.

Inoculating loop A laboratory tool used to transfer microorganisms by streaking or spreading them onto a culture medium.

Liquid handling The process of transferring liquids between containers (eg. vials or tubes) in a laboratory, generally for testing purposes

Petri dish (aka Petri plate) A shallow, lidded dish used in laboratories for culturing microorganisms or cells on a nutrient medium

Pipette A laboratory tool used to measure and transfer small volumes of liquid with precision.

Sample inoculation The process of introducing a sample (e.g., bacteria or other microorganisms) onto or into a growth medium to allow for cultivation and analysis.

Streaking A microbiological technique used to spread bacteria on an agar plate to isolate individual colonies.

Swabbing Collecting a sample from a surface, wound, or body site using a sterile swab for testing or culture.

Veterinary Relating to the diseases, injuries, and treatment of animals.

Wet lab A laboratory where chemicals, biological samples, or other liquids are handled for experiments, testing, or research.

2 Project Context

2.1 Project Background and Motivation

In the world of diagnostics, time is critical—whether for humans or animals. While human healthcare systems benefit from high-throughput laboratories and advanced automation, veterinary labs operate in a vastly different reality. With an average annual healthcare expenditure of $14,570 per person compared to just $243 per animal, veterinary diagnostics often suffer from underfunding, space constraints, and significant delays in identifying infections.

These disparities present a unique design opportunity. Veterinary diagnostic labs are burdened by labor-intensive workflows that rely heavily on manual processing, especially in bacterial culturing using Petri dishes. These processes—sample inoculation, streaking, sterilization, and incubation—are time-consuming, repetitive, and prone to human error. The result is inefficiency, technician fatigue, and delayed treatment.

Recognizing this unmet need, Hamilton Company partnered with our team to redefine veterinary diagnostics by introducing animal-centric automation solutions. With strong R&D capabilities and leadership in lab automation, Hamilton sought our collaboration to explore scalable and impactful interventions tailored to the veterinary context.

2.2 Corporate Partner

Hamilton Company is an international technology company that focuses on the development of precision measurement devices, automated liquid handling workstations, and sample management systems. Today, with 3,000 employees and 22 locations worldwide, Hamilton is the largest automated liquid handling company in the world [2].

Hamilton primarily operates in the B2B market, serving biotech, pharmaceutical, and diagnostic industries with its precision laboratory equipment and automation systems. The headquarters are located in Nevada, Massachusetts, Switzerland, and Romania [2]. The company competes with firms like Tecan, Beckman Coulter, and Sarstedt. While it excels in automated solutions, the company faces challenges from high product costs and evolving market regulations. However, it remains well-positioned due to its scalable manufacturing and robust R&D capabilities.

In the veterinary diagnostics field, bacteria culturing remains a fundamental process for detecting various animal infections, including urinary tract infections, gastrointestinal infections, and septicemia. The standard lab instrument for this process is the petri dish, which requires several labor-intensive steps: media preparation, sample inoculation (streaking), incubation, monitoring, and passaging/isolation. Additional processes include labeling, sealing, and imaging. These repetitive and tedious tasks present an opportunity for automation that could significantly improve laboratory efficiency.

Hamilton has recognized an opportunity to redefine veterinary lab processes with animal-centric automation solutions, specifically targeting the bacteria culturing workflow. Through this project, Hamilton aims to leverage its expertise in laboratory automation to develop innovative solutions that

Strengths	Weaknesses
• World leader in laboratory automation with extensive experience in liquid handling systems • Strong R&D capabilities for developing precision instruments • Existing expertise in workflow automation that can be applied to petri dish handling • Established manufacturing infrastructure to support new product development • Experience with integration of similar laboratory equipment and systems • Access to advanced technology for automating repetitive lab tasks	• Limited previous experience in petri dish automation specifically for veterinary applications • High cost of existing automated solutions may be prohibitive for smaller veterinary labs • Current systems may not accommodate the variability in sample types encountered in veterinary diagnostics • Training requirements for new automation systems can be extensive • Traditional focus on human healthcare applications rather than veterinary
Opportunities	**Threats**
• Growing demand for efficient bacteria culturing in veterinary diagnostics • Increasing labor costs make automation more attractive • 28.1% time savings demonstrated in initial prototypes suggests significant ROI potential • Reducing human error in petri dish preparation and handling improves diagnostic reliability • Potential to expand from veterinary to food safety and agricultural applications • Lower regulatory barriers in veterinary market allow faster product introduction	• Competition from specialized laboratory automation companies targeting veterinary markets • Resistance from technicians accustomed to manual petri dish handling processes • Variability in petri dish sizes and media types across different labs • Budget constraints in veterinary facilities limiting adoption of new technologies • Need for high reliability in critical diagnostic processes

Table 2.1: *SWOT analysis for Hamilton's Petri Dish Automation Project*

reduce technician workload, increase testing efficiency, and ultimately improve animal healthcare outcomes.

To pursue this opportunity, Hamilton has chosen to partner and sponsor our ME310 team. This collaboration offers Hamilton access to Stanford's state-of-the-art laboratories across a wide variety of disciplines, allowing the company to leverage university resources to gather valuable information and identify current and future needs in veterinary diagnostics. Having collaborated with the ME310 class in previous years, Hamilton's decision to return suggests the partnership has yielded beneficial results in exploring new market applications for their automation expertise.

2.2.1 Corporate Liaisons

Our ME310 team is working directly with Travis Bow, Research and Development Project Manager at Hamilton's Reno location.

2.3 Trends

The veterinary care and pet services industry has experienced significant growth in recent years, reflecting changing societal attitudes toward animal welfare and evolving demands of pet owners. Key industry trends highlight substantial opportunities for innovative solutions such as our Petri dish automation project:

- **Growing Demand for Veterinary Diagnostics:** The global veterinary diagnostics market is projected to grow significantly, with a compound annual growth rate (CAGR) of 8.9% from 2023 to 2030, driven by rising pet ownership, increased spending on pet health, and greater awareness of animal diseases [3].
- **Rise of Laboratory Automation:** The laboratory automation market is rapidly expanding, anticipated to grow at a CAGR of 6.8% from 2023 to 2030 [4]. This growth is driven by the increasing need for precision, efficiency, and scalability in lab operations.
- **Increasing Focus on Antimicrobial Resistance (AMR):** The veterinary sector faces rising challenges associated with antimicrobial resistance, elevating the demand for precise bacterial susceptibility testing. This has increased reliance on accurate and standardized bacterial culture processes [5].
- **Adoption of the One Health Initiative:** The adoption of the One Health framework, emphasizing interconnected human, animal, and environmental health, has prompted more rigorous diagnostic practices in veterinary labs [6]. This highlights the critical role of efficient diagnostic platforms, like our automated Petri dish system.
- **Laboratory Technician Shortages and Automation:** Veterinary labs face high technician turnover rates (18-22% annually) and rising labor costs [7]. Automation in laboratory processes is becoming essential to counteract these workforce challenges by reducing dependence on manual labor.
- **Regulatory Changes and Standardization:** Increased regulatory scrutiny and standardization efforts are reshaping the veterinary diagnostics landscape, pushing labs toward adopting reliable automated systems to ensure compliance and reproducibility [8].

These industry and societal trends collectively underscore the importance and potential market success of our automated Petri dish prototype, making veterinary laboratory practices more precise, scalable, and aligned with future industry standards.

These trends also highlight the growing importance of automation and efficiency in veterinary diagnostics, as well as the need for innovative solutions that address key challenges in laboratory workflows. Our project, which focuses on automating bacteria culturing processes, aligns with these broader industry developments and responds to the evolving needs of veterinary diagnostic laboratories. The challenge presented by Hamilton centers on redefining veterinary lab processes

with animal-centric automation solutions. This broad directive encouraged our team to investigate various veterinary laboratory workflows to identify specific pain points where automation could bring substantial improvements in efficiency and accuracy.

During our comprehensive needfinding process **(detailed in Appendix A.1)**, we explored veterinary lab practices and conducted interviews with actual users to understand their perspectives on current challenges. After identifying petri dish workflows as an area of significant interest, we sought user input to pinpoint the most tedious and time-consuming parts of the process. Conversations with Jiawei Sun, a PhD student in the KC Huang lab, revealed a clear need for automation in genomic library creation workflows, which involve repetitive tasks prone to error **(detailed in Appendix A.1.2)**. Additionally, during a tour of the Veterinary Service Center, Minoo Fazel emphasized the utility of integrating imaging techniques to remotely assess colony growth in petri dishes within incubators, reducing the frequent manual interventions currently necessary **(detailed in Appendix A.1.4)**. In our discussion with Jiawei Sun, we further clarified that automation is especially desirable during repetitive testing phases involved in generating genome libraries.

The standard petri dish workflow in veterinary laboratories consists of several distinct phases: media preparation, sample inoculation (including repetitive genome library testing), labeling, incubation, and colony counting. The manual processes involve numerous labor-intensive steps that significantly impact efficiency and introduce opportunities for human error.

Petri dish workflows in veterinary labs typically encompass media preparation, sample inoculation, labeling, sealing, incubation, colony counting, and subsequent analysis. These tasks require meticulous precision and can be tedious and time-consuming. Manual labeling and tracking throughout diagnostic processes frequently lead to mistakes, potentially compromising patient care and diagnostic accuracy. Furthermore, repetitive manual handling tasks can cause fatigue and repetitive strain injuries among lab personnel.

Through conversations with the Hamilton team, they expressed particular interest in practical automation solutions addressing foundational lab workflow needs—solutions adaptable broadly across veterinary diagnostic facilities rather than niche specialized applications. Our targeted approach to automating petri dish handling addresses these fundamental needs, offering solutions that can be widely implemented in diverse laboratory settings.

Our refined focus centers on addressing the following primary challenges:

- **Repetitive Manual Tasks:** Processes such as petri dish preparation, lid handling, inoculation, labeling, and sealing cause fatigue, inefficiency, and increase the risk of repetitive strain injuries.
- **Sample Traceability and Identification Errors:** Manual identification methods introduce potential inaccuracies affecting traceability and reliability in diagnostics.
- **Diverse Sample Compatibility:** Veterinary laboratories handle samples from multiple species, requiring adaptable and versatile automated solutions.
- **Space Constraints:** Veterinary diagnostic facilities typically have limited available workspace, necessitating compact and modular automation designs.
- **Real-time Colony Imaging:** Frequent manual checks of incubating petri dishes are inefficient and disrupt the incubation process; integrated automated imaging can significantly enhance workflow efficiency.

Addressing these challenges through targeted automation can significantly streamline veterinary laboratory operations, reducing errors and enhancing diagnostic accuracy, ultimately improving animal healthcare outcomes.

3 Design Development

Our design process for the InoQ began with a broad exploration of the veterinary diagnostic space and gradually narrowed into a focused, highly functional prototype through multiple user-driven iterations. The development was shaped by three core principles: understanding user pain points, prototyping with purpose, and continuously refining based on feedback.

3.1 Exploring the Problem Space

Through a series of needfinding interviews and lab observations, we identified several key pain points in the manual handling of petri dishes. These interviews, conducted with veterinary technicians, lab managers, and researchers, provided valuable insights into the inefficiencies and risks associated with current processes. A detailed account of these interviews can be found in **Appendix A.1**.

We found that laboratory workflows in veterinary and human biolabs share some fundamental processes but differ significantly in their operational demands, sample handling procedures, and automation requirements. While human biolabs typically manage high sample volumes with a strong emphasis on automation, veterinary labs operate at a smaller scale–processing around 30 Petri dishes per day—and often require 2 to 4 hours of technician time daily with different logistical considerations, such as external sample collection and limited in-lab agar preparation, as noted in **Appendix A.1**. These distinctions impact how automation solutions can be applied in each setting. The following **Table 3.1** provides a structured comparison of veterinary and human lab workflows, highlighting key similarities and differences. This section summarizes the key differences and similarities between workflows in veterinary and human labs.

These insights highlighted the need for an automated solution that could streamline the petri dish handling process while maintaining the precision and reliability required for veterinary diagnostics. In particular, we observed that streaking remained one of the most tedious and time-consuming tasks for technicians—yet it was also one of the most critical steps for ensuring sample consistency and diagnostic accuracy. With these pain points in mind, we began generating concepts for potential solutions, starting with our initial prototypes for testing and validation in Winter quarter, as noted in **Appendix A.3**.

3.2 Design Explorations and Pivots: Navigating Alternative Directions

During the winter quarter, our team explored several alternative design directions that aligned with our overarching goal of improving veterinary diagnostic workflows. One of the most ambitious ideas was to build a fully modular automation system for Petri dish handling. This concept envisioned a flexible work cell with interchangeable modules—such as labeling, storage, lid removal, and dish presentation—allowing lab technicians to configure the system based on their needs and space constraints.

Aspect	Veterinary Labs	Human Labs
Sample Collection	Clinics/ranchers collect samples and send them to labs.	Samples taken directly from patients in labs.
Agar Preparation	Use pre-prepared agar (Chocolate, Blood).	Agar prepared in-house.
Sample Volume	Process 20 petri dishes per day.	Handle hundreds per day.
Petri Dish Handling	Stored upside-down to prevent condensation.	Stored upright or Sealing with Parafilm.
Incubation	37°C for 24-48 hours.	Same.
Colony Observation	Manual monitoring, color-based reactions.	Manual monitoring.
Picking & Streaking	Manual using sterile tools.	Mostly manual, some automation.
Sealing	Rarely used.	Common for contamination prevention.
Automation Needs	Selective automation (picking, streaking).	High demand for full workflow automation.

Note: This comparison is based on our limited needfinding and observations. Practices may vary widely across different veterinary and human bio labs.

Table 3.1: *Comparison of workflows between veterinary and human labs.*

To evaluate these directions, we developed a series of early-stage prototypes, including mechanical mockups, critical experience prototypes (CEPs), and functional prototypes. These were tested with users to better understand ergonomics, workflow integration, and failure points. This hands-on prototyping gave us valuable insight into both mechanical challenges and user interaction needs, ultimately shaping our design criteria and informing later development. (See **Appendix A.3** for details.)

Later in the quarter, during Spring Break, we traveled to Norway to engage with our global partners and conduct further needfinding. These conversations sparked an exploration into on-farm diagnostic tools, specifically for mastitis testing in cows. The idea was to create a portable, farmer-operated system for on-site sample analysis and treatment guidance. Though compelling in terms of accessibility and user empowerment, the on-farm direction posed significant technical and operational challenges. For instance, accurate diagnostics required multiple culturing steps and expert identification of bacterial colonies—difficult to replicate reliably outside a controlled lab environment.

After evaluating the feasibility and potential impact of these alternative directions, we ultimately refocused on a lab-based solution with a refined emphasis on automated streaking. This decision reflected a synthesis of our earlier modular vision with the practical realities of veterinary lab operations. The pivot to streaking automation—described in the following sections—became the foundation of our final prototype. Additional details on the prototypes explored during this phase can be found in Section 3.5.

3.3 Spring Pivot: Refocusing on Automated Streaking

Given the challenges of on-farm testing—particularly the need for expert identification of bacterial colonies and multiple culturing steps—we decided to pivot back toward a lab-based solution, but with a refined focus.

Rather than fully automating the entire petri dish workflow, we redirected our efforts toward a system centered on automated streaking. In this approach, the user simply loads a sample and selects a few key parameters (such as dish type, quantity, and streaking pattern), and the machine carries out the inoculation process. This concept builds directly on one of our earlier ideas, inspired by 3D printing, and promises advantages in speed, consistency, and reduction of plastic waste from disposable inoculating loops.

This pivot allowed us to preserve our winter quarter vision of improving efficiency and reliability in petri dish workflows—while better addressing the technical and operational constraints identified through our spring needfinding.

The shift in focus also informed how we interpreted existing market solutions, as discussed in the following benchmarking section.

3.4 Benchmarking: Understanding the Gaps in Existing Solutions

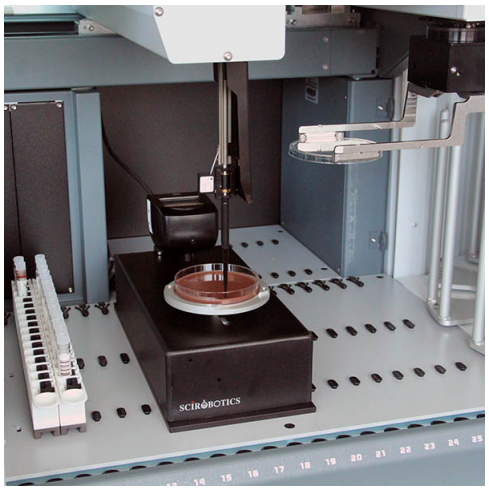
To contextualize our design within the broader landscape of laboratory automation, we analyzed several leading commercial systems—such as those from **SciRobotics**[1], **Beckman Coulter**[9], and **Interscience**[10]—and evaluated their relevance for veterinary diagnostic labs. While these systems demonstrate impressive throughput and automation in high-volume human labs, they reveal significant limitations when considered for small-scale veterinary use.

SciRobotics offers automation solutions such as the **PetriPlater** shown in **Figure 3.1a** for automated streaking, **Pickolo** shown in **Figure3.1b** for colony picking, and **AutoCount** shown in **Figure 3.1c** for imaging and colony counting. While these solutions are well-integrated into high-throughput human labs, their applicability to veterinary settings remains limited. We break down key areas for evaluation in **Appendix A.2**. SciRobotics' products are designed to automate specific aspects of laboratory workflows, with each machine specializing in a distinct function. While these individual solutions enhance efficiency, precision, and contamination control, they also introduce challenges related to cost, lab space, and seamless integration between different machines.

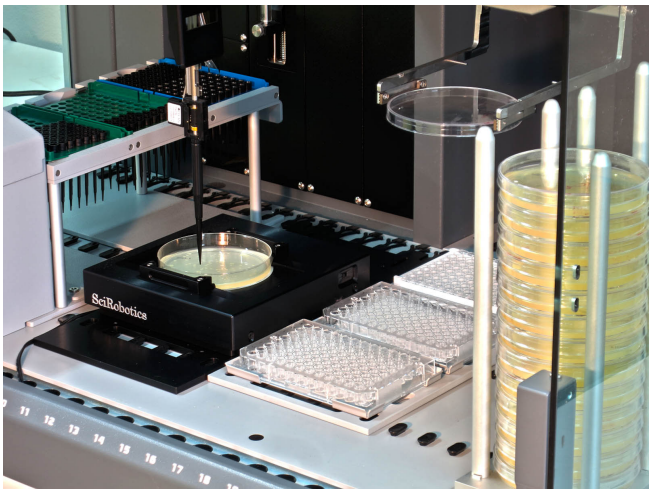
For example, the Tecan Fluent 480 Automation Station shown as Figure 3.2a, when paired with the Petri Plater and Petri Dish Stacker from SciRobotics, has a combined hardware cost of over **$300,000—$215K** for the base station and **$85K** for the plating and stacking modules—plus an additional **$75K** or more annually for the software. Similarly, Interscience's ScanStation 100 starts at **$150,000**, and even their more limited EasySpiral streaking device shown as Figure 3.2b costs over **$21,000.**

Despite their capabilities, these products share key drawbacks:

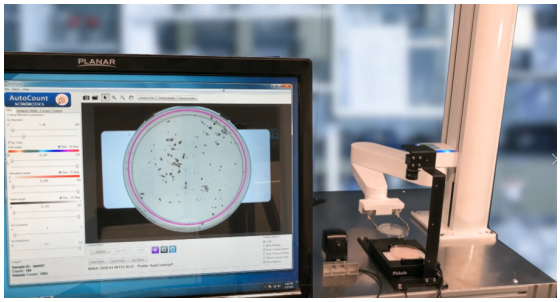
- **High cost:** Even minimal systems cost upwards of $100K–$150K, and often do not include software licensing or required accessories.
- **Designed for human labs:** Most systems are built for labs processing **hundreds of petri dishes per day**—throughputs that vastly exceed the needs of veterinary labs, which typically handle fewer than **30 dishes daily**.



(a) *PetriPlater*



(b) *Pickolo*



(c) *PreciseCountWithScreen*

Figure 3.1: *SciRobotics Inc Products [1]*

- **Space-hungry:** These machines are often **too large to fit inside a standard biosafety hood**, making them impractical for small labs with limited bench space.
- **Complex operation:** Many systems require **swapping modules**, **reprogramming**, and **lengthy technician training**, further increasing the barrier to adoption in smaller, lower-resource labs.

This benchmarking strongly affirmed the need for a device that is:

- **Compact** – designed to fit into existing lab spaces, including culture hoods.
- **Budget-friendly** – within reach for small veterinary clinics and diagnostic labs.
- **Intuitive to use** – simple enough to operate with minimal training or setup.

These insights directly informed our design direction and validated our belief that a focused, task-specific solution would be far more impactful and accessible than overbuilt industrial alternatives.



(a) *Tecan Fluent 480 Automation Station [9]* (b) *EasySpiral[10]*

Figure 3.2: *Commercial Automated Petri Dish Systems*

3.5 Key Concepts Evaluation

As we pivoted our main concept from having users perform streaking manually to automating the streaking process within the machine, our design priorities shifted accordingly. In the updated system, the user only needs to load the sample and select the agar type and streaking pattern—streamlining the entire workflow.

Fortunately, we were able to recycle valuable experience from our previous functional prototype, particularly in the development of two core modules: the lid lifter and the Petri dish cartridges.

3.5.1 Lid Lifter

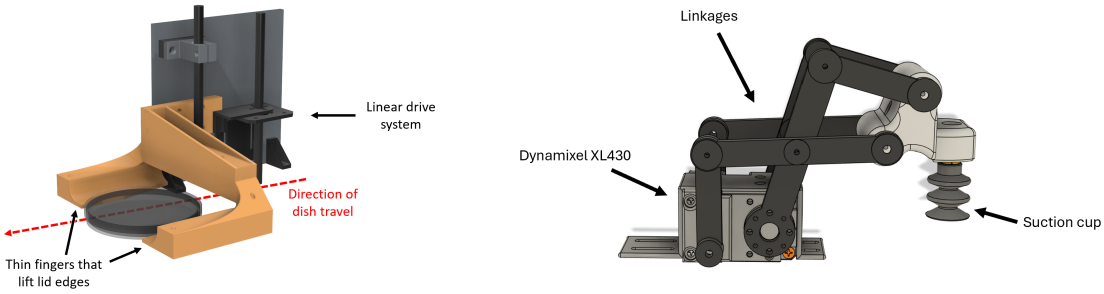
In our earlier design, the lid lifter relied on a gripper mechanism (Figure 3.3a) with passive fingers that slid under the lid of the Petri dish. As the dish was moved into position by the carousel, the end effector would raise the lid while leaving the base stationary for streaking.

However, this approach proved unreliable. Due to the thinness of the Petri dish lid and the positional variation introduced during dish transfer, the gripper frequently failed. The mechanism required extremely high precision to operate effectively—something that was difficult to maintain in real-world conditions.

To address this, we explored the use of a suction-based solution. Our final design, shown in Figure 3.3b, features a six-bar linkage system paired with a **bellows-type suction cup** (details are shown in 5.4). Initially, we experimented with a standard flat suction cup, but it struggled with reliability during the 90-degree lifting motion. The lid would often jam against the dish base.

By switching to a bellows suction cup, we introduced a small vertical compliance in the suction interface. This additional degree of freedom helped the suction cup better align with the dish lid and reduced jamming incidents significantly. The compliant vertical motion provided by the bellows

allowed for smoother engagement and disengagement of the lid, ultimately resulting in a more robust and repeatable unlidding process.



(a) *Previous Design* (b) *Final Design*

Figure 3.3: *Design Iteration of the Unlidding Mechanism*

3.5.2 Petri dish cartridges

Throughout the development process, we consistently adhered to a user-friendly design philosophy—aiming to make cartridge loading as simple and intuitive as possible. In earlier versions, we implemented an under-table cartridge system actuated by a linear rail as shown in Figure 3.4a. While this design functioned in principle, it was not easy for users to load Petri dishes accurately, and small tolerance mismatches often led to mechanical failures or misalignment.

For the final product, we developed a more complete and refined system that balances complexity in mechanism design with simplicity in user interaction (details are shown in Section5.2). As shown in Figure 3.4b, the cartridge uses an **iris mechanism** (details are shown in Figure 5.6)at its base to retain dishes with mechanical tabs before and after insertion into the machine.

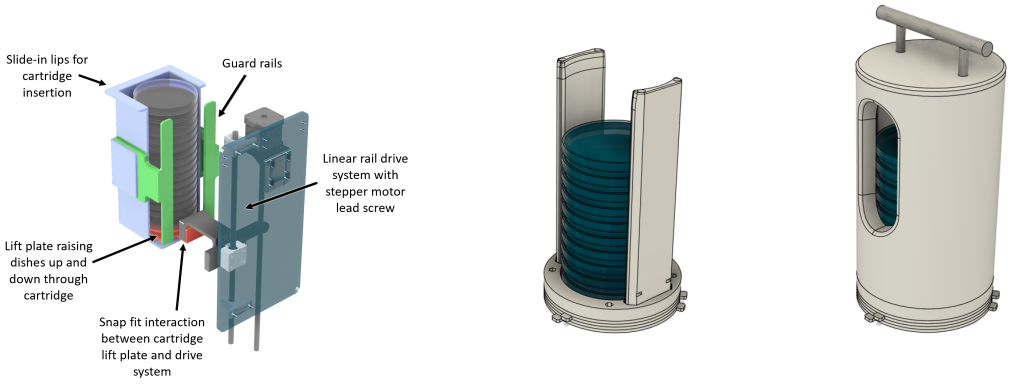
To operate, the user simply twists the cartridge once it is placed into the machine. This rotational motion actuates the iris mechanism, rotating the internal tabs and allowing a single dish to drop onto the retrieval mechanism below. The simplicity of the user action—twist to load or unload—hides the internal mechanical complexity, resulting in an interface that is both elegant and robust.

This final cartridge design not only improves usability but also significantly enhances reliability by eliminating the precision-alignment issues seen in the earlier linear rail design.

3.5.3 Summary

The design of our system evolved from a broad modular concept to a streamlined solution focused on automated streaking—one that more directly addresses the practical needs of veterinary lab technicians. Early in the project, we envisioned a configurable system capable of labeling, storage, lid removal, and dish presentation, tailored to the specific needs of lab technicians. However, field research conducted during spring break, including time spent with our global team in Norway, challenged some of our initial assumptions.

Explorations into on-farm mastitis testing revealed both market potential and major technical barriers—especially around bacterial identification and the complexity of field-based culturing. After investigating these challenges and comparing them to our lab automation direction, we pivoted



(a) *Previous Design* (b) *Final Design*

Figure 3.4: *Design Iteration of the petri dish cartridges*

back to a streaking-focused system that better aligned with our timeline, technical resources, and user constraints.

This narrowed focus didn't mean starting from scratch. Instead, we iterated on and refined many components from the earlier design—such as reengineering the lid lifter with a compliant suction cup, introducing a cartridge system with an iris-based release mechanism, and improving the revolver for dish handling. These changes allowed us to simplify the user experience without compromising on reliability or functionality. In doing so, we shifted our goal from building the most capable system to building the most usable one for small-scale veterinary labs.

4 Design Requirements

The delivered final prototype successfully streamlines the bacterial culturing process, significantly improving efficiency, reliability, and user experience during laboratory procedures. The requirements outlined in this section reflect the refined functional capabilities and physical characteristics of the completed device. By the end of the Spring Quarter, our focus shifted from conceptual validation to ensuring robust performance, ease of use, and alignment with real-world lab workflows—culminating in a product ready for deployment in veterinary diagnostic environments.

4.1 Functional Requirements

Table 4.1 outlines the functional requirements for InoQ.

4.2 Physical Requirements

Table 4.2 describes the physical requirements for InoQ.

4.3 Opportunities

During development, the following opportunities were considered:

- Integrate the device with existing laboratory equipment and transportation systems.
- Maintain a modular approach adaptable to diverse lab environments and future extensions.
- Evaluate and optimize mechanisms for efficient and safe handling of Petri dishes.

4.3.1 Assumptions

- Petri dishes are the primary method of sample containment.
- Operations occur within typical laboratory environments.
- Users have baseline familiarity with laboratory equipment and standard procedures.

Requirement	Metric	Rationale
Reduces technician time spent hands on with dish streaking	Time $\leq$ current time spent streaking dishes (eg. 2 hours for 30 dishes)	Lab techs can spend more time diagnosing and less time on tedious tasks.
Protects user from biohazardous materials	User only comes into contact with biohazardous sample once during unlidding process.	Safer for lab technicians to reduce extended proximity with bio materials.
Cartridge dish capacity	Cartridges hold $\geq$ 15 dishes each.	Enables efficient handling of sample quantity, based on dish per day averages of users in veterinary diagnostic labs.
Set-up time	Loading a cartridge with dishes and inserting it into the machine must take $\leq$ 45 seconds.	Minimal overhead time is important for efficiency. Long set-up time discourages frequent use.
Ease of set-up and use	Loading and unloading cartridges, as well as any other set-up tasks, require zero tools.	Tools are easily lost and add extra difficulty to user experience.
Compatibility with current workflow	Dishes can be loaded into cartridges in the same form that they are packaged and received.	Minimizes clumsy set-up work required of users.
Compatibility with standard Petri dish size	Device supports usage of nominal 100 mm diameter Petri dishes.	Most common dish size for standard bacteria tests is 100 mm.
Completed cartridge inversion	Cartridge holding inoculated dishes can be inverted and still stand alone.	Dishes are often incubated flipped over such that condensation does not gather on lid.
Simple user interface	Beginning the inoculation process for a sample takes less than 5 taps on the touchscreen.	Easy and quick user experience with fewer avenues for user error.
Machine production cost	Device costs less than $2000 to produce.	Device can be sold at $\leq$ $5000 price point to users to pinpoint small lab market space.
Growth medium variety accommodation	Device accommodates $\geq$ 3 types of agar growth mediums by separating them in $\geq$ 3 different cartridges.	There are 3 common types of growth medium used in veterinary applications: agar, chocolate, and blood.
Streaking pattern variety	Device can perform at least 2 different streaking patterns.	There are two main types of streaking patterns used for either urine or other material applications.
Visibility for user confirmation	User is able to see streaking occur to confirm satisfactory operation.	Gives user confidence in effective machine operation.

Table 4.1: *Functional Requirements for InoQ*

Requirement	**Metrics**	**Rationale**
Lightweight and portable	Device weight less than 11 kg.	Ensures ease of transport and portability. No machinery or professional help needed to lift and set up.
Compact height and footprint	Device dimensions should not exceed 50 × 70 × 50 centimeters.	Device should fit inside of standard culture/fume hoods with room for other tasks to be performed next to it. Also allows for convenient storage.
Durable materials	Device withstands at least 400 use cycles and 100 cleanings without part failure or material degradation.	Because of biohazardous liquids, the device will need to undergo frequent sanitization.
Stability during operation	Stable under up to 4.5 kg lateral force.	Safe and efficient operations when under use. Physical external disturbances should not cause process failures.
Cartridge weight	Loaded cartridge weighs less than 2.5 kg.	User can easily lift and maneuver cartridges with one arm.
Ergonomic cartridge carrying	User can hold and install/uninstall cartridges with one hand, comfortably.	User will need to interact and carry cartridges regularly during set-up and incubation.

Table 4.2: *Physical Requirements for InoQ*

5 Design Specifications

Focused on meeting the design requirements discussed in the previous section, we designed and built a beta prototype of the InoQ Petri swabbing system, with dish loading, lid removing, and streaking capabilities. In this section, we will discuss several elements of the InoQ machine prototype in detail.

- The **structure and housing** that support and enclose machine elements and operations.
- **Petri dish cartridges** that the user loads and unloads from the system.
- The **dish retrieval system** that brings Petri dishes down from cartridges for swabbing and raises completed dishes up for storage.
- The **lid lifter** that removes the dish lid for streaking and replaces it when streaking is complete.
- The **swabbing mechanisms** used to complete the actual sample collection and swabbing onto the agar surface.
- The **loading components** for inserting samples and removing contaminated swabber cut-offs.
- The **electronics components and controls** for operating the prototype and GUI.

These elements are shown in Figure 5.1.

The four elements and an overview of the electronics currently developed through our work on the functional prototype will be discussed in detail in the following sections.

5.1 Structure and Housing

The machine's structure is divided into three main levels: the top plate, the mid plate (sometimes referred to as the dish track), and the bottom/base plate. These are shown labeled in Figure 5.2. The top plate is where cartridges are loaded by the user from above, and it carries the dish grippers that prevent the dishes from falling out of the cartridges. The mid plate is the level upon which the individual dish being worked upon moves throughout the system (hence the name "dish track"). Mounted to the mid plate is the dish "handler" which holds and guides the active Petri dish, the lid lifter mechanism, the rack and pinion dish retrievers, and the front loading components (sample holder, disposal box, and tip cutter). The bottom plate is the base of the system, to which the upper levels are mounted by support rods. The suction dish rotator is also mounted to the base, along with the majority of electrical board and components, and the pneumatic components.

5.1.1 Physical specifications

The three structural layers are made of 6 mm thick laser-cut acrylic, designed to fit just under the 18x24 inch limit of the PRL AMPS laser cutting machines, while maximizing available internal space for machine components and operations. This led to a machine footprint of 450 mm by 682

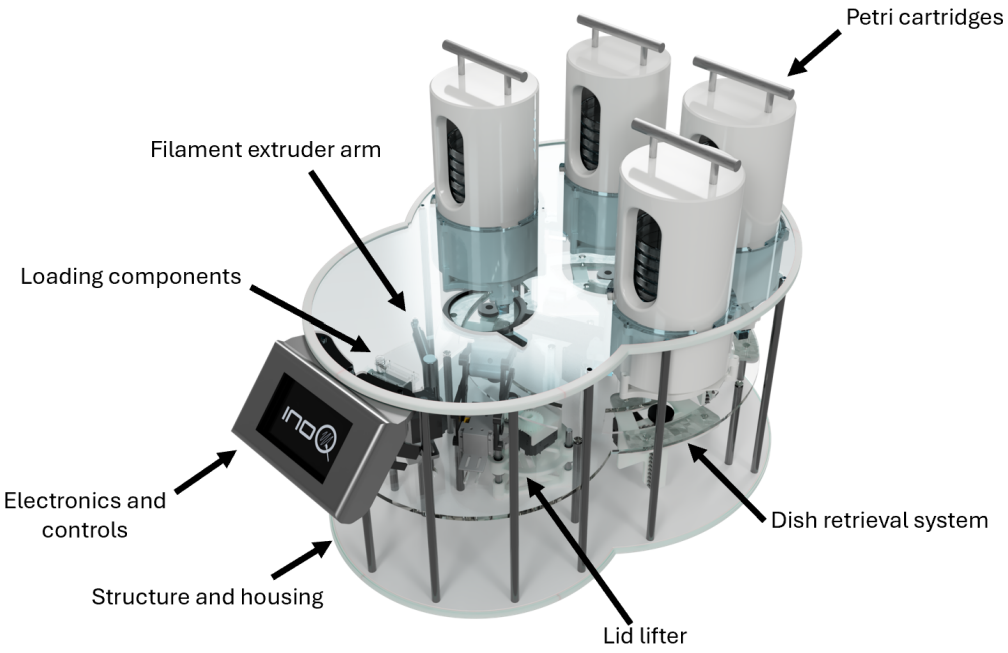


Figure 5.1: *CAD render of interior of InoQ prototype with labeled components.*

mm, as shown in Figure 5.3. The height of the machine from base to the top of the top plate is 290 mm, while the height to the very top of the cartridge handles is 475 mm. The footprint remains below the design requirement we set, while the height just slightly extends past our goal of 400 mm with the cartridges in place.

The mid plate is mounted by 10mm diameter aluminum support rods that are 120 mm long and tapped at both ends with M5 threads. The support rods for the top plate are also 10mm in diameter but are 280 mm in length. Holes on the top plate, mid plate, and base plate were countersunk with 90 degree bits so that sunken screw faces did not interfere with Petri dishes or the ground.

The housing was made of 1.2 mm thick polycarbonate sheets. The polycarbonate is held in its curved shape by 3D printed PLA brims superglued to the top and base plate edges. These brims act as outer walls guiding the curve of the polycarbonate, as shown in Figure 5.4.

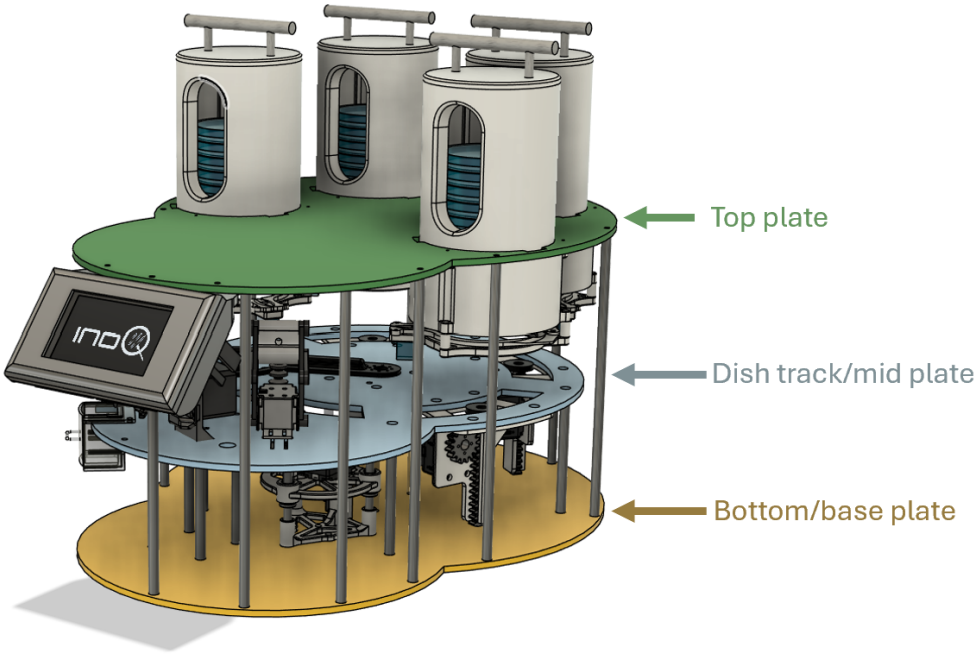


Figure 5.2: *Isometric view of machine CAD model with highlighted structural layers.*

5.2 Petri dish cartridges

The cartridges are the user's first touchpoint with the system. They are used both for dispensing Petri dishes into the system and carrying completed dishes out and into an incubator. One of the functional requirements for the cartridges was that they can be loaded with dishes that are in the same form as they are packaged when received by labs. From our lab visits, we learned that most dishes are stacked and wrapped in plastic or plastic bags. As such, we designed our cartridges to accommodate the user placing dishes in as one complete stack. Another requirement was that the loading and unloading process does not require any tools. The system was designed with guides and magnets for easy by-hand assembly. The loading process has four steps: (1) placing the dishes into the cartridge, (2) sliding the cartridge cover into place from the top until magnets lock, (3) sliding the cartridge into the InoQ machine through holes in the top plate, and (4) twisting the cartridge by the handle to lock it in place and release the tabs constraining the dishes at the bottom. Figure 5.5 shows what a filled cartridge looks like with and without the cover in place.

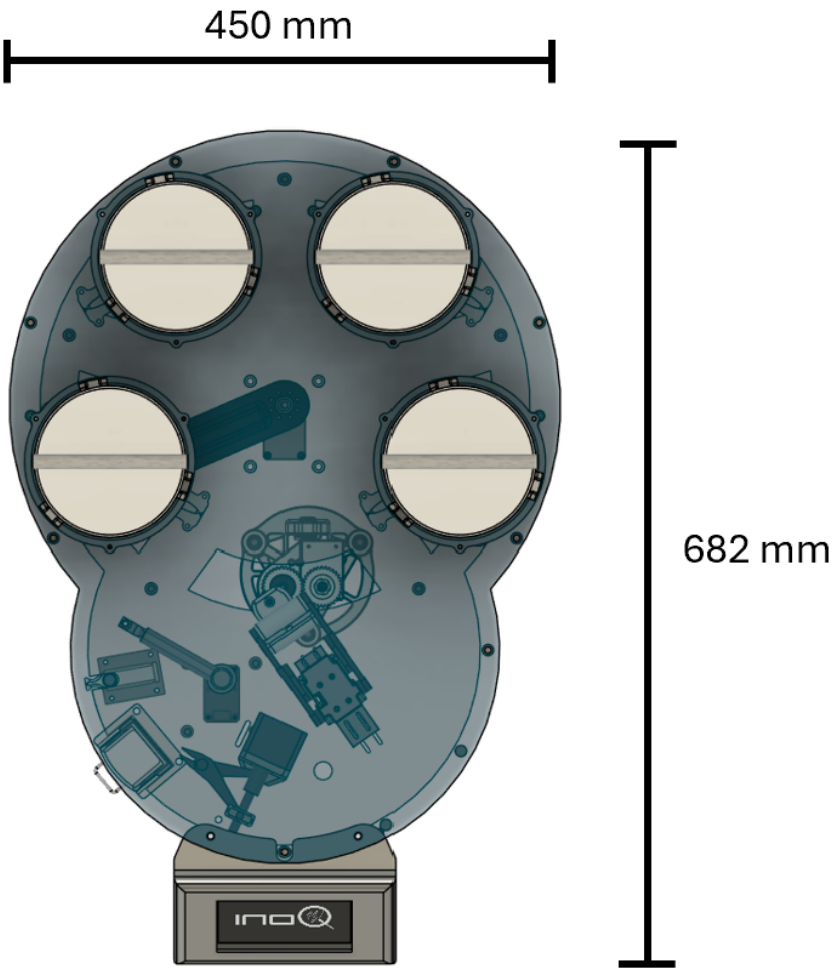
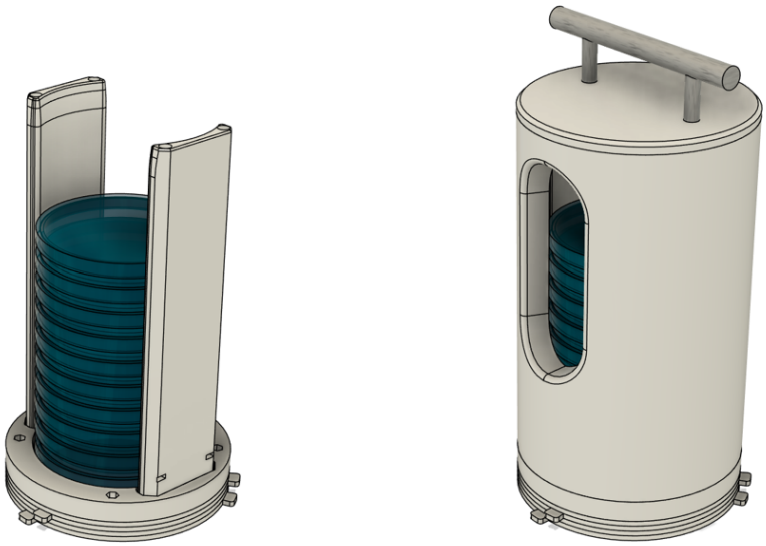


Figure 5.3: *Top view of machine CAD model denoting machine footprint.*



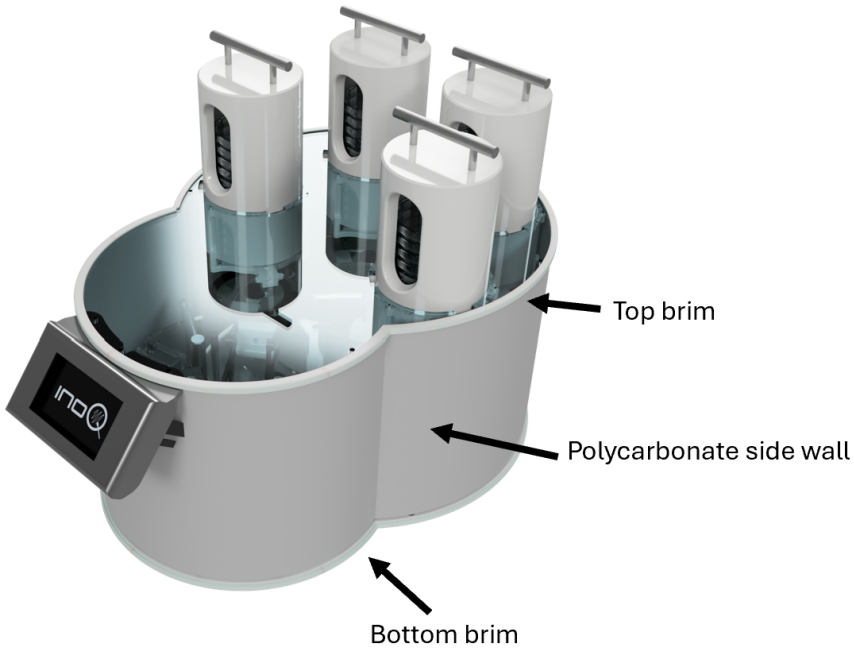


Figure 5.4: *CAD render of prototype displaying side walls and brims for housing.*

The cartridge uses an iris mechanism (shown in Figure 5.6) at the base to retain the dishes with tabs prior to being loaded into the machine and after being removed from the machine. Twisting the cartridge inside of the machine rotates the tabs such that the dishes can fall through the cartridge base onto the retrieval mechanism. A holder (Figure 5.7) carries the cartridge and interacts with the iris tabs. At the base of the holder is a spring-loaded dish gripper mechanism to carry the dish stack. The retrieval and gripper mechanisms will be discussed in the following section.

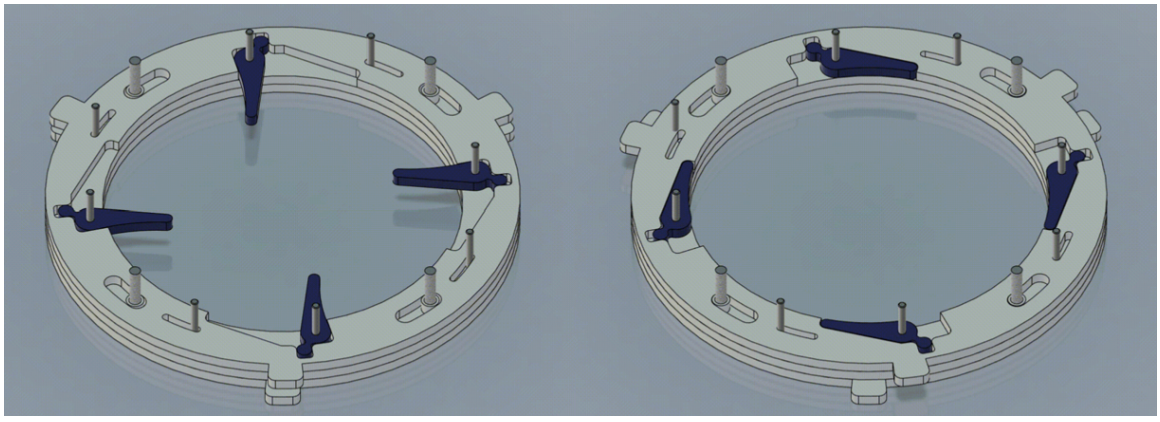


Figure 5.6: *Closed and open configurations of cartridge iris mechanism.*

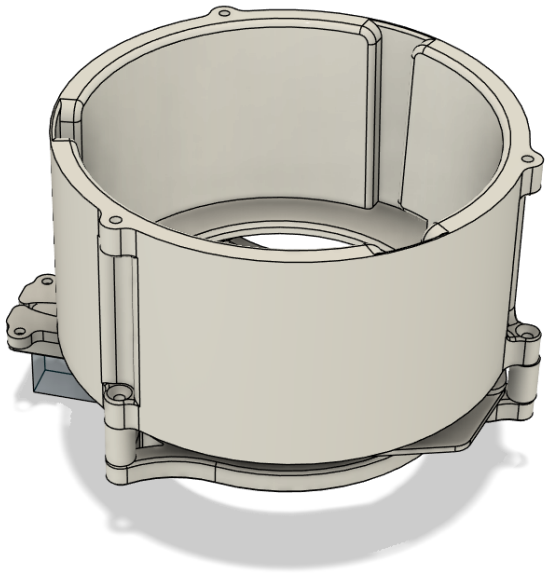


Figure 5.7: *CAD model of cartridge holder.*

5.2.1 Physical specifications

For the InoQ prototype, the cartridges were primarily 3D printed in several pieces out of PLA. The iris mechanism components at the base were laser cut from 3 mm acrylic, and steel 2 mm dowel pins were used as bearings for the tabs and connecting rods for the rotating rings. The vertical dish guides were printed as separate pieces from the base and super glue was used for adhesion. Magnets were slotted into the cartridge cover and the cartridge base to hold the cover closed, and a steel handle was screwed into the cover for an ergonomic and aesthetic handhold. The closed cartridge exterior is 124 mm in diameter and 250 mm tall, making it comfortable and easy to carry in one hand, and small enough to fit inside of an incubator.

5.3 Dish retrieval system

A two-part mechanism is used for lifting Petri dishes down from and up to the cartridges. As the cartridges have an open bottom once they've been loaded into the machine to let dishes out the base, we still need a method for retaining the dishes vertically, such that the entire stack does not fall onto the mid plate dish track level. The mechanisms used for this are (1) a spring-loaded dish gripper and (2) a rack and pinion lift. These two mechanisms are located below each cartridge. The dish gripper, as shown in Figure 5.8 is composed of two semi-circular arms, an extension spring and a small servo that actuates the arms. The gripper is loaded such that the closed position is its natural state, and the servo only actuates briefly when the gripper must be opened to allow a dish to pass through.

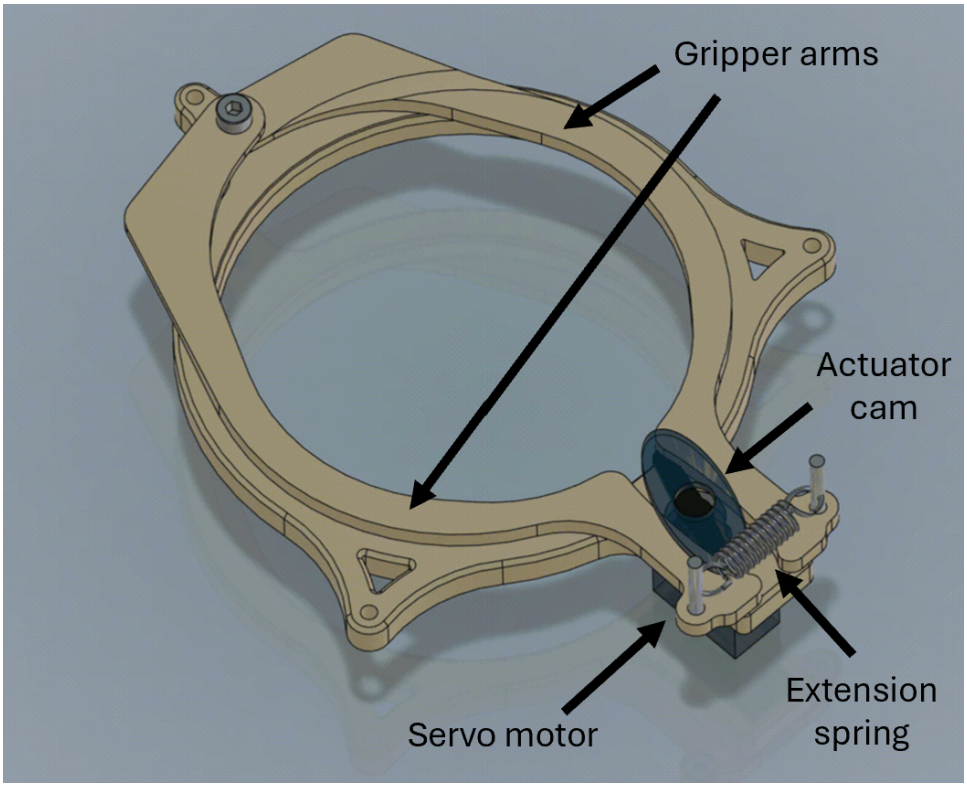


Figure 5.8: *Labeled diagram of dish gripper mechanism.*

The gripper mechanism works in tandem with the rack and pinion lift. This is a simple vertical linear motion mechanism that allows us to raise and lower dishes from the cartridge in a controlled manner (a large improvement from an original prototype involving dropping the dish from a moderate height above the track and handler). The rack and pinion mechanism (shown in Figure 5.9 has a 16 tooth pinion, a 111 mm long rack, a mounting guide, and a circular pad that surfaces with the dish bottom. It is driven by a Dynamixel XL430 (a continuous rotation, position based servo) and the whole component mounts directly to the bottom side of the mid plate.

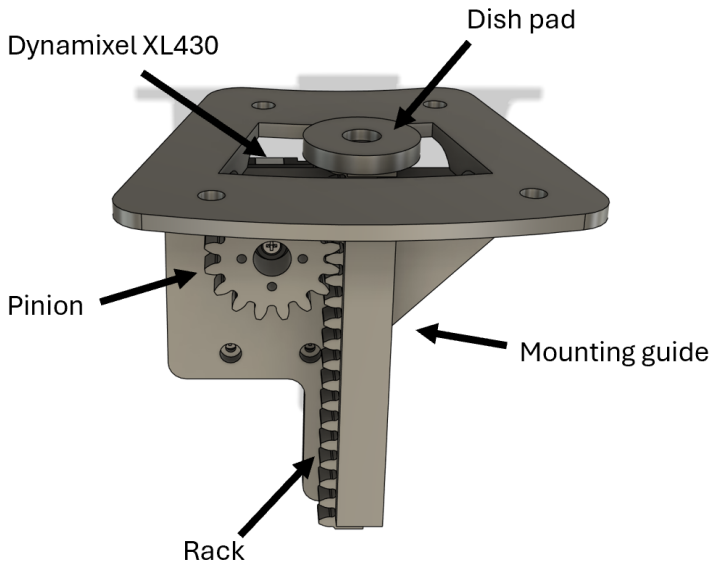


Figure 5.9: *Labeled diagram of rack and pinion lift mechanism.*

The dish retrieval system lowers dishes into a dish handler. This component has a chamfered circle cut out that "catches" a dish and moves it along the dish track to the working area where streaking is performed and to below the completed cartridge. It is directly driven by a Dynamixel XM540. The handler is shown in Figure 5.10.

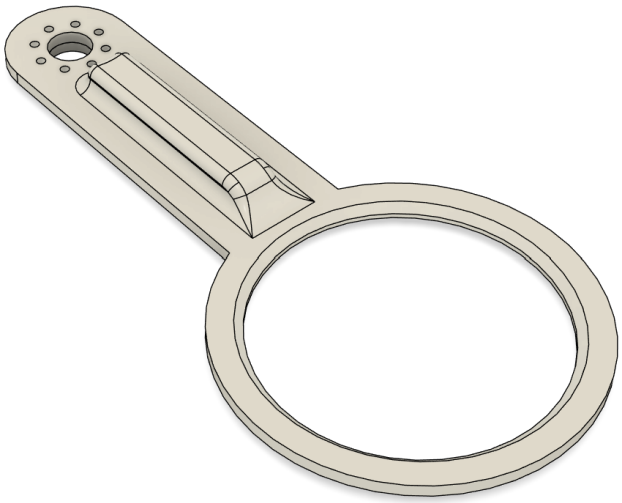


Figure 5.10: *CAD model of dish handler part for moving Petri dishes along dish track.*

There are repeatable procedures using the retrieval mechanism for loading and unloading cartridges from the system. To load a cartridge into the machine, a set-up program is run in which the gripper opens and the rack rises to an "upper" level at which it just supports the weight of the dishes rather than the cartridge tabs taking the load once locked in. Once the cartridge iris mechanism is opened, the rack lowers to its "top" level position, at which the bottom dish it is supporting is in line with the gripper such that the gripper can then close and retain the entire dish stack from falling onto the track below. The rack is then lowered to its "bottom" position below the track level. A near reversal of this is done for cartridge unloading. The rack rises to "top", the gripper opens, the rack moves to "upper", and the cartridge can then be rotated by hand to close the iris before being removed. Note: There is one more position that is useful to note for the dish retrieval process which we call the "mid" position. At this position, the rack is raised such that the second dish (the dish just above the bottom dish) is aligned with the gripper.

The instructions below show the process for retrieving a single dish from a loaded cartridge.

1. Move empty handler to under this cartridge.
2. Raise rack to "top".
3. Open gripper.
4. Lower rack to "mid".
5. Close gripper.
6. Lower rack to "bottom".

This process ends with a dish loaded into the handler while the rest of the stack remains held up in the cartridge by the gripper. To raise a dish and store it in a completed cartridge, we perform another similar but slightly reversed set of actuations.

1. Move handler with swabbed dish under completed cartridge.
2. Raise rack to "mid".
3. Open gripper.
4. Raise rack to "top".
5. Close gripper.
6. Lower rack to "bottom".

Likewise, this process ends with a dish newly stored at the bottom of the completed cartridge stack and an empty handler. With this design, where the rack mechanism extends upwards through the handler, it is important to never actuate the handler when a rack is raised above the bottom position, as it is possible to cause jamming or to break a component through collision. As such, we implemented a preventative block that only allows the handler to rotate when all 4 racks are down.

5.3.1 Physical specifications

The dish gripper mechanism is primarily made of 3D printed PLA, with the semicircular grippers sized to exactly fit the outer diameter of the Petri dishes we used for testing (87 mm). Four of these were replicated to be mounted to the bottoms of each of the four cartridge holders. The rack and pinion lift was also entirely 3D printed from PLA in four parts: the pinion, the rack, the mounting guide, and the dish pad. Using M5 heat set inserts, the dish pad was screwed into to the rack end and the assemblies were mounted to the mid plate. The Dynamixel XL430 motor direct drives the pinion gear. The dish handler is also 3D printed with PLA, with a thick rib along the length to improve rigidity.

5.4 Lid lifter

In order to perform swabbing on the agar surface inside the dish, we must first remove the lid to gain access. Previous quarters' prototypes for lid removal involved mechanical fingers of some sort (compliant or actuated). However, we found these to be challenging methods for interacting with the lids mainly because the lids sit very loosely on the dish bases and thus, the lid location when they reach the lid lifting mechanism varies greatly dish to dish. In the spring quarter, we've pivoted to using suction to grab the dish lid, which has worked much more smoothly. We use a linkage mechanism to lift and rotate the lid 90 degrees in a compact space, as we wanted to minimized vertical space needed for lid clearance as well as the mechanism's footprint. A suction cup with three bellows was used to increase the directly vertical travel of the lid when being raised and lowered onto the dish, which helps prevent jamming from the angle at which the lid meets the dish. A labeled diagram of the lid lifting mechanism is shown in Figure 5.11. The suction is driven by a diaphragm pump and pneumatic solenoid for pressure release. The linkage mechanism is driven by a Dynamixel XL430 motor.

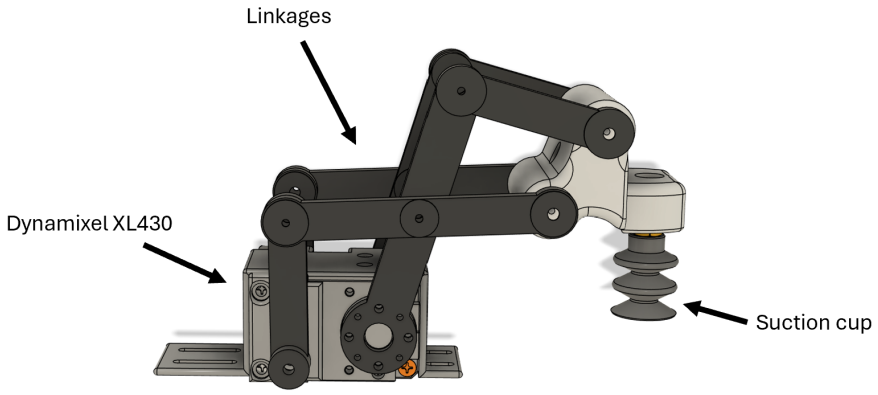


Figure 5.11: *Labeled CAD model of suction-activated lid lifting mechanism.*

5.4.1 Physical specifications

The linkages were resin 3D printed for strength and good surface quality for low friction. Small ball bearings were located at several linkage joints. The suction cup was an off-the-shelf rubber component. The mounting piece was also 3D printed with long slots for adjustable mounting on the mid plate.

5.5 Swabbing mechanisms

The actual sample pickup and swabbing of bacteria onto the agar is done by a plastic filament tip extruded (without heat) from a nozzle at the end of a rotary arm. This rotary arm, combined with rotating the Petri dish with a revolving suction cup that attaches to its bottom, allows for complete access to any point on the Petri dish agar surface, through inverse kinematics for this polar coordinate-like setup. In this section, we will discuss both the arm and the suction revolver. The swabbing mechanisms are shown in Figure 5.12.

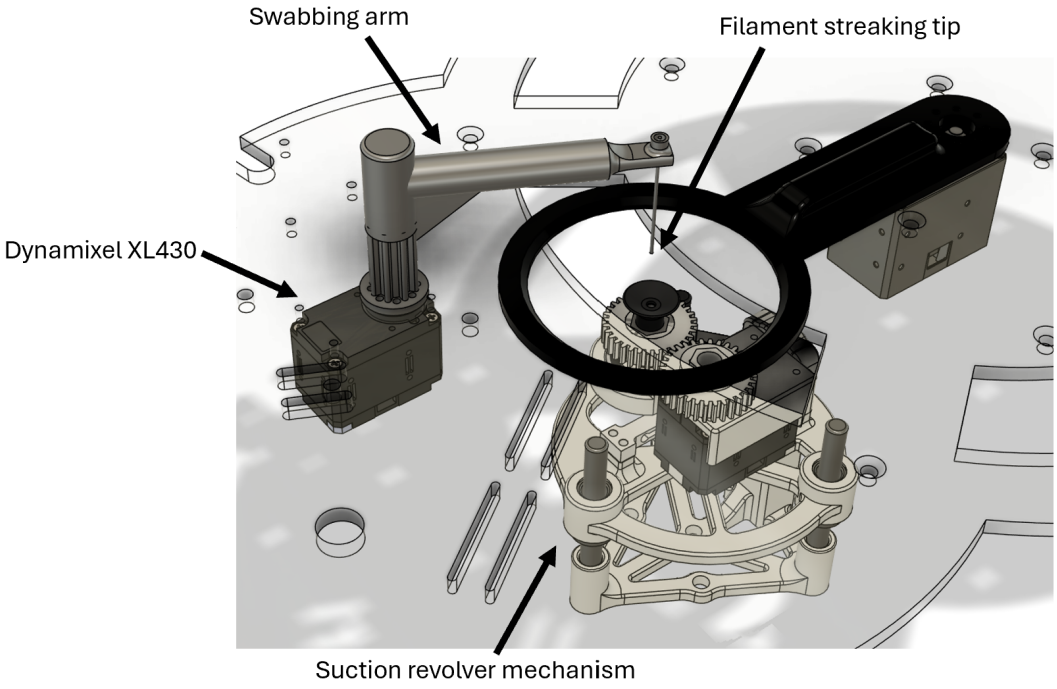


Figure 5.12: *Labeled CAD model of components for swabbing.*

The swabbing arm rotates on a path that also allows access to the sample container and filament cutter at one end. The other end of the path brings the end of the arm, where the tube containing filament is located. The arm is directly driven by a Dynamixel XL430 motor which allows us fine positional control.

The suction revolver mechanism involves a suction cup screwed into a 360 degree pneumatic fitting that allows for smooth rotation without twisting or tangling of tubing. We also attached a gear to the suction cup such that we are able to rotate the dish once suction has secured the dish to the cup. Rotation is controlled by a Dynamixel XL430 motor. The entire rotation mechanism is mounted on 3 linear slides, as we need some small vertical motion to make secure contact with the dish bottom, without getting caught on the dish base's lips around the outer edge when it moves into place. The vertical motion is achieved with a very small linear actuator. In order to detect when the filament has made contact with the agar solution as we extrude down to reach it, a load cell is mounted to measure vertical load on the suction cup. The revolving mechanism is shown in more detail in Figure 5.13.

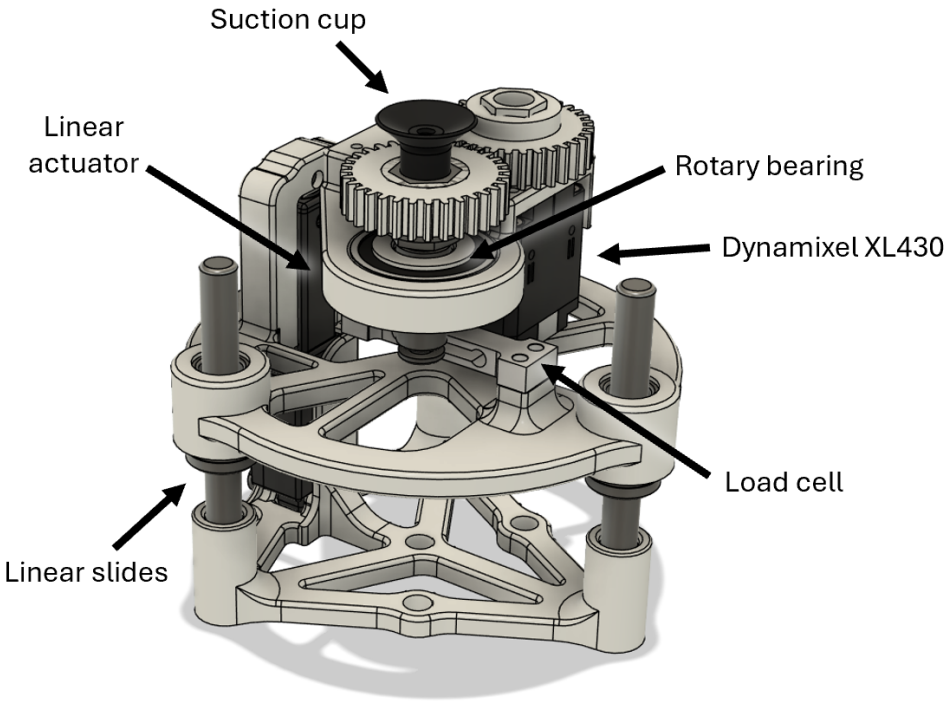


Figure 5.13: *Labeled CAD model of suction revolving mechanism.*

5.5.1 Physical specifications

The extruder arm was 3D printed with PLA and is directly attached to the XL430 motor, which is mounted to the base of the mid plate. Most of the structural components of the suction revolver are 3D printed PLA, while the linear slide rods are steel. The gears are also made of PLA. This entire mechanism mounts to the top of the base plate with screws inserted from the bottom.

5.6 Loading components

The most forward mechanisms that the user interacts directly with are the sample drawer and the disposal box. Above the disposal box is the cutter mechanism which disposes of contaminated filament. These are shown in place in Figure 5.14. Before instructing the machine to exercise a set of streaking preparations, the user must insert the sample into a small drawer such that the filament tip can access it and pickup or collect some sample material. The drawer is easily pulled out with a thumb tab and snaps into place with minimal force on reentry. The disposal box similarly utilizes a snap fit and can be pulled out and pushed back into place. Unlike the sample holder, this should only be done by users occasionally, when the disposal box becomes filled with contaminated tips. The filament cutter mechanism makes use of two blades to cut the plastic filament after enough is extruded over the disposal box such that the cutter will not contact any potentially contaminated surface. The cutter is driven with a stepper motor.

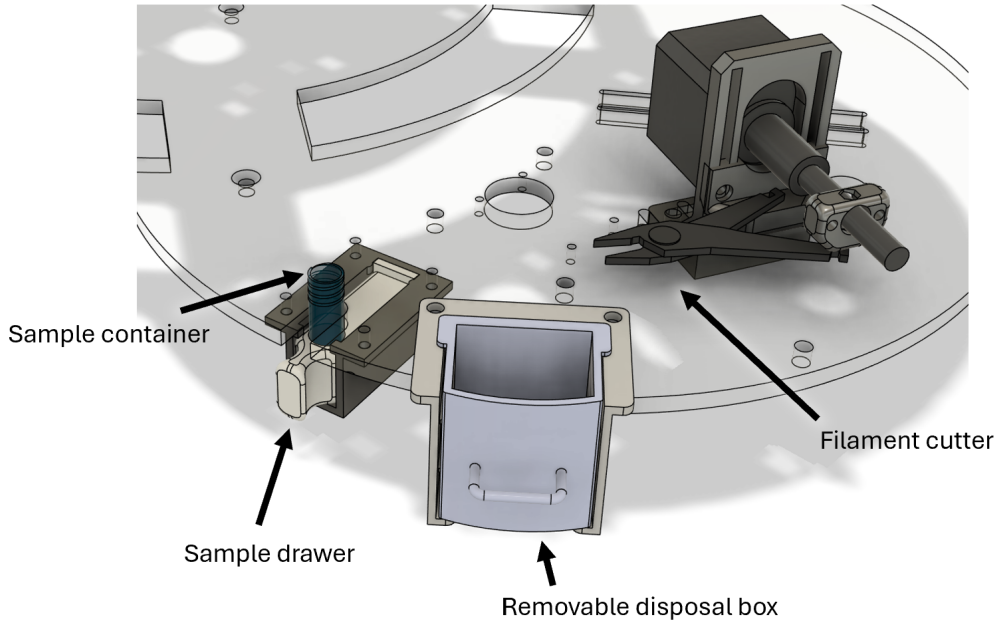


Figure 5.14: *Labeled CAD model of front user interaction loading components.*

5.6.1 Physical specifications

Most of the front loading components are printed from PLA. The sample drawer and the drawer slot (or “cupboard”) are both 3D printed. Likewise, the disposal box and box slot, as well as the cutter mounting bracket are all 3D printed PLA parts. The cutter uses the front part of steel wire cutters, and uses a lead screw mechanism driven by a NEMA 17 stepper motor to drive the cutting action, squeezing the two blades of the wire cutters together. All of these loading components are mounted to the mid plate.

5.7 Electronics Architecture

5.7.1 Overview

Our system is divided into one main controller host computer that handles the logic of the program and three main microcontroller units that work in coordination to handle different aspects of the system's operation. The system operates under the coordination of a Python-based GUI controller running on an Intel NUC computer that implements a command-response protocol. The main display is a 5“ capacitive touch screen connected via HDMI and USB to the NUC. Commands are transmitted as text strings over the serial connections, with each microcontroller responding with standardized status confirmations. The host computer coordinates the complete workflow by sending sequential commands to the appropriate controllers and waiting for confirmation responses before proceeding to the next operation, ensuring synchronized operation across all subsystems. The distributed architecture allows each controller to specialize in its designated functions while maintaining precise coordination through the central Python controller.

5.7.2 Power Distribution

The system is powered by two primary external sources. The first is a 12V DC power supply connected via a barrel jack, which powers the majority of the system's actuators, including all Dynamixel motors and the relay-controlled pneumatic valves. A DC-DC buck converter steps down this 12V line to 6V to power the diaphragm pumps and servo motors, which require a lower operating voltage. The second source is a dedicated 19V power adapter used to supply the Intel NUC, which serves as the main controller. This ensures stable operation of the compute unit.

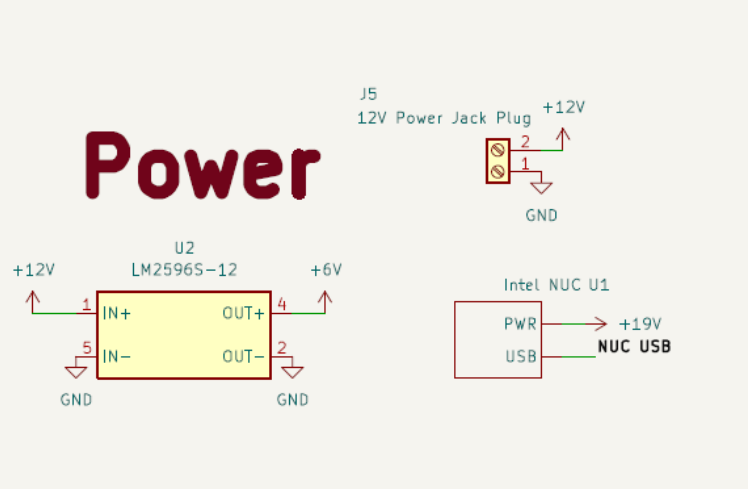


Figure 5.15: *Power Distribution Schematic*

5.7.3 Microcontroller Subsystems

5.7.3.1 Servo Motors and Pneumatic System (ORB1)

The first controller is a ROBOTIS OpenRB-150 (designated as ORB) that communicates via serial port COM11 at 115200 baud and serves as the primary motion control unit.

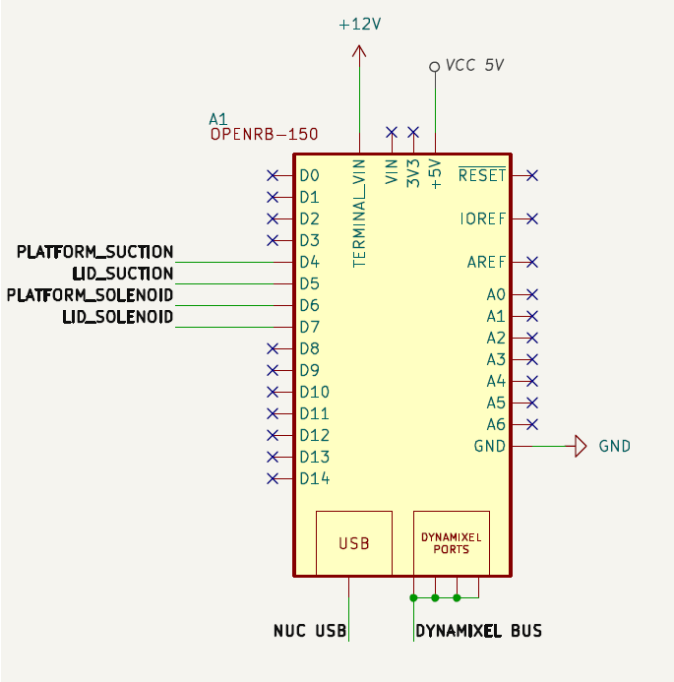


Figure 5.16: *Robotis OpenRB-150 Schematic*

This controller manages eight Dynamixel servo motors through a TTL serial network operating at 57600 baud, including the Lid Lifter Motor (ID 1) for removing and replacing petri dish lids, the Polar Arm Motor (ID 2) that positions the main robotic arm between sample vials, cutting stations, and the streaking platform, the Platform Motor (ID 3) which provides precise rotational control of the dish during streaking operations, the Handler Motor (ID 4) that rotates the entire dish handling mechanism between different cartridge positions and the work area, the Restacker Motor (ID 5) for vertical positioning of the storage cartridge, and three additional cartridge motors - Cartridge 1 Motor (ID 8), Cartridge 2 Motor (ID 6) and Cartridge 3 Motor (ID 7).

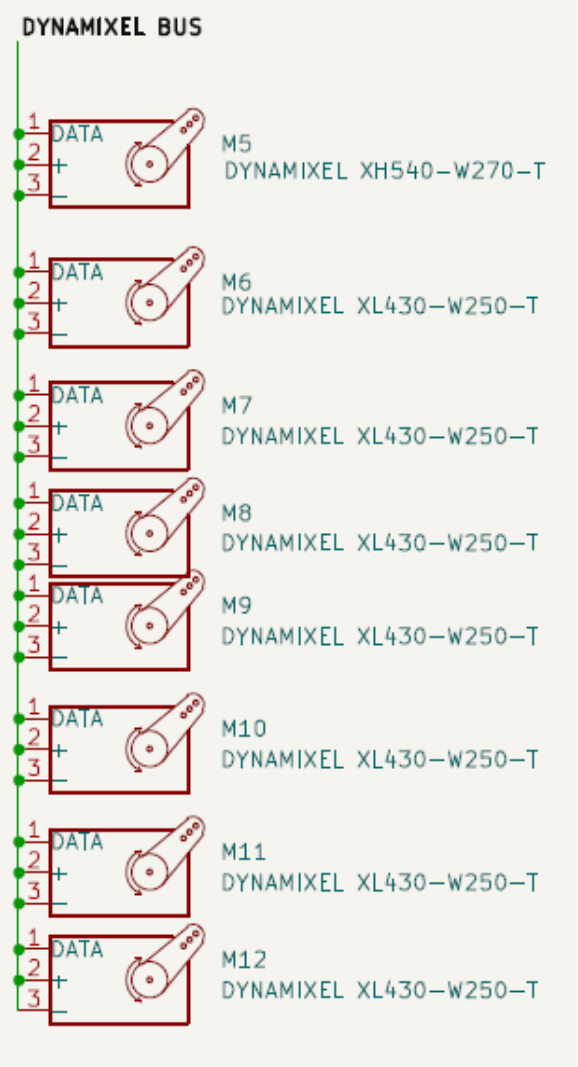


Figure 5.17: *Dynamixel servo motors connected on a shared TTL bus.*

Figure 5.17 illustrates the Dynamixel bus architecture used in the system, with eight servo motors daisy-chained via TTL communication. This configuration allows all motors to be controlled through a single UART port on the OpenRB-150 microcontroller, simplifying wiring and enabling synchronized motion control across components.

This primary controller also manages the pneumatic system through digital output pins connected to a 4-channel relay module. The OpenRB-150 controls both the lid suction system and the platform suction system.

5.7.3.2 Cutting Mechanism, Sample Extrusion and Load Cell (MEGA)

The second controller is an Arduino Mega 2560 (designated as MEGA) communicating through serial port COM12 at 115200 baud, which specializes in sample handling and precision extrusion operations. This unit controls two stepper motor systems using the AccelStepper library: the main extruder stepper motor, and the cutting mechanism stepper motor.

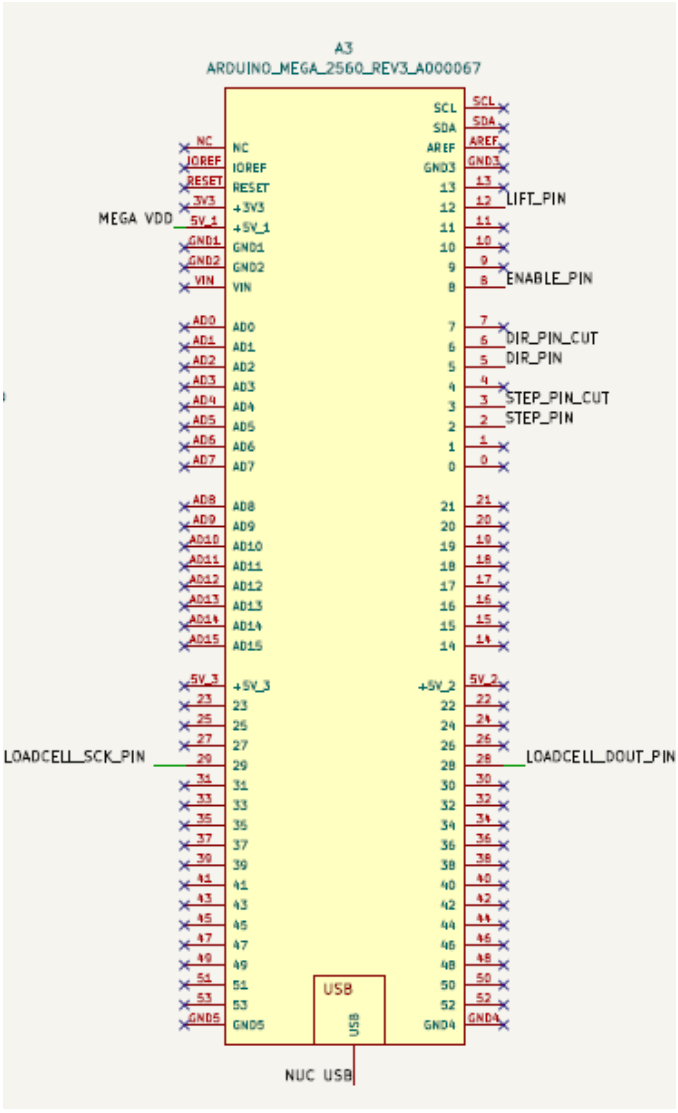


Figure 5.18: *Arduino Mega 2560 Schematic*

To facilitate communication with the stepper motors, we use a WWZMDiB CNC Shield along with DRV8825 motor drivers. The MEGA also integrates a precision load cell system using an HX711 amplifier, which provides real-time feedback during sample extrusion to ensure the sample touches the agar. Additionally, this controller manages a linear actuator connected to for platform lifting operations, coordinating the vertical positioning of the work surface during different phases of operation.

5.7.3.3 Gripper Operations (ORB2)

The third controller is another ROBOTIS OpenRB-150 (designated as ORB2) operating through serial port COM15 at 115200 baud, dedicated to gripper operations. This specialized controller coordinates all the gripper mechanisms that handle the grab and release operations for each cartridge type, allowing dishes to be precisely picked up from storage cartridges and placed onto the work

platform, then later moved to the completed dish storage area. While all gripper operations could have been implemented on the primary OpenRB-150 controller, we opted to use a second unit to support modular testing and development. This separation allowed for easier debugging, parallel subsystem integration, and clearer software architecture during the prototyping phase.

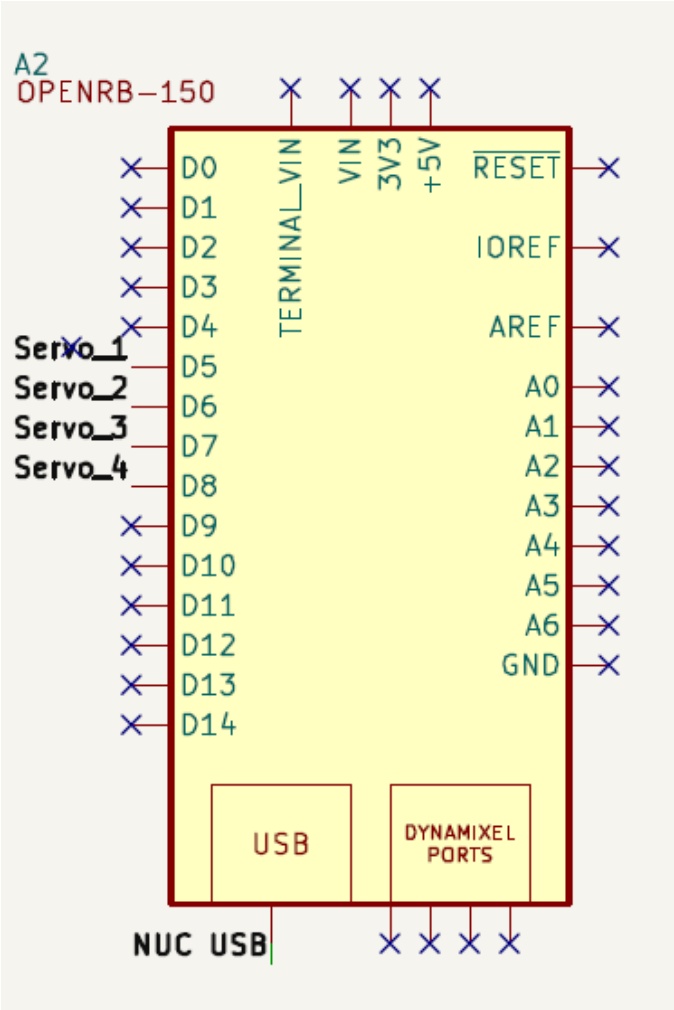


Figure 5.19: *Auxiliary OpenRB-150 Schematic*

The complete schematic describing the connections is included in Appendix 5.

5.8 Software Architecture

5.8.1 Overview

The communication between the host and embedded systems utilizes a robust command-response protocol implemented over serial connections. The host Python application sends standardized text-based commands such as ”MOVE WORK AREA“, ”LIFT NORMAL UP“, or ”SUCTION ON“ to the appropriate microcontroller, which executes the requested operation and responds with

confirmation messages like ”MOVE COMPLETED“, ”LIFT UP“, or ”SUCC ON“. This protocol ensures sequential operation coordination where the host waits for confirmation of each step before proceeding, preventing race conditions and ensuring synchronized operation across all subsystems.

The software architecture provides a clear separation of concerns where the host computer handles high-level logic, user interface, workflow orchestration, and error management, while each embedded controller specializes in real-time hardware control within its designated domain. This distributed approach enables modular development and testing, allows for independent optimization of each subsystem, and provides robust fault isolation where issues in one controller do not compromise the entire system operation. The Python host maintains overall system state and implements the complete petri dish processing workflow by coordinating commands across all three embedded systems according to the process flow established in the system design.

The automated processing workflow consists of the following main operational sequences:

1. System initialization and homing of all actuators to safe starting positions
2. User input selection for dish type, streaking pattern, and batch quantity
3. Cartridge dish retrieval through coordinated lift and gripper operations
4. Handler positioning to move dish to the work area
5. Platform preparation including lifting and suction activation
6. Lid removal using the pneumatic lid lifter system
7. Sample collection from the specimen vial with precise positioning
8. Controlled sample extrusion with load cell feedback onto agar surface
9. Streaking pattern execution through coordinated polar arm and platform rotation
10. Cutting operations to sever the sample filament cleanly
11. Platform securing and lid replacement sequence
12. Completed dish storage in the restacker cartridge
13. Queue management for processing multiple specimens sequentially

The complete command specifications are detailed in Appendix G, and the complete system logic flowchart is provided in Appendix F.

5.8.2 Host Computer Software

The host computer software is implemented as a multi-threaded Python application built using the Tkinter GUI framework, designed to provide an intuitive interface while coordinating with the microcontroller units. This main controller maintains system state including selected dish types, streaking patterns, queue management, and current operation progress.

The interface guides operators through a logical workflow starting with dish type selection (Macconkey , Blood, or Chocolate agar), streaking patterns (Line, Quadrant, or Spiral), batch

quantity, operation confirmation, and real-time process monitoring with progress indicators and completion status.

Navigation between screens is handled through a centralized screen management system that maintains the current screen index and provides forward/backward navigation capabilities, ensuring operators can review and modify selections before committing to processing operations. The interface incorporates visual feedback systems including progress bars, status indicators, and real-time operation updates that keep operators informed of system status throughout the automated processing sequence.

Error handling and safety features are integrated throughout the Python application, including timeout management. The software provides diagnostic information to assist with troubleshooting.

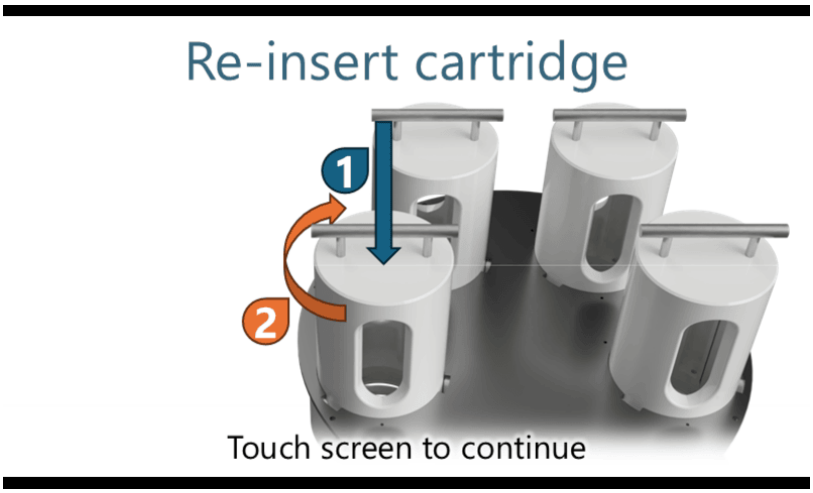


Figure 5.20: *Cartridge installation procedure showing the two-step loading process*

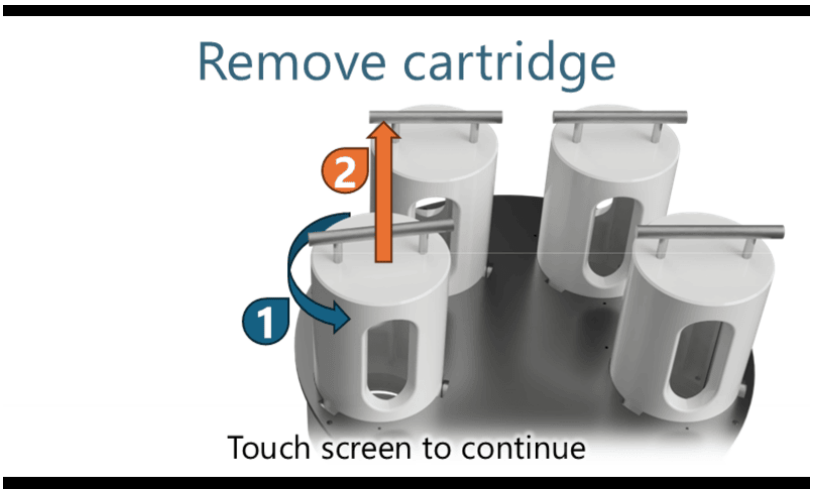


Figure 5.21: *Cartridge installation procedure showing the two-step removal process*

Figure 5.20 and Figure 5.21 provide an example of the GUI displayed to the user. The visual instruction format with numbered arrows provides clear guidance for operators to safely handle the

cartridge system without damaging the precision-aligned mechanisms or contaminating the sterile dishes stored within.

5.8.3 Primary Motion Control (ORB1)

The firmware architecture is built around two primary classes: CommandHandler for serial communication and command parsing, and HardwareControl for low-level hardware abstraction and motor coordination. This modular design separates high-level command interpretation from hardware-specific implementation details, enabling maintainable and extensible control software.

The command handling system implemented in CommandHandler.cpp receives serial commands from the host Python application and parses them into structured operations. The system supports a comprehensive command set including movement commands (MOVE WORK AREA, MOVE STRG), lifting operations (LIFT NORMAL UP, LIFT ALL DOWN), pneumatic control (SUCTION ON, LID OPEN), and specialized functions (FETCH, CUT, PATTERN). Each command is validated, executed through the hardware abstraction layer, and acknowledged with standardized response messages to maintain synchronization with the host controller.

Hardware abstraction is provided through the HardwareControl class in Hardware.cpp, which interfaces with eight Dynamixel servo motors via the Dynamixel2Arduino library. The system manages complex motor coordination including the Lid Lifter for petri dish lid manipulation, the Polar Arm for positioning between sample collection and streaking locations, the Platform motor for precise dish rotation during streaking operations, the Handler for rotating between cartridge positions, and four cartridge lifting motors for vertical positioning of dish storage systems. Motor control incorporates safety interlocks that prevent handler movement when cartridge motors are in elevated positions, avoiding mechanical collisions.

Finally, pneumatic system control is integrated directly into the motion control firmware, managing vacuum pumps and solenoid valves through digital output pins connected to relay modules.

5.8.3.1 Rotational Swabbing Implementation

The rotational swabbing system operates by coordinating two primary actuators: a polar arm that moves radially from a fixed pivot point, and a rotating platform that holds the petri dish, together creating a polar coordinate system that can reach any point within the dish's circular boundary. This approach eliminates the need for larger cartesian positioning systems while providing precision and repeatability.

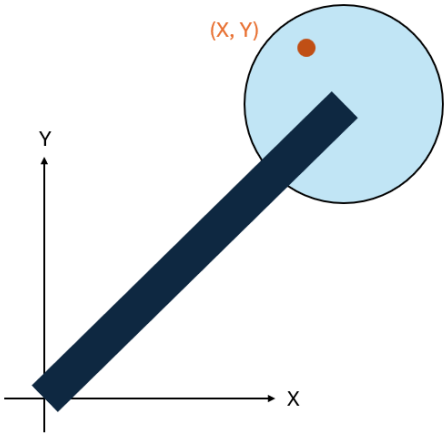


Figure 5.22: *Target Point Definition*

Any target point (x, y) on the petri dish surface must simultaneously satisfy two geometric constraints: it must lie within the reachable workspace of the polar arm, and it must be achievable through platform rotation. The system treats each target coordinate as the intersection point of two circles - the first circle represents all positions reachable by the polar arm at its fixed extension length of 99mm, centered at the arm's pivot point, while the second circle represents the distance of the point from the platform center. The simultaneous solution algorithm calculates both possible intersection points using circle-circle intersection and derives two complete solutions where each solution includes both the required polar arm angle and the corresponding platform rotation angle.

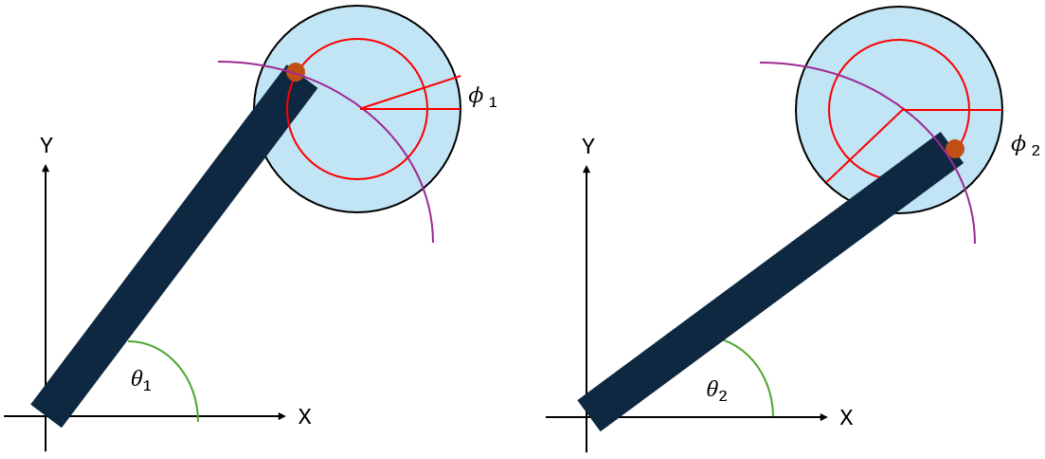


Figure 5.23: *Simultaneous Solution Calculation*

Rather than arbitrarily selecting one of the two mathematical solutions, we evaluate the total angular displacement required for each configuration. The optimization algorithm computes the absolute angular difference between the current polar arm position and each potential target angle, adds the absolute angular difference between the current platform rotation and each required platform angle, and selects the solution that minimizes the sum of these movements.

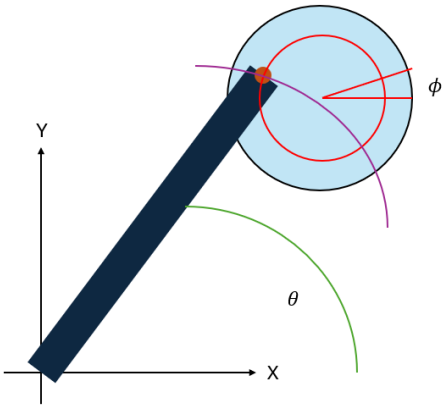


Figure 5.24: *Optimized Solution Selection*

The coordinated motor control implementation ensures that both the polar arm and platform motors reach their target positions simultaneously, maintaining precise sample contact with the agar surface throughout the movement.

Error handling includes automatic constraint of out-of-workspace points to valid positions within the dish boundary, and management of singularities where the constraint circles are tangent or non-intersecting.

5.8.4 Precision Operations (MEGA)

The Arduino Mega 2560 manages precision sample handling through a finite state machine controlling two stepper motors via AccelStepper library and DRV8825 drivers. The system coordinates sample collection (FETCH), controlled dispensing with HX711 load cell feedback (EXTRUDE), and filament cutting (CUT) operations. The load cell provides real-time feedback to detect agar contact during extrusion, ensuring consistent sample deposition. The controller also manages a linear actuator for platform lifting and implements timeout-based error handling while coordinating with the primary ORB1 controller.

5.8.5 Gripper Coordination (ORB2)

The auxiliary OpenRB-150 controller exclusively handles gripper operations for all cartridge types (NORMAL, BLOOD, CHOCOLAT, STRG) through coordinated GRAB and RELEASE sequences. This dedicated controller was implemented separately from ORB1 to enable modular development and testing during prototyping. The firmware coordinates precisely with ORB1's cartridge lifting operations to ensure safe dish handling without mechanical interference.

6 Project Management

6.1 Overview of Spring Quarter Activities

The spring quarter was focused on finalizing the product design, iterating on critical functional elements, and preparing for final demonstrations. We emphasized system-level integration, user experience, and documentation for handoff.

Our prepared timeline for the quarter can be viewed in Appendix I. While this Gantt chart served as an excellent planning tool at the start of the quarter, our execution diverged from it due to new insights, necessary redesigns of some mechanisms, and iterative feedback from testing. We did not follow this timeline exactly, but it was a critical foundation that helped us structure and prioritize our prototyping efforts.

Timeline

- **Week 1 (Apr 3–Apr 9)**
  - The team will begin with initial documentation and align on the overall Spring plan.
  - Design direction will be finalized to guide upcoming technical work.
- **Week 2 (Apr 10–Apr 16)**
  - System diagrams will be developed and a manufacturing plan will be outlined.
  - Part X will be defined, and a biological sampling plan will be set in motion.
- **Week 3 (Apr 17–Apr 23)**
  - Materials and components will be ordered.
  - Initial assembly of Part X will begin; system design will continue in parallel.
- **Week 4 (Apr 24–Apr 30)**
  - Streaking functionality will be advanced.
  - Final refinements to Part X and preparation for Critical Function Prototype (CFP) testing will take place.
- **Week 5 (May 1–May 7)**
  - Prototype testing will be conducted and design iterations will follow.
  - Tip and filament optimization will be explored.
  - A closed-loop flow system will be implemented, followed by user testing.
- **Week 6 (May 8–May 14)**
  - GUI and user experience elements will be built out.

  - Features such as labeling, input options, and function selection will be explored.

- **Week 7 (May 15–May 21)**
  - Mechanical subsystems including unlidding, restacking, and cartridge extraction will be finalized.
  - Further user testing will be performed to evaluate interaction flow.
- **Week 8 (May 22–May 28)**
  - Integration of final submodules will be completed.
  - Final system modifications and feedback loops with NTNU collaborators will occur.
- **Week 9 (May 29–Jun 4)**
  - Brochure and poster drafts will be created.
  - Final round of user testing and documentation compilation will take place.
- **Week 10 (Jun 5–Jun 11)**
  - Final brochure and poster will be completed.
  - Team will prepare for EXPE and finalize all documentation for submission.

6.1.1 Collaboration and Development

The spring quarter began with extensive design discussions and system planning. Weeks one and two were primarily dedicated to outlining what features we wanted the final product to include and determining how they would be incorporated into a compact and cost-effective physical footprint. During this phase, we considered how mechanical, electronic, and software components would interface. This early stage was essential for narrowing down the architecture of our device and ensuring we had a realistic understanding of the constraints.

Once the product structure was scoped, we transitioned to developing individual modules of the system. These included the lid gripper, the modular cartridges, and the most mathematically intensive subsystem—automated streaking. The streaking module posed the greatest challenge due to the complexity of generating smooth and varied streaking patterns. Developing inverse kinematics to control the streaking arm required a considerable investment of time and energy. We had to first understand the geometrical limitations of the mechanism and then implement algorithms that would let us move precisely across the Petri dish surface.

Simultaneously, cartridge development was ongoing and posed a unique set of design constraints. The cartridge needed to satisfy four core requirements: it had to allow users to easily load Petri dishes into the system; it had to be insertable and removable without much effort; it had to reliably dispense one dish at a time to the dish handler; and finally, it had to allow for efficient restocking of streaked dishes into a separate collection unit. Balancing mechanical simplicity with user-friendly operation was a central challenge, but one that shaped many of our critical decisions.

As we progressed into late May, our Global team arrived at Stanford. Their arrival significantly accelerated our efforts. We divided the remaining tasks into clearly scoped subtasks and onboarded each Global team member based on their interests and capabilities. They contributed meaningfully

to the design and fabrication of the cartridge, the electronics system, and the GUI. This distributed workload allowed us to progress in parallel and remain on schedule despite the rising complexity of the build.

As a group, we collaborated closely in the final two weeks of the quarter to complete the final system build and prepare presentation materials. We collectively worked on designing the final poster, brochure, and EXPE presentation. These deliverables were slightly delayed due to ongoing iterations on both the mechanical and electronic fronts. However, this iterative process was instrumental in achieving the level of reliability and user experience we ultimately desired.

By the end of the quarter, we had a fully functional system that integrated mechanical automation, graphical user interaction, and robust dish handling into a cohesive and compact prototype. The subsystems—gripping, unlidding, streaking, restacking, and GUI—functioned harmoniously. The team's resilience, iterative thinking, and cross-functional collaboration were key in bringing the system to life.

6.2 Planning and Reflection

This quarter, we continued to apply a strategic *backward-planning* approach by identifying the requirements of our final demonstration and working in reverse to structure our intermediate milestones. This method allowed us to account for time-consuming tasks such as CAD design, electronics integration, and mechanical fabrication early on, while also making room for iterations and last-minute improvements. Although our initial Gantt chart provided a valuable starting point, we found ourselves off-track for much of the quarter due to a series of hurdles and unforeseen challenges.

Many of these setbacks stemmed from the evolving complexity of our design. Subsystems that initially seemed straightforward—such as the cartridge or streaking arm—demanded unexpected redesigns due to mechanical constraints, manufacturing limitations, or compatibility issues between modules. In some cases, newly ordered components did not arrive on time or required additional adaptation, which caused ripple effects across our timeline.

Despite these disruptions, the experience reinforced the value of flexibility in planning. One key lesson we learned was to anticipate change as part of the process, rather than as a deviation from it. Our modular approach helped here: by isolating components like the lid gripper, dish handler, streaking mechanism, and cartridge system, we were able to work in parallel and prevent one delayed subtask from halting overall progress.

We also recognized the importance of functional system diagrams and a detailed Bill of Materials early in the quarter. These tools helped us visualize interdependencies and plan accordingly, even if implementation had to be modified on the fly. For example, we knew from the outset that the streaking module would be mathematically and mechanically intensive. The inverse kinematics and motion planning demanded focused iteration and troubleshooting over several weeks, and having this foreseen in our schedule gave us the space to explore, test, and refine.

Coordination was a challenge and a strength. Regular check-ins—both in-person and virtual—allowed us to reallocate resources and adjust priorities dynamically. We took an agile approach, revisiting plans weekly based on test results, bottlenecks, and team bandwidth. When hardware failed or late deliveries occurred, we relied on pre-built slack in our schedule and the ability to reprioritize.

As we neared EXPE, planning extended beyond engineering. We dedicated time to storytelling and communication—developing the poster, brochure, and presentation as a unified narrative. Though these tasks were pushed later than we initially hoped due to ongoing iterations, they were completed with strong team collaboration and technical clarity.

In reflection, although we deviated frequently from our original timeline, this quarter taught us the value of adaptable planning, strong modular foundations, and clear internal communication. These lessons ultimately enabled us to deliver a cohesive and well-functioning final prototype under tight constraints.

6.3 Budget Management

Our budget was carefully managed throughout the quarter, with spending divided across hardware and electronics components. In total, we spent approximately $3770, staying close to our target of $3500 set at the beginning of the spring quarter. This target was chosen to keep prototype costs under 40% of the overall project budget and to allow flexibility for unanticipated needs.

Hardware-related expenses accounted for roughly $1333.30 and included materials such as aluminum rods, custom cartridges, bearings, vacuum cups, and structural components. We also utilized significant 3D printing and laser cutting, which helped reduce fabrication costs.

Electronics and control systems accounted for approximately $2,366.70 of our spending. A major contributor to this was the main motor used to rotate the Petri dish during the streaking process, which alone cost about $600. This motor was chosen for its reliability and torque capacity, as we were concerned that lower-cost alternatives might fail or degrade before EXPE, potentially compromising the demonstration.

In addition, we used around 10 Dynamixel motors, each priced at approximately $50. While this added significantly to our expenses, we prioritized performance and consistency given the critical role these motors played in handling and actuation across the system.

We also purchased about 10 OpenRB-150 control boards, each costing around $30. These boards were essential for running and synchronizing multiple motors. Over the course of extensive testing, we burned out three of them—not due to wiring or power issues, but from sustained heavy usage during development. To mitigate risk during the final demonstration, we procured extras as backup.

Lastly, a $150 linear actuator was used to implement the raising and lowering mechanism for the dish rotation and suction module. Although these investments pushed our electronics budget higher than anticipated, they were justified by the stability and reliability they provided in the final prototype.

6.4 Milestone Completion and Responsibilities

This quarter, our primary milestone was to deliver a fully functional, aesthetically presentable prototype ready for demonstration at EXPE. Our work began with refining the product architecture and identifying the core subsystems that would require parallel development: the cartridge mechanism, lid gripper, dish handler, streaking system, and electronics integration.

To manage this complexity, we divided responsibilities early in the quarter. The local team focused on system design, CAD modeling, component sourcing, and early-stage prototyping. Sig-

nificant time was spent figuring out mechanical layouts that would fit within our compact footprint while supporting modular upgrades.

Once the Global team arrived in the final weeks of May, their involvement allowed us to significantly accelerate development. Tasks were divided based on individual strengths and interests. Some members focused on finalizing the cartridge system, others tackled GUI development and electronic wiring, while a few led the physical construction and testing of mechanical subsystems. We conducted daily sync-ups to align progress, share challenges, and coordinate dependencies.

Despite facing multiple iterations, hardware delays, and a steep learning curve with inverse kinematics for the streaking module, the team maintained strong coordination and problem-solving momentum. We adapted quickly and adjusted our plans week by week based on testing results and component availability.

By the end of the quarter, we successfully delivered a prototype that not only met our functional expectations but also reflected thoughtful engineering, cohesive design, and collaborative effort. The final product was something every team member—both local and global—could take pride in. Our shared investment in the process ensured that each feature, mechanism, and interface was not just functional, but the result of collective ownership and teamwork.

6.5 Procurement Resources

Throughout the development of InoQ, we relied on a variety of trusted vendors and facilities to procure components and materials efficiently and cost-effectively. These resources were essential to our iterative prototyping and rapid development cycles:

- **Stanford Product Realization Lab (PRL):** We used the PRL extensively for 3D printing (primarily PLA prototypes) and laser cutting acrylic panels for the housing and internal components. Access to in-house fabrication greatly accelerated our design iterations.
- **Amazon:** A large portion of our electronics (such as Arduino boards, sensors, jumper wires, and power supplies), as well as miscellaneous hardware items and consumables like Petri dishes, were sourced through Amazon due to its fast delivery and wide selection.
- **McMaster-Carr:** For high-quality mechanical components and general hardware—including fasteners, shafts, brackets, and precision parts—we relied on McMaster-Carr. Its industry-grade reliability and same-day shipping were critical to maintaining our build schedule.
- **TAP Plastics:** We sourced various shades and types of acrylic sheets and plastics from TAP Plastics to construct both functional and aesthetic elements of the device housing. Their customizable cuts and color options helped us refine the visual and ergonomic appeal of the machine.

Leveraging these resources enabled us to stay within budget, avoid delays, and ensure that our prototypes closely mirrored final production intent.

7 Team Profiles and Reflections

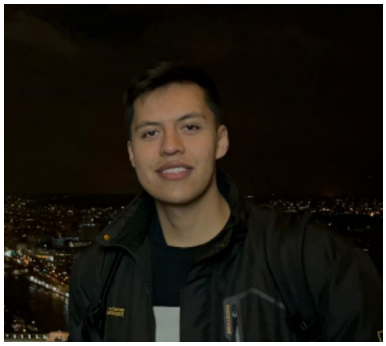
7.1 Stanford Team

Team Hamilton is a team of individuals with unique backgrounds, engineering interests, and education. With such different ways of thinking and ideation, the team members have a heterogeneous approach at finding solutions at every level.



Cadence Boronkay
Status: M.E. Graduate Student
Contact: cwxb@stanford.edu
Skills: CAD, Fabrication, Rapid Prototyping, Machine Design

I grew up in San Jose, CA, not far from Stanford, and did my undergraduate studies in Mechancal Engineering with a minor in French at MIT. My academic interests include design, controls, and particularly the intersection between creative art and engineering. I spend my free time dancing, doing photography, and spending time with family and friends.



Jorge Garcia
Status: ME MS Student
Contact: jalgarci@stanford.edu
Skills: Manufacturing, Robotics, Mechatronics

I was born and raised in Mexico City. I attended college at the University of California, Davis for my undergraduate degree in mechanical engineering, and now I am pursuing a graduate degree at Stanford. My academic interests intersect in the areas of design, mechatronics, and robotics. In my spare time, I like to play hike, produce music, and try new food places.



Tian-Ao(Teo) Ren
Status: ME PhD Student
Contact: tianao@stanford.edu
Skills: Manufacturing, Simulation, Embedded system, Mechanical design

I grew up in Shaanxi, China, where a famous ancient city called Xianyang served as the capital of Qin Shi Huang, the emperor who built the Great Wall. I received a Bachelor of Engineering Degree in Robotics Engineering from Beijing University of Chemical Technology in 2023. I am interested in robotics, with a special focus on soft robotics, hardware design, medical robots, and sim2real applications. Now I'm gradually becoming a hiking enthusiast.



Yug Shah
Status: ME MS Student
Contact: yug2711@stanford.edu
Skills: Manufacturing, Design, Bio-Mechanics

I was born and raised in Ahmedabad, India. I did my Bachelors in Mechanical Engineering from Pandit Deendayal Energy University in 2022. After completing my Bachelors degree, I joined Pioneer Engineering Services Ltd. as a Manufacturing Engineer. I have vast experience in metal casting and injection molding. Currently, I am pursuing MS in Mechanical Engineering at Stanford University with a focus on design and biomechanics. Apart from academia, my interests lie in travelling and playing sports like table tennis and cricket.

7.2 Global Partner Team

These team members are collaborating with us from the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway.



Aleksander Auflem
Status: PhD student, Mechanical Engineering TrollLabs NTNU
Contact: aleksander.auflem@ntnu.no
Skills: Prototyping, Mechatronics, Fusion

I'm a first-year PhD student at NTNU, researching skiing technology. Before starting my PhD, I earned a Master's degree in Mechanical Engineering with a specialization in product development from TrollLabs NTNU. My PhD project is in collaboration with Madshus, Brav, and the Norwegian Olympic Committee. My research involves developing new methods to evaluate current competition skis, controlled laboratory growth of artificial snow crystals, and exploring innovative technologies to enhance ski performance.



Brage Bartnes
Status: PhD-student, NTNU / Lardal Medical AS; Product developer, Laerdal Medical AS
Contact: brage.bartnes@stud.ntnu.no
Skills: Rapid prototyping, Mechatronics, CAD

I'm Brage Bartnes, 26 years old from Stavanger (Norway). I have a Master's degree in mechanical engineering, specialized in Product Development, and as of August 2024 I've started my PhD on personalized medicine and medical simulation training.



Jonas Rossavik Johannessen
Status: PhD-student, NTNU
Contact: jonas.r.johannessen@ntnu.no
Skills: Prototyping, Mechatronics, CAD

I am pursuing a PhD in biomedical engineering at TrollLabs, NTNU, and am in my first year. Before this I completed my masters in mechanical engineering at the same university, with a specialization in product development. My main strengths are practical skills in prototyping.



Eirik E. Semb
Status:PhD-student, NTNU TrollLabs
Contact: eirik.e.semb@ntnu.no
Skills: Rapid Prototyping, Robotics, Sensor Systems

I am currently pursuing a PhD in sports science together with the Norwegian University of Science and Technology (NTNU) and the Norwegian Olympic Committee. Prior to this, I received my carpenters diploma in 2019 and finalized my Ms.c in Mechanical Engineering at NTNU. My main interests involve high performance sports analysis, robotic systems, and live multi-sensor systems in the loop.

7.3 Personal Reflections

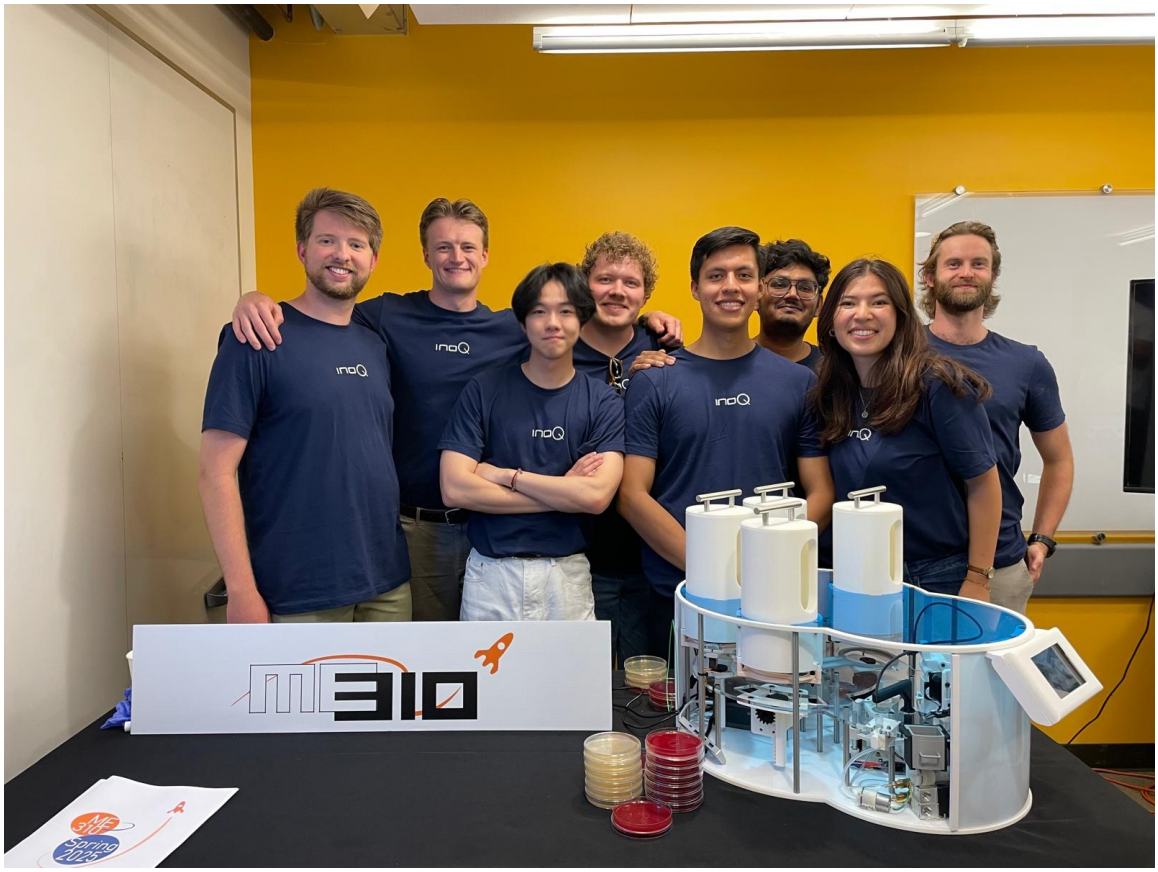


Figure 7.1: *InoQ Team*
From left to right: Aleksander, Eirik, Teo, Jonas, Jorge, Yug, Cady, Brage

7.3.1 Yug Shah

The Spring Quarter was a defining phase of this project—marking the transition from iterative development to final delivery. With our objectives clearly defined and most design components already prototyped, this quarter demanded sustained execution, rapid troubleshooting, and detailed coordination across systems.

I focused heavily on finalizing and refining the cartridge system, ensuring it met both functional and ergonomic requirements. My responsibilities expanded to include integration work across various components, but rather than leading the entire structural design, I contributed through continuous mechanical support, part replacements, and iterative testing.

One of the most important lessons I learned this quarter was the value of careful task management—balancing deadlines, procurement delays, and unexpected design revisions while still keeping the team on track. With limited time, every small decision mattered, and I found myself improving at prioritizing effectively under pressure.

Testing played a central role this quarter. Many late-stage issues—such as servo fatigue, component misalignments, and unexpected wear—surfaced only during full-system trials. Working through these challenges strengthened my ability to debug physical systems quickly and work collaboratively to find practical fixes.

Above all, seeing the final device working reliably and safely with minimal user intervention was incredibly fulfilling. This project taught me how meaningful interdisciplinary teamwork and incremental progress can be—especially in high-stakes, real-world product development.

Moving forward, I'm excited to carry this hands-on experience into future projects, especially those requiring thoughtful user-centered design and robust mechanical systems built under tight constraints.

7.3.2 Tian-Ao(Teo) Ren

What a wonderful journey ME310 has been—especially in this final quarter, where the entire experience felt elevated to a new level. One of the most memorable parts was our global travel to Norway. Together with my team, we immersed ourselves in a different culture, engaged in deep needfinding, and aligned with our global partners not just technically, but personally. The goal of the trip was to lock in a technically feasible direction for our final solution. That process wasn't without friction. We pivoted away from our initial lab-based automation idea toward an on-field mastitis testing concept. To be honest, I wasn't very enthusiastic about this new direction at first. But we kept exploring, prototyping, and pushing through.

After two to three weeks of trying to make the on-farm idea work, we had a pivotal conversation with George and reassessed the market and feasibility. That led us back—almost in reverse—to an earlier idea inspired by 3D printing: an automated streaking mechanism. Unlike our winter plan, which left streaking to the user, the new system automated it entirely. The technical details are well documented in our report, so here I want to focus on the personal lessons I've learned.

First, our team has a tendency to operate under pressure. In fact, I'm writing this reflection at the last minute too. But honestly, sometimes that pressure brings out our best. I remember Mark asking me the week before EXPE, "Do you really think your system is going to work?" At the time, we had only tested partial functionality. But I was confident. I told him, "We just need to put it all together." And I believed it. Even though we didn't have a fully integrated system until the Monday of EXPE week, we pulled through. We finished integration by Wednesday, polished it through the night until 4 AM, slept three hours, and then delivered a flawless demo. Not a single failure. The system ran robustly for two hours straight. Many people said it looked like a commercial product—and I agree. It's one of the things I'm most proud of. Whether last-minute execution is good or bad depends on the person, but for me, it's part of how I work best. Deadlines can be brutal, but they push you. It's not always ideal—but it works for me. Still, I hope I can plan better in the future.

Working with such a talented team also reminded me how hard it can be to bring people into your vision. Everyone on the team was smart and had strong opinions. I found it difficult to persuade others, particularly across language barriers or when working remotely with the global team. Early on, it felt like we were just talking past each other. Even after everyone arrived, we still had technical disagreements. For example, I took ownership of the lid-lifter design and believed strongly in using a flexible suction cup. When it initially didn't work, teammates pushed for a scissor mechanism instead. But I felt it wouldn't work. Rather than argue endlessly, my solution became simple: just build it, and show them. That's my current philosophy—don't waste time trying to convince brilliant people with words; show them something that works. That speaks louder.

But perhaps the most lasting lesson came from how this class changed my way of thinking. In research, I've often started with a cool technical idea and then looked for applications to match it—sometimes forcing a use case that doesn't quite fit. ME310 flipped that on its head. It taught me to start with the need and the market. The solution doesn't need to be fancy; it just needs to work—efficiently, effectively, and profitably. This mindset shift is profound. Now, when I see any product or design, I find myself asking: "Why is it like this? Who was it designed for? Is this still the right solution if the user changes?" For example, while discussing my PhD project on ultrasound robotics, a senior student pointed out that ultrasound handles are designed for doctors—not robots. That simple insight, born from ME310's way of thinking, reshaped how I approach my research.

ME310 has taught me to always ask "why"—to question assumptions, challenge norms, and dig deep into user needs before jumping to solutions. I'm deeply grateful for the freedom and support from our teaching team, sponsor, and my teammates (especially after the global team arrived!). We didn't spend much time sightseeing, but we built something remarkable together. No matter how many pivots, arguments, or stressful nights we had, in the end, we had a happy ending!!!! And that's more than enough.

7.3.3 Jorge Garcia

Looking back on the past nine months, I've realized just how much I've grown. Coming from a purely mechanical engineering background, I hadn't previously developed a strong understanding of design beyond technical execution. This course gave me a much broader vision—one rooted in empathy, modular thinking, and rapid iteration. My team and I engaged with users meaningfully, identified real pain points, and designed solutions that genuinely fit their needs. It's important to have a real sense of why you're building something before you even start creating it. I discovered the value of building quick and focused prototypes. Of course, this was something that did not happen overnight, and it took a while as a team to get there.

We were a little nervous about how everything would come together for the final project. On the last day, we were up at 4 a.m. wrapping everything up for presentation and EXPE. I definitely think we had many areas for improvement, but at the end of the day, we were able to come up with a prototype that people were really surprised by.

I think our system was very ambitious, and I believe another crucial aspect of this experience was collaboration. I had the opportunity to work with a highly technical and globally diverse team, and I'm extremely grateful for what I learned from them. We each brought something essential to the table, and I believe every team member was a key link in the chain. Having the chance to practice hands-on mechanical design while also navigating cross-cultural teamwork, like working closely with our partners in Norway, added a rich layer of personal and professional development. Managing schedules, running interviews, and adjusting our communication style for different audiences, from teammates to stakeholders, became part of our weekly routine. Moreover, it was exciting to see how everyone was working on a very specialized part of the system, yet it was all coming together in the final days.

This quarter was intense, both mentally and physically, with countless activities and constant demands. But it was also deeply fulfilling. I'm proud of the project we built, proud of the process we followed, and proud of how we adapted and persevered. I truly appreciate everything I learned from my team and the instructors, especially the lessons that live outside of slides and syllabi. As I look to the future, I'll carry these skills and memories with a sense of pride and gratitude.

7.3.4 Cadence Boronkay

The third and final quarter of ME 310 was a whirlwind of a time, and a stressful, but rewarding end to the Team Hamilton 2025 experience. With a final pivot in direction already a week and a half into the Spring quarter, the approximately 8 week timeline for developing a prototype for the (at the time unnamed) inoQ machine was daunting to the point that it seemed nearly impossible. We were still doing component prototypes several weeks in, when based on our timeline, we needed to be in the development phase, rather than the exploratory phase. I remember at about week 5, during one of our weekly check-in meetings with our global teammates at NTNU, we started discussing whether we actually should use pickable streaking tips rather than a spooled filament for swabbing. It was discouraging and a little jarring to be having such a fundamental debate over the vision when we had so little time left. It also was an example of how difficult it is to communicate thoughts, progress, and ideas, with teammates, let alone virtually and time zones apart.

Our schedule was really on a negative looking path for quite some time. Frankly, it was in the last 3 and a half days that the machine really came together and that we were able to at least begin to think we'd have a mostly functional machine by EXPE. The number of individual mechanisms that needed to be designed, developed, tested, and integrated into one cohesive system made this an ambitious project. It became much more manageable when our global teammates joined us in person as it felt we had double the manpower, especially after we sat down and aligned on what really was our vision: designing this machine with an emphasis on the user experience. If I had to give one main piece of advice to future students, it would be to decide as a team early on what the "goal" of the prototype is. Of course, it shouldn't be purely aesthetic or only technically functional, but when you have such a small time to build a prototype, it is impossible to have a perfectly polished prototype. When we realized that the innovation we really wanted to bring was in user experience and compactness for lab automation equipment, we were able to focus on those design requirements rather than on other tasks like making the actual streaking pattern as precise and robust as possible. While that would be important should this machine actually hit the market, we realized it was much lower in importance when it came to showcasing what we thought was special about our idea. Being able to prioritize tasks after aligning on our goals was vital to our success in building a prototype we were proud of.

Throughout this entire year, I've learned a lot about how to design for users rather than for yourself, as well as about working in and managing design teams. The importance of team dynamics and curating a balanced team with a diverse set of skills and perspectives is so important to a project's success. While our team hit many roadbumps and u-turns on the road to EXPE, we were ultimately able to show the product we wanted to show, and in general, received a positive "WOW" response. Showcasing inoQ at the EXPE presentations and trade show was a very memorable experience, and I will bring what I've learned from ME 310 both technically and personally to future endeavors.

7.3.5 Aleksander Auflem

ME310 has been a truly rewarding experience, filled with a wide range of emotions. Having the opportunity to travel across the Atlantic and experience how product development methodologies are applied at Stanford, and in other ME310 collaborative international universities, has been a great privilege. It's an experience that I will carry with me as a meaningful part of my development as a researcher. Travelling to Stanford in early January to meet the team in person was important to the success of our project. It allowed us to build an understanding of one another, not only in how we

worked together on the project, but also on a social level, which proved equally important. Building personal connections outside of the project helped spark more valuable discussions and foster a better understanding of each other's ideas. After our visit to Stanford, we entered a longer period of weekly video meetings, working on the project from both universities. The contrast between in-person collaboration and remote meetings was noticeably. When working together in person, we were able to accelerate progress and align more easily. In contrast, video meetings often led to misunderstandings and made it harder to maintain a shared mindset, which affected our efficiency. The same dynamic was again observed when the Stanford team visited us in Norway, and later during our second visit to Stanford for EXPE 2025. I'm proud to have been part of ME310 2025 and of what we achieved with our final project. I'm truly grateful for the experience and for the opportunity to work alongside such a great team.

7.3.6 Jonas Rossavik Johannessen

ME310 has been a great journey and experience and I am happy to have partaken. When we flew to the US and met the team, we got introduced to their needfinding process, and quickly got started doing some experience prototyping followed by crude cardboard prototypes. This was on petri dish handling, and it felt like we had a great course ahead. After going back to Norway, working separately and doing more research, the spark we felt for the idea was lost, as many team members struggled to see the innovation in simply making an existing product for a new market. This led to us trying our best at doing more needfinding to try to find a more innovative project. Abandoning this and going back to the petri dish automation, we were left a little short on time before EXPE. We had some late evenings and long nights to finish our project, but I am very happy with the result in the end.

My main takeaways from ME310 are that there is in fact a lot of innovation to be had during redesign. Performing the same tasks can become a whole different engineering problem when different requirements are at play. I also learned a lot from our needfinding at veterinary offices, animal hospitals, and labs, which has been interesting. Global collaboration also taught me a lot of the limitations of digital collaboration, even though you have full control of verbal communication, you lose out on so much more communication especially crucial in physical prototyping. I am happy to have met my teammates, along with other classmates in ME310, and I hope I get to see them again.

7.3.7 Eirik E. Semb

Looking back at the last half year, I am very grateful to have gotten the opportunity to partake in ME310. The course has taught me valuable lessons on collaboration and the entire product development process. The Norwegian team entered the Hamilton global team in January 2025. We got thrown straight into the needfinding process, revolving around the medical equipment company Hamilton. Our American team mates displayed several interesting ideas, and after a few days of ideation and research, we started making our dark horse prototype for petri dish automation. After our January visit to the US, the development process stagnated a bit, maybe due to the increased threshold for communication. We also lost some of our motivation for the product when we realized that the market was already filled with machines similar to our idea. With this in mind we entered our second team gathering, this time in Norway. The American team mates joined us for one week, where we pushed hard on new need finding and visited several veterinary practices, and had

countless phone calls with experts and vets. The process culminated in an idea of providing farmers and travelling veterinarians with an easy to use test kit for antibiotic resistance. Feedback from our professors did however make us turn back to our original plan of making a system for desktop automated petri dish streaking and handling. During our final visit to Stanford in May, we worked quite hard to finish our product in time. The amount of work that can be done in the last 48 hours still amazes me. My main takeaways from ME310 are the value of speaking to users, and combining these experiences with a diverse set of engineering eyes in the development process. As a group, I feel like we have expressed all our opinions, and condensed them into our final product. I have also, once again, confirmed for myself that physical interaction is key for efficient development processes. Comparing our online collaboration periods with the time we spent together in the same room, there is no doubt which is more efficient. Another thing I have learnt to value is the social interactions we had at the beginning of the course. I believe that these hours spent on socializing have paid off well in our collaboration and group dynamic. Thank you team mates, professors, and coaches, it has been a pleasure.

7.3.8 Brage Bartnes

Participating in ME310 has been an enriching academic experience. The course challenged me to step far outside my comfort zone—both technically and interpersonally—and I'm genuinely proud of how our team handled the ups and downs along the way (especially the last 48 hours). During our trip to Stanford in January, the project officially started for us. It was the first time we met our teammates and began working together. That week was foundational—not just in terms of getting started with prototyping and ideation, but in forming the bonds that shaped how we would work as a team. One evening in particular, we had a social night that really changed the dynamic. It allowed us to connect beyond the project itself, get to know each other on a personal level, and break the ice in a way no workshop or meeting could. After that night, we weren't just a group of individuals working on the same task—we felt like a real team. The project itself took a number of unexpected turns. There were moments when our motivation dipped—especially when it felt like we were treading familiar ground rather than exploring something truly innovative. On top of that, working across time zones and relying on remote meetings added another layer of complexity. It was often hard to keep the same momentum and clarity we had during our in-person sessions. Misunderstandings were more frequent, and syncing progress between teams wasn't always smooth. In the end, I think our final product reflects the group's persistence and dedication. It's not just a functional prototype—it's the result of hours of difficult decisions, creative problem-solving, and shared ownership. Seeing it all come together at EXPE was incredibly rewarding. I'm grateful for the long nights, the laughs, the frustrations, and the breakthroughs that came with this process. ME310 taught me that innovation doesn't always look like a radical new idea—it can also be about refining and adapting existing solutions to new contexts. It taught me the value of direct user engagement and the irreplaceable power of in-person teamwork. But most of all, it reminded me how motivating it is to work with people who care deeply about what they're doing. I'm proud of our team, and I'll carry this experience with me for a long time.

8 Resources

Name	**Contact Info**	**Role**
Jamie Cross	jamiecross@stanfordalumni.org	A polo player and a rancher in Wyoming
Jiawei Sun	jsun2019@stanford.edu	Phd Student in KC Huang Lab, Stanford
Valerie Perez-Medina	vaperez@stanford.edu	Phd Student in Mayalu Lab, Stanford
Dr. Rohita Roy	rohita02@stanford.edu	Postdoctoral researcher in Mayalu Lab, Stanford
Minoo Fazel	mfaz0001@stanford.edu	Microbiologist at Stanford's Animal Diagnostics Lab

Table 8.1: *List of Relevant Lab Technicians and Lab Members*

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A Appendix

A.1 Needfindings

A.1.1 Jamie Cross Interview Summary

1. Veterinary Testing & Disease Management on the Ranch:
    a) When a cow gets sick, initial steps involve on-site diagnosis, followed by testing based on key health markers.
    b) Some tests are conducted in-house, while others require external labs, impacting turnaround time.
    c) Disease containment strategies include quarantine protocols, tracking, and vaccination schedules.
    d) Various tracking devices are used for health monitoring and containment.
2. Supply Chain & Product Usage:
    a) Regularly ordered veterinary supplies include test kits, vaccines, and dewormers.
    b) Lead times and supplier reliability can pose challenges, affecting timely access to critical supplies.
    c) Integrating new data-tracking tools could streamline inventory management and operational workflows.
3. Business & Operational Pain Points:
    a) Key challenges include testing efficiency, needle disposal safety, and turnaround time for lab results.
    b) Improving data tracking for herd health could enhance decision-making and operational efficiency.
    c) Potential opportunities to explore automated tracking, digital health records, and supply chain optimizations.
4. Vaccination & Preventative Car:
    a) Routine vaccinations follow a structured schedule at key stages: birth, branding, weaning, breeding, and pregnancy.
    b) Essential vaccines include Alpha 7, Vision 7 Plus Salmonella, Vista Once, Multimin, Nasalgen 3 PM, Ivermectin, Safeguard, Brucellosis Vaccine, Vira Shield 6 Plus L5, Scour Bos 9, and Scour Bos 4.
    c) These protocols help ensure herd immunity and prevent widespread disease outbreaks.

A.1.2 Jiawei Sun Interview Summary

1. **Overview:**

   In our interviews with Jiawei Sun, we had two in-depth discussions about his research involving bacteria and the use of petri dishes.

2. **First interview:**

   Jiawei detailed his work, which involves cultivating large quantities of bacteria. These bacteria are often grown in petri dishes, and once they reach a certain stage, they need to be transferred to different dishes or vials. This process is currently done manually, requiring a lot of repetitive work, often performed by undergraduate or graduate volunteers. Jiawei emphasized the **need for automation** to handle these repetitive tasks more efficiently.

   We also inquired about the specific applications and challenges he faces. He shared that after cultivating bacteria for **24 or 48 hours**, the next step involves transferring them into different containers. He emphasized how **labor-intensive** this is and expressed a strong need for automation to reduce manual workload.

3. **Second Interview:**

   After developing an **initial prototype** that automated the capping of petri dishes, we demonstrated it to Jiawei. While he found the feature useful, he pointed out that it only addressed a **basic aspect** of his needs. He expressed a desire for **more advanced automation**, such as **auto-streaking** to handle different phases of bacteria growth. Additionally, he highlighted a significant need for **remote monitoring capabilities**.

   Jiawei wanted a system that could allow him to **monitor bacterial growth from home**, providing **regular updates** and tracking the development over time. This would enable him to observe bacterial cultures' growth status periodically, **reducing the need for physical presence** in the lab.

4. **Conclusion:**

   This feedback guided our next steps, particularly focusing on **enhancing the prototype** to include **monitoring capabilities** and more complex automation solutions like **auto-streaking**. Jiawei's feedback underscored the need for automation in handling both **repetitive tasks** and those requiring **high precision**.

   Overall, our discussions with Jiawei highlighted the importance of developing **comprehensive automation solutions** for biology labs, addressing both **repetitive tasks** and more complex needs like **remote monitoring** and **precise bacterial cultivation processes**.

A.1.3 Lab Visits and Interviews

A.1.3.1 Mayalu lab with Dr. Rohita Roy and Valerie Perez-Medina

1. **Overview:**

   We visited **Professor Michaëlle N. Mayalu's lab** and had a discussion with **Postdoctoral researcher Dr. Rohita Roy** and **PhD student Valerie Perez-Medina**. Their lab is unique

in that, despite being under the **Mechanical Engineering Department**, they focus on bio-related research. A key aspect of their work involves **petri dish-based bacterial cultivation**, requiring specialized knowledge and precise handling techniques.

2. **Agar Preparation and Colony Growth:**

   A distinct feature of their workflow is that they often **prepare their own agar** rather than using pre-made plates. The agar must be stored in a **heated incubator** to maintain its consistency. When needed, they take out the agar, allow it to **cure**, and then use it as a medium for bacterial growth.

   Once the bacteria are introduced onto the petri dishes, they **seal the plates with Parafilm** and place them back into the **incubator for approximately 24 to 48 hours**. This ensures the bacterial colonies grow sufficiently before further processing.

3. **Colony Selection and Automation Needs:**

   After incubation, the plates are removed, and the next step involves **colony picking**, a labor-intensive process. Each petri dish may develop **hundreds of colonies**, requiring researchers to **precisely isolate individual colonies** for further cultivation.

   During our discussion, they expressed strong interest in **automating this workflow** and shared potential ideas. One concept involved using a **needle array mounted on a tool**, which could be **automatically aligned using image processing techniques**. The idea is that the system would detect colony locations, align the needle array accordingly, and allow the user to **dap down once to pick up all selected colonies simultaneously**. These colonies could then be transferred to separate containers for further cultivation.

4. **Conclusion:**

   This feedback highlights the **need for precise, automated colony selection and transfer mechanisms**, reducing manual effort and increasing efficiency in bacterial culture processing.

A.1.4 Stanford Veterinary Services Center with Minoo Leeda

1. **Overview:**

   This quarter, we visited the **Stanford Veterinary Center** and spoke with **Minoo Leeda, a lab technician**, to gain insights into veterinary lab workflows. Our goal was to **compare the veterinary lab environment with human biolabs**, identifying differences in **workflow and equipment needs**.

   Mino provided a **detailed overview of his daily workflow**, which helped us uncover several interesting distinctions between the different lab settings.

2. **Veterinary Lab Workflow:**

   One major difference between **veterinary labs** and **human biolabs** is how their workflow begins. In veterinary labs, the process typically starts when **clinicians, rachers, or pet owners** notice issues with an animal and request a test from the **Veterinary Center**. Based on the type of test required, **Minoo** prepares and ships the appropriate **petri dishes with chocolate agar, blood agar, or other specialized solutions** to the requesting party for sample collection. Once the samples are collected and returned, the laboratory process begins.

3. **Sample Processing and Cultivation:**

   Upon receiving a sample, **Minoo** follows a standardized workflow:

   - The sample undergoes **a series of complex preparations** to extract necessary components.
   - The processed sample is then applied to a suitable **petri dish containing the required agar medium**.
   - Using **streaking techniques**, the bacteria or culture is distributed across the petri dish.
   - The petri dishes are placed **upside-down** in an **incubator set at 37°C** to promote bacterial growth.

   A notable aspect of this process is the need to **invert the petri dishes** before incubation. This prevents **condensation buildup** inside the dish, which could **damage the bacterial colonies**. The **incubation temperature of 37°C** is consistently used across various biological laboratories, as it provides optimal growth conditions for most bacterial colonies.

4. **Colony Observation and Picking:**

   After **24 to 48 hours**, Minoo inspects the colonies. Some plates may exhibit **color-based reactions indicating positive or negative results**. This highlights the importance of **real-time monitoring**, both for tracking bacterial growth and assisting lab technicians in determining colony viability.

   During our last visit, **Minoo demonstrated a common workflow**: Once the bacteria have grown sufficiently (as observed by the technician), the technician uses a **pipette** to **pick up a colony** and transfer it into a **vial array filled with solution**. This process is somewhat similar to **at-home COVID-19 testing**, where a swab is dipped into a solution for further processing.

5. **Key Insights and Findings:**

   One surprising discovery was that our initial assumption regarding **sample processing volume** was incorrect. We originally hypothesized that a veterinary center might handle **hundreds of samples per day**, similar to a human biolab. However, **Minoo clarified that they typically process only around 20 samples per day**, significantly lower than expected. This insight challenges our prior assumptions about laboratory throughput and helps refine our approach to **automation solutions in veterinary diagnostics**.

6. **Conclusion:**

   Our discussions with Minoo provided **valuable insights into the veterinary lab workflow**, highlighting differences in **sample collection, processing, colony monitoring, and throughput** compared to human biolabs. These findings will help shape future automation strategies, focusing on precise **colony picking and streaking mechanisms**, as well as **real-time monitoring** to assist lab technicians.

A.2 Benchmarking Details

A.2.1 Sample Processing Volume

Veterinary labs typically process fewer samples per day compared to human labs. While SciRobotics' solutions cater to high-throughput environments, there is an opportunity to develop compact, cost-effective automation tools suited for veterinary labs that handle lower daily volumes.

A.2.2 Colony Picking and Streaking

Veterinary labs still rely on manual colony picking and streaking. SciRobotics' *Pickolo* provides automated colony picking for high-throughput labs, but its adaptability for mid-scale veterinary applications is uncertain. Developing an accessible, modular streaking and picking system could greatly benefit these labs.

A.2.3 Real-time Imaging and Monitoring

The *AutoCount* system enables automated colony counting, but its real-time tracking capabilities could be expanded. Enhancing continuous monitoring of bacterial growth would reduce manual intervention and improve workflow efficiency in both veterinary and human labs.

A.2.4 Sealing Methods

Unlike human labs, where automated sealing is common, veterinary labs rarely use sealing due to differences in sample processing workflows. Investigating alternative sealing techniques tailored to veterinary applications could offer workflow improvements while maintaining sample integrity.

A.2.5 Data Integration and Management

SciRobotics' products generate reports in standard formats such as CSV and XML. However, further integration with Laboratory Information Management Systems (LIMS) could improve sample tracking and data accessibility across both veterinary and human labs.

A.2.6 Advantages and Disadvantages of SciRobotics' Products

A.2.6.1 Advantages

- **High Precision:** SciRobotics' automated colony pickers and streaking devices ensure accuracy and reproducibility, reducing human errors.
- **Time-Saving:** Automation accelerates the streaking and colony picking process, freeing up technicians for more complex tasks.
- **Reduced Contamination:** Automated systems minimize human contact with samples, lowering the risk of cross-contamination.
- **Scalability for High-Throughput Labs:** SciRobotics' products are designed for large-scale labs, improving efficiency in high-volume environments.

- **Integration with Digital Tracking:** Automated colony counters and data export features allow seamless tracking and documentation of results.

A.2.6.2 Disadvantages

- **High Cost:** The advanced automation features come at a premium, making them less accessible to smaller or mid-scale labs.
- **Limited Flexibility for Low-Volume Labs:** Veterinary labs, which handle fewer samples, may not fully benefit from high-throughput automation solutions.
- **Compatibility Issues:** Some SciRobotics products are optimized for specific liquid handling platforms, limiting integration with other systems.
- **Training and Maintenance Requirements:** Operators need specialized training, and regular maintenance is necessary to ensure optimal performance.
- **Over-Automation Risks:** Certain workflows, such as manual evaluation of colony health, may still require human expertise, making complete automation impractical.

A.2.7 Conclusion

Benchmarking SciRobotics' automation solutions against veterinary lab workflows highlights the need for modular, adaptable tools that bridge the gap between high-throughput human labs and specialized, lower-volume veterinary labs. Addressing these automation gaps could lead to greater efficiency and accessibility in both fields.

A.3 Initial Prototype Development in Winter Quarter

A.3.1 Critical Experience Prototype (CEP)

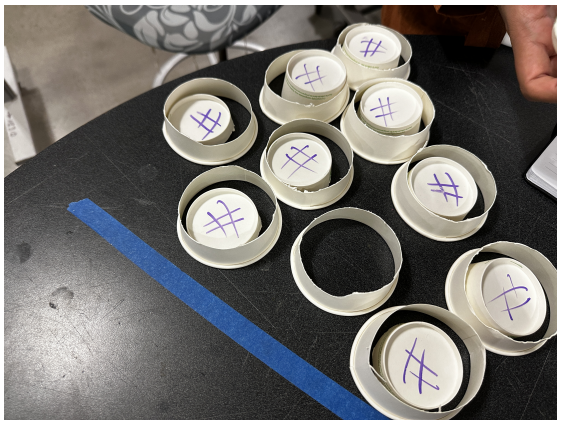
To explore the potential of automating the petri dish handling process, we conducted a Critical Experience Prototype (CEP) using paper cups to simulate petri dishes. The goal of this prototype was to test different levels of automation and measure their impact on workflow efficiency. We defined three levels of automation:

- **Minimal Automation:** Presenting the user with a prepared agar dish.
- **Semi-Automation:** Providing the user with a prepared agar dish and automatically removing the lid.
- **Full Automation:** Providing the user with a prepared agar dish, automatically removing the lid, holding the dish in place for swabbing, and restacking the dish after use.

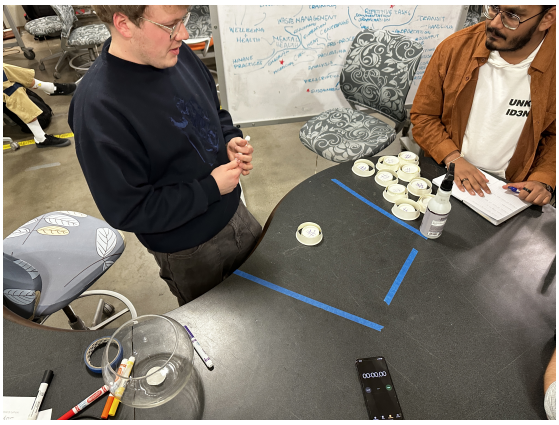
The results of the CEP demonstrated significant time savings across all levels of automation. Without automation, the average time to handle a petri dish was **1 minute and 45 seconds**. The time savings for each automation mode were as follows:

- **Minimal Automation:** 13.7% time saved, reducing the handling time to **1 minute and 30 seconds**.
- **Semi-Automation:** 18.4% time saved, reducing the handling time to **1 minute and 25 seconds**.
- **Full Automation:** 28.1% time saved, reducing the handling time to **1 minute and 15 seconds**.

These results validated the potential benefits of automating the petri dish handling process and informed the development of our next prototypes.



(a) *Petri dishes and initial prototypes used for user testing*



(b) *Team conducting user workflow testing with the Critical Experience Prototype*

Figure A.1: *Initial prototype and user workflow testing during the design development phase*

A.3.1.1 Takeaways and Learnings

The CEP provided several key insights that guided the next phase of our design process:

- **Time Savings:** Automation, even at minimal levels, significantly reduces the time required for petri dish handling.
- **User Preference:** Users preferred semi-automation and full automation over manual processes, citing improved efficiency and reduced physical strain.
- **Workflow Integration:** The prototype highlighted the importance of integrating automation seamlessly into existing lab workflows to ensure user adoption.

These learnings informed the development of our next iteration, where we focused on creating a more refined and functional prototype based on the feedback from the CEP.

A.3.2 Dark Horse Prototype

Building on the insights from the Critical Experience Prototype (CEP), we developed the Dark Horse prototype as a more realistic and refined implementation of our CEP concept. The Dark Horse

prototype aimed to practically address the key pain points identified during needfinding—such as repetitive tasks, contamination risks, and workflow inefficiencies—while retaining and validating the time-saving benefits observed in the CEP. This prototype represented a step closer to a real-world solution, integrating user feedback and usability improvements into its design.

> *Note: For the Dark Horse prototype, the term "automation" refers to scenarios where another person manually performed certain tasks to simulate automated actions. From the user's perspective, these steps appeared automated, as this was an early-stage prototype designed primarily to test workflow and user interactions.*

A.3.2.1 Design Concept

The Dark Horse prototype introduced a semi-automated system for petri dish handling, focusing on automating the most time-consuming and error-prone steps in the process. The key features of the Dark Horse prototype included:

- **Stacked Dish Organization:** Fresh and swabbed petri dishes were organized in a vertical stack to minimize the device's footprint, addressing the space constraints in veterinary labs.
- **Lid Removal Mechanism:** An automated lid removal system reduced the need for manual handling, lowering the risk of contamination.
- **Dish Holding and Restacking:** The prototype held the dish in place during swabbing and automatically restacked it after use, further reducing technician workload.



(a) *Schematic of the Dark Horse prototype, showing the stacked dish organization and lid removal mechanism.*

(b) *Physical implementation of the Dark Horse prototype, demonstrating the stacked dish design and automated features.*

Figure A.2: *Design and implementation of the Dark Horse prototype.*

A.3.2.2 Testing and Results

The Dark Horse prototype was tested in a simulated lab environment to evaluate its practical performance and usability. Key findings from the testing phase included:

- **Lid Removal Challenges:** Laser-cut components exhibited inadequate tolerances, resulting in frequent jamming that prevented reliable automation of the lid removal process. Users had to manually intervene frequently, undermining the intended workflow improvements.
- **Effective Dish Retention:** The one-way valve mechanism designed to hold petri dishes securely after swabbing performed exceptionally well, consistently maintaining dish stability during restacking.
- **Reliable Pusher Mechanism:** The mechanism responsible for pushing dishes into position proved highly dependable, reliably positioning plates for user interaction without jamming or misalignment.
- **Space Efficiency:** The vertical stacking approach effectively minimized the prototype's footprint, demonstrating potential suitability for smaller or space-constrained laboratory environments.

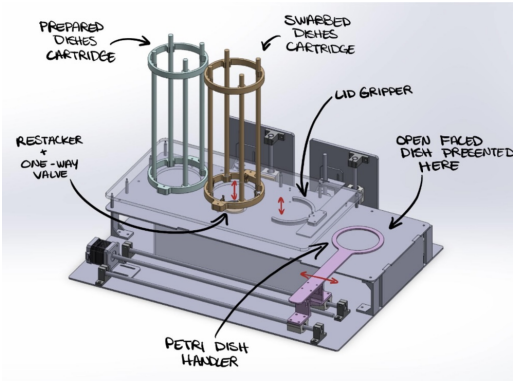
Overall, the testing provided clear insights into necessary design adjustments, particularly highlighting the importance of precise manufacturing tolerances for reliable automation.

A.3.3 Funky Prototype

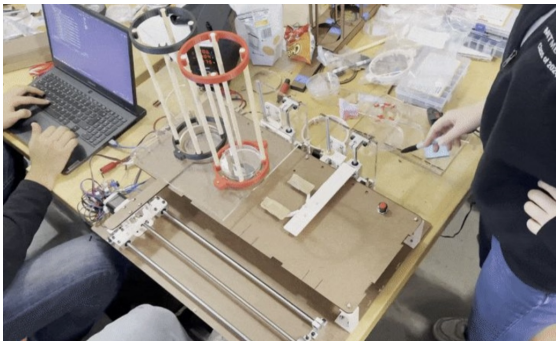
The Funky prototype represented the next iteration following the Dark Horse prototype, incorporating essential design improvements based on earlier learnings. This prototype aimed to address the limitations observed in previous designs, particularly focusing on the reliability of the lid removal mechanism and efficiency of dish handling.

A.3.3.1 Key design improvements in the Funky prototype included:

- **Improved Lid Gripping Mechanism:** Redesigned to enhance reliability and reduce jamming issues encountered with laser-cut parts in the Dark Horse prototype.
- **Optimized Dish Handling:** The implementation of a reliable pusher mechanism for accurate and efficient dish positioning.
- **Vertical Restacking:** Continued utilization and refinement of the one-way valve mechanism to securely restack dishes after swabbing.
- **Testing and Feedback Integration:** Validation with users to assess genuine time-saving impacts and exploration of potential large-scale implications for batches of 100-500 petri dishes.



(a) *CAD model of the Funky prototype*



(b) *Physical assembly and testing of the Funky prototype*

Figure A.3: *Funky prototype design and testing*

A.3.3.2 Learnings and Takeaways

Testing the Funky prototype in a simulated lab environment provided valuable insights, highlighting both improvements and areas for further refinement. Key learnings included:

- **Enhanced Reliability:** Significant improvements in the lid removal and dish positioning mechanisms were achieved, notably reducing issues observed in earlier prototypes.
- **Speed and Efficiency:** User feedback indicated that, despite improvements, further enhancements in speed were necessary for practical in-lab application. Faster mechanical alternatives, such as lever arm or belt drive systems, were recommended.
- **Scalability Considerations:** Users highlighted the need to explore implications and adaptations of the prototype for larger-scale operations, specifically batches ranging from 100 to 500 petri dishes.

A.3.4 Functional Prototype

Incorporating all learnings and insights from our Dark Horse and Funky prototypes, we proceeded to the development of our Functional Prototype. This iteration aimed to implement refined mechanisms and address previously identified challenges, bringing us closer to a practical and deployable solution.

Focused on meeting the design requirements discussed in the previous section, we designed a functional prototype of the petri dish handling system, with unlidding, labeling, and stacking capabilities. The prototype consists of four main system elements:

- **Petri dish cartridges** that the user loads and unloads from the system.
- A **rotating dish carousel** that automatically moves cartridges between operations.
- An **unlidding station** that presents the user with an open-faced dish ready to be streaked.
- A **labeler** that prints relevent information onto the bottom of the petri dish.

The four elements are shown in Figure A.4. Using this layout as our basic arrangement for the Spring device, we aim to improve the functionality and reliability of these four operations, while also augmenting the system with additional modules to perform tasks such as automated streaking and sealing.

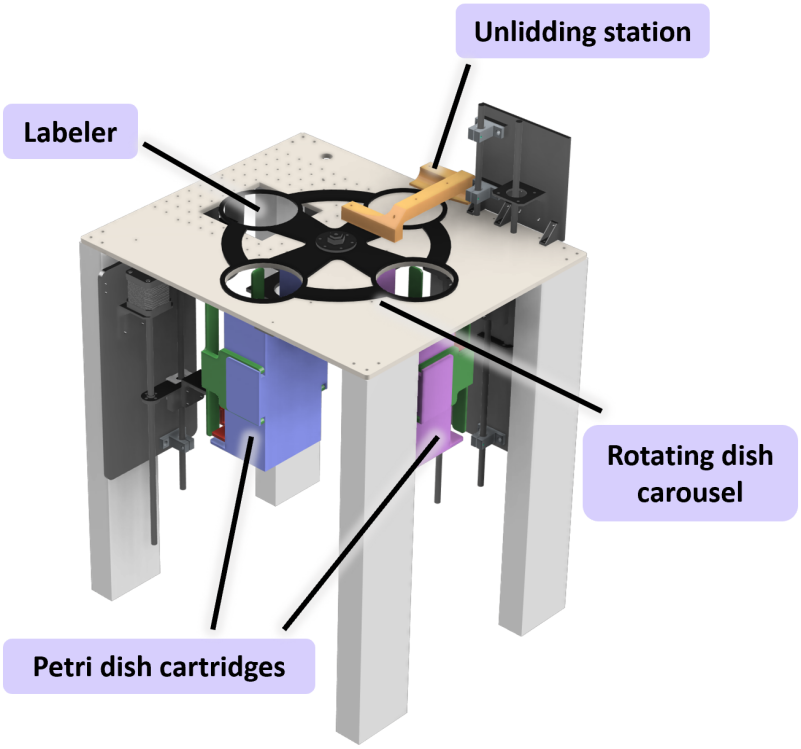


Figure A.4: *CAD render of functional prototype with labeled components.*

The four elements and an overview of the electronics currently developed through our work on the functional prototype will be discused in detail in the following sections.

A.3.4.1 Petri dish cartridges

The cartridges are the user's first touchpoint with the system. One of the functional requirements for the cartridges was that they can be loaded with dishes that are in the same form as they are packaged when received by labs. From our lab visits, we learned that most dishes are stacked and wrapped in plastic or plastic bags. As such, we designed our cartridges to accommodate the user placing dishes in as one entire stack. Another requirement was that the loading and unloading process does not require any tools. The system was designed with slots and snap fits for easy by-hand assembly. The loading process has four steps: (1) placing the dishes into the cartridge, (2) snapping guard rails in to prevent dishes from falling out, (3) sliding the cartridge into place underneath the tabletop, and (4) clipping the lift plate to the cartridge drive system. These four steps are pictured in Figure A.5.

The prototype cartridge is composed of four 3D-printed PLA pieces: the case, two guard rails, and the lift plate. The case is 95 x 125 x 220 mm, and carries 15 dishes with these dimensions.

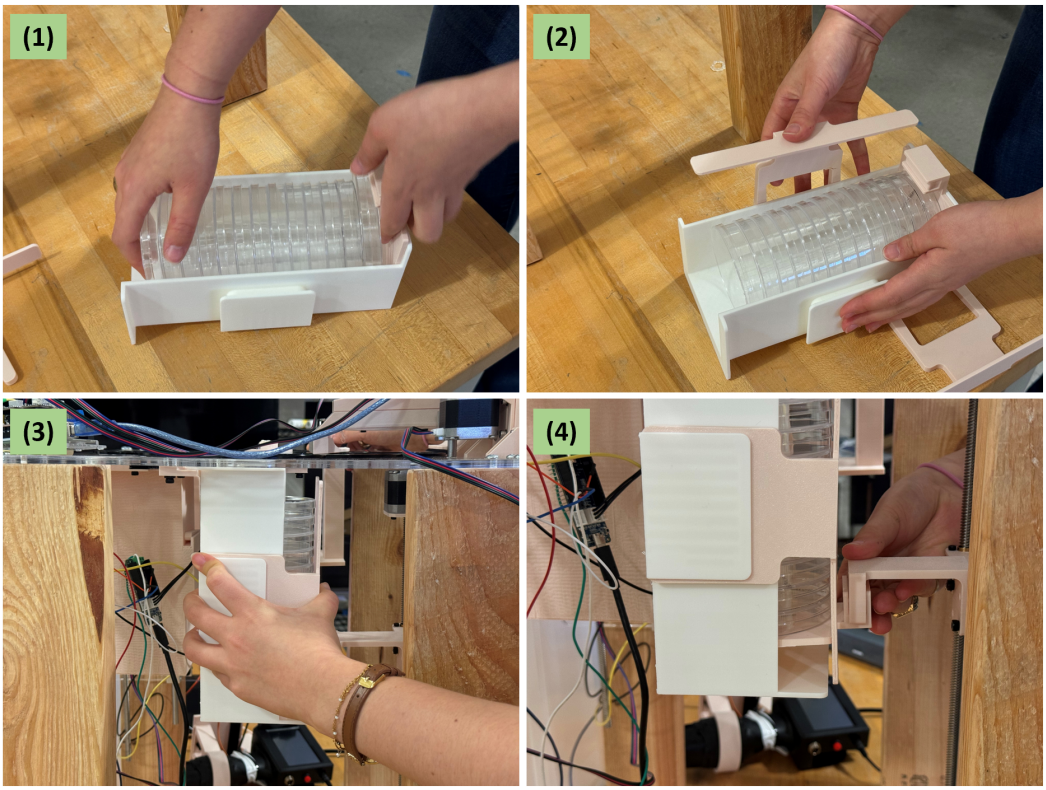


Figure A.5: *Four-step process of cartridge loading.*

The guard rails attach to the case, and the lift plate was designed to freely move vertically to raise dishes up and down. Once the cartridge is inserted into the system, the lift plate is clipped to the drive system carriage, consisting of an 8 mm diameter linear rail, bearing block, and NEMA 17 stepper-driven 350 mm lead screw, mounted to a laser-cut acrylic plate. The prototype cartridge design can be seen in Figure A.6.

A.3.4.2 Rotating dish carousel

The rotary, non-sequential path of the dish handling in this functional prototype was a major improvement from the sequential path of the previous Funky prototype. With this new carousel layout, four dishes could be operated upon at a time at different steps in the process. With small design adjustments, more than four can be handled simultaneously.

The carousel consists of a laser cut 3 mm acrylic plate with four 93 mm holes that guide dishes along the prototype's tabletop. The carousel is directly driven by a Dynamixel XH540_W270 DC servo motor, which has an integrated reduction gearhead and controller. They are connected via a 3dD-printed hex axle mounted to the motor's servo horn and a 3D-printed hub that press fits onto the axle and screws into the carousel plate.

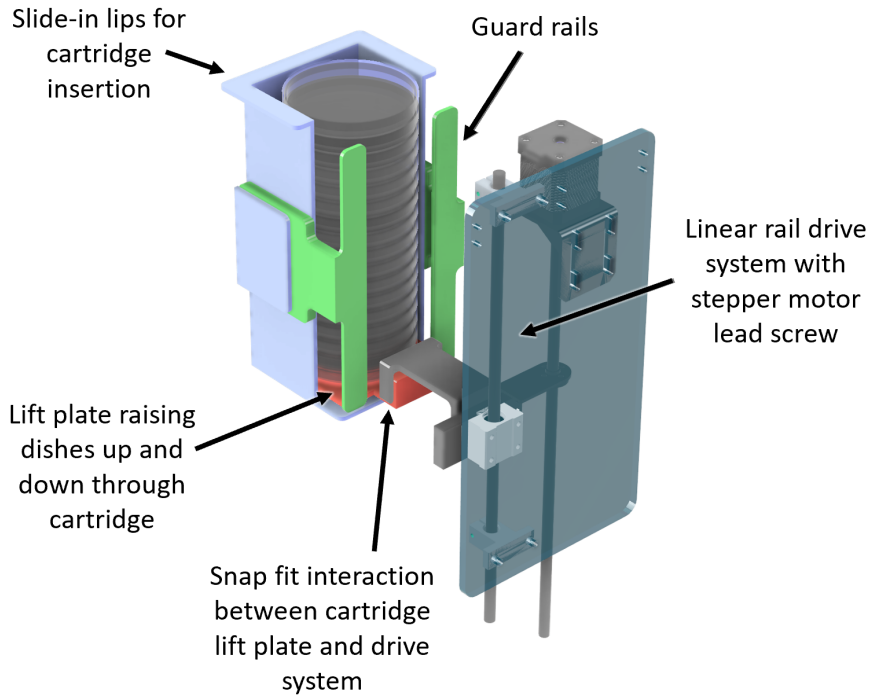


Figure A.6: *Labeled CAD render of cartridge and cartridge drive system.*

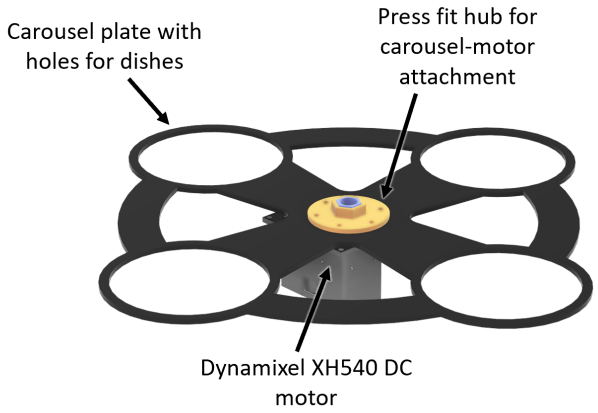


Figure A.7: *Labeled CAD render of petri carousel system.*

A.3.4.3 Unlidding station

The unlidding station uses a linear drive system similar to the cartridges and the previous funky prototype, with a lead screw coupled with a bearing block on a linear rail. The end effector for this component has passive fingers that slide under the lid of the dish that is moved into this station by the carousel. When the end effector is raised, only the dish lid is removed while the dish remains

on the tabletop for streaking.

The end effector components, consisting of the fingers and the bridge connecting them, are 3D-printed, made of PLA. Unlike the funky prototype's compliant gripper for lid removal, this version has empty space on both the front and back of the gripper, such that one-way entry and exit through the system is feasible, as noted in Figure A.8. The drive system is powered with a NEMA 17 stepper motor and mounts to an acrylic plate.

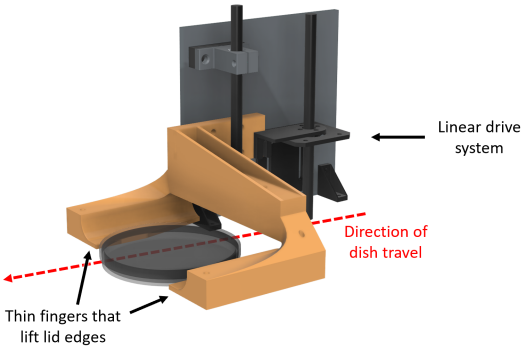


Figure A.8: *Labeled CAD render of unlidding station.*

A.3.4.4 Labeler

To label dishes with relevant sample information and/or barcodes containing such information, a thermal inkjet printer was used to write on the bottom of the dishes. A handheld printer was used temporarily for this prototype for compactness and adjustabilty.

The printer was mounted to the underside of the table using 3D-printed PLA pieces screwed into the table, and shims to fine-tune the height, as distance between the printing face and the bottom of the dishes was an important factor in print success. A Fitech FS90 mini servo was used to activate the printer's trigger when dishes passed across the printer surface.

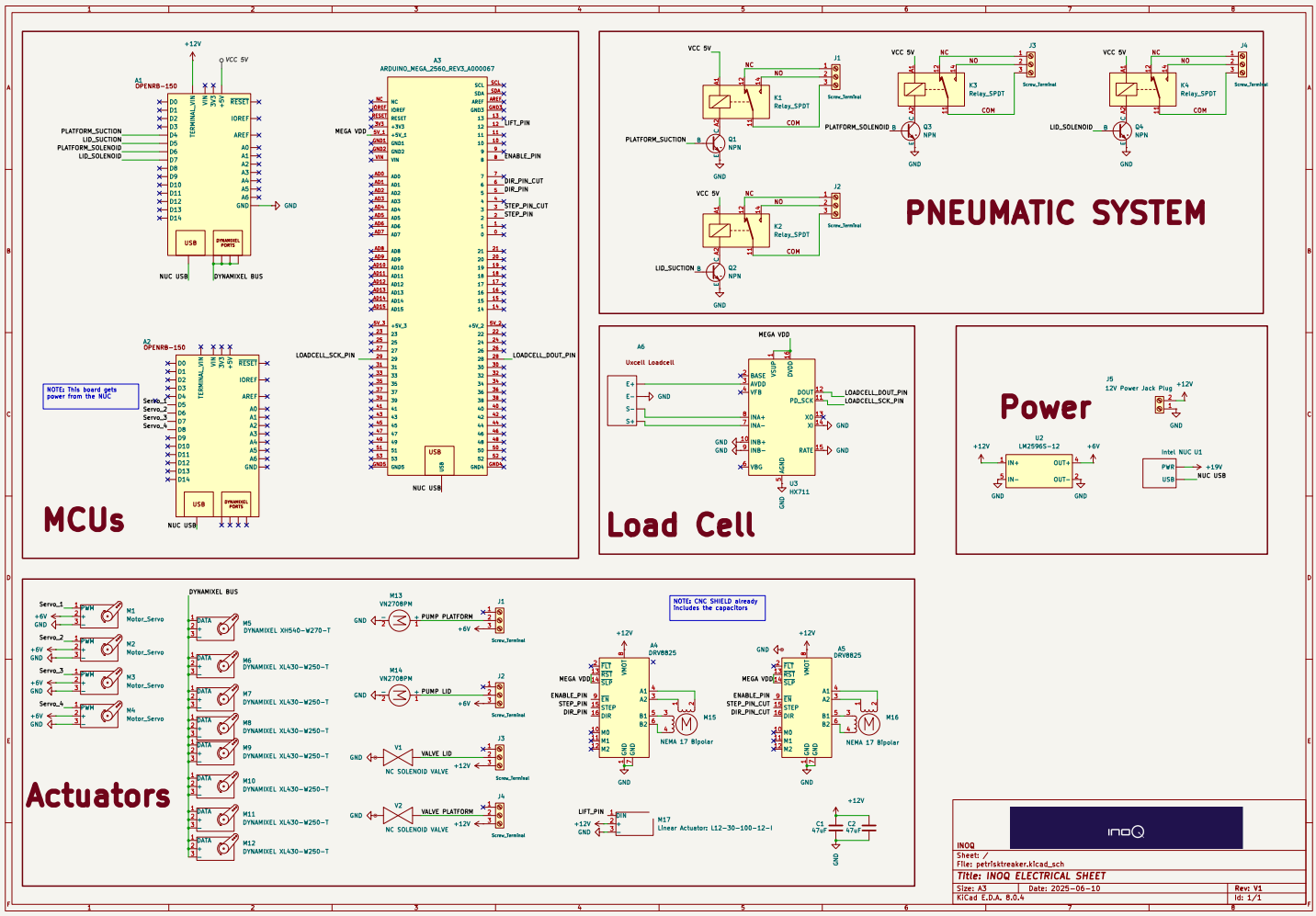


Figure A.9: *Labeled image of thermal inkjet printer.*

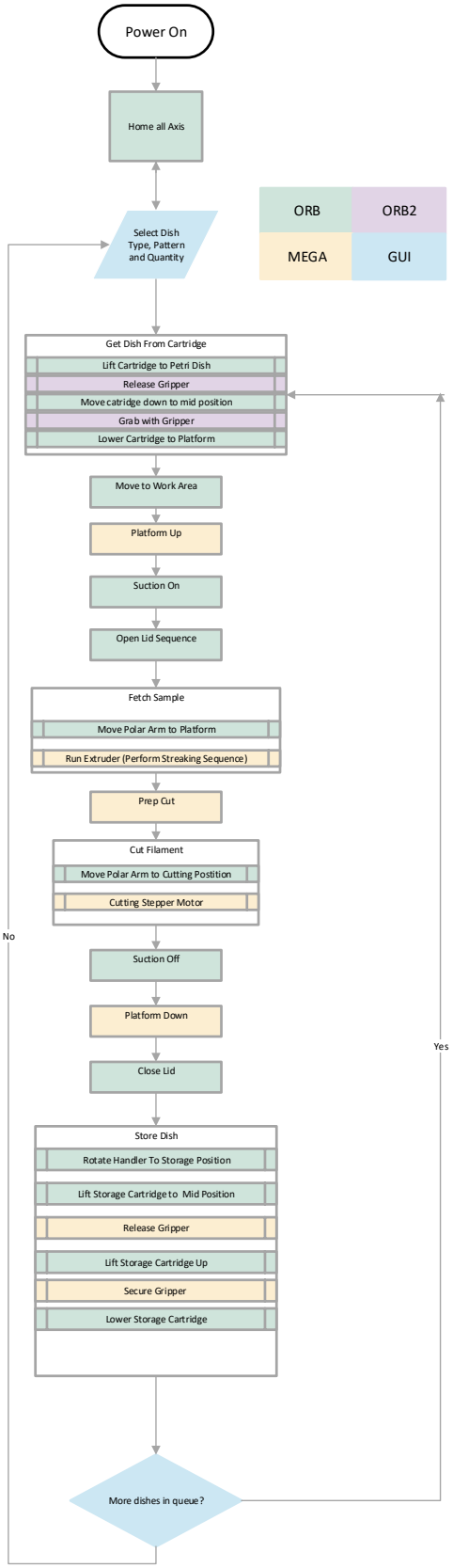
B Code Appendix

All source code relevant to this work has been made available in the following GitHub repository: [ME310: InoQ Source Code]

C Full System Schematic


MCUs
PNEUMATIC SYSTEM
Load Cell
Power
Actuators
NOTE: This board gets power from the NUC
NOTE: CNC SHIELD already includes the capacitors
INOQ
Sheet: /
File: petriskbreaker.kicad_sch
Title: INOQ ELECTRICAL SHEET
Size: A3
Date: 2025-06-10
Rev: V1
KiCad E.D.A. 8.0.4
Id: 1/1

D High Level System Flowchart Logic


Power On
Home all Axis
Select Dish Type, Pattern and Quantity
ORB
ORB2
MEGA
GUI
Get Dish From Cartridge
Lift Cartridge to Petri Dish
Release Gripper
Move catridge down to mid position
Grab with Gripper
Lower Cartridge to Platform
Move to Work Area
Platform Up
Suction On
Open Lid Sequence
Fetch Sample
Move Polar Arm to Platform
Run Extruder (Perform Streaking Sequence)
Prep Cut
Cut Filament
Move Polar Arm to Cutting Postition
Cutting Stepper Motor
Suction Off
Platform Down
Close Lid
Store Dish
Rotate Handler To Storage Position
Lift Storage Cartridge to Mid Position
Release Gripper
Lift Storage Cartridge Up
Secure Gripper
Lower Storage Cartridge
More dishes in queue?
No
Yes

E Poster

InoQ

Automating Lab Work one Dish at a Time

HAMILTON

VISION

Equip local veterinary offices with compact and intuitive automation equipment to enable rapid and reliable in-lab testing at a low cost, and allow technicians to spend their time on dynamic tasks and animal care.



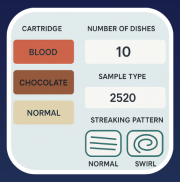
1. Load and insert cartridges

Place stacks of 10 prepared Petri dishes in the cartridge, and place and lock the cartridge inside the InoQ

2. Load biological sample

Place your subject sample in the designated spot





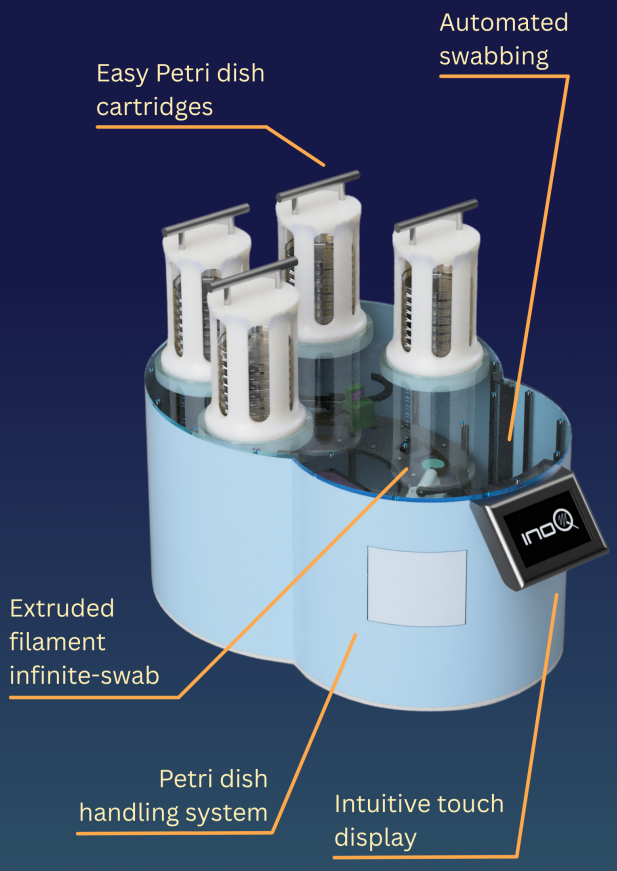
3. Select program

Specify your specific streaking needs for the samples and the amount using our intuitive GUI

4. Press play

Start the program and focus on the bigger picture.





Compact **Sustainable** **Low-Cost**

WHY?

- Veterinarians have limited access to in-house testing tools
- Available equipment is bulky and costly
- Repetitive tasks are time consuming
- Sample transportation between labs leads to high C02 emissions



Cadence Boronkay · Jorge Garcia · Tian-Ao Ren · Yug Shah · Liaison Travis Bow · Mentor Vinod Baya · Mentor Kent Frankovich · Eirik Semb · Brage Bartnes · Aleksander Auflem · Jonas Johannessen

NTNU

F Brochure

inoQ

Automating Lab Work One Dish at a Time

Projected Growth of Animal Healthcare Industry:
$5.7 billion to **$20** billion

With the growing interest in animal healthcare, **small** veterinary labs need a **budget-friendly** and **compact** solution to adapt to the demand.



A key to diagnose infections in animals is **inoculation**. A process which is crucial but can also be **repetitive** and **time consuming.**



OUR VISION

Equip local veterinary offices and labs with ***compact*** and intuitive ***automation*** equipment to enable rapid and reliable inoculation at a low cost, allowing technicians to increase their capacity and reduce time on repetitive tasks.

OUR USER

- Veterinary Technician in a small lab
- **Repetitive tasks** and **physical strain** reduce efficiency and increase the risk of occupational diseases.



Cadence Boronkay

Jorge Garcia

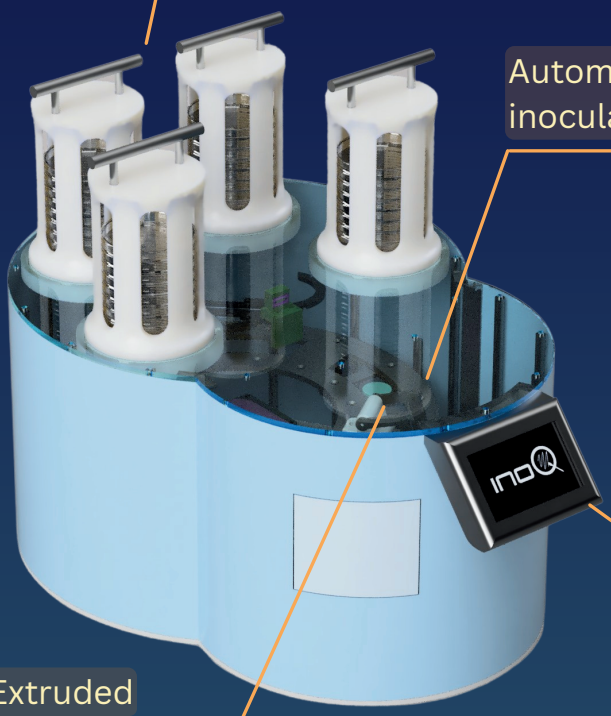
Tian-Ao Ren

Yug Shah

Travis Bow


OUR SOLUTION:

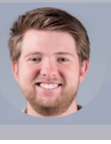
Fully automated and compact petri dish inoculation



BENEFITS

- Automated inoculation with customizable patterns
- Easy to use and fits under the cell culture hood
- The system can handle up to 30 dishes at a time
- Less waste production compared to other products

The current market average machine footprint is 2.2 [m^2]. Our system is 0.2 [m^2], a ***size reduction of 90%!***

Vinod Baya  Kent Frankovich  Eirik Semb  Brage Bartnes  Aleksander Auflem  Jonas Johannessen NTNU

G Photos and Videos of Final Product

The final prototype of the automated Petri dish inoculation device was fully assembled, tested, and validated during the Spring Quarter. Below is a link to a shared folder containing high-resolution photos and demonstration videos of the working product in action, including cartridge loading, lid lifting, streaking, and unloading functionalities.

Drive Link

These visuals showcase the performance, interface design, and compact form factor of our device, validating its applicability in space-constrained veterinary diagnostic labs. Our prepared timeline for the quarter can be viewed

H Full System Commands

ACTION	COMMAND	ARGUMENT
Move handler	MOVE "position"	NORMAL/BLOOD/CHOCOLAT/STRG/WORK_AREA
Lift/Lower PetriDish	LIFT "position" "dir"	NORMAL/BLOOD/CHOCOLAT/STRG; UP/DOWN/MID/TOP
Grab Petridish	GRAB "position"	NORMAL/BLOOD/CHOCOLAT
Release petridish	RELEASE "position"	NORMAL/BLOOD/CHOCOLAT
Platform lift control	PLATFORM LIFT "dir"	UP/DOWN
Start/Stop suction	SUCTION "device" "state"	ROT/LID
Lid handler	LID "state"	OPEN/CLOSE
Fetch sample	FETCH	N/A
Cut sample	CUT	N/A
Extrude sample	EXTRUDE	N/A
Prepare for cut	PREP CUT	N/A
Lift all	LIFT ALL "dir"	UP/DOWN/MID/TOP
Grab all	GRAB ALL	N/A
Release all	RELEASE ALL	N/A
Execute streak pattern	PATTERN "id"	0/1/2/3
Sample extrude	SAMPLE EXTRUDE	N/A
Sample retract	SAMPLE RETRACT	N/A
Home all axes	HOME ALL	N/A
System status	STATUS	N/A
Reset system	RESET	N/A
Start automated cycle	CYCLE START	N/A
Abort current operation	ABORT	N/A
Pause system	PAUSE	N/A
Resume system	RESUME	N/A

Expected response OpenRB1	Expected response MEGA	Expected result OpenRB2
MOVE COMPLETED	N/A	N/A
LIFT UP/DOWN/MID/TOP		N/A
GRAB COMPLETED	N/A	GRAB COMPLETED
RELEASE COMPLETED	N/A	RELEASE COMPLETED
PLATFORM LIFT UP / PLATFORM LIFT DOWN	N/A	N/A
SUCC ON	N/A	N/A
LID REMOVED / LID ON	N/A	N/A
FETCH RDY	FETCH START -> FETCH COMPLETED	N/A
CUT RDY	CUT START -> CUT COMPLETED	N/A
N/A	EXTRUDE START -> EXTRUDE COMPLETED / EXTRUDE FAILED	N/A
N/A	PREP START -> FILAMENT RDY	N/A
ALL LIFT UP /ALL LIFT DOWN /ALL LIFT MID /ALL LIFT TOP	N/A	GRAB ALL COMPLETED
N/A	N/A	RELEASE ALL COMPLETED
N/A	N/A	N/A
PATTERN COMPLETED	N/A	N/A
N/A	SAMPLE EXTRUDE START -> SAMPLE EXTRUDE COMPLETED	N/A
N/A	SAMPLE RETRACT START -> SAMPLE RETRACT COMPLETED	N/A
HOME COMPLETED	HOME COMPLETED	N/A
STATUS OK / STATUS ERROR	STATUS OK / STATUS ERROR	N/A
RESET COMPLETED	RESET COMPLETED	N/A
CYCLE STARTED	N/A	N/A
OPERATION ABORTED	OPERATION ABORTED	N/A
SYSTEM PAUSED	SYSTEM PAUSED	N/A
SYSTEM RESUMED	SYSTEM RESUMED	N/A

COMMENT
Move handler to specified position
Gripper grab action
Gripper release action
Engage/disengage platform with dish
Complete lid open/close sequence
Move polar arm to sample vial
Prepare for cutting
Mega handles extrusion
Mega prepares cutting
Lift all cartridges together
Grab all grippers
Release all grippers
Execute predefined streaking pattern
Mega handles sample extrusion
Mega handles sample retraction
Initialize all motors to home position
Get current system status
Reset system to initial state
Start automated dish processing cycle
Safely abort current operation
Pause current operations
Resume paused operations

I Prepared timeline


Task name
03.04.2025
10/04/2025
17.04.2025
24.04.2025
01/05/2025
08.05.2025
15.05.2025
22/05/2025
29.05.2025
05.06.2025
12/06/2025
ME 310 Spring Plan
Initial Documentation
Finalize Design Direction
System Diagram
System Design
Spring Hunting Plan
Manufacturing Plan
Part X
Decide what Part X is
Order / Purchase materials
Build Part X
Part X
Streaking
Finalize Design
CFP / Testing
Figure out the Filament and Tip
Purchase the materials
Making closed loop
User Testing
GUI
UX/UI
Options for Different Functions
Labelling
User Inputs
Flow of Things
Unlidding
Restacking
Extracting from Cartridges
Streaking
Penultimate Tasks
Penultimate Review and NTNU returns
Final System Modifications
User Testing
EXPE and Final Documentation
Brochure Draft
Poster Draft
Final Brochure
Final Poster
Prepare for EXPE
EXPE
Final Documentation
Final Documentation Due