Final Design Review for
Portable Elastic Light Scattering (ELS) Detection System

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CDR Recapitulation

The Critical Design Review (CDR) demonstrated the proof of concept of the team's design for the Portable Elastic Light Scattering (ELS) Detection System (ELSTAR 2.0), through the use of theoretical analysis and validation plans. Keeping in mind the findings from the Preliminary Design Review (PDR), where the problem of existing bacterial identification methods was defined, the team designed ELSTAR 2.0 to be a non-destructive, low-cost (BOM target < $2,000), and portable ELS device to allow for rapid, on-site pathogen identification, with a separate compatible incubation system for ease of use when testing multiple samples.

The design concept for the ELSTAR 2.0 system from the CDR was a fleshed-out design that met portability needs by minimizing dimensions at 5.94" × 5.74" × 5.74" and weight at 1.45 kg, staying within the goal of 6" sides and a 1.8 kg weight limit. The primary concern of the design was precision and speed to locate and scan the bacterial colonies through combining multiple systems - an Arducam 12.3MP IMX477 Wide-Angle Camera (4056 x 3040 pixels) that imaged the 88 mm Petri dish and used a software algorithm to flatten the image and map colonies to a grid, then a rotating Petri dish bed sat on a low-friction Delrin ring in tandem with a rotating arm affixed with a bearing that centered the colonies under a laser that was received on the other end of the arm to capture the colonies light scatter pattern. The combination of mechanical movements ensured 360-degree full-area coverage of the Petri dish plate, and the inclusion of friction management systems with the Delrin and bearing ensured that the system could smoothly and quickly move through each colony for identification. The internal body of the system puts emphasis on space allocation for easily accessible mounting of electronic components, allowing for a cohesive and assembleable design. A separate incubation device was also developed, measuring 5.75" × 5.75" × 8" and was controlled with a 10 W resistive heater. The device held 3 Petri dish samples at a time, maintained relative humidity between 50% and 70%, maintained a temperature of 37°C, and remained insulated by incorporating an 8 mm air gap with a 3 mm EVA foam layer.

With the successful prototyping and calculations for the proof of concept, the Final Design Review (FDR) now focuses on advancing this concept by calibrating the design, identifying shortcomings or limitations within it, and optimizing the device for consumer use. Primary feedback from the CDR revolved around the last of safety measures and internal checks within the device, as well as the lack of specificity with the testing and validation plans. This feedback has been considered and addressed, with internal calibration methods being included in the programming of the device and tests with specific parameters being introduced for the final design checks. Further tasks of the FDR focused further on risk negation and next-step identification, delving deep into the design to note any areas of potential improvement for future teams to further optimize the design for speed, precision, and cost-reduction.

Key Risks

Risk prioritization was done using FMEA (see **Appendix B**), with the highest Risk Priority Numbers ($RPN = Severity * Occurrence * Detection$) driving the focus of the final design and subsequent validation plan. In the process of conducting CDR, high-priority risks were found to relate directly to the core optical and mechanical performance requirements of the ELS system. The highest risk identified was the Top Camera Detecting Glare on the Petri Dish (RPN 90), carrying a high Detection rating (D=5) because glare is difficult to prevent entirely, thus will only be fully detected after image processing occurs, leading to a worsened device function (S=6 for colony location failure). This risk has been greatly mitigated in the final design, with a glare prevention cover being added to the camera arm, showing immediate improvements to colony detection, which already started at a high value of 85%. Introducing this cover is the strategy of mitigation selected, and to further work to eliminate the risk, further experiments could be conducted with slight design iterations being made to the guard to optimize glare reduction.

For another high-priority risk identified, Reflections Entering the Bottom Camera Sensor (RPN 80), where core functionality is impacted by the capture of scatter patterns being disrupted (S=5). The identified cause of this is light bouncing off the internal body of the device, and the introduced mitigation strategy was to use a black, light-absorbing material for the inner flash plate that fully encloses the bottom camera sensor. This strategy has completely mitigated the risk, and scatter patterns have been fully captured in multiple tests, thus the camera sensor can fully operate with intended functionality.

A final high-priority item identified was the Gear Wearing Over Time (RPN 63), which identifies the risk of the gear wearing due to the device's high-precision mechanical rotation completed in each cycle, something that was sought to be mitigated by using materials with high life-cycles to confirm long-term usability. Due to purchasing constraints, a gear made of a strong brass alloy could not be incorporated into the design, so in order to reduce the risk of wear a 3D printed gear was designed to optimize for long-term durability by thickening teeth and increasing the root radius from prior iterations. In all tests of the overall functionality, wear has yet to be noticed, but in future design iterations it is recommended to introduce a stronger gear material to take this risk from reduced state to fully eliminated.

Manufacturing and Assembly

The primary manufacturing method was Fused Deposition Modeling (FDM) 3D printing. The team made use of the 3D Printing Lab (ME 1191) in the Purdue Mechanical Engineering Building, as well as a Bambu Lab P2S 3D printer, which belonged to one of the team’s members. This allowed for fast iterations and the ability to reprint whenever tolerances or the design had to be adjusted. There were a total of 17 components that were 3D printed to be a part of the final prototype, and these components can be seen in Figure 1.

Figure 1. All 3D Printed Components of Final Assembly

Additional components were fabricated in the Purdue Mechanical Engineering Machine Shop (ME G039), where aluminum sheet and acrylic parts were laser cut to the required dimensions. The drawings for these components can be seen in **Appendix E**.

Assembly followed a chronological order as it began with preparing all 3D printed parts by sanding rough edges and embedding heat inserts in their designated locations. Once the components were ready, the electronics were mounted onto the top and bottom arms of the ELSTAR unit, followed by securing the arm lid and shaft to the casing with mounting screws. Wiring was routed through the arm, shaft, box lid, bearing, and flash plate to connect all components to the Raspberry Pi and control boards. The ELSTAR floor was attached to the walls using screws, and the flash plate was mounted inside the box while the bottom arm was fixed directly to the servo. After verifying all connections, the remaining wires were tucked in, and the box top and reading arm were secured. Then the petri dish bed and gate assembly was assembled and placed onto the ELSTAR, ensuring proper meshing with the Servo. The incubator's inner and outer shells were assembled next, including the acrylic-windowed door, magnets, and seal strips for proper closure. The heater and power supply were connected to the temperature controller, and all electronics were mounted in the housing before attaching the housing and door to the incubator body.

During the build process, several challenges showed up, including small tolerance mismatches between printed parts and the PCB, thermal leakage at the corners of the incubator, and cable congestion inside the enclosure. These were solved by increasing clearances, adding seals at the corners, increasing enclosure dimensions, and adding anchor points for cable management. Another issue during assembly came from the electronic components, specifically the Raspberry Pi. During testing, the Raspberry Pi and a PCB board were shorted and were no longer operating as intended. This was a huge issue as the Raspberry Pi was the main control interface of the ELSTAR. This issue delayed the final assembly for over a week as we had to order replacement parts. Once these parts were delivered, the final assembly was able to be finished, and subcomponents were able to resume testing and validation. An image of the final assembly and the working subsystems can be seen below in Figure 2.

Figure 2. Complete Assembly of Final Prototype

Analysis Approach and Key Results

The analysis performed in the CDR to systematically address design decisions and mitigate the high-priority risks identified in the Failure Mode and Effects Analysis (FMEA) remained the same because the required precision mechanics for positioning and laser alignment, and the required thermal stability of the external incubator, were constant. Thus, no additional analysis was done.

Validation and Testing Results

The validation plan laid out by the CDR consisted of three main tests to verify the separate subfunctions of ELSTAR 2.0: the colony locating, the rotational motion of the servos, and the ELS pattern acquisition. Success for these tests will result in a fully working system, as laid out in **Figure 3**.

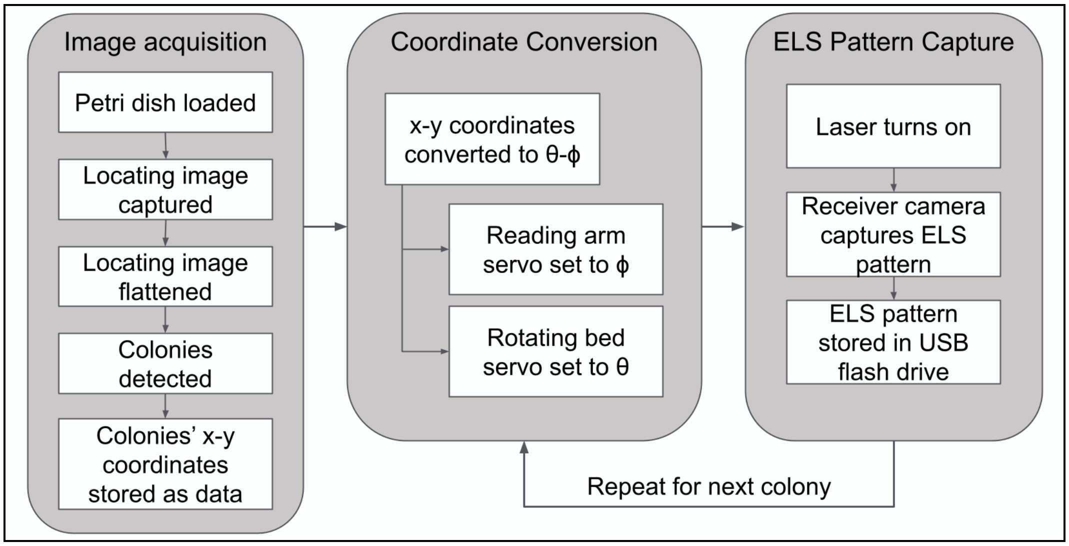

Figure 3. System's Software Workflow

The first test was to verify the successful detection of colonies, which falls under Image Acquisition. Sub-tests, such as Top Camera functionality and calibration tests, were done in the ME 463 PEARL Lab and were crucial in setting up the later algorithm. Top camera functionality was verified after wiring it up, and a live camera feed was obtained through the Raspberry Pi. Success for this sub-test was being able to capture the full view of the 88mm Petri dish with a clear resolution, which the team was able to meet after minor height adjustments to the Reading Arm's height. Camera calibration was crucial to ensure accurate colony mapping later; the standard procedure for calibrating a wide-angle lens for flattening was done to acquire the camera characteristics of the camera intrinsic matrix and distortion coefficients. The team tested the camera calibration results with a checkered paper. The raw images taken with the wide-angle fisheye camera will show the bulging effect, where the checker squares will not have uniform straight lines, but instead are visibly closer together around the edges, and more spread out towards the center. A successful camera calibration will result in the image being processed so that the checkered squares are uniform and equidistant, as seen in **Appendix D, Figure D.1**. After ensuring the image processing capabilities of flattening, the next step was to locate the bacterial colonies. To do this, a blob detection algorithm was developed, utilizing the OpenCV contour analysis, which compiled a list of the found centers of the bacterial colonies relative to the Petri dish center with x-y coordinates. To tune the algorithm, since the team did not have immediate access to actual bacterial colony plates, the team used black dots printed on a sheet of white paper that fit into the petri dish plate to simulate grown bacterial colonies on agar. Tuning and testing confirmed that each colony was at least 50 pixels in diameter, which aligned with the CDR analysis of exceeding the minimum requirements of 10 pixels. With the mock plates, the team achieved a 95% with bacterial-colony-sized dots, with accuracy in detection increasing with dot size. The team got the chance to do further colony locating testing at Purdue Veterinary School Cytometry Laboratory (PUCL) and worked with Kocuria. From these tests, the colony locating algorithm had a 85% success rate; the lower success rate is due to a lack of samples for fine-tuning the algorithm parameters. **Appendix D, Figure D.2** shows the flattening of the locating image, the detected colonies by the algorithm, and the mapped ideal path.

Taking the found x-y coordinates from the colony locating algorithm, Coordinate Conversion was necessary to translate the Reading Arm and the Petri Dish Bed to the proper position to align the laser with the center of the colony. Success in this test would look like proper alignment of the laser on the detected dots or bacteria. A sub-test in this part of the validation process included validating the function of the servos. To do this, the just the Petri Dish Bed was meshed with the servo pinion gear, and the gear was set to turn the smallest step possible. From visual observation, the resolution that the gears provide is more than sufficient, which confirms the Gear Ratio's Adequacy for precise relocation and the proper fitment of the gear, which respectively address the high-priority failure modes of "Rotational displacement inaccuracy" and mitigate "Gear wear over time." The Coordinate Conversion algorithm consists of coordinate transforms and inverse kinematics to translate the x-y coordinates into θ-ϕ coordinates, where θ is the position of the servo controlling the Petri Dish Bed's rotation and ϕ is the position of the servo controlling the Reading arm. To test this algorithm, the same mock plates from the colony locating test were used. The list of compiled colony centers output from the colony locating algorithm is input into the Coordinate Conversion algorithm, and then results in the corresponding motion in the Petri Dish Bed and Reading Arm. The testing done during this stage resulted in consistent positional translations and verified the inverse kinematic theory that was developed for the Coordinate Conversion algorithm. However, due to time constraints, the team was not able to perfect the alignment of the laser to the dots. Thus, the current status of ELSTAR is able to map out the colonies, but has some errors in the translation to θ-ϕ coordinates. In **Appendix D, Figure D.3,** the laser is nearly centered on the targeted dots drawn on the Petri dish paper. The algorithm and hardware work to achieve close accuracy to the target, however further centering and stability in the parts would improve the alignment to colony centers. The relative positional accuracy of inter-colony location fares well, but the locating of the colony relative to the dish still requires development. Thus, this test resulted in a partial success.

As previously mentioned, the team was able to test with a Kocuria sample at the PUCL, and one test that verified a crucial function was the ELS Pattern Capture test. Because at the time, the servos were experiencing last-minute communication issues, this test was a manual test. The team moved ELSTAR 2.0's Petri Dish Bed and Reading Arm so that the laser in the arm lines up directly with the bacterial colony. Upon aligning the laser with the colony, an image was captured with the Receiver Camera. The results of this test can be referenced in **Appendix D, Figure D.4**. As shown, the team successfully captured an ELS scatter pattern, which validated the functionality of the laser and Receiver Camera. Something to note is that the resulting ELS patterns from the figures are cut off along the edges; the reason for this is that the Kocuria colonies from the sample were slightly smaller than full-grown, and thus scattered the laser more.

Design Decisions, Lessons Learned & Next Steps

Since the CDR, the team had learned many lessons through iterations of the manufacturing and troubleshooting processes. Many design changes were made from the design proposed in the CDR. One such design decision was the addition of ventilation grilles in the main body of ELSTAR because, during testing, the electrical components were found to be heating up significantly. To mitigate any potential for thermal damage, the ventilation grilles were added to the design so that the heat generated by the electronics can leave the system. Additionally, the designated mounting for the custom power distribution PCB was repositioned so that the wiring was made as neat as possible and did not interfere with the moving components of ELSTAR 2.0.

One major design decision the team had to consider was related to the Petri Dish Bed's gear procurement. The team's original intended vendor is a Chinese vendor; however, Purdue University recently started enforcing a policy where no purchases can be made from foreign adversaries, with China being on the list. Thus, the team had to look for a domestic vendor. The biggest concern was the price spike, where the Chinese vendor had a price of $80 for a completely custom part; the cheapest domestic vendor that sold the service of custom parts was in the $400s. The team also needed to weigh the trade-off between cost and time, as the cheapest option would take two to three weeks to come, while the most time-idealistic choice of receiving the gear in just a week would be well over $1000. A third option was a cheaper on-shelf gear that fits the bare minimum of the team's gear design, but would require a bit of manufacturing alteration work to fit into the ELSTAR system as intended. However, regardless of choice, the purchase of a gear would put the team over budget, so the team reached out to the sponsor for the decision and the pitch of options. After communication with the sponsor, the third option was chosen for its return on investment, as it was the cheapest option that would work and would provide learning opportunities for the team, in the context of manufacturing. However, the vendor was out of stock on the part, and the order became a made-to-order part, which meant the team was not going to receive the part for months, way past the project timeline. Thus, the order was cancelled, and the team resorted to using a 3D printed gear, which provided sufficient resolution and function, with only concerns of long-term wear. The big lesson learned from this design decision was how the impact of global economics and politics can affect an engineer's project. Engineers must plan ahead and take into consideration all variables that might affect project procurements and be timely in purchases so that buffer time is available to deal with issues that arise.

Another big decision that the team had to discuss with the project sponsor before moving forward was increasing the Reading Arm's height so that the Colony Locating Camera was able to capture the entire Petri Dish. The alternative was to solve the issue from a software perspective, but this method would have been much more complicated and risked error stacking in rotating the Petri dish and the Reading Arm. The sponsor agreed that raising the arm height was the easiest and most reliable solution, so the team raised it to 6.28 inches, which is just over the 6-inch desired height identified in the Problem Definition. The tradeoff between going over the height limit slightly was worth it for the design conveniences and reliability.

A major roadblock that the team experienced was unexpectedly losing proper communication with the servos that controlled the Petri Dish Bed and the Reading Arm. The team did thorough troubleshooting and ruled out potential causes like software bugs, bad wiring connections, and improper power supply. Eventually, the team identified the cause to be a hardware issue on the Serial Bus Servo Driver Board, since there was communication from the Pi to the servos, but no feedback from the servos to the Pi. Since getting the servos to work was a crucial part of the device's functionality, the team ordered a replacement for the broken board immediately. However, this issue put a halt to the software integration work since no testing could be done without the servos. During the troubleshooting process to narrow down the cause of the issues with the servo, the Pi experienced irreparable damage. With little time to get a replacement Pi ordered and received in time, the team used the Pi from the first iteration of ELSTAR. The servos issue was eventually resolved with the new board. These last-minute servo issues caused the team to deliver an unfinished project, where the software still needs tuning. This experience taught the team what engineering is really about – taking a problem and going through the steps to cover all bases, find the cause, and develop a solution. It also taught the lesson of the importance of the project timeline. Because there were delays in the work of other parts of the project, the final integration was rushed and ultimately incomplete.

The final prototype that was delivered in this project is ELSTAR 2.0, which has the full physical functionality required of this project. The only thing that was undelivered was a fully automated and precise software. Besides the delay due to the servo issue, the other significant limitation of the team was the skills gap in software integration experience. The team was short on experience to be able to develop software quickly. The team has developed the foundation of the software that will require tuning to complete the prototype's functionality. The team believes the next step for this project is to hand off ELSTAR 2.0 to talents in software engineering to complete the software integration.

<u>**Appendix A: Final System Diagram**</u>

Note: Updates from the CDR are highlighted for easy reference.

Table A.1: System Definition

What is included in the system?	ELS Device with Incubator system, Petri dish with bacteria, USB flash drive for data
What is not included in the system?	User actions, power source

Table A.2: System Inputs

Input Flow Type	**Description**
Energy	Power from the wall outlet
Material	Petri dishes with bacteria, wet towels for incubator, USB drive
Information	Inputs from the user

Table A.3: System Outputs

Output Flow Type	**Description**
Energy	Heat from the incubator system
Material	Scanned Petri dishes with bacteria
Information	Bacteria scatter patterns on USB

Table A.4. Major Subsystems and Components

#	**Subsystem / Component**	**Primary Function**
1	Petri dish, dish bed, dish gate	Receive Petri dish
2	Camera, laser, CMOS sensor	Locate cell colonies
3	Servos, servo bus, Raspberry Pi	Move Petri dish
4	Incubator (temperature controller, sensor, wet towel)	Maintain set temperature and humidity
5	Camera, Raspberry Pi, USB drive	Process photo data

Table A.5: Energy, Material, and Information Flow

From	**To**	**Flow Type**	**Description**
External Power Source	ELS Device	Energy	Power from the wall outlet
External/User	ELS Device & Incubator	Material	Petri dishes with bacteria, wet towels for incubator

User	ELS Device	Information	Inputs from the user
Incubator System	External Environment	Energy	Heat from the incubator system
ELS Device	External/User	Material	Scanned Petri dishes with bacteria
ELS Device	USB Flash Drive	Information	Bacteria scatter patterns

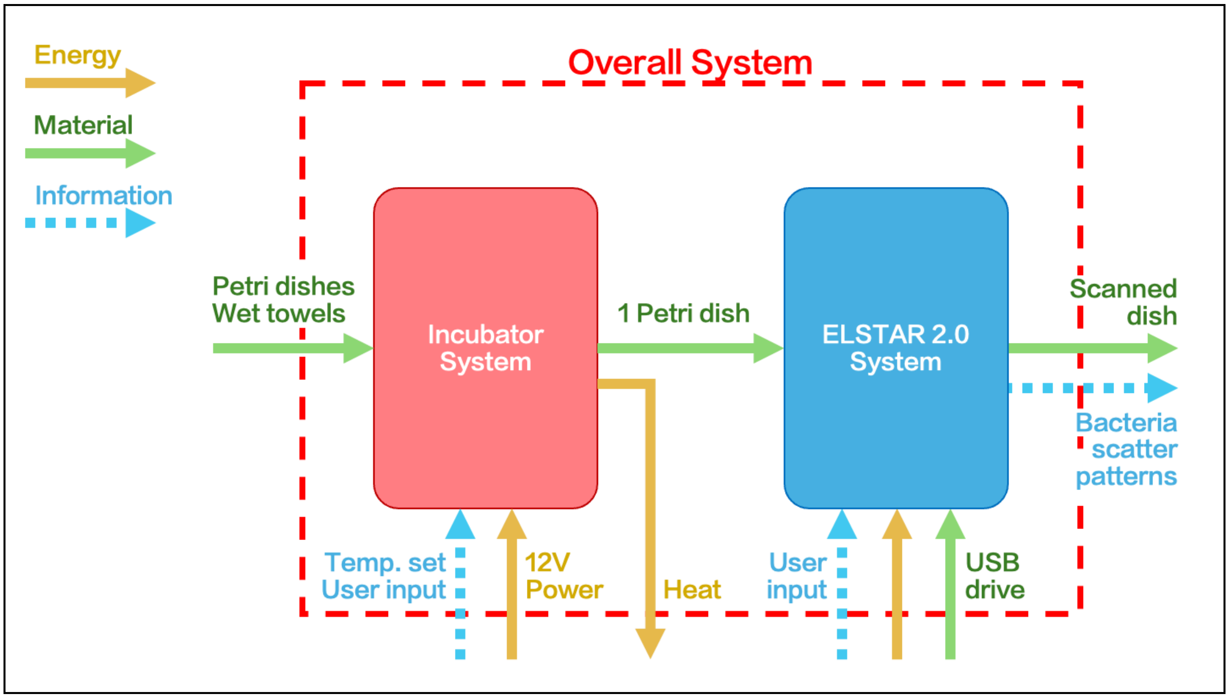

Figure A.1: Overall System Diagram

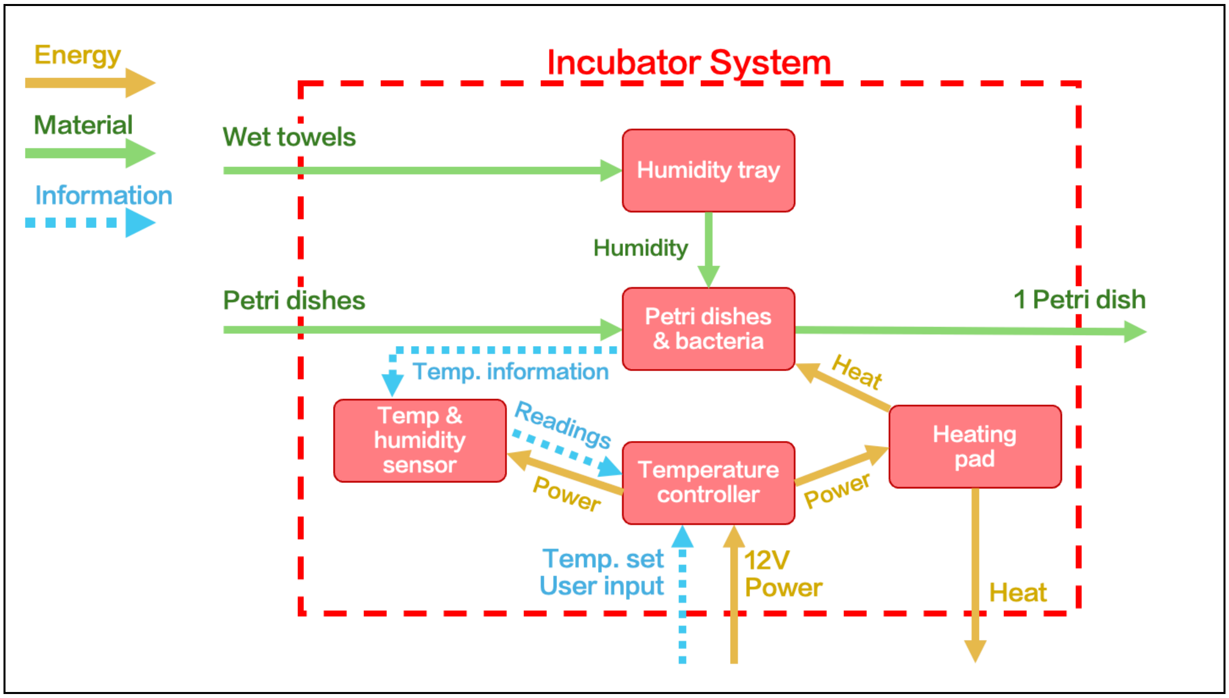

Figure A.2: Incubator System Diagram

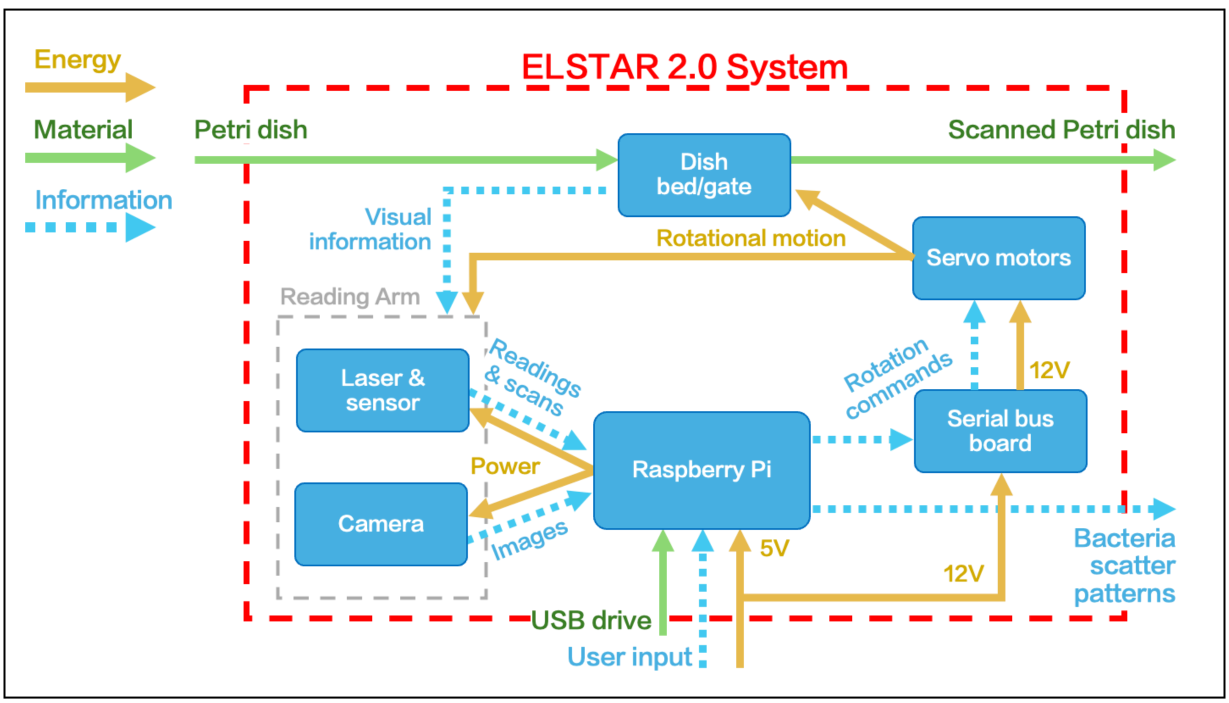

Figure A.3: ELSTAR 2.0 System Diagram

Appendix B: FMEA

Table B.1: FMEA Matrix

Component / Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Cause(s)	Occurrence (O)	Controls (Prevention or Detection)	Detection (D)	RPN = S x O x D	Recommended Action(s)
Bed Gears	Gear wearing over time	Increased backlash, loss of accuracy in turns	7	Gear contact friction, improper tolerancing	3	Detect via visible notice of inaccuracy of scatter pattern location	3	63	Conduct life cycle analysis of gears
Motors	Rotational displacement inaccuracy	Systems moves to wrong location, arm could be in way of picture, gate not in proper location for loading/unloading	8	Error stackup in motor turning, gear backlash	6	Induce calibration in system startup	1	48	Implement a calibration system
Gate Hinge	Snapping under load when open	Gate would break off and need replaced	8	User putting weight on the gate while it is open and hanging over edge	2	Obvious detection, no prevention mechanisms	1	16	Strengthen hinge to prevent breakage as much as possible
	Snapping due to bed rotating while open	Gate would break off and need replaced	8	User leaves gate open, starts system, and gate arm catches on camera arm and snaps at hinge	1	Prevent system from starting while unlatched, prevent system from rotating CCW	1	8	Ensure system always rotates CW, thus closing arm naturally if it is open
Cameras + Laser	Top camera detects glare on petri dish	Colony locations not detected properly	6	Room lighting, unclean petri dish	3	Minimize external light on dish	5	90	Create light cover for top of system
	Light reflections enter bottom camera sensor	Disruption of scatter pattern capturing	5	Light of room bounces off body, reflecting into camera	4	Use black material to absorb external light	4	80	Use black material body
Flash Plate	LEDs light on plate burn out	Improper lighting causes initial locating image to fail	7	LEDs burn out over time	5	Visually detect if LEDS are out	1	35	Create an accessible way to easily replace LEDs
Bed/Lid Contact	Surfaces can wear over time	can cause inconsistent rotation of petri bed	3	High friction between surfaces can cause wear	2	Ensure parts with wear are easily and regularly replaced	4	24	Use replaceable, minimum friction materials (delrin ring, aluminum ring)
LED/Buttons	LED lights burn out and buttons wear	Inconvenience or difficulty using device	3	Overuse of ELS device	5	Visually detect if LEDs are out and if buttons are worn	2	30	Create an accessible way to easily replace these components if needed
Petri Dish/Bed Contact	Petri bed can potentially slip	Can cause inconsistent rotation of petri dish	7	Low friction between surfaces	3	Image processing will not work as expected	2	42	Design components out of different materials with higher friction
Incubator Heating	Heating pads overheat or underheat	Bacteria growth can be stunted	4	Wires shorted or controller not regulating voltage	2	Visually check temperature on screen	1	8	Implement a hard stop if temperature gets too hot
Incubator Door Seal	Incubator can loose heat due to poor seal	Incomplete contact between door	3	Rubber seal worn down over time	3	Visually check seal	4	36	Do analysis on rubber seal life

Appendix C: Analysis Plan and Results

Table C.1: Analysis Plan

Analysis Objective	Method and Justification for Choice	Assumptions	Output(s)	Design Impact
Will the selected gear ratio allow for petri dish rotation within allotted angular resolution? [FMEA Mode #1 RPN 63 and Mode #2 RPN 48]	Hand calculations to determine minimum tooth requirement based upon maximum desired angular resolution, then verified through CAD animations to ensure alignment accuracy in design and through physical displacement testing.	Hand calculations based on 20 degree pressure angle, assuming no backlash or clearance, perfect encoder fidelity, no wear on gears.	Minimum tooth count for gear, output angular resolution of geared system.	Validates gear diameter, determines gear tooth count, validates pinion selection, validates petri dish rotation method accuracy.
Will the selected camera height allow for the camera to fully view the petri dish and have proper backlight visibility? [FMEA Mode #5 RPN 90 and Mode #8 RPN 80]	Hand calculations to determine minimum camera arm height based upon camera minimum FOV and petri dish diameter, then verify through camera imaging that the petri dish is fully in view at specified height and back lighting is appropriate.	Hand calculations based on 105 degree minimum FOV, standard 88mm diameter petri dish, assuming diffuse agar gel and negligence of outside light interference.	Minimum camera arm height for full imaging of petri dish.	Validates camera/laser arm height, validates diffuse gel assumption, allows for cell cluster detection algorithm development.
Will the selected servo allow the reading arm to rotate within allotted distance resolution? [FMEA Mode #2 RPN 48]	Hand calculations to determine the minimum turning distance based on the angular resolution of the servo, verify through physical displacement tests using the servo and the reading arm.	Hand calculations based on sensor resolution of 0.088°, neglecting error in servo rotations, and neglecting friction resistance due to bearing usage.	Resolution of reading arm as it is turned by smart servo.	Verification of servo usability, ensuring it meets minimum resolution requirements.
Will the selected heat source be powerful enough	Hand calculations to determine the amount of heat loss through	Hand Calculations based on thermal	Minimum power needed for	Validates current incubator

to keep a constant temperature of 37°C. [FMEA Mode #11 RPN 8 and Mode #12 RPN 36]	conduction to ensure the heater has enough power to maintain a temperature of 37°C, then test design with temperature sensors after assembling the incubator.	resistance network of double-walled insulation with an air gap and EVA foam, neglecting heat loss through convection and radiation.	the heater to keep a steady temperature of 37°C.	design, ensuring it can keep a constant temperature.

Hand Calculations

<u>Gear Dimensions Hand Calculations</u>

Angular Resolution Verification

VARIABLE DEFINITIONS:

Gear 1 is dish gear, Gear 2 is pinion gear

C → Center Distance Between Gears

d → Gear Diameter

z → Gear Tooth Count

R → Counts Per Revolution

θ → Angular Resolution

$$C = \frac{d_1 + d_2}{2} = \frac{100mm + 9.6mm}{2} = 54.8mm$$

$$z_2 = \frac{2C}{m} - z_1 = \frac{2 * 54.8mm}{0.8mm} - 12 = 125$$

$$R_{out} = R_{servo} * \frac{z_2}{z_1} = 4096 * \frac{125}{12} = 42666.67$$

$$\theta_{out} = \frac{360^\circ}{R_{servo}} * \frac{z_{pinion}}{z_{gear}} = \frac{360^\circ}{4096} * \frac{12}{125} = 0.0084375^\circ$$

$$\theta_{max} = 0.05^\circ \geq \theta_{out}$$

NOTE: Gear Diameter: 1 set at 100mm due to geometric limitations. The above calculations verify that the diameter and tooth count will be adequate for our desired angular resolution.

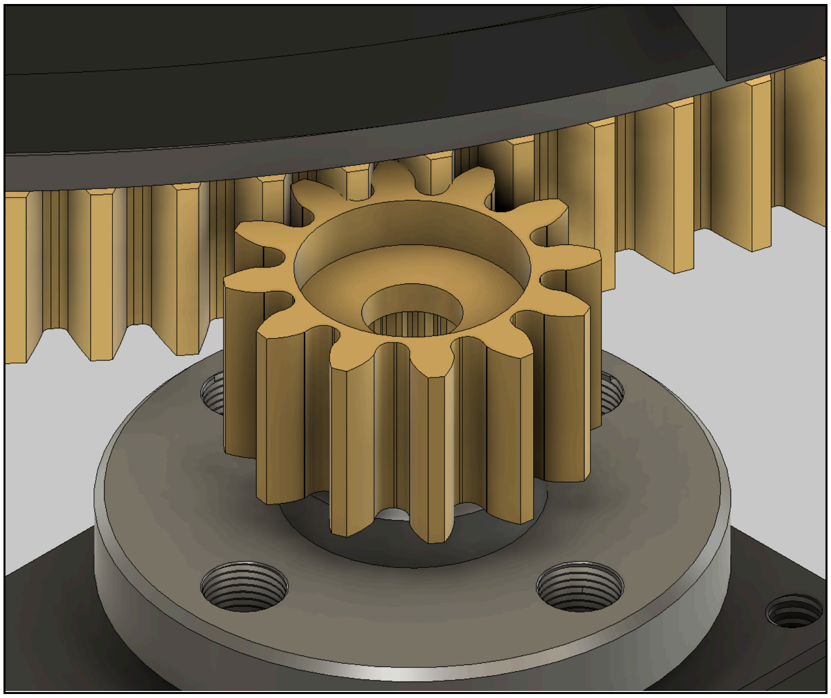

Figure C.1: Gear Meshing Interface of Petri Dish Bed

Design Decision: Based on calculations showcasing the angular resolution being sufficient to the teams goals, the custom manufactured gear (100mm effective diameter, 125 teeth, 0.8 modulus, 20° pressure angle) has been approved for system integration.

Trade-off: Due to the selection of a gear that requires custom manufacturing, cost is significantly increased. The usage of brass also increased weight compared to alternatives. The benefit is increased performance in terms of resolution and increased durability due to the material properties of brass as opposed to a 3D-printed plastic gear.

Camera Arm Height Hand Calculations

VARIABLE DEFINITIONS:

H → Arm Height (Minimum)

r → Petri Dish Radius

FOV → Minimum Camera Field of View

$$H = \frac{r}{tan(FOV / 2)} = \frac{44mm}{tan(105 / 2)} = 33.76mm$$

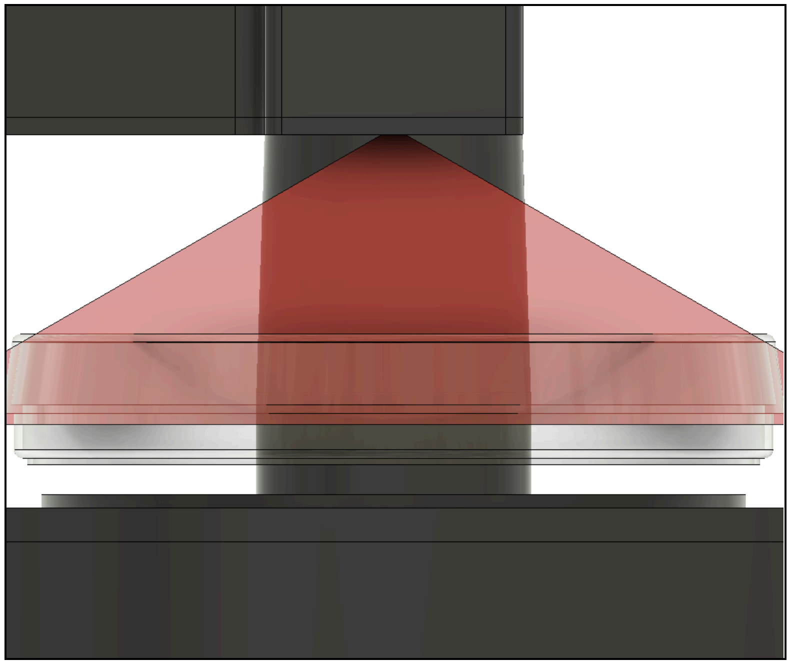

Figure C.2: Field of View Encapsulation of Dish Representation

Camera Resolution Hand Calculations

Max resolution: 4056 × 3040 Pixels

Plate Diameter = 88 mm

Colony Diameter = 1mm

Assume dish only fills up half the image: $Pixel_{plate} = 4056/2 = 2028$

Pixels per mm = $\frac{2028}{88} = 23.045$ pixel/mm

Pixels per colony = $1 \times 23.045 = 23.045$ pixels > 10 pixels

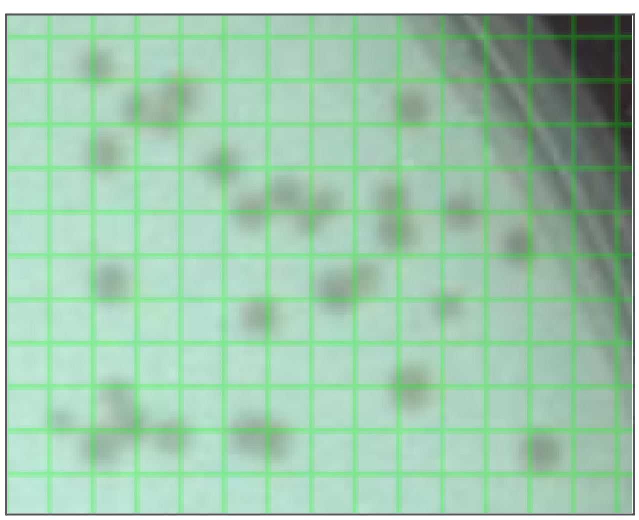

Figure C.3: Colonies in a 1280 x 1024 Pixel Image

Design Decision: Based on calculations showcasing the minimum arm height for the camera to fully view the Petri dish, the reading arm height has been set at 33.76mm from the Petri dish. Calculations completed on pixel resolution validate the purchase of the Arducam 12.3MP IMX477 Wide-Angle Camera, with a 4056 x 3040 pixel resolution.

Trade-off: Due to the introduction of a camera in general, overall system cost and complexity is increased - especially due to the pixel resolution demands. The use of a minimum arm height leads to maximum distortion which increases system complexity by requiring a strong flattening algorithm. In comparison to other solutions which require locating colonies by rotating the reading arm and petri dish bed to scan the dish point by point, this solution introduces serious speed and efficiency improvements and lessens wasted motion.

Arm Servo Resolution Hand Calculations

VARIABLE DEFINITIONS:

L → Pivot to Plate Penter = 75 mm

θ_{servo} → Position Sensor Resolution = 0.088°

r → Laser Radius = 0.5 mm

S → Arc Length

$$s = \frac{r}{\theta} = L\left(\frac{\theta_{servo} * \pi}{180}\right) = 0.1152 < 0.25 \text{ mm}$$

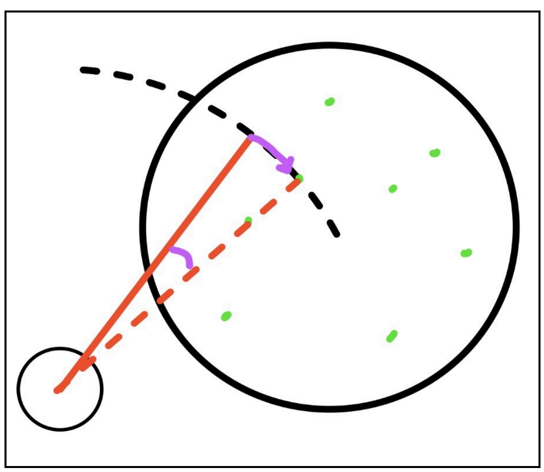

Figure C.4: Visual Representation of Reading Arm Path Over Petri Dish

Design Decision: Based on calculations the minimum step size to be 0.1152 mm using the Waveshare ST3-25 Serial Bus Servo, which is less than the maximum desired adjustment of 0.25mm, the servo was selected for implementation into the system.

Trade-off: Due to the tight tolerance of the desired adjustment, a more accurate servo was required, which increased costs and limited dimensional flexibility through purchasing of other servo motors. However, the improved accuracy is vital for system performance.

Incubator Heat Loss Hand Calculations

VARIABLE DEFINITIONS:

Q → Power required

ΔT → Temperature difference = 14 K

L → Wall Thickness = 8 mm

l → EVA Thickness = 3mm

P → Heater Power = 10 W

A = Surface area

R = Thermal Resistance

$$k_{EVA} = 0.033 W/(m \cdot K)$$

$$k_{Air} = 0.026 W/(m \cdot K)$$

$$k_{PETG} = 0.20 W/(m \cdot K)$$

$$A_{total} = 2(0.113 \times 0.100 + 0.113 \times 0.106 + 0.100 \times 0.106) = 0.06776\, m^2$$

$$A_{door} = 0.113 \times 0.100 = 0.0113\, m^2$$

$$A_{walls} = 0.06776 - 0.0113 = 0.05646\, m^2$$

$$R_{EVA,w} = \frac{l}{k_{EVA}A} = \frac{0.003}{(0.33)(0.05646)} = 0.16$$

$$R_{air,w} = \frac{L}{k_{Air}A} = \frac{0.008}{(0.026)(0.05646)} = 5.45$$

$$R_{PETG,w} = \frac{L}{k_{PETG}A} = \frac{0.008}{(0.02)(0.05646)} = 0.71$$

$$R_{door} = \frac{L}{k_{PETG}A} = \frac{0.008}{(0.2)(0.0113)} = 3.54$$

$$R_{walls} = 0.71 + 0.16 + 5.45 + 0.71 = 7.03$$

$$R_{total} = \frac{1}{7.03} + \frac{1}{3.54} = 2.36\, K/W$$

$$\dot{Q}_{required} = \frac{37-23}{2.36} = 5.93\, W$$

$$P_{heater} = 10\,W\ > 5.93\,W$$

Figure C.5: Double Wall Insulation Design

Design Decision: Based on calculations showcasing the heat loss through conduction through the walls, a 10W heater is sufficient to keep the internal temperature at 37°C with current incubator design.

Trade-off: With the goal of the incubator being a small footprint, it is important to ensure that neither the heater is too big or the design of the incubator is too bulky. With choosing a smaller heater rated for 10 W, the incubator had to make sure we did not lose much heat through conduction. To solve this issue we had to design a complex two walled design to ensure that we had enough power to combat the heat loss.

NOTE: Due to lack of high loading, no computational analysis required

Appendix D: Validation Plan & Results

Note: Updates from the CDR are highlighted for easy reference.

Table D.1: Validation Plan

Validation Objective	Failure Mode (from FMEA)	Method and Justification for Choice	Conditions	Metrics / Acceptance Criteria	Link to Analysis	Design Impact
Confirm gear ratio is adequate for precise relocation of petri dish via rotation	Rotational displacement inaccuracy	Physical measurement displacement test using marked starting point and interval measurements	Normal loading, max motor speeds, predicted gear ratio	Displacement error < 0.434°	Compare to gear ratio requirement calculations	Change gear ratio if tolerance unmet
Confirm camera calibration allows software to flatten and normalize the image	Rotational displacement inaccuracy	Verify the distanced between the squares of a checkerboard pattern post-flattening	FOV of camera is 105°, and the given checkerboard pattern consists of perfect squares	The pixel length of all squares are equal for all sides	N/A	Tune parameters of the software algorithm is criteria unmet
Confirm camera arm height is adequate to view entirety of petri dish in captured image	Camera inadequately captures image	Take image of petri dish using camera when in resting position, flatten image using algorithm to ensure data is properly captured	FOV of camera is 105°, data is maintained through flattening algorithm	Full petri dish is in view of camera and image can be appropriately flattened	Compare to camera arm height calculations	Camera arm height or camera selection changed if criteria unmet
Confirm servo motor selection is adequate for step size resolution in reading arm rotation	Rotational displacement inaccuracy	Physical measurement displacement test using marked starting point and interval measurements	Normal loading, max motor speeds	Step size < 0.25mm	Compare to reading arm step size calculations	Change servo motor selection if tolerance unmet

Confirm incubator is sufficient in temperature in humidity maintenance and can sustain bacterial colonies	Heating pads overheat or underheat, incubator can lose heat due to poor seal	Long-duration incubation tests ensuring bacterial colonies are sustained and that temperature and humidity meet expectations to ensure system can thrive for long periods during testing	Colonies thrive at 37°C, wet pocket efficient in maintaining humidity, perfect seal on door	Bacterial colony survival, temperatures maintained between 36°C and 38°C	Compare to heat source power calculations	Change heating system or improve insolation if criteria unmet

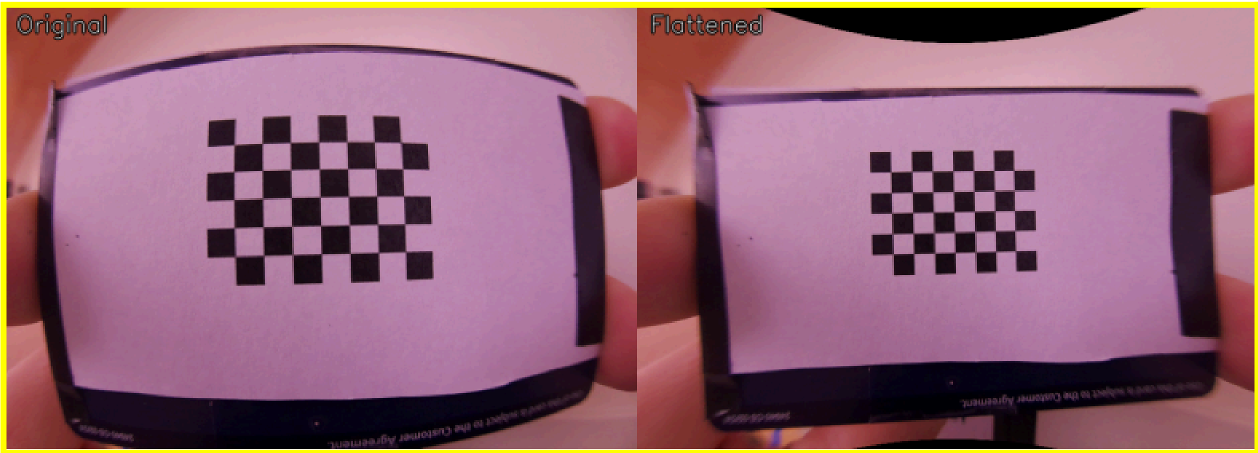

Figure D.1: Camera Calibration Results

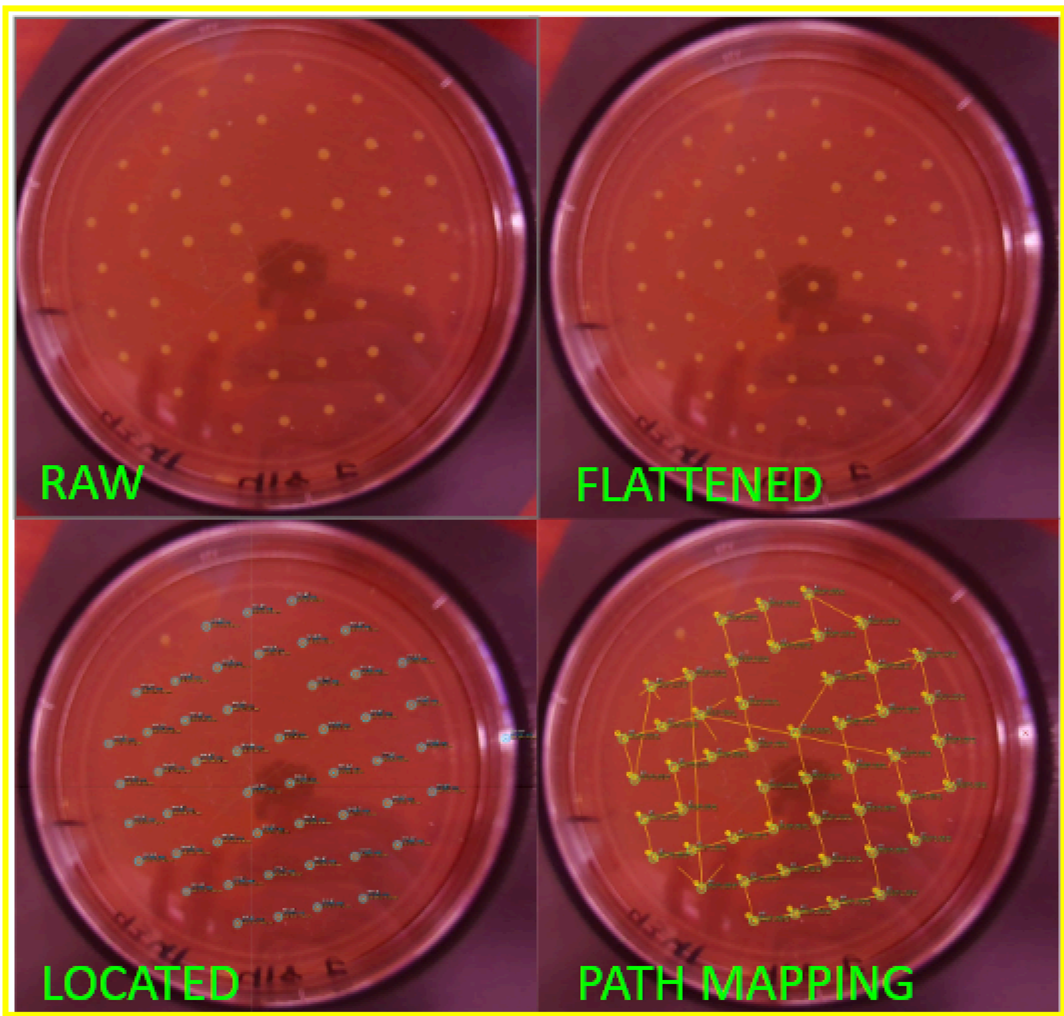

Figure D.2: Detected Colonies by Software Algorithm

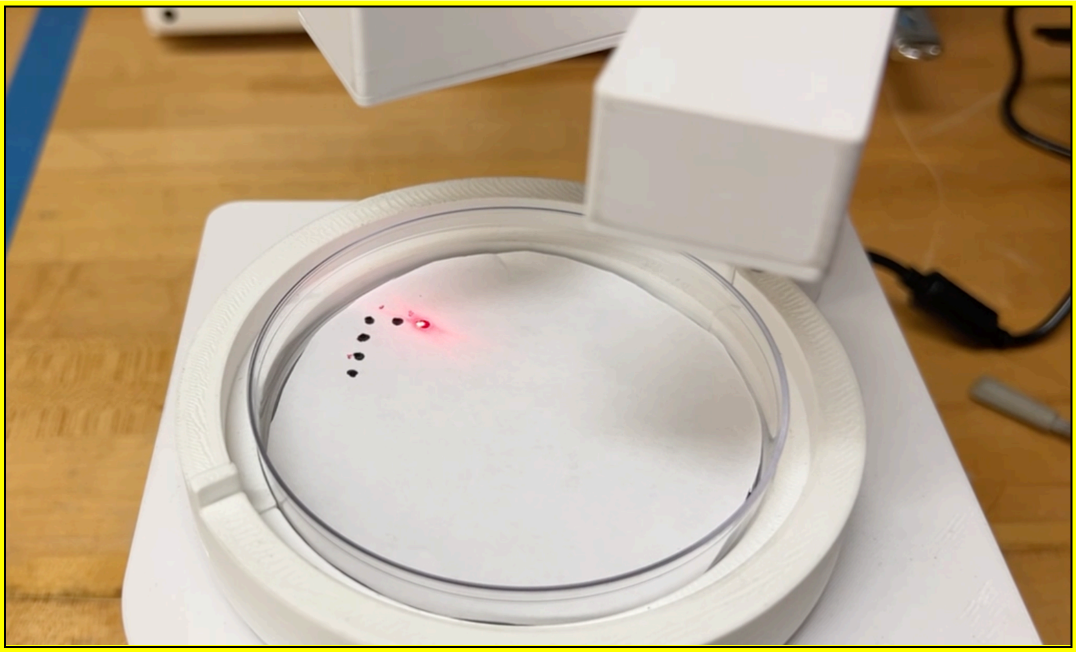

Figure D.3: Laser Alignment with Colonies

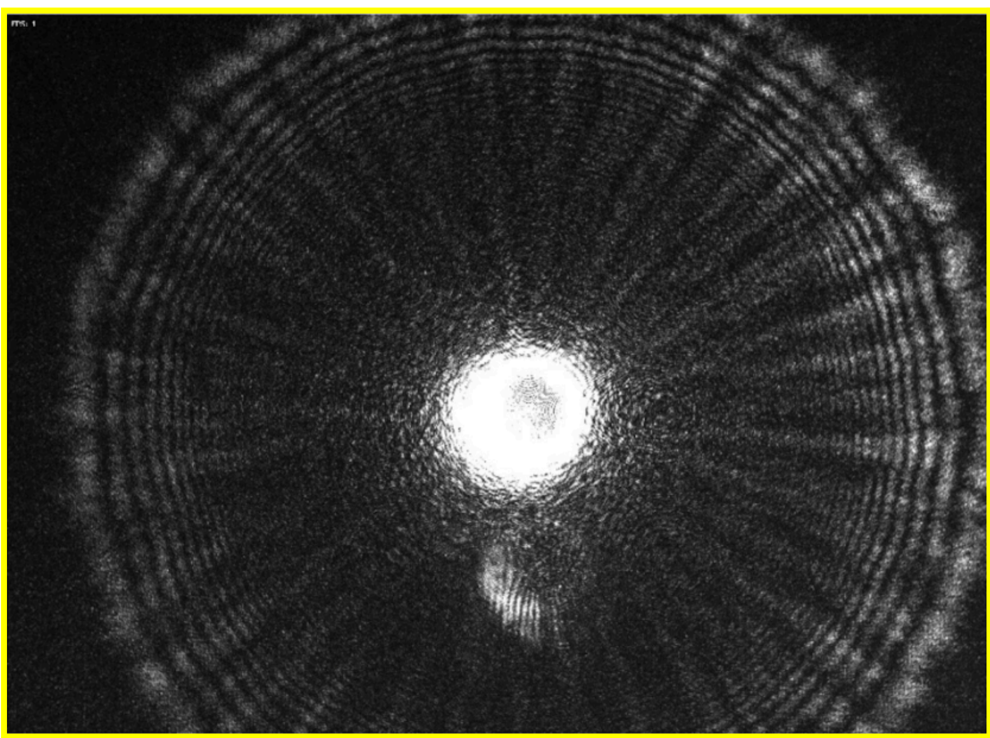

Figure D.4: ELS Pattern of Kocuria

Appendix E: Final Mechanical Drawings & CAD

NOTE: All CAD files can be found in the Teams folder named “CAD Files” under their respective figure name. Drawings shown for parts requiring manufacturing besides 3D printing.

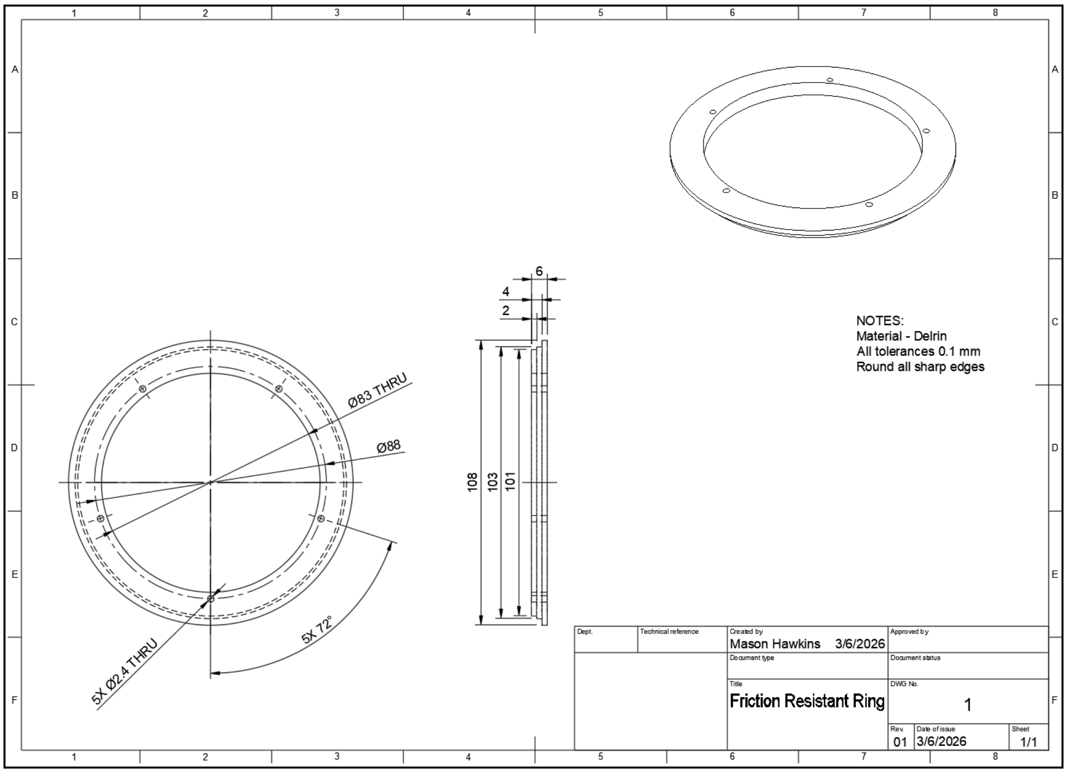

Fig. E.1: Friction Resistant Nylon Ring Drawing

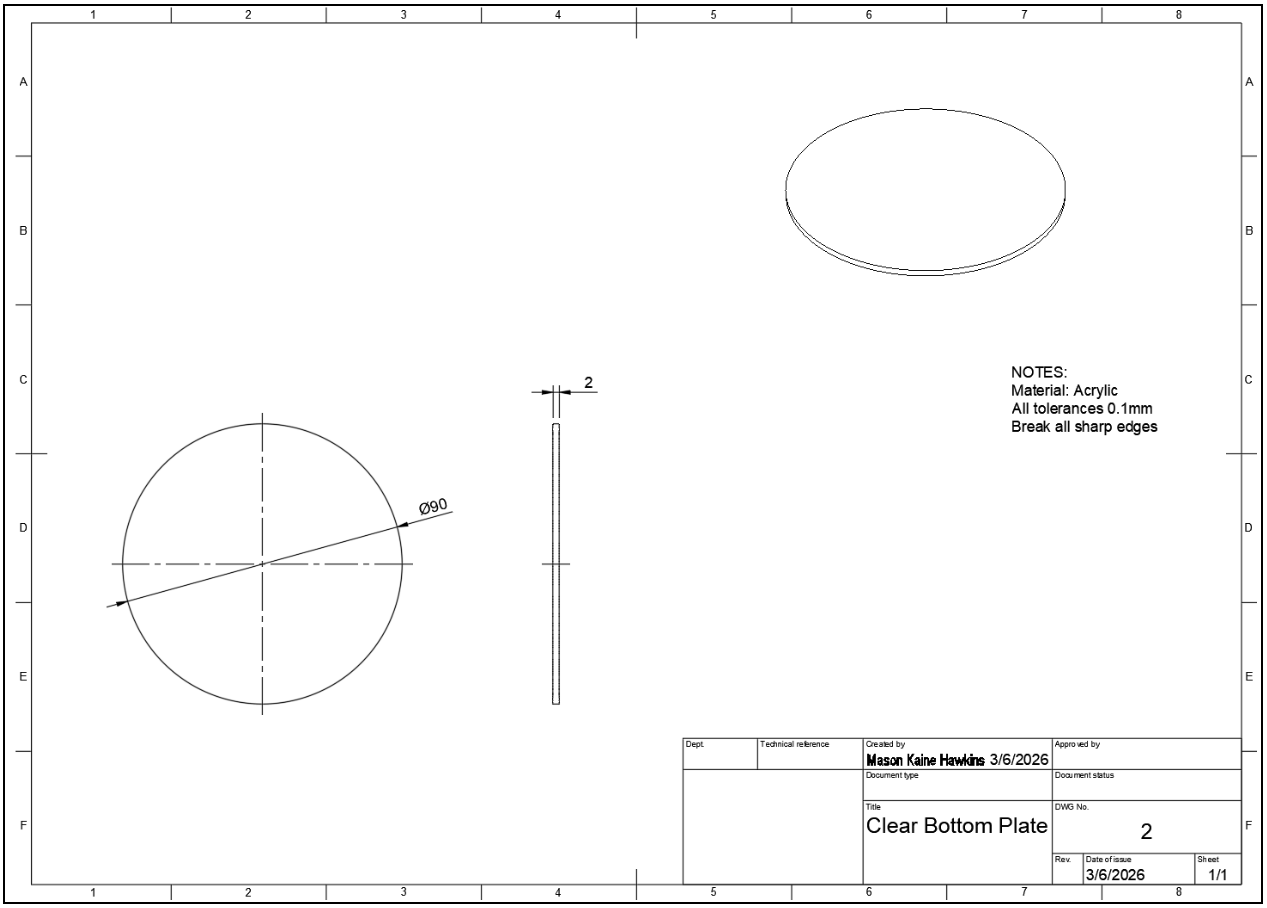

Fig. E.2: Clear Acrylic Bottom Plate Drawing

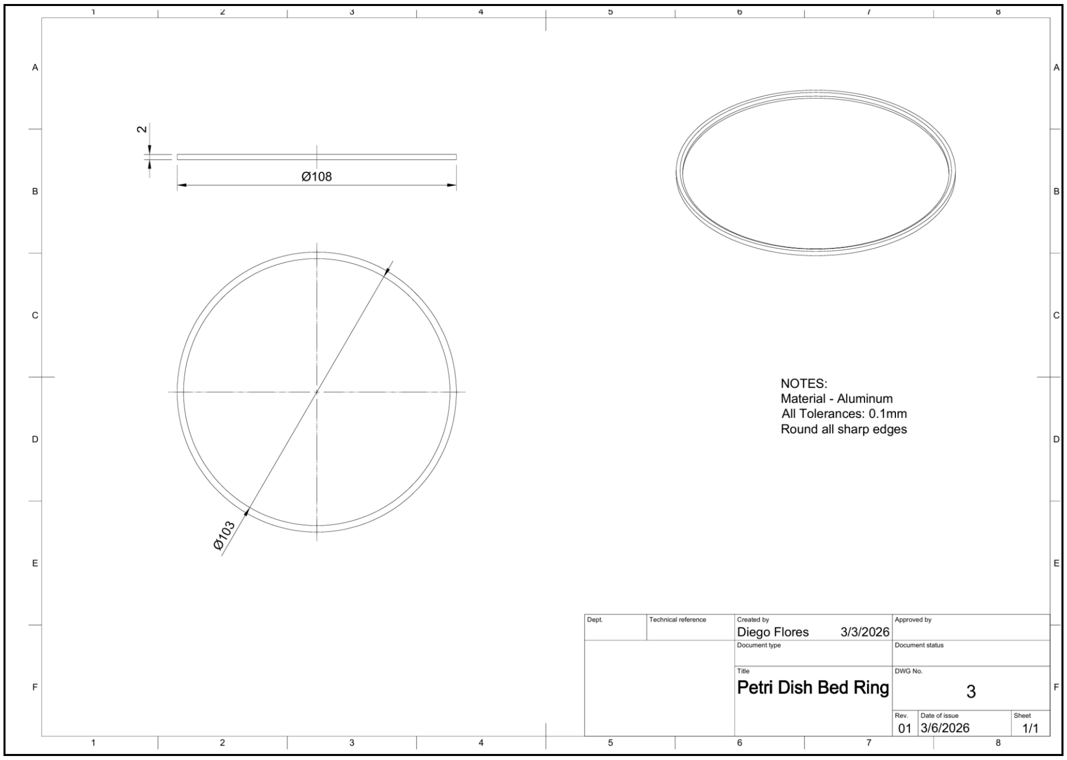

Fig. E.3: Aluminum Ring Drawing

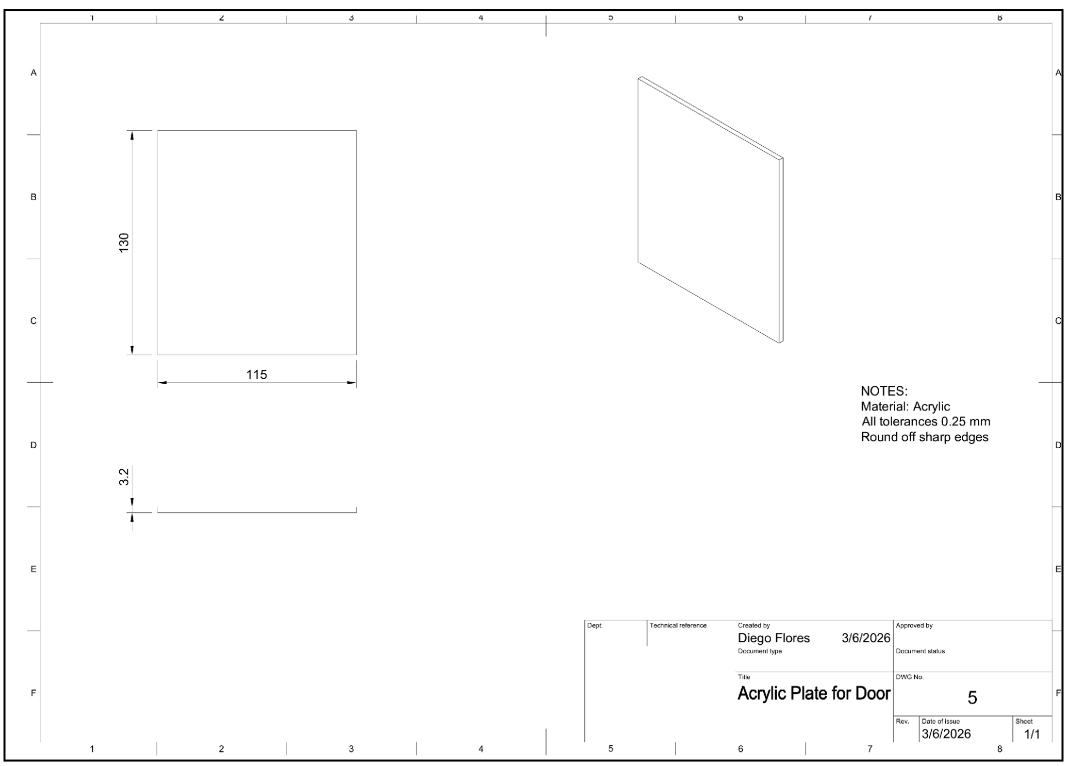

Fig. E.4: Acrylic Incubator Door Window Drawing

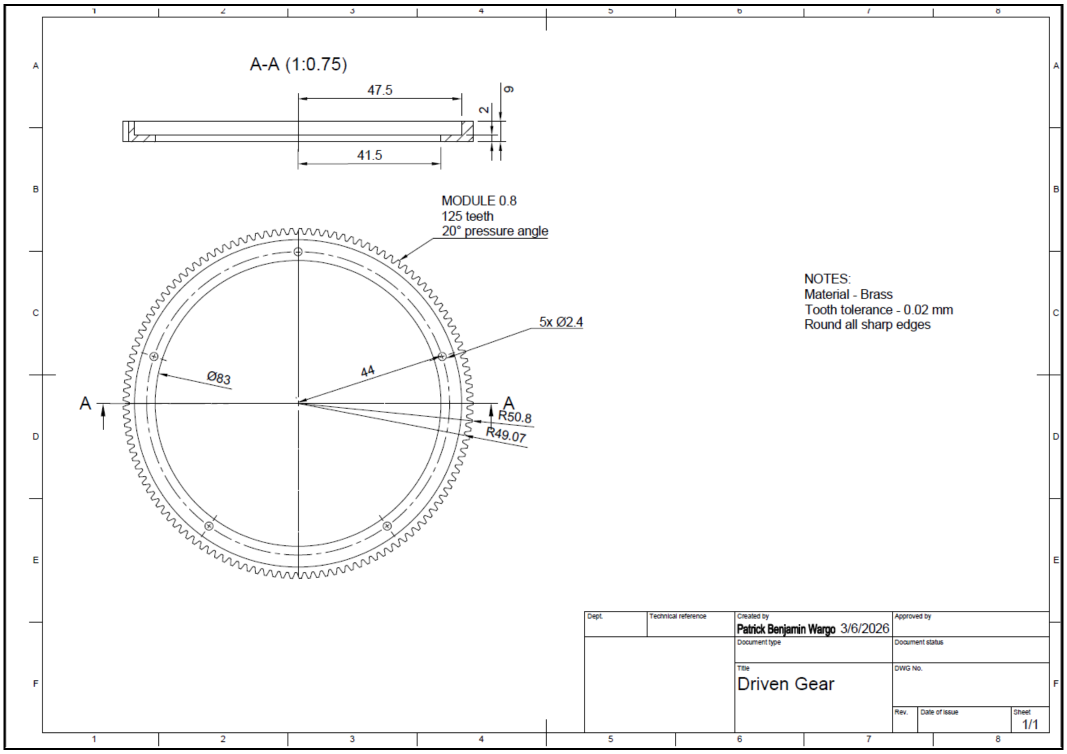

Fig. E.5: Driven Gear 2 Drawing

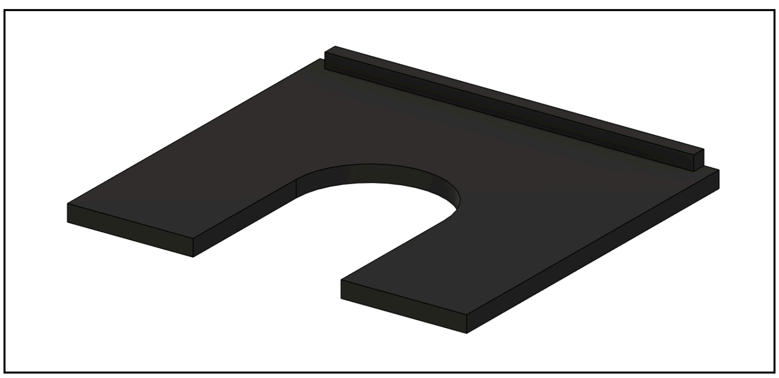

Fig. E.6: Incubator Shelves CAD

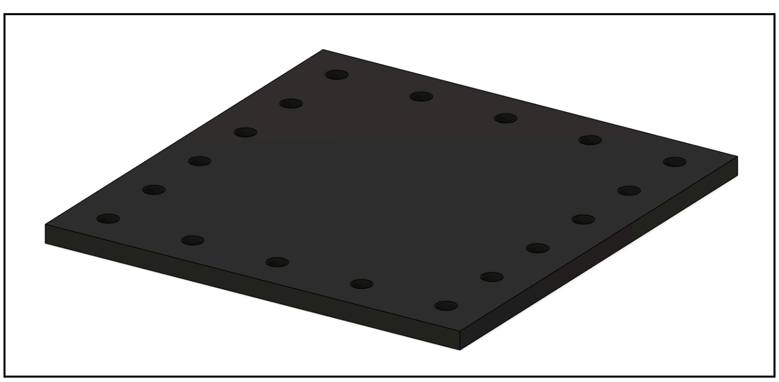

Fig. E.7: Incubator Bottom Base CAD

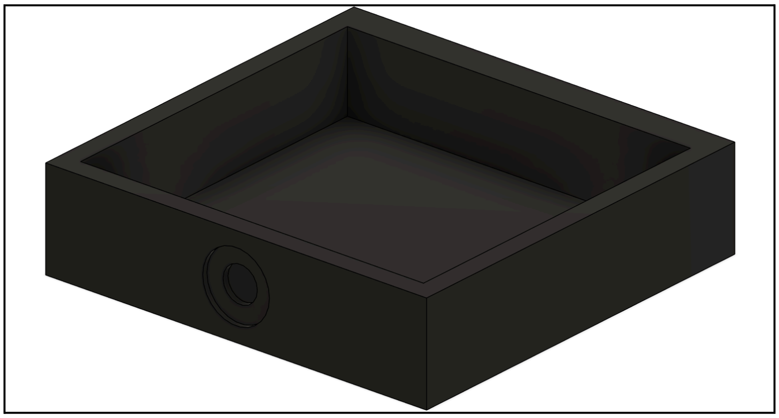

Fig. E.8: Incubator Humidity Drawer CAD

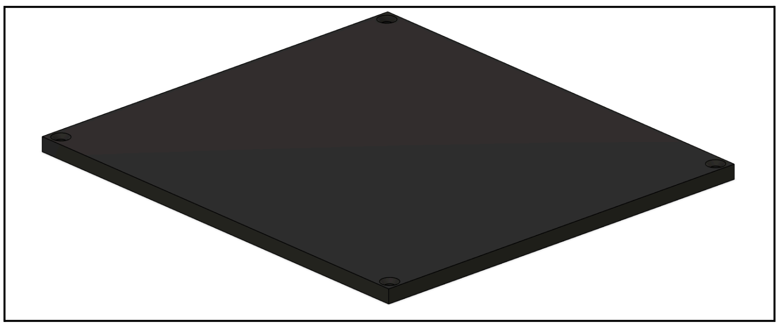

Fig. E.9: Incubator Top Lid CAD

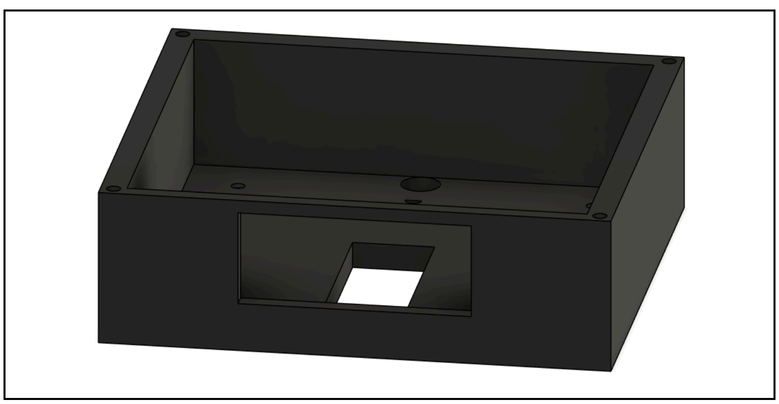

Fig. E.10: Incubator Electrical Housing CAD

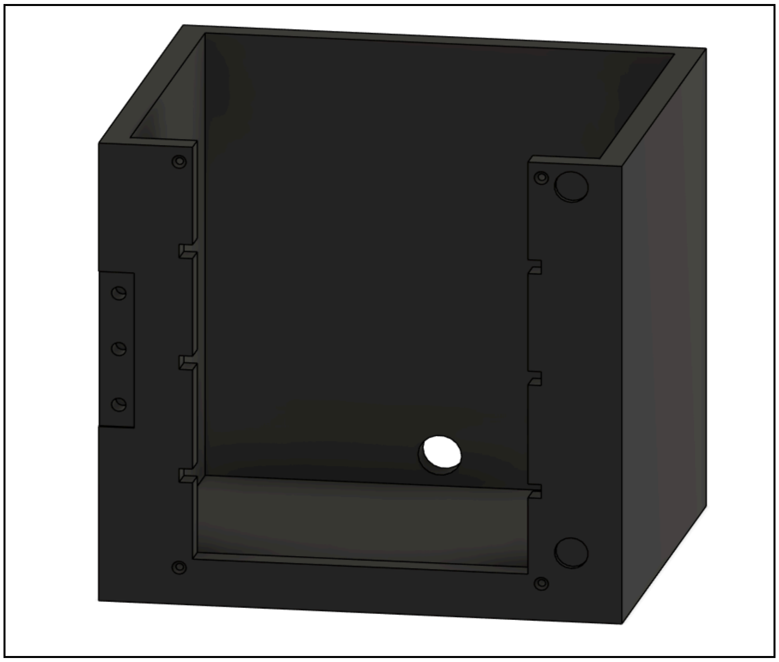

Fig. E.11: Incubator Outer Shell CAD

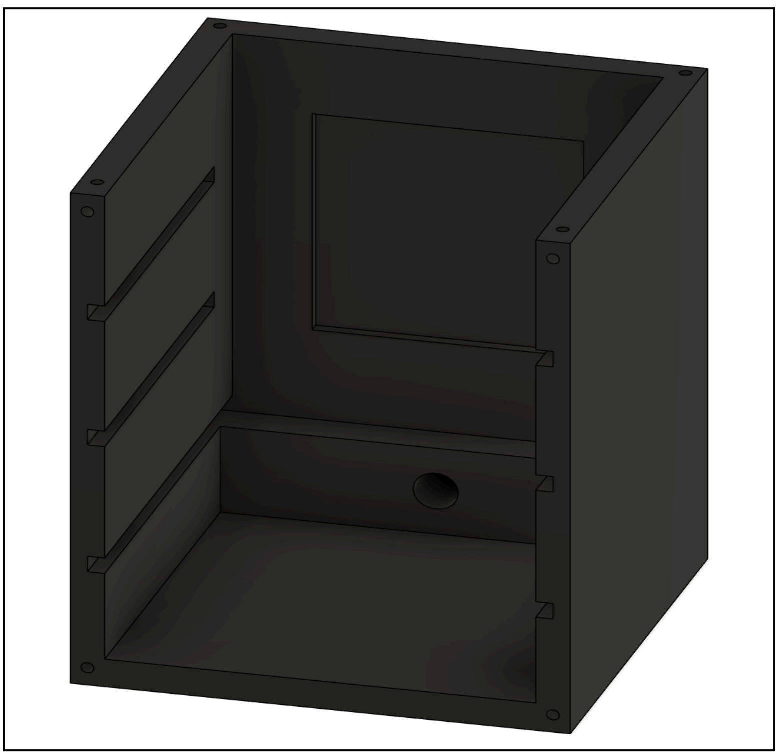

Fig. E.12: Incubator Inner Walls CAD

Fig E.13: Incubator Door Fame CAD

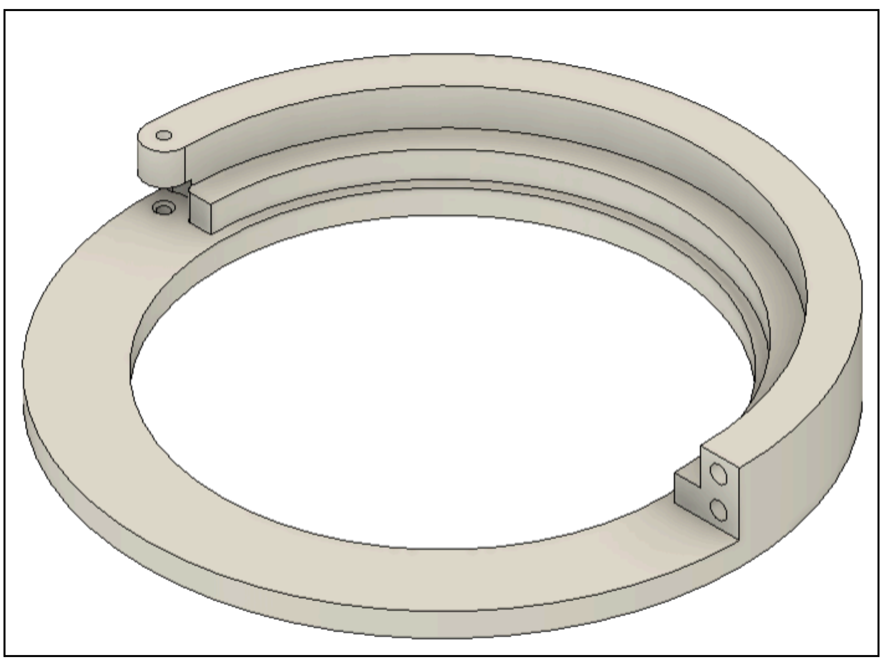

Fig. E.14: Petri Bed Base CAD

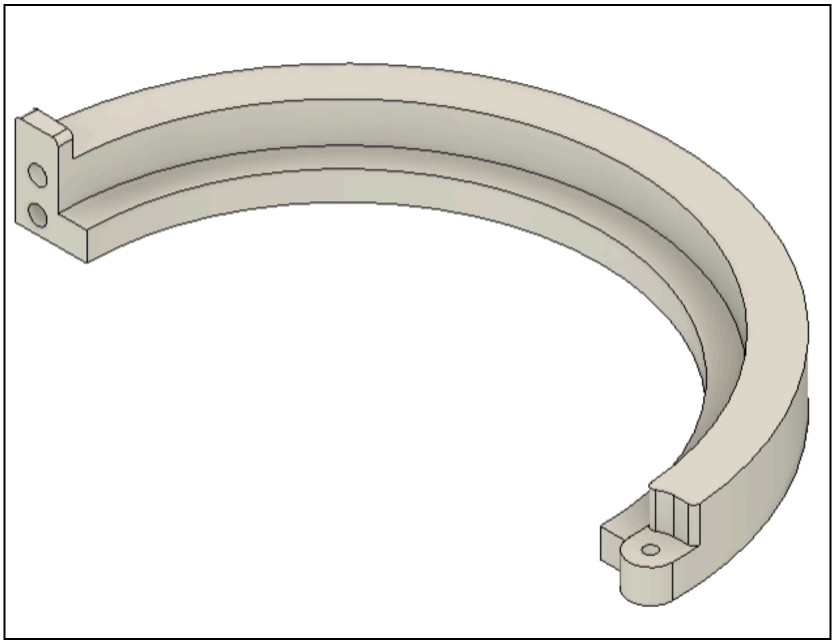

Fig. E.15: Petri Bed Gate CAD

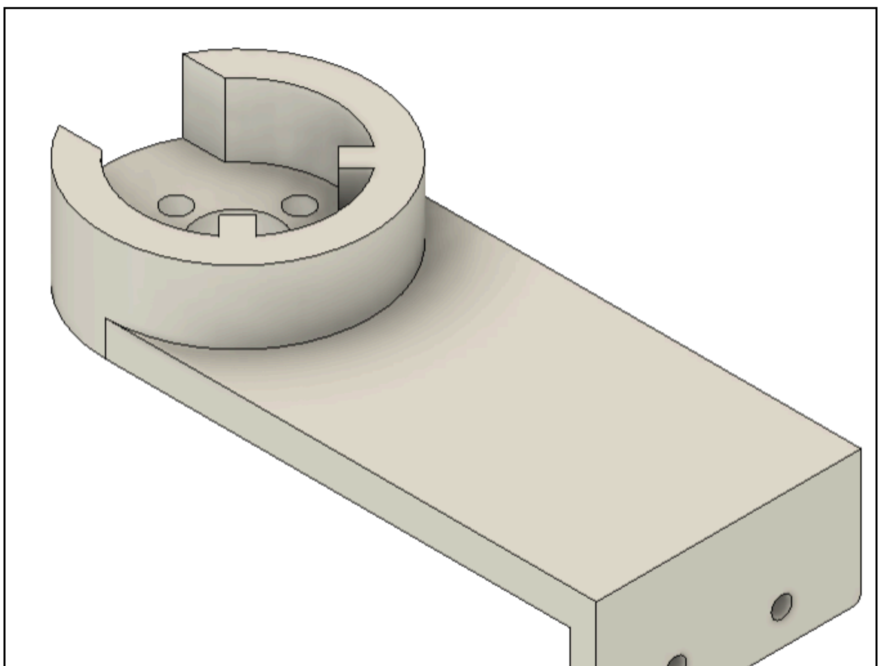

Fig. E.16: Lower Arm CAD

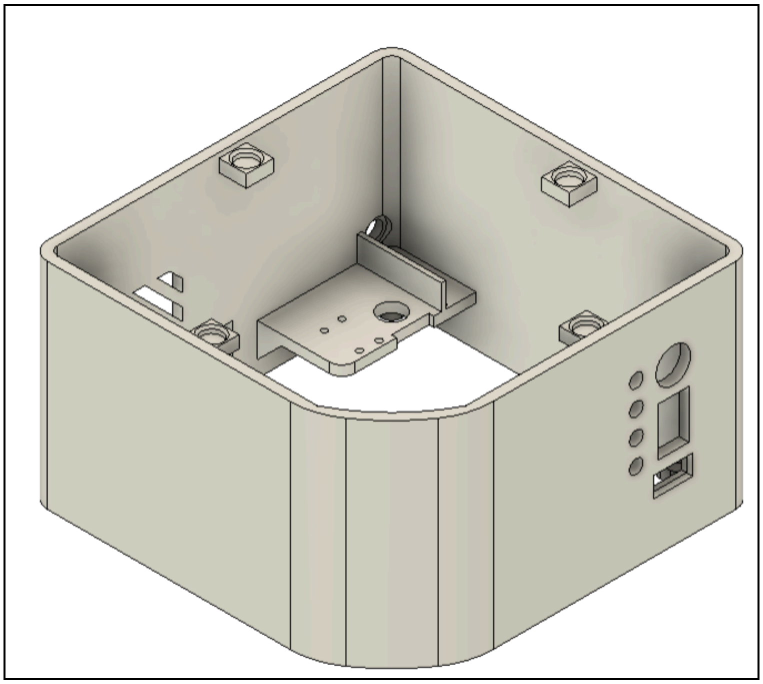

Fig. E.17: ELS Box Walls CAD

Fig. E.18: Backlight Enclosure CAD

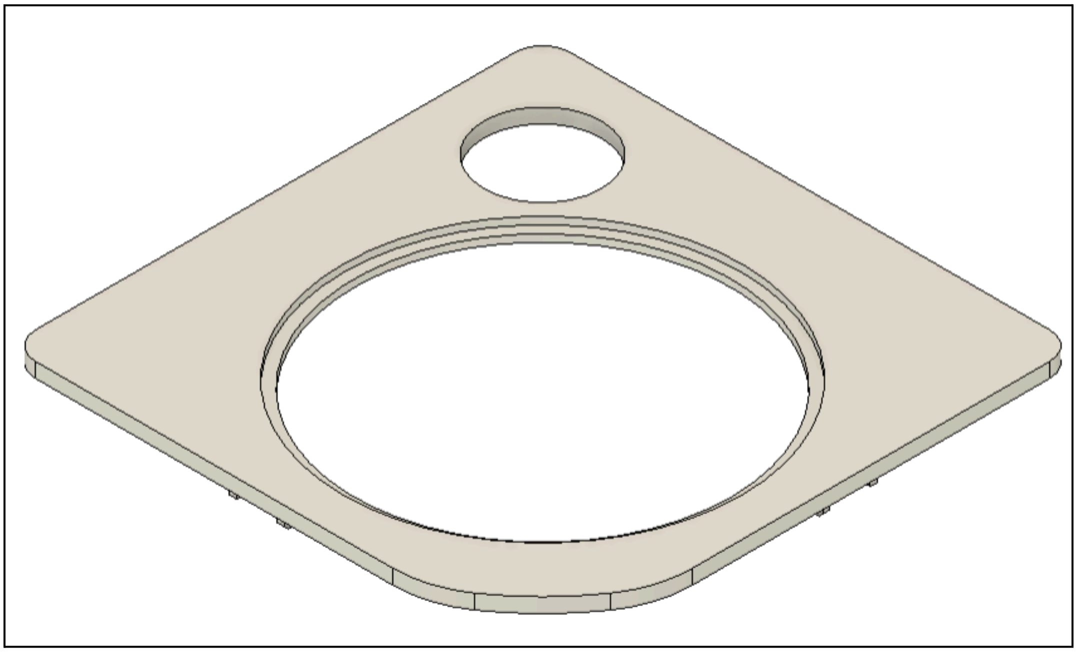

Fig. E.19: ELS Top CAD

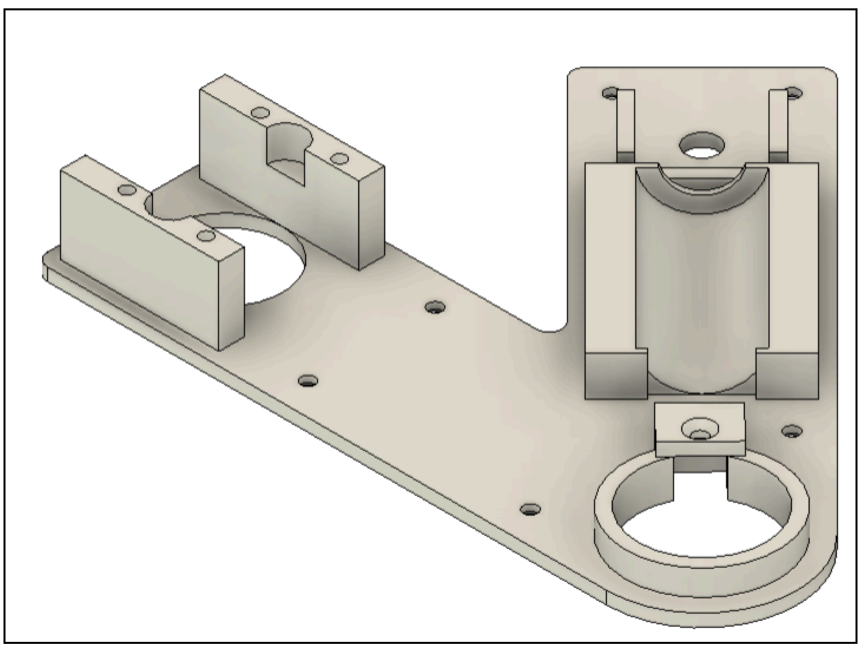

Fig. E.20: Top Arm CAD

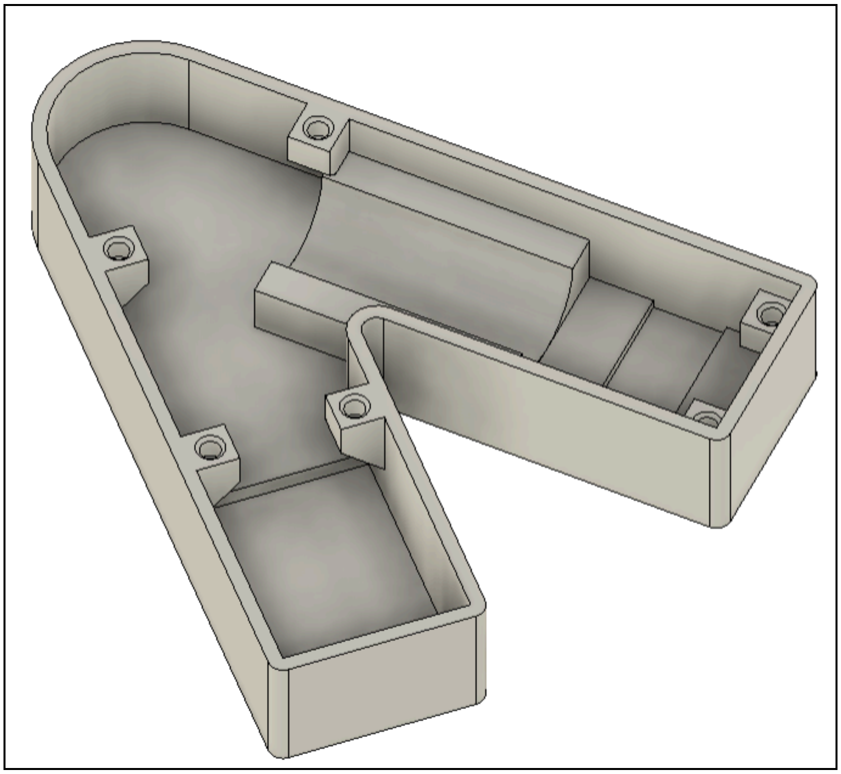

Fig. E.21: Top Arm Cap CAD

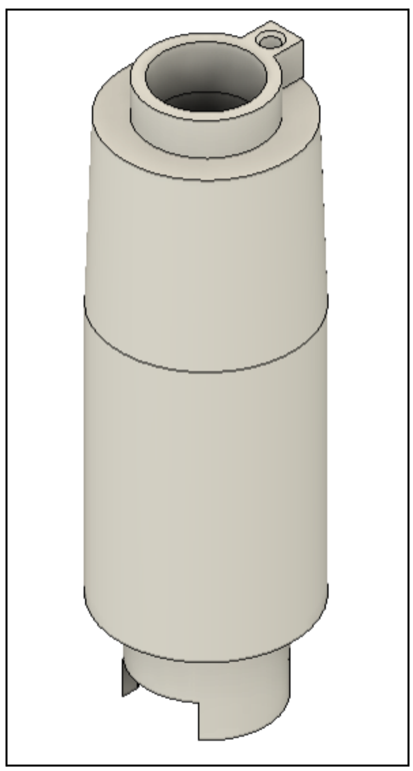

Fig. E.22: Arm Shaft CAD

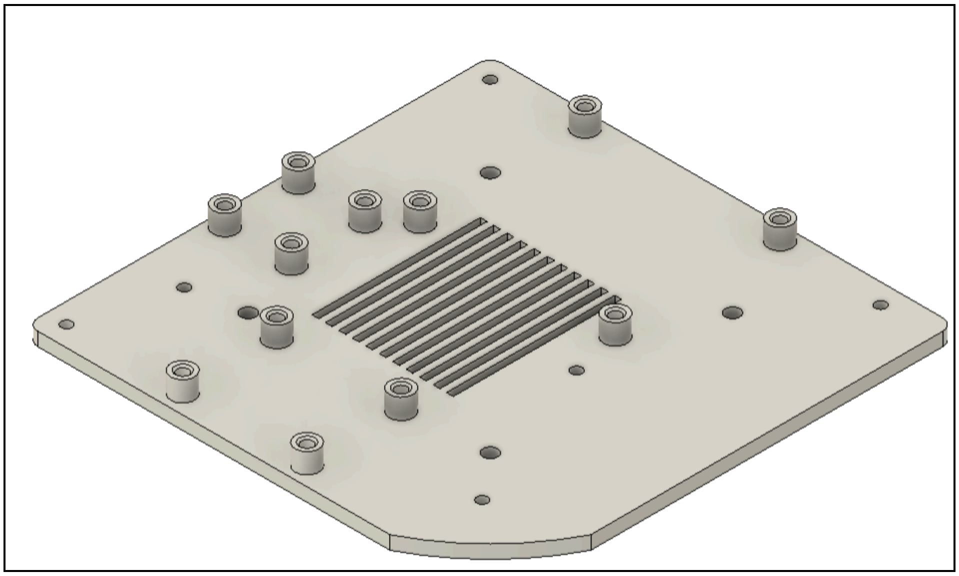

Fig. E.23: ELS Floor CAD

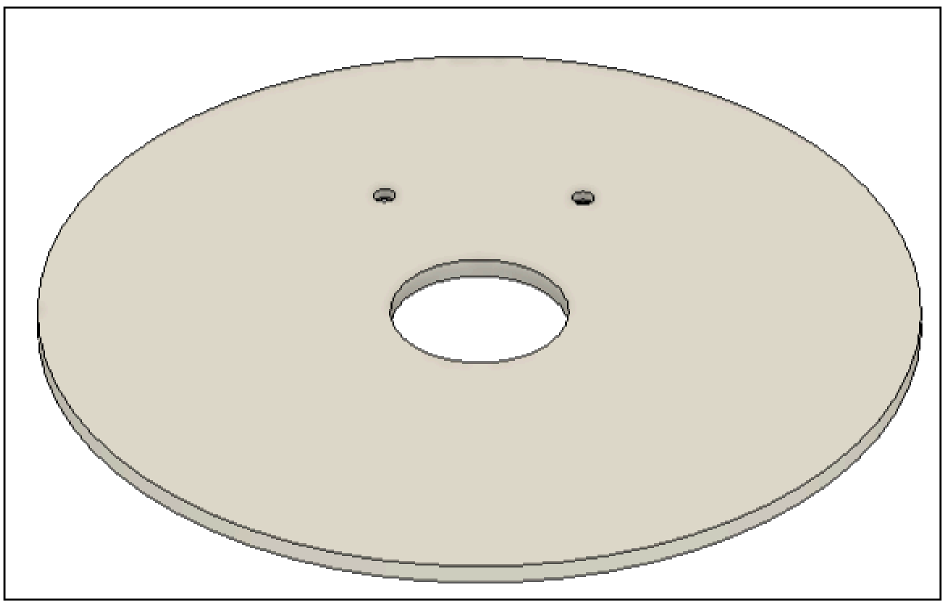

Fig. E.24: ELS Flash Guard CAD

Appendix F: Final Electrical Drawings

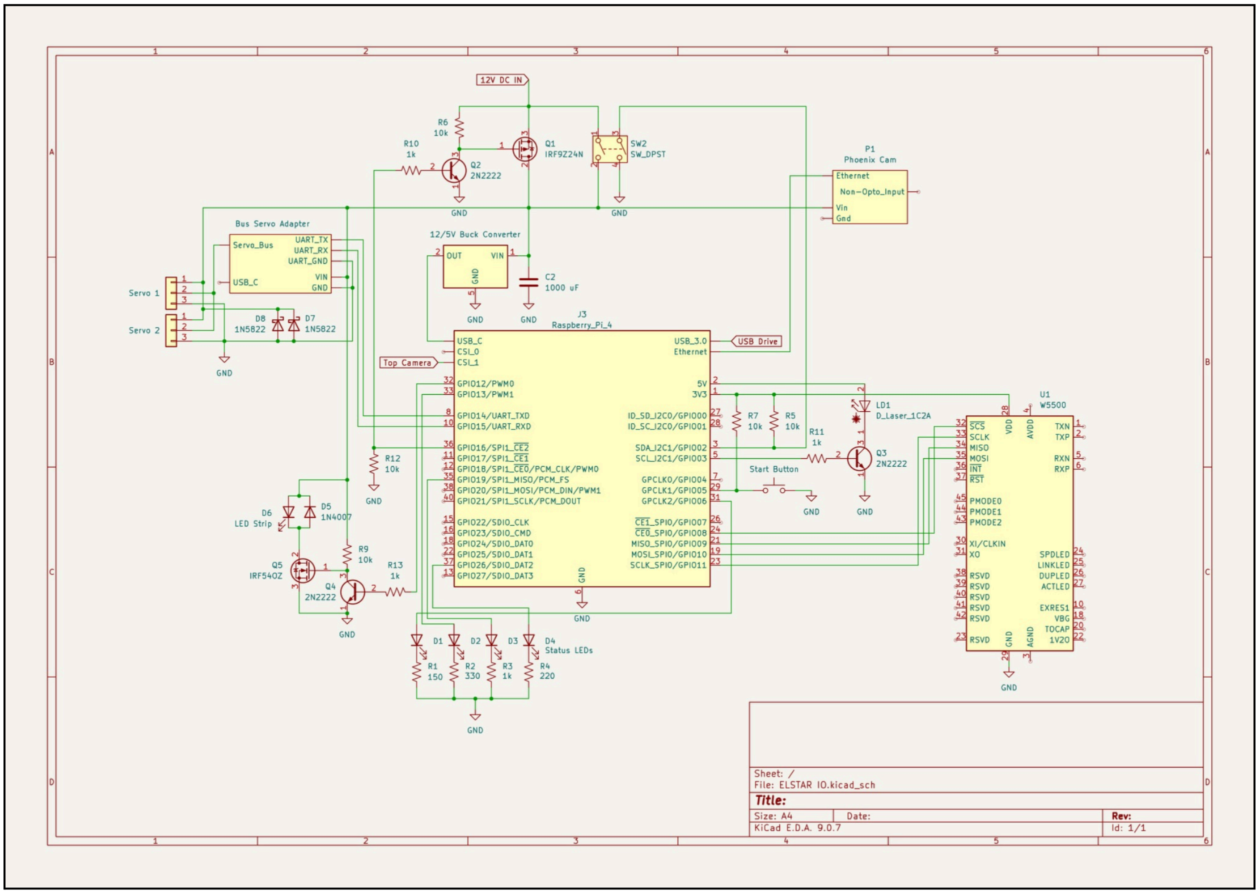

Fig. F.1: Electrical Schematic of ELSTAR2.0 System

Appendix G: Final Bill of Materials

Table G.1: ELSTAR 2.0 Bill of Materials

#	Item Name (Brief)	Description (Full Name)	Manufacturer/ Source/Vendor	Unit Cost	Quantity	Item Cost		Part Number with Link		
1	Petri bed	3D printed PETG filament	3D printed	$ -	1	$ -			Total cost:	$ 1,731.05
2	Petri bed gate	3D printed PETG filament	3D printed	$ -	1	$ -				
3	Top arm cap	3D printed PETG filament	3D printed	$ -	1	$ -				
4	Top arm casing	3D printed PETG filament	3D printed	$ -	1	$ -				
5	Arm shaft	3D printed PETG filament	3D printed	$ -	1	$ -				
6	Lower arm	3D printed PETG filament	3D printed	$ -	1	$ -				
7	Backlight enclosure	3D printed PETG filament	3D printed	$ -	1	$ -				
8	Backlight enclosure wing	3D printed PETG filament	3D printed	$ -	1	$ -				
9	Box top	3D printed PETG filament	3D printed	$ -	1	$ -				
10	Box floor	3D printed PETG filament	3D printed	$ -	1	$ -				
11	Box walls	3D printed PETG filament	3D printed	$ -	1	$ -				
12	Driven gear	3D printed PETG filament, 32 DP 20º PA 1	3D printed	$ -	1	$ -				
13	Rubber feet	3D printed TPU filament	3D printed	$ -	4	$ -				
14	Nylon ring	Low-friction nylon to support aluminum ring	3D printed	$ -	1	$ -				
15	Aluminum ring	Aluminum ring inside of the dish bed to slid	ME Machine Shop	$ -	1	$ -				
16	Diffuse material	Light-diffusive material for LED backlights	Sponsor	$ -	1	$ -				
17	microSD Card	SanDisk Ultra microSDHC UHS-I Card 16 (	ME E-Shop	$ -	1	$ -				
18	Push button	Circular momentary push-button switch	ME E-Shop	$ -	1	$ -				
19	On/off switch	DPST Rocker 2-state switch	ME E-Shop	$ -	1	$ -				
20	Protoboard	Prototyping PCB, 40 x 60mm	ME E-Shop	$ -	1	$ -				
21	Wires	22 AWG stranded core, 16 AWG stranded c	ME E-Shop	$ -	20	$ -				
22	Resistors	150Ω, 220Ω, 330Ω, 1kΩ QTY4, 10kΩ QTY	ME E-Shop	$ -	12	$ -				
23	Capacitors	1000 μF	ME E-Shop	$ -	1	$ -				
24	Transistors	IRF9Z24N, 2N2222 QTY2, IRF54OZ	ME E-Shop	$ -	4	$ -				
25	Diodes	1N5822 QTY2, 1N4007	ME E-Shop	$ -	3	$ -				
26	LEDs	5mm LED (Green, Yellow, Blue, Red)	ME E-Shop	$ -	4	$ -				
27	M2.5 screws	Electronic board mounting screws, ~4mm	ME E-Shop	$ -	12	$ -				
28	M2.5 standoffs	Electronic board brass mounting standoffs,	ME E-Shop	$ -	4	$ -				
29	Driving pinion gear	2305 Series Brass, MOD 0.8, Servo Gear (	ServoCity	$ 8.99	1	$ 8.99		SKU: 2305-0025-0012		
30	PETG filament	Black MH Build Series PETG Filament - 1.7	MatterHackers	$ 24.99	1	$ 24.99		M-3MY-2VQG		
31	Acrylic clear plate	CALPALMY (2-Pack) 12 x 12" Clear Acrylic	CALPALMY	$ 9.99	1	$ 9.99		ASIN: B081R3VCLL		
32	Magnets	76 Pack, 8 Sizes, with 1 Pickup, Mini Magn	VECTYSMAG	$ 8.62	1	$ 8.62		ASIN: B0FLPRMNFG		
33	Ball bearing	Steel Ball Bearing, Open, Trade Number R	McMaster-Carr	$ 10.89	1	$ 10.89		60355K508		
34	Heat inserts	3D Printing Brass Nuts Threaded Inserts M	ERHT	$ 19.99	1	$ 19.99		UPC: 796042423463		
35	Screws	1715Pcs M2 M3 M4 M5 Screw Kit - 3D Prir	AvrestYPT	$ 14.99	1	$ 14.99		UPC: 643241521721		
36	Prism mirror	Right Angled Triangular Prism, N-BK7 (K9)	NYJLGD	$ 9.99	1	$ 9.99		zj-th-15		
37	Laser	VLM2, 635 nm, 0.95 mW, Circular Beam, M	Coherent	$ 299.00	1	$ 299.00		VLM2		
38	Bottom CMOS sensor	Lucid Vision Labs Phoenix™ PHX124S-MC	Lucid Vision Labs	$ 870.00	1	$ 870.00		PHX124S-MC		
39	Top Camera	Arducam for Raspberry Pi HQ Camera, 12.	Arducam	$ 45.99	1	$ 45.99		477M		
40	Camera FPC cable	[400mm 22 pin cable] uxcell 5pcs FFC Flex	uxcell	$ 6.69	1	$ 6.69		ASIN: B0FKBQPPT8		
41	Camera GPIO cable	GPIO 8-pin 20cm JST Cable	Lucid Vision Labs	$ 3.00	1	$ 3.00		GPIO-8P20		
42	Raspberry Pi	Raspberry Pi 5 - 8 GB RAM	Canakit	$ 125.00	1	$ 125.00		PI5-8GB		
43	USB F-to-M coupler	USB 3.0 Type A Adapter Superspeed 5Gbp	ZJKJHJY	$ 8.99	1	$ 8.99		ASIN: B0F58WCDSJ		
44	Ethernet cable	Monoprice Cat6 Ethernet Patch Cable - Sn	Monoprice	$ 4.48	1	$ 4.48		134211		
45	Ethernet breakout board	Adafruit Wiz5500 Ethernet Co-Processor B	Adafruit	$ 19.95	1	$ 19.95		6348		
46	LED strip	SUYOOULIN LED Strip Lights, SMD 2835	SUYOOULIN	$ 15.99	1	$ 15.99		LS-001-CW		
47	Serial bus servo driver	Serial Bus Servo Driver Board, Integrates S	Waveshare	$ 10.55	1	$ 10.55		Wonrabai Servo Driver Board		
48	Servo motors	Waveshare 40kg.cm Metal Serial Bus Serv	Waveshare	$ 94.99	2	$ 189.98		ST3025_Servo		
49	12V DC power supply	ALITOVE DC 12V 5A Power Supply Adapte	ALITOVE	$ 12.99	1	$ 12.99		ALT-1205		
50	Buck converter	DC 12V/24V to 5V USB C Step Down Conv	Klnuoxj	$ 9.99	1	$ 9.99		524672e6-32ee-468d-8300-a4608828a4ba		

Table G.2: Incubator System Bill of Materials

#	Item Name (Brief)	Description (Full Name)	Manufacturer/ Source/Vendor	Unit Cost	Quantity	Item Cost		Part Number with Link		
1	Outer walls	3D printed PETG filament	3D printed	$ -	1	$ -			Sum cost:	$ 103.77
2	Inner walls	3D printed PETG filament	3D printed	$ -	1	$ -			Reused ELSTAR materials	$ -53.96
3	Top lid	3D printed PETG filament	3D printed	$ -	1	$ -			Final incubator material cost	$ 49.81
4	Electronics housing	3D printed PETG filament	3D printed	$ -	1	$ -				
5	Shelves	3D printed PETG filament	3D printed	$ -	2	$ -				
6	Bottom shelf	3D printed PETG filament	3D printed	$ -	1	$ -				
7	Humidity drawer	3D printed PETG filament	3D printed	$ -	1	$ -				
8	Bottom base	3D printed PETG filament	3D printed	$ -	1	$ -				
9	Door frame	3D printed PETG filament	3D printed	$ -	1	$ -				
10	Door front	3D printed PETG filament	3D printed	$ -	1	$ -				
11	Rubber feet	3D printed TPU filament	3D printed	$ -	4	$ -				
12	Wires	22 AWG stranded core	ME E-Shop	$ -	10	$ -				
13	Door hinge	Surface-Mount Hinge with Holes Brass, No	McMaster-Carr	$ 3.24	1	$ 3.24		1603A7		
14	Magnetic latch	Push-to-Open Magnetic Latch Press Fit Mc	McMaster-Carr	$ 3.64	1	$ 3.64		15735A66		
15	Foam insulation	MEARCOOH Premium EVA Foam Sheet,3ı	MEARCOOH	$ 9.96	1	$ 9.96		ASIN: B0B53D7X5R		
16	Acrylic clear window	CALPALMY (2-Pack) 12 x 12" Clear Acrylic	CALPALMY	$ 9.99	1	$ 9.99	X	ASIN: B081R3VCLL	Reused materials	
17	Magnets	76 Pack, 8 sizes, With 1 Pickup, Mini Magn	VECTYSMAG	$ 8.99	1	$ 8.99	X	B0FLPRMNFG	Reused materials	
18	Screws	1715Pcs M2 M3 M4 M5 Screw Kit - 3D Prir	AvrestYPT	$ 14.99	1	$ 14.99	X	UPC: 643241521721	Reused materials	
19	Heat inserts	3D Printing Brass Nuts Threaded Inserts M	ERHT	$ 19.99	1	$ 19.99	X	UPC: 796042423463	Reused materials	
20	Heating pad	MECCANIXITY Silicone Heating Pad, 12V	MECCANIXITY	$ 8.99	1	$ 8.99		mea230826ee000138		
21	Temperature controller	STC-3028 Temperature Controller 12V Ten	SHUTAO	$ 13.99	1	$ 13.99		UPC:687117717115		
22	12V DC power supply	ALITOVE 12V DC Power Supply 3A 36W L	ALITOVE	$ 9.99	1	$ 9.99		AL12V3A		

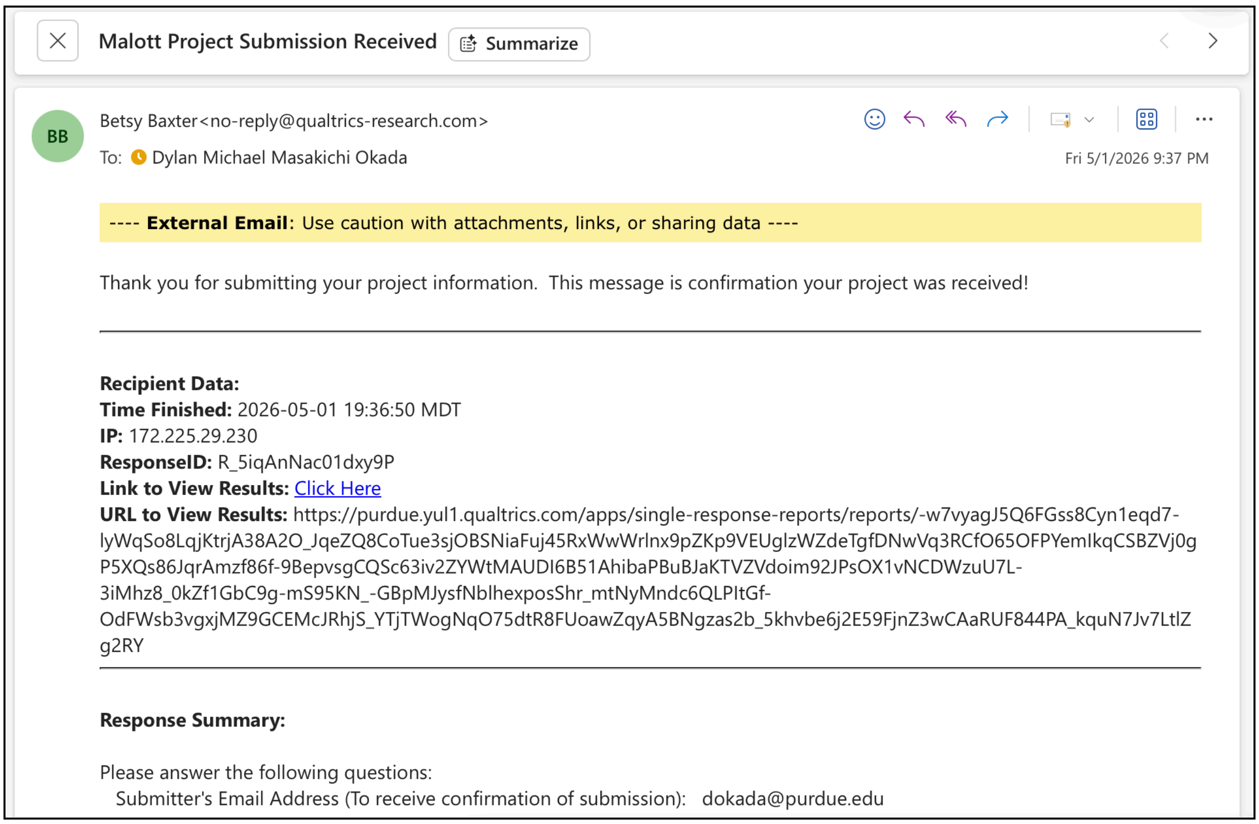

Figure G.1: Acknowledgement Email of Total Project Cost Survey