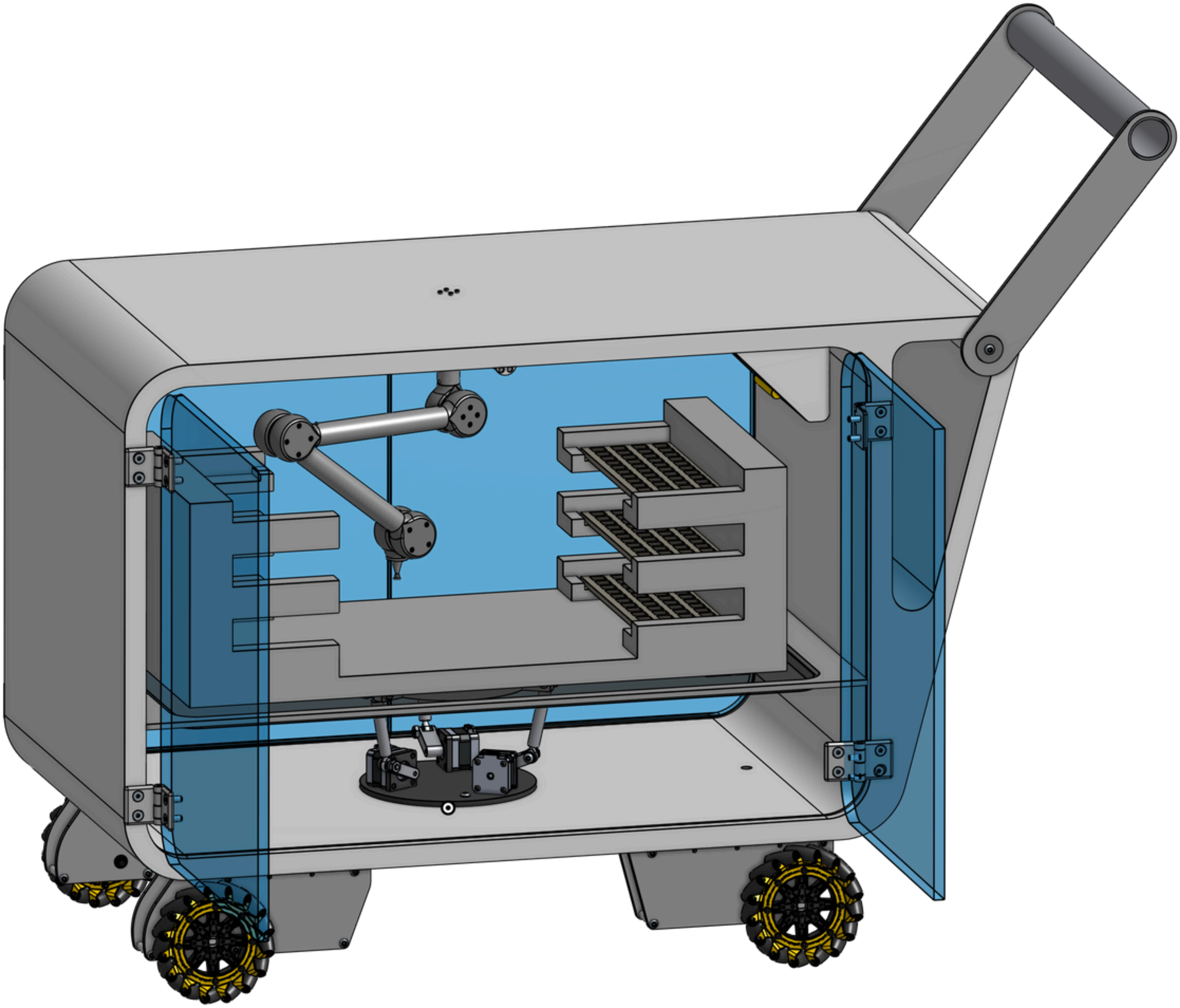
C.A.R.E.

Cleanroom Automated Robot Entity



Group 3: Ivan Kuang, Justin Kim, Oliver Chang

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Challenge Overview

Challenge

Design a scalable material handling solution for semiconductor fabrication environments.

Design Criteria

- Load Capacity: Should accommodate loads ranging from 5 to 50 pounds.
- Precision Handling: Must minimize vibrations and static discharge.
- Size & Maneuverability: Should fit within cleanroom aisles and workstations, adhering to typical ISO Class 1-5 cleanroom space constraints.
- Material Compatibility: Must use materials that do not generate particles or contribute to contamination.
- Safety: Should prevent accidental dropping, misalignment, or contamination of wafers and other sensitive components.
- Ease of Use: Must be operable with minimal training and avoid adding extra complexity to fab operations.
- Speed & Efficiency: Should be faster and more reliable than manual handling without increasing risk to semiconductor materials.

Introduction of Product:

- The overall product is a self maneuvering autonomous vehicle which is capable of traversing a mapped environment, specifically a cleanroom that adheres to typical ISO Class 1-5 space constraints
- It is capable of handling semiconductors and transporting it through our robotic arm which eliminates the need for human intervention while minimizing vibrations and static discharge through an insulator
- Auto stabilizer which balances out and maintains parallel to the horizontal component of any surface level or slant.
- Offers a closed and contained space that prevents unwanted particles from interacting with what is being transported.
- Capable of upholding up to 50 LBs of components.

Design Analysis

Self-Set Design Requirements

Upon understanding the design challenge, we set design requirements we wanted that would accomplish:

Maneuverability:

- Our solution must both be manually and autonomously driven to ensure ease of human-use along with precision and consistency.
- Must be able to strafe to navigate the cleanroom with less movement.
- Must drive smooth to minimize vibrations.
- Must have a low center of gravity to minimize the chance of tipping.
- Must be made of parts sufficiently clean and lack of particles generated to adhere to ISO Class 1-5 cleanroom space constraints.

Sensitive Material Containment

- Must be capable of storing sensitive materials in an enclosed sterile space to minimize contamination.
- The surface the materials rest on must stay level and flat to prevent material slippage and damage.
- Must be able to hold 5 to 50 pounds of sensitive materials.

Sensitive Material Handling

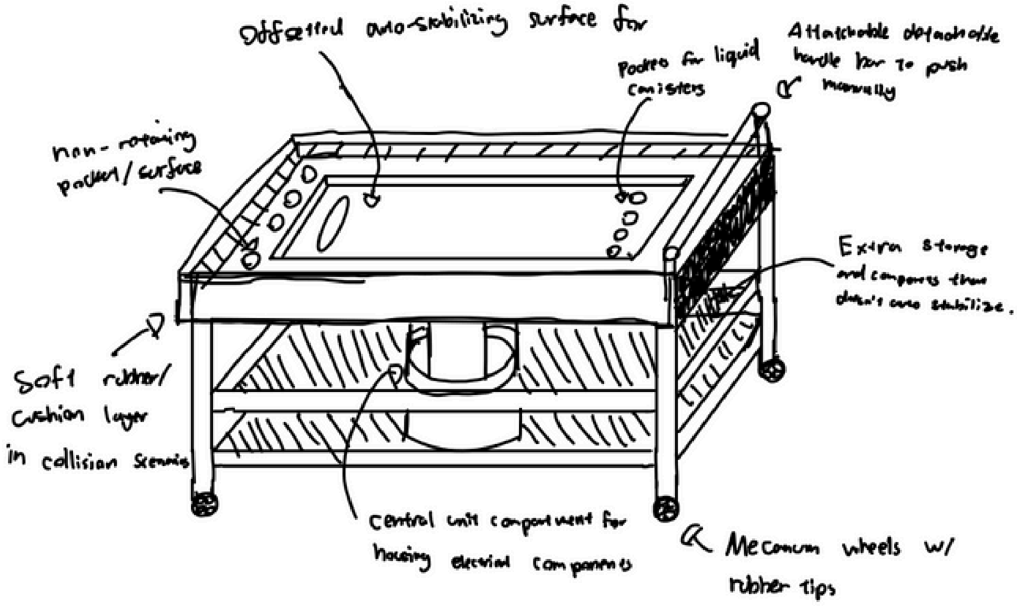
- Sensitive materials must be capable of being picked up and placed within the enclosed sterile space.
- Sensitive materials must be capable of being picked up and placed from an outside workstation to the sterile space, and vice versa.
- Handling the materials must be automated to maintain precision, speed, and consistency.

To satisfy all three categories of our requirements, we developed three main subsystems: the Cart, the Stabilizer, and the Robotic Arm.

Brainstorming

Initial Prototype

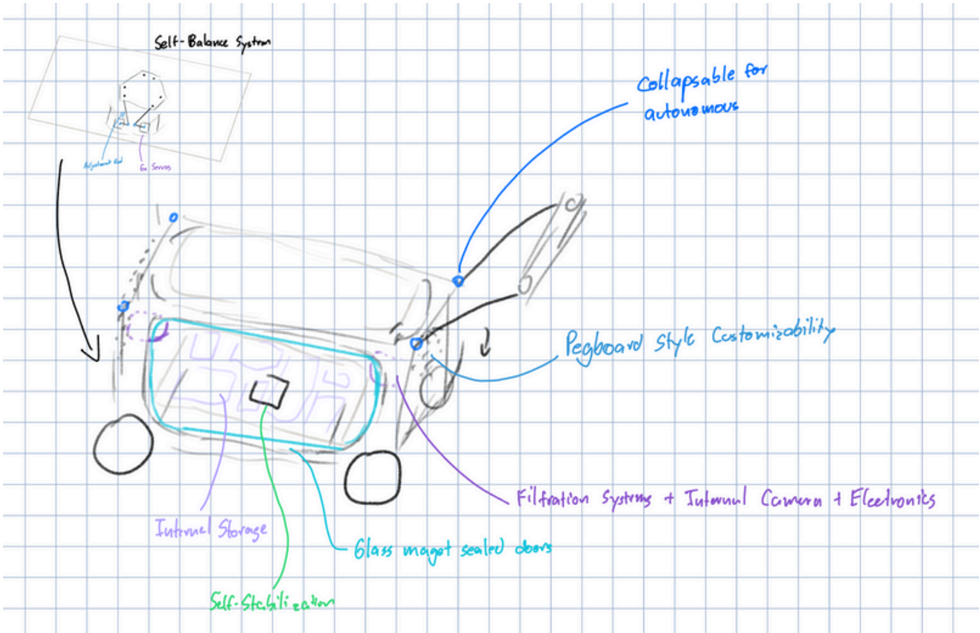
Our initial design considered an exposed surface cart with an internal auto-stabilizing table.



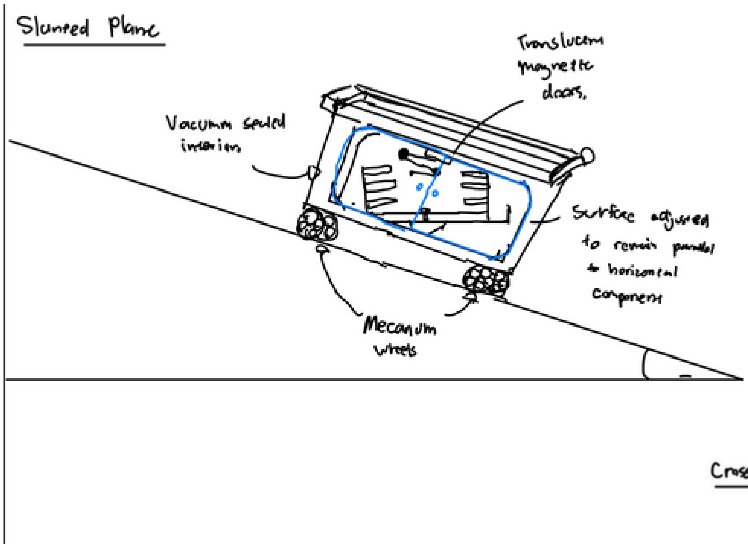
Issues with this design

- Exposed and unprotected electrical components, thus potentially allowing debris and other substances from interacting with semiconductors.
- Requires some form of human intervention to push around.
- No way to store electrical components for the automations needed for self stabilizer and cameras
- Manually operated, thus vulnerable to human contamination.

Revised Prototype

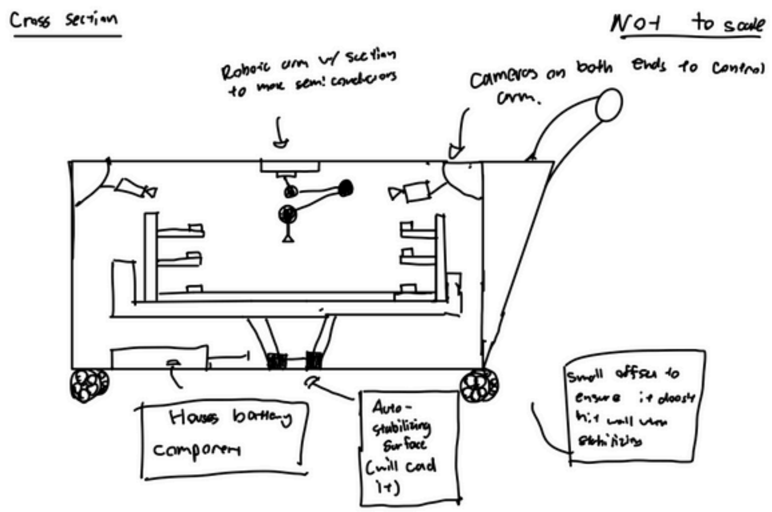


Brainstorming



View of Vehicle in a Slanted Plane

The Cross Section of our Vehicle



Key Highlights of Revised Plan

- We kept the auto-stabilizing plate, and also attached a shelf along with trays that can hold semi conductors on top of it.
- Introduced a robotic arm alongside cameras that can self navigate and move semiconductors inside sealed environment.
    - The arm utilizes suction to move around the semiconductor chips
- Implemented an electrical box compartment that houses all the batteries and necessities which allows the cart to move by itself.
- Placed tray holders on top of the self-stabilizing plate to hold more items.

Mechanical Design Process

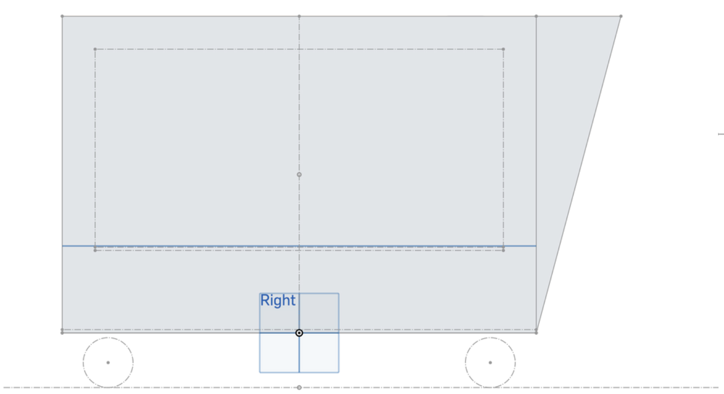
While the CADathon is over just 12 short hours, we made it a priority to supplement our design process with as much of the iterative process as possible.

Software Used:

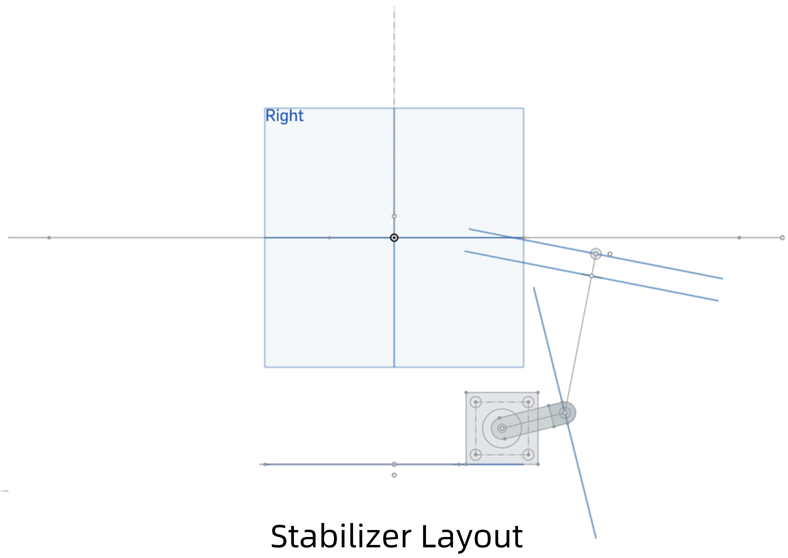
- Notability for digital sketching and brainstorming to communicate ideas
- Onshape for cross-team collaboration and accessibility across cloud
- Solidworks for visualization renders & simulations

The Process:

- 2D: layout drawings enable us to translate our brainstorming sketches into Onshape, confirm design geometry, check for interference between mechanisms, and calculate all motor placement. This is a key part of communication, as it creates space allocations for subsystems, ensuring that integration is possible.
- 3D: 3D Modeling Parts within Onshapes Parts Studio and creating assemblies brings out designs to life.
- Feedback: Midway through the CADathon, we were able to get valuable feedback from senior MechE students, who gave insights into the practical of our design as well as areas of improvements.
- Re-Designs: Utilizing the feedback, we incorporated their suggestions about increasing the sterilization as well as material selection into our CAD and justifications



Cart Layout



Stabilizer Layout

Cart

Requirements:

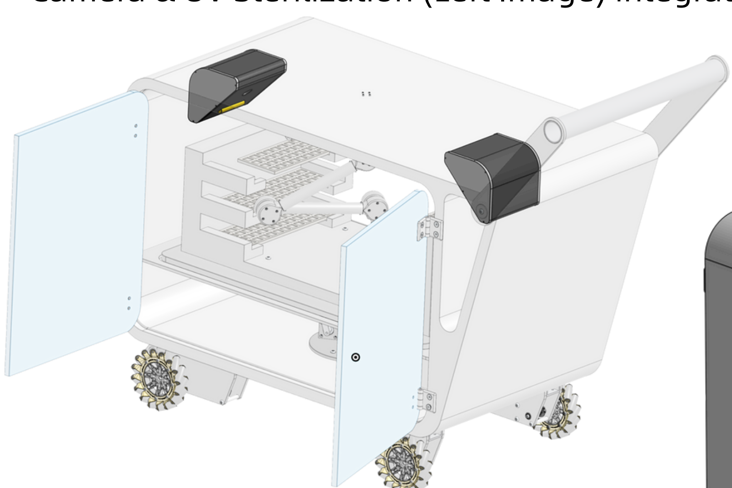
- Enclosed and properly sealed space that minimizes or fully eliminates any form of possible contamination
- Door or access way that connects the inside of the car to the outside world yet also create an enclosed sterile space
- Capable of upholding
- Manual handling bar option in the event of autonomous failure
- Cart size adhere to ISO Class 1-5 cleanroom space constraints
- Wheels offer multiple axis of translation for the autonomous vehicles

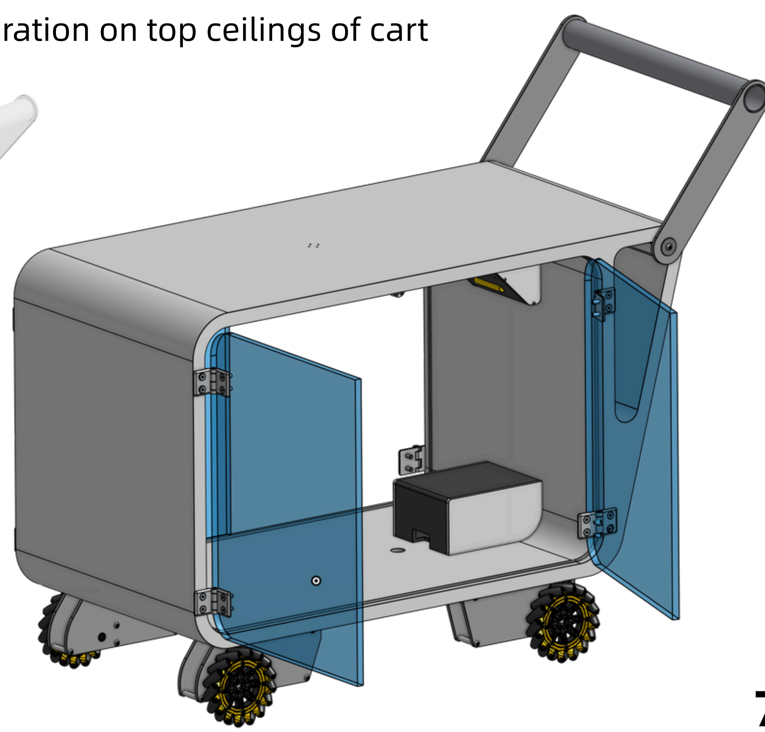
Inspiration:

- Cart exterior inspiration drawn from a standard industrial supermarket push cart.
- Rubber sealed doors that mitigates particle leakage from outside
- Mecanum wheel forklifts inside warehouse

Design Highlights:

- A cart of dimension 30" by 18" by 30" (excluding the handle)
- Polycarbonate magnetic sealed doors with rubber outlines around the door to prevent any leakage that could contaminate the sterile environment inside
- An attachable and detachable handle bar that allows manual handling of the cart around the factory
- Mecanum wheels which allows movement in any direction.
- A dedicated section to housing electrical components which powers cameras for our attachable robotic arm and our cart's autonomous drive.
- Holes (not exposed whole way through) to allow for attachment and detachment.
- Camera & UV Sterilization (Left Image) integration on top ceilings of cart



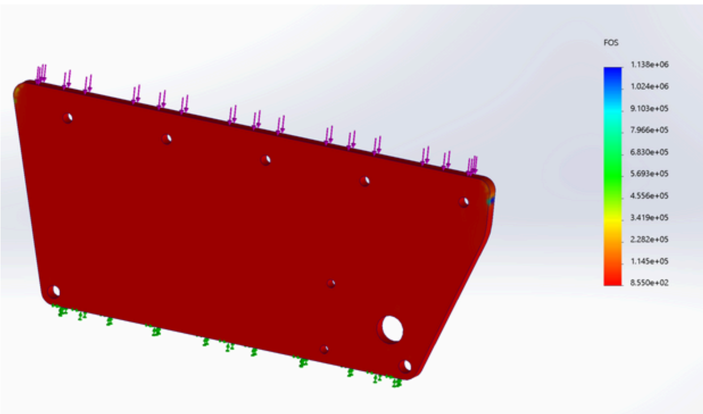


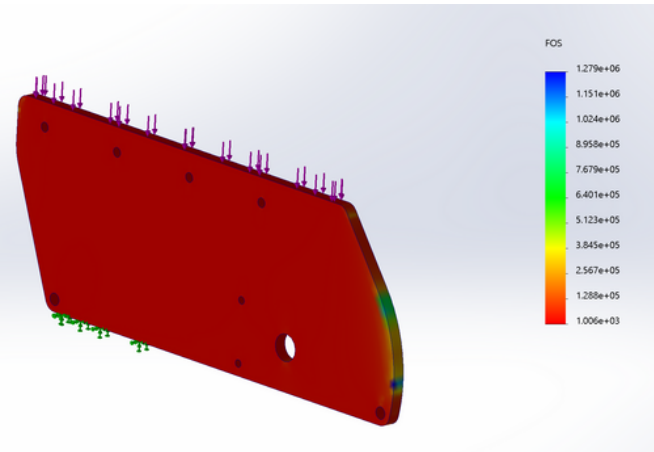
Cart

Simulations:

To check whether our cart's wheel is capable of handling 50 LBs, we ran a simulation on the connecting part between the primary cart and the wheels. We chose to test this part because as the connectors, it is the most fragile and part of our cart system. If this component of the cart fails first, the entire cart would lose its ability to move.

Materials of object used: Aluminum 7075 (due to its strength light weight)



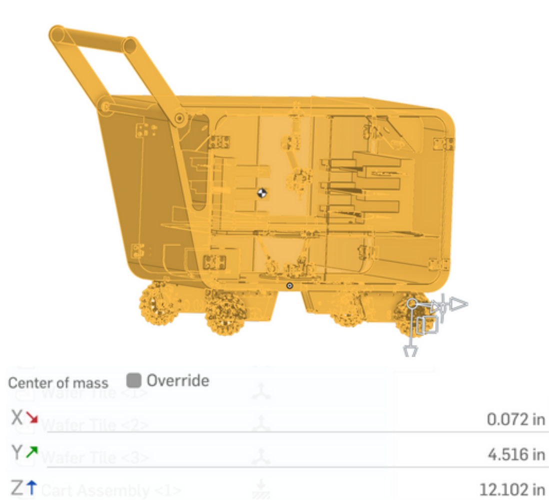


The simulations placed the fixtures on the bottom and a applied static force of 50 LBS.

The results shown indicate a factor of safety greater than 800, suggesting that the cart clearly will not fail under observed circumstances. In addition, we calculated that our connecting part of the cart's main body to the wheel is capable of handling up to 113 LBS.

We attached goBILDA 140 mm OD mecanum wheels and their respective planetary motors with built-in encoders (from their Strafer Kit SKU: 3209-0012-0002) due to their cheap cost and past knowledge in their smooth movement compared to other COTS mecanum wheels.

Height and CG

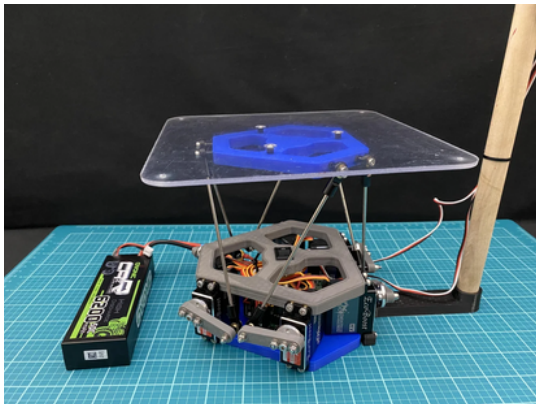


- Center of Gravity: 12.102307 in
  - Good, as it means that the cart's CG is relatively close to the ground, meaning that it will be harder to tip.
- Footprint: 42" (Length) x 21" (Width) x 36" (Height)
  - Choose specific footprint to traverse narrow spaces, while being ergonomic for manual cart transportation

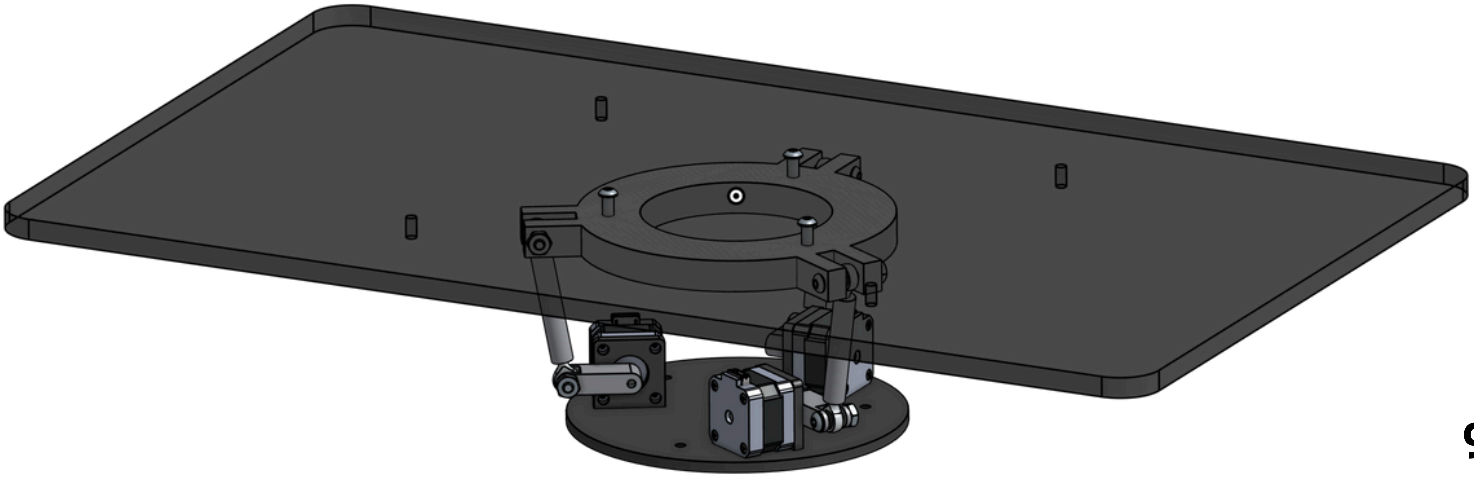
Stabilizer

Requirements:
- Maintain tray platform stability during cart movement and turning
- Minimize vibration transmission to sensitive wafer carriers (5-50 lb)
- Prevent rocking or oscillation during loading/unloading
- Fit within compact footprint and not interfere with door operation
- Ensure ESD-safe and cleanroom-compatible material use
- Allow easy integration with modular tray and frame systems

Inspiration:
- Inspired by ball-balancing robots that actively stabilize on a single contact point
- Compared designs for camera rigs and gimbals that allow cameras to film smoothly. We wanted to apply this principle here!
- Reference Photos:

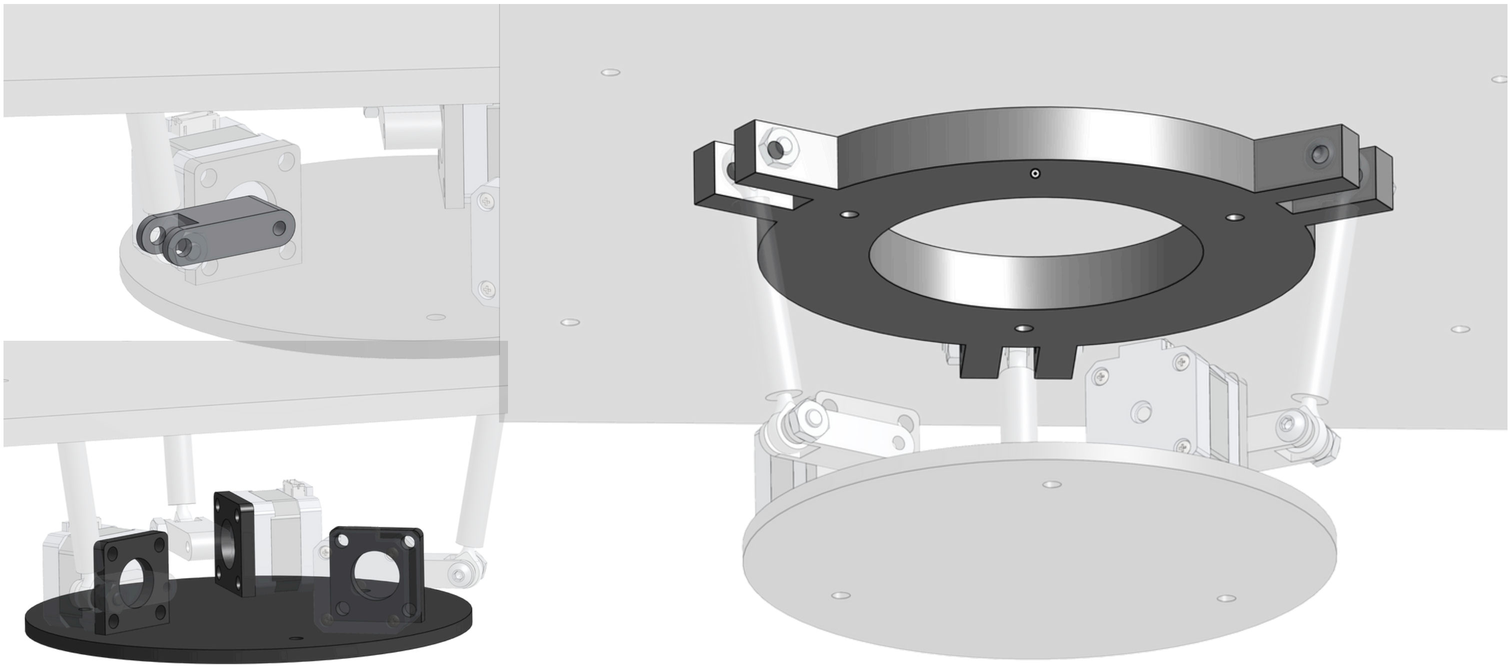


Key Highlights:
- 3 Degrees of Freedom (DOF): Pitch, Roll, and Yaw all accounted for
- Geometry: 3-point isolator layout forming a kinematic triangle under the tray
- Precision Fits: Constrained translational movement while allowing flexure
- Material Choice: Stainless steel was chosen for its strength, durability, and cleanroom compatibility, while polycarbonate was selected for its impact resistance, lightweight properties, and visual transparency to support inspection and handling.
- Manufacturing Processes: All possible to made via CNC & Lathe capabilities!

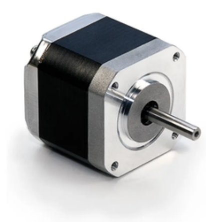


Stabilizer

Component Highlights:



- Motor Mounting: Mounts 3 Stepper Motors (chosen for precise, low-speed control, strong holding torque, and simple integration).



- Pushrod & Joint: Stainless steel pieces maintaining sufficient DOF with eye bolts
- Top Connector: Solid stainless steel piece machined for eye bolts, with unoptimized thicknesses (overestimated) to account for extra forces.

Robotic Arm

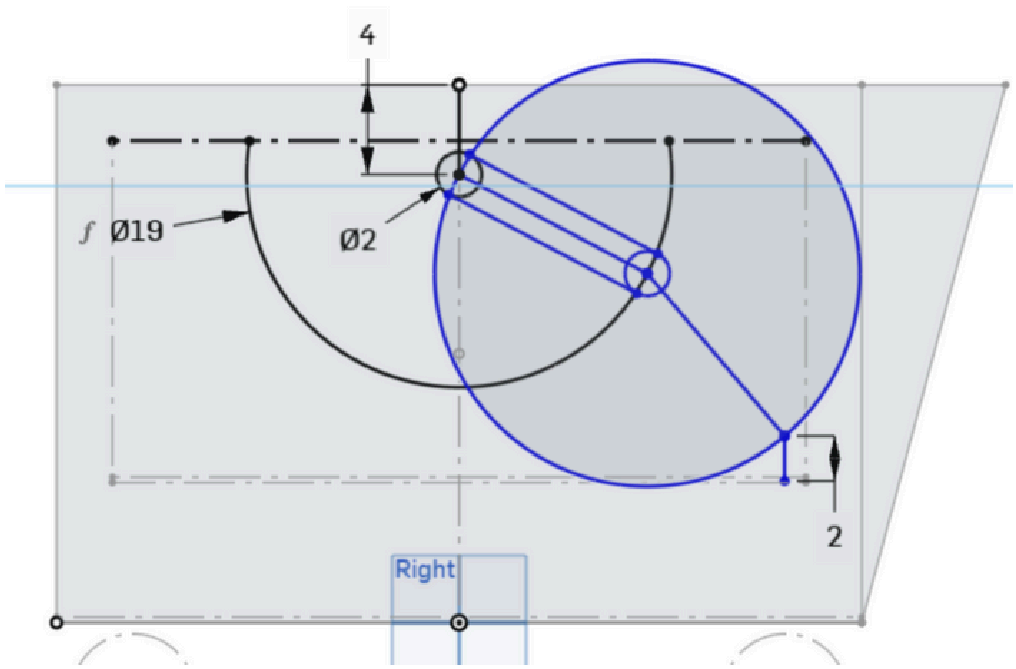
To reiterate, we need a mechanism that can:

- Pick up and place sensitive materials within the enclosed sterile space.
- Pick up and place sensitive materials from an outside workstation to the sterile space, and vice versa.
- Be automated to maintain precision, speed, and consistency.

To implement all three criteria, our initial idea was to:

- Use a robotic arm because of its ability to maneuver to all locations on the level surface,
- Its ability to reach out of the car due to its length,
- Its ability to implement motors to completely automate the process of moving sensitive materials within the sterile space.

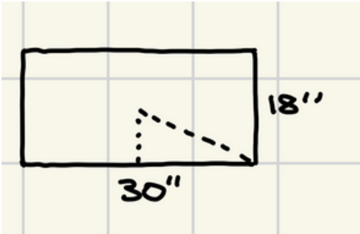
Design Sketch

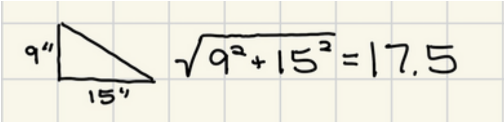


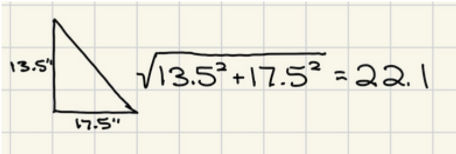
- By creating a system of circles, we could simulate the area covered by the robotic arm.

Design

- We determined that we would need three joints, with the last arm always staying vertical to ensure any materials it carried would stay level. This would be done through software and gyros implemented into each joint.
- We then calculated the length the arms would need:



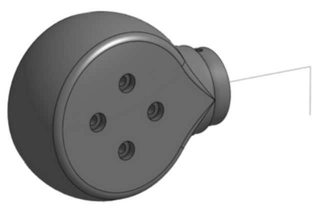




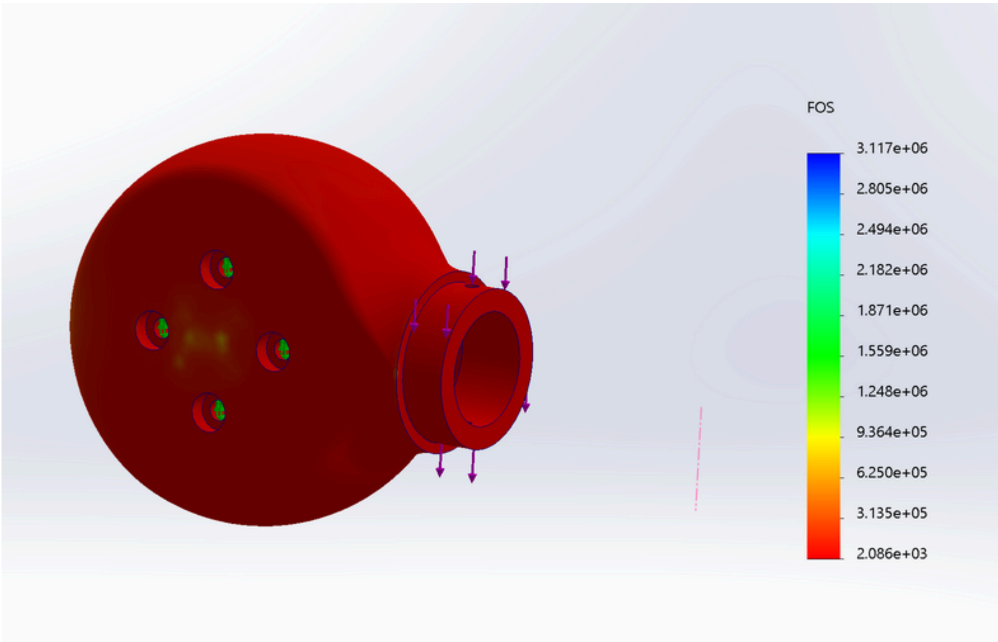
Robotic Arm

- We then chose a shaftless brushless DC motor that we would use for the robotic arm. Each arm could then be screwed to each side of the motor.

- With the geometry of the motor, we designed the encasing for it. We wanted this encasing to secure the motor to the arms that would be made out of tubes.
- The encasing would be made out of Onyx 3D print material made with the MarkForged.
- We used 1 in. OD COTS aluminum 6061 tubes for a cheap, strong, and light material.
- With that, we created our first iteration of the encasing.

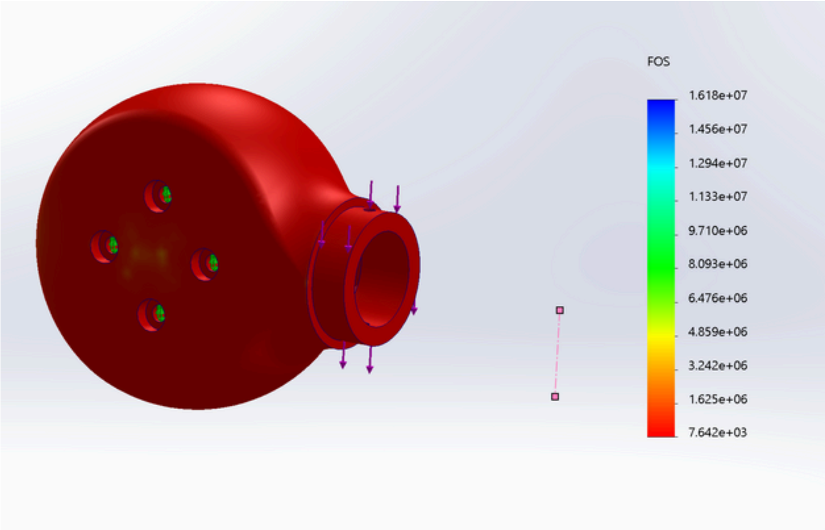


- Using SolidWorks, we tested the strength of Onyx using FEA (estimating a load of 0.6 N from a measured mass of 0.58 kg):



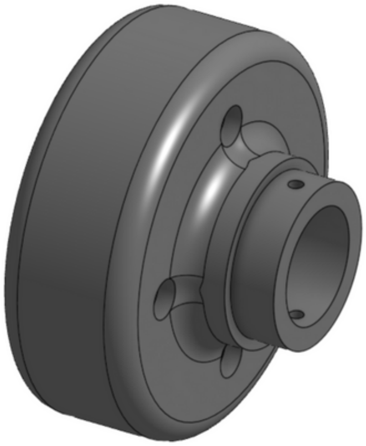
Robotic Arm

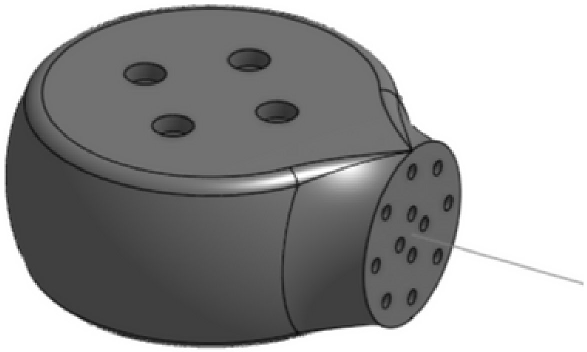
- However, upon doing further research on the material selection, we swapped the material to stainless steel, which would release less particles through degradation inside the sterile environment. This would be manufactured using a CNC Mill.
- This resulted in a much higher factor of safety, too, decreasing the likelihood of part failure.



- We also swapped the aluminum tubes to fiberglass because of fiberglass's lighter weight and since aluminum can release more particles if scratched, which would harm the sterile environment.

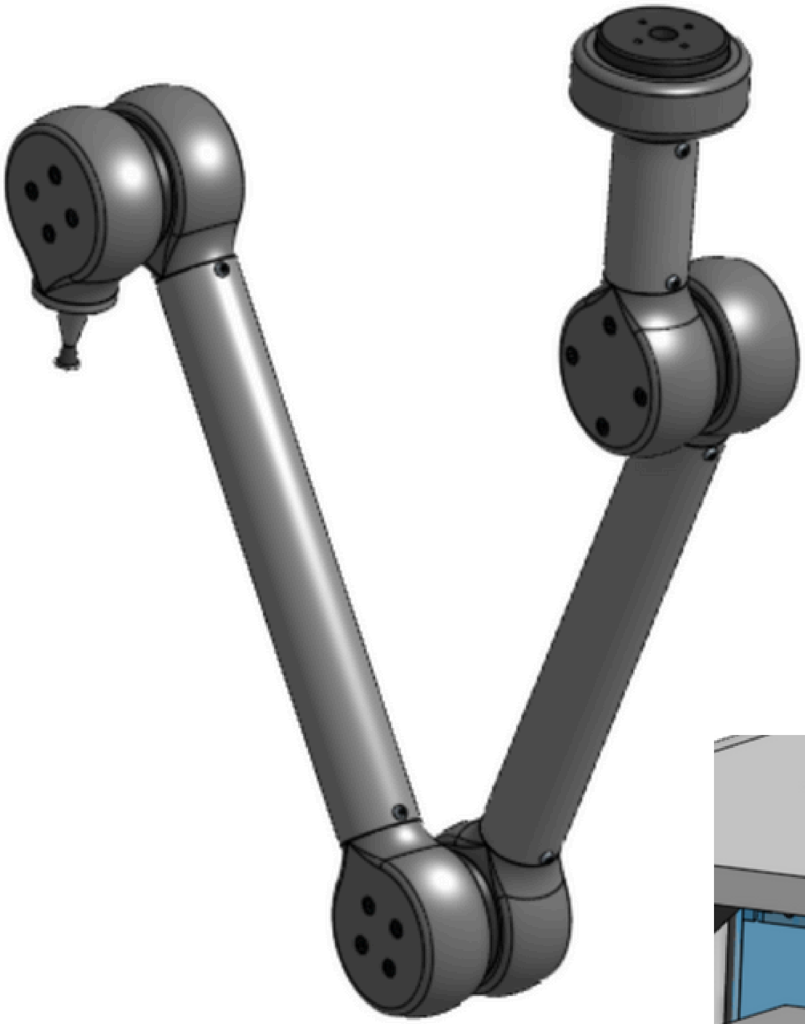
- After designing the mounting mechanism along with a mount for an end effector, the robotic arm was completed.

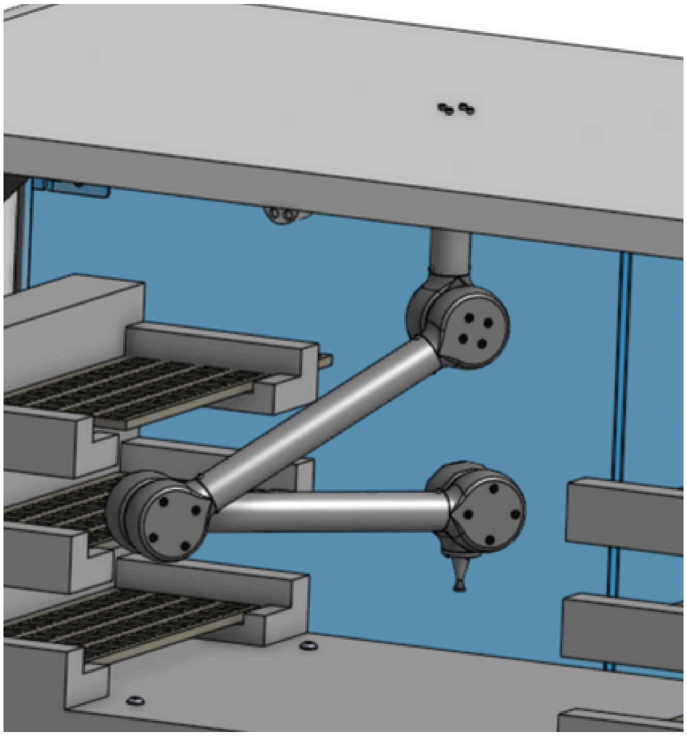




Robotic Arm

- For demonstration, we also designed a basic vacuum tip end effector, which is often used for picking up and placing semiconductor chips.
- Lastly, to ensure the constantly moving motors could lead to a release of more particles, all joints will be covered by mylar, a material known for its strength and insulation that can also help with static discharge.





Sensors and Electronics

Electronics Needed:

- Microcontroller: Raspberry Pi Pico
- Stepper Motor Drivers: TMC2209
- Motors: NEMA 17 Stepper (Stabilizer), 12V DC Gear Motors w/ Encoders (Drive)
- IMU Sensor
- Limit Switches: Endstop sensors for tray zeroing
- Battery Pack
- Voltage Regulator

Electronics Mounting Considerations:

- CAD includes mounting locations for motors, camera, and battery
- Open space below the stabilizer for rest of wiring and electronics systems
- Hole for wires to go from drive base to inside of cart, secure airtight with flexible, sealed cable passthrough to ensure sterilization of cart interiors.
- Apply similar techniques used by NASA to protect satellite electronics (sealed enclosures, low-outgassing materials, and conformal coatings)

Stabilizer System

- 3-axis IMU monitors tilt angle of tray in real time feeds into microcontroller to control stepper motors.
- Use PID loop to damp out slow angular drift or restore level position

Arm Controls

- Uses inverse kinematics for position targeting, soft stops to avoid colliding with tray
- Capability to reach outside of the cart for loading of wafers
- Integration with dual cameras at either side for vision system to understand environment

Drive System

- Uses 4 encoder-based DC motors with mecanum wheels for omnidirectional movement
- Motor speeds calculated using inverse kinematics matrix
- Control system enables strafe, rotate, forward, and diagonal movement

Autonomous Upgrades:

- IMU + wheel encoders provide dead-reckoning
- ToF distance sensors + AprilTags/QR markers around the fabrication facilityallow positional feedback
- Potentially add LiDAR or vision system (e.g. OpenMV Cam) for SLAM/localization

Reducing Static Discharge

- Add ground strap for contact between cart and floor
- Usage of stainless steel and discharge safe materials
- Insulated electronics mounting for all electronic components

Market Analysis in User Interactions

Current Market

- Key Players: Brooks Automation, Omron, Mobile Industrial Robots (MiR) - used in ISO 5-7 spaces
- Solution Types:
  - Overhead rail systems
  - Fixed conveyor networks
  - Manual carts and trays

Pros	Cons
• High precision in positioning and tray alignment • Fully automated integration with MES and fab scheduling • Proven reliability and cleanroom certification • Reduced manual labor and fewer handling errors	• Extremely high cost and long deployment times • Poor flexibility in small or reconfigurable cleanroom layouts • Many systems are non-modular and require custom infrastructure • Large footprint not suited to tight ISO 1–3 aisleways • Difficult to customize for specific fab workflows or research settings

Our Solution

- Operators manually push carts or carriers between bays OR program carts to be autonomous
- Decreases risk of contamination from human contact or misalignment with robot arm
- Real-time location and status tracking for an entire fleet
- Less ergonomic strain and inefficiencies from heavy loads
- Modular tray system supports various carrier types without hardware swaps
- Compact footprint fits into tight ISO 1-3 workspaces
- Upgradeable automation path ensures long-term flexibility

Costs

- Our CART is aimed to provide provides 95% of the functionality (tray stabilization, modularity, partial automation) at <5% of the cost of commercial robotic solutions
- Parts costs of under $2000 compared to over $100,000 for high-end models
- Good for academia, startups, and R&D (small-medium scale) fabs

Future Improvements

Cart

- Developing our own mecanum wheels could have allowed us to create a design that allowed for even smoother maneuvering.
- The doors for the cart could have been modified to let in less light that could impact the sensitive materials inside.
- If we had more time, we wanted to refine our design’s details to be able to maintain a vacuum inside the sterile environment, since some semiconductor manufacturing are done in a vacuum setting.

Stabilizer

- Using 6 servos as opposed to 3 would have greatly increased the stability and precision.

Robotic Arm

- More available time could allow us to run more calculations for arm geometry to ensure every square inch of the space provided in the sterile space is used.
- The arm could also have been modified to reach further outside of the cart.
- More time would also give us the chance to look into motors more and run proper torque calculations for an ideal motor.

Materials

- While a lot of the materials were optimized for effectiveness, if we had more time, we could have definitely done more research into a better and more cost-effective material.
- We wanted to run more simulations to ensure the integrity of every part.

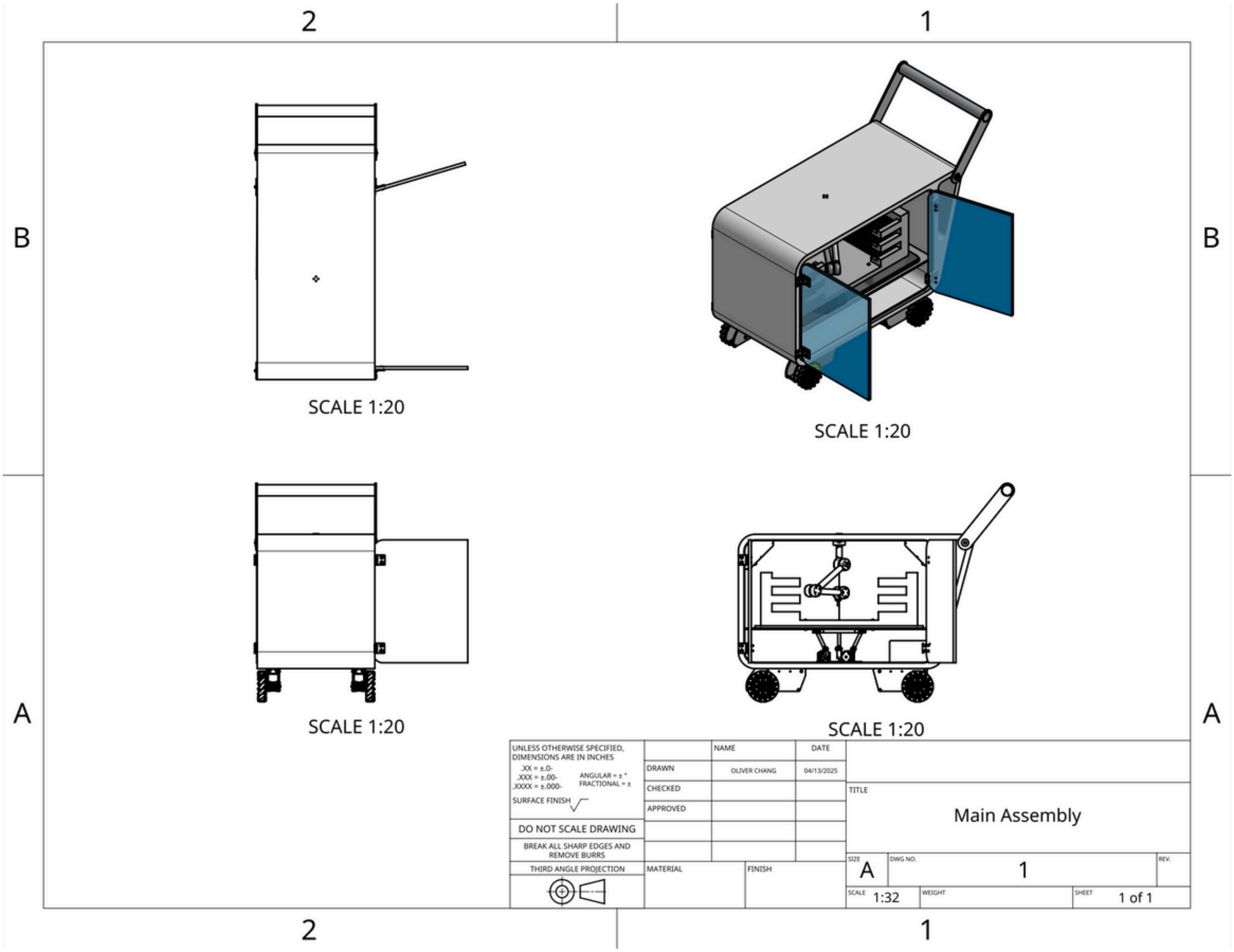
Semiconductor Transportation

- The cart designed is only able to house trays with small semiconductors.
- Dedicated too much space to having the auto-stabilizer and robotic arm equipped, thus reducing the overall capacity for more components.

Appendices

CAD Documents:

- https://cad.onshape.com/documents/e21e595c2b41c6a9e6150ccc/w/1f5b5f20c86b32ead133de35/e/2fa93277960bd4d77ce7d06e
- https://cad.onshape.com/documents/39bc930c086176667c0d107c/w/c5a851bdb4c0c5ef23ef32ea/e/b38bd2f25534f76f6f3b390a?renderMode=0&uiState=67fb2b439fd7d81eb4f32dcc



Appendices

Bill of Materials:

- https://docs.google.com/spreadsheets/d/1Ik8FijrsKaq5JRgfwaPD10qD16Rg_RBiY89sEgYueB0/edit?usp=sharing

C.A.R.E | BOM					
Item	Name	Quantity	Mass	Material	Description
1	Robotic_Arm_Mount1	2	0.499 lb	300 Series Stainless Steel	
2	Robotic_Arm_Mount2	3	0.498 lb	300 Series Stainless Steel	
3	Robotic_Arm_TOP_MOUNT	1	0.468 lb	300 Series Stainless Steel	
4	Robotic_Arm_BOTTOM_MOUN	1	0.406 lb	300 Series Stainless Steel	
5	VacuumPenMount	1	0.043 lb	300 Series Stainless Steel	
6	Motor Mount	1	0.531 lb	Polyetheretherketone	
7	Wafer Holder	1	38.236 lb	Polyetheretherketone	
8	Plug Insert	2	0.022 lb	Polyetheretherketone	
9	Battery Case	1	1.229 lb	Polyetheretherketone	
10	Alu Arm Tube2	2	0.051 lb	Acetal (Delrin)	
11	Alu Arm Tube Top	1	0.014 lb	Acetal (Delrin)	
12	#10-32 Ball Joint Rod End (#10	6	0.026 lb	Carbon Steel	#10-32 Ball Joint Rod End (#10 Clearance, Right-hand Threaded)
13	Socket button head screw M3x0	8	0.004 lb	Hardened Alloy Steel	Socket button head screw M3x0.5 x 30 Hardened Alloy Steel
14	Top Plate	1	11.582 lb	Polycarbonate	
15	Door Front	2	7.982 lb	Polycarbonate	
16	Door Rear	2	7.982 lb	Polycarbonate	
17	UV Light	2	0.023 lb	Polycarbonate	
18	VacuumPenSuction	1	0 lb	Silicone Rubber	
19	Door Plug Left	2	0.212 lb	Silicone Rubber	
20	Long Pushrod	3	0.137 lb	Stainless Steel	
21	Short Pushrod	3	0.152 lb	Stainless Steel	
22	Top Connect	1	6.667 lb	Stainless Steel	
23	Socket button head cap screw 1	7	0.027 lb	Stainless Steel	Socket button head cap screw 1/4-20 x 1.75 Stainless Steel
24	Heavy hex jam nut 1/4-20	10	0.01 lb	Stainless Steel	Heavy hex jam nut 1/4-20 Stainless Steel
25	Socket button head cap screw 1	3	0.017 lb	Stainless Steel	Socket button head cap screw 1/4-20 x 1 Stainless Steel
26	Socket button head cap screw 1	9	0.014 lb	Stainless Steel	Socket button head cap screw 1/4-20 x 0.75 Stainless Steel
27	Main Rim	1	8.152 lb	Stainless Steel	
28	Socket button head screw M2.5:	12	0.001 lb	Stainless Steel	
29	Hex socket head cap screw M2.	28	0.002 lb	Stainless Steel	
30	Socket button head screw M2.5:	4	0.001 lb	Stainless Steel	
31	Hex socket head cap screw M2.	4	0.003 lb	Stainless Steel	Hex socket head cap screw M2.5x0.45 x 25 Stainless Steel
32	Main Structure	1	873.12 lb	Stainless Steel	
33	Front Wheel Plate Outer	2	2.731 lb	Stainless Steel	
34	Rear Wheel Plate Outer	2	2.437 lb	Stainless Steel	
35	Front Wheel Plater Inner	2	2.731 lb	Stainless Steel	
36	Rear Wheel Plate Inner	2	2.437 lb	Stainless Steel	
37	ROUND Spacer 1.75 in	8	0.017 lb	Stainless Steel	
38	Front Wheel Tube 1.75"x1"x7.5"	2	1.266 lb	Stainless Steel	
39	Rear Wheel Tube 1.75"x1"x9"	2	1.516 lb	Stainless Steel	
40	Handle	1	3.52 lb	Stainless Steel	
41	Handle Pivot	1	0.88 lb	Stainless Steel	
42	Handle Plate	2	2.167 lb	Stainless Steel	
43	Socket button head screw M6x1	32	0.009 lb	Stainless Steel	Socket button head screw M6x1 x 12 Stainless Steel
44	Hex nut grade A & B M6x1	16	0.006 lb	Stainless Steel	Hex nut grade A & B M6x1 Stainless Steel
45	Camera Holder	2	4.298 lb	Stainless Steel	
46	Camera Plate Left	3	1.225 lb	Stainless Steel	
47	Socket button head screw M6x1	32	0.011 lb	Stainless Steel	Socket button head screw M6x1 x 16 Stainless Steel
48	Socket countersunk head cap sc	32	0.013 lb	Stainless Steel	Socket countersunk head cap screw 1/4-20 x 0.75 Stainless Steel
49	Plug Washer	2	0.021 lb	Stainless Steel	
50	Battery Plate	2	2.176 lb	Stainless Steel	
51	1.45mm Washer	8	0 lb	Stainless Steel	