MCE401 Mechatronic Engineering Program Capstone Project

# Automatic Whiteboard Cleaner Using Arduino

A Senior Project Submitted to Faculty of Mechatronic Engineering

Vaughn College of Aeronautics and Technology

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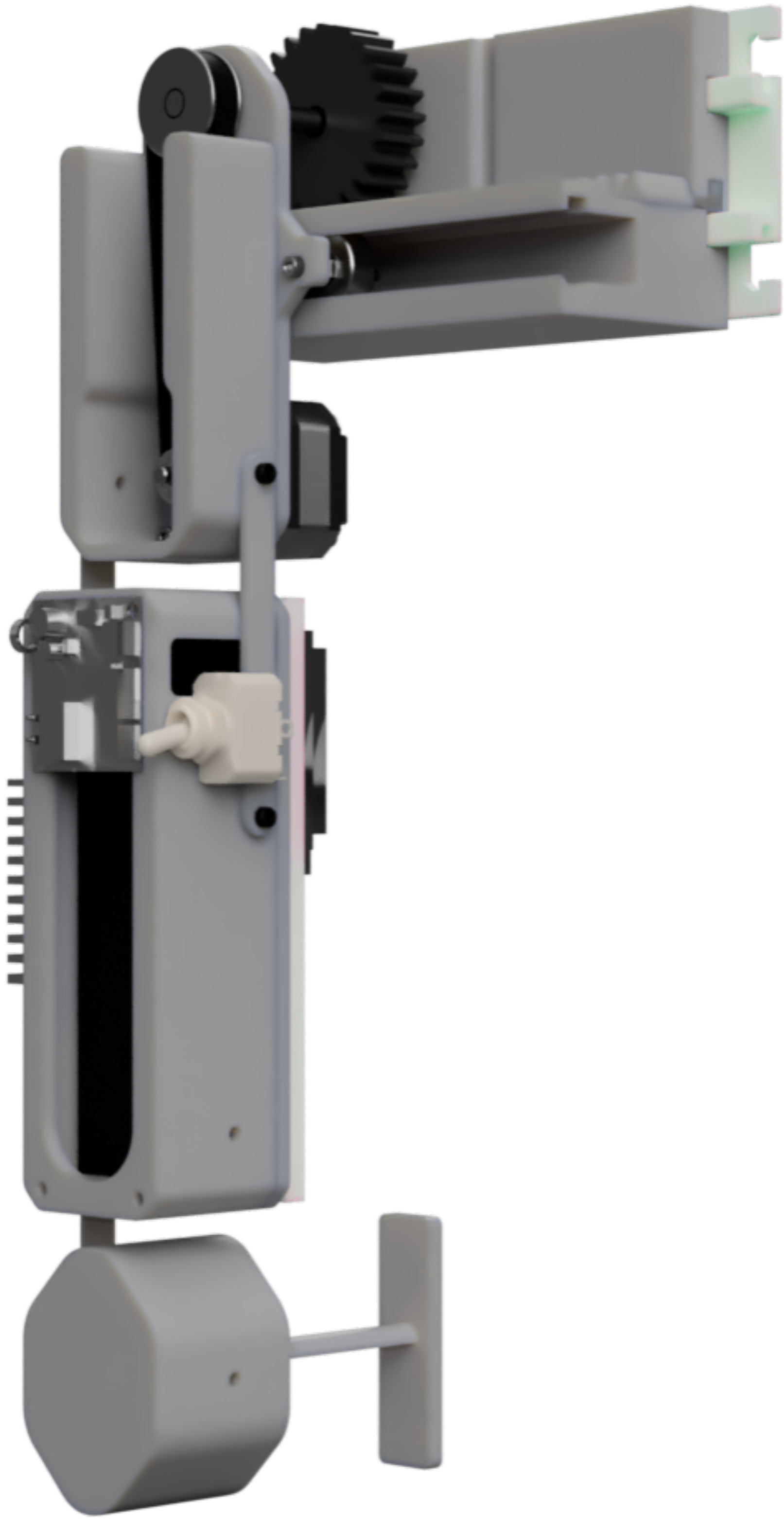

# Abstract

This project presents *OTO*, an automated whiteboard cleaning system designed to reduce classroom downtime and improve surface maintenance. Built using Arduino, the prototype employs a rack-and-pinion mechanism powered by a stepper motor and TMC2209 driver. Dual limit switches are implemented to define travel boundaries, and modularity enables physical expansion at a cost of approximately $3.73 per 0.5 ft in either direction. The current working system covers a 1.5 ft × 0.5 ft area and was developed for $136.87. Cleaning is triggered via a single push-button interface and performs ten consistent sweeps per cycle. All components were designed in Fusion 360 and 3D printed with PLA+, supporting low-cost repairability and open-source iteration. Compared to existing solutions, OTO balances simplicity, affordability, and practical function. Future improvements include implementing sensorless homing to avoid overtravel and mechanical jamming, and exploring more adaptive wiping mechanisms for larger board coverage. This project demonstrates how accessible hardware and modular design can address overlooked pain points in educational and collaborative environments.

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# 1. Problem Statement

### 1.1 Need

Whiteboards are essential tools in classrooms and professional spaces, yet their maintenance remains inefficient. Manual cleaning consumes time, interrupts instructional flow, and is often performed inconsistently, leading to residual markings and surface degradation. In a standard classroom setting, thorough erasure of a full-sized 4 ft × 8 ft board can take up to two minutes. Repeating this process across multiple sessions results in substantial cumulative time loss, up to 50 minutes per week, directly impacting productivity.

Residual ink and ghosting reduce visual clarity, making content harder to read and distracting for students or attendees. Instructors frequently skip proper cleaning due to time constraints, accelerating wear on board surfaces. These issues are exacerbated in high-throughput environments where whiteboards are in constant use.

Despite the clear need, available solutions are limited. Existing robotic cleaners are either prohibitively expensive, mechanically unreliable, or lack adaptability to various board sizes. A scalable, cost-effective solution is needed, one that automates erasure reliably, integrates into standard board setups, and requires minimal user input.

### 1.2 Objective

This project aims to design, fabricate, and test OTO, an Arduino-powered Automated Whiteboard Cleaner optimized for educational and collaborative environments. The system is engineered for:

- Full traversal of whiteboards up to 8 ft in width via a modular rack-and-pinion rail
- Precise, repeatable movement using a single NEMA 17 stepper motor and TMC2209 driver
- Boundary detection through dual normally open limit switches to establish home and end positions
- A single-button interface with built-in calibration logic for ease of use and system recovery
- A sub-$150 total cost, with expansion support at ~$3.73 per additional 0.5 ft
- Fabrication using PLA+ printed components and common off-the-shelf electronics

### 1.3 Background Research

Whiteboard cleaning automation has been an area of growing interest in academic and maker communities, particularly due to the repetitive nature of the task and its implications for time management and surface longevity. While several projects and commercial products have attempted to address this problem, most suffer from critical limitations in terms of cost, scalability, adaptability, or robustness.

**Wipy – Arduino Whiteboard Cleaner**

Wipy is a DIY project built on an Arduino platform that attaches magnetically to the board surface and uses infrared sensors to detect the board edges. It includes features such as an LED interface and automatic wiping logic. While innovative for its time, Wipy demonstrates several shortcomings:

- It lacks structural stability, relying on friction and magnetic force alone to maintain board contact.
- The system does not traverse the full height or width of large boards, making it unsuitable for full-surface cleaning.
- The device operates slowly and lacks the torque or pressure to erase heavily marked areas effectively.
- Being magnet-based, Wipy is only compatible with metallic or magnetic whiteboards, excluding many glass or polymer boards commonly found in modern settings.

Wipy highlights the potential of low-cost embedded solutions but ultimately proves too limited for classroom-scale deployment.

**swiperWHITE – Automatic Whiteboard Cleaner**

swiperWHITE is a commercially available automatic whiteboard cleaning device that employs dual motors: one for horizontal movement and another for the cleaning pad's actuation. It features a user-friendly push-button interface and achieves relatively fast traversal speeds (approximately 200 mm/s). Its notable strengths include:

- Mechanically sound structure and consistent surface contact.
- Simple UI and autonomous operation without external systems.

However, it also exhibits significant drawbacks:

- The unit is priced over $400, which places it well outside the procurement range for most classrooms, particularly in public institutions or underfunded districts.
- It is built as a fixed-length unit and cannot adapt to different board sizes or mounting styles without customization.
- The system does not support modular upgrades or low-cost part replacement, reducing its maintainability.

While more robust than Wipy, swiperWHITE is too costly and rigid for scalable use across varied educational environments.

**DIY Whiteboard Cleaner Prototypes**

Multiple open-source or hobbyist prototypes have been published on platforms such as Instructables and YouTube. These designs often use DC motors, rubber wheels, or simple track systems to automate board wiping. They typically emphasize simplicity and budget constraints but often sacrifice functionality and repeatability. Common limitations include:

- Lack of feedback mechanisms (limit switches or sensors), resulting in uncontrolled motion or stalling.
- Poor material choices leading to mechanical instability or wear over time.
- No calibration features to adapt to board size or correct drift after extended use.
- No modularity or expandability, requiring redesign if applied to larger boards.

Despite their low barrier to entry, most DIY builds remain experimental and are rarely tested in actual classroom conditions. Their designs serve as learning exercises rather than deployable tools.

**Robotic Alternatives and Autonomous Systems**

Some research groups have explored adapting mobile robotics to whiteboard cleaning, often using repurposed Roomba-style robots or mobile manipulators. These systems are more complex, integrating camera vision or SLAM navigation to autonomously locate, approach, and clean board surfaces. While intellectually valuable, such systems face practical constraints:

- They introduce unnecessary complexity and computational overhead for a task that is linear and planar.

- Their cost and maintenance requirements far exceed what is viable for typical users.
- Mobility introduces new sources of error, including misalignment, collision, and uneven surface contact.

These systems emphasize novelty over practicality and are not suitable for low-cost replication or deployment at scale.

# 2. Social Impact

The automation of routine tasks in educational and professional environments has become increasingly relevant as institutions seek to improve efficiency and reduce operational overhead. Although whiteboard cleaning may seem minor in isolation, the cumulative effects of manual erasure across classrooms, offices, and meeting spaces represent a measurable loss of time and productivity. In high-traffic learning environments, instructors may clean whiteboards up to five times per day, leading to nearly 50 minutes of instructional time lost each week per room. This time loss, when scaled across departments or entire campuses, becomes a significant inefficiency.

The social value of OTO lies in its potential to alleviate this inefficiency by automating a simple but repetitive task. By reducing time spent on manual cleaning, the system enables instructors and facilitators to transition smoothly between sessions without interruption. This improves lesson pacing and overall classroom management, particularly in institutions where session transitions are tightly scheduled.

Additionally, consistent erasure contributes to better visual clarity and reduces cognitive strain for students, especially those seated farther from the board. Clean writing surfaces are particularly important in STEM classrooms, where dense, symbolic content is frequently used. OTO ensures that boards are cleaned evenly with each cycle, avoiding the residual ghosting and shadowing that often accumulates due to incomplete manual wiping.

From a maintenance perspective, repeated manual erasure, especially when rushed, can contribute to board damage over time. Erasers may apply uneven pressure or trap debris that scratches the surface. By contrast, OTO applies consistent contact force during each sweep, improving surface longevity and reducing the frequency of whiteboard replacement, which is particularly valuable in schools operating under budget constraints.

Moreover, OTO’s low-cost, open-source design makes it accessible to underserved schools and educational institutions. Unlike commercial automation systems that require significant investment, OTO can be replicated using consumer-grade 3D printers and widely available microcontrollers. Its modular structure also allows institutions to scale the system based on classroom size and resources.

Finally, the project fosters broader awareness of how small-scale automation, when applied thoughtfully, can contribute to systemic improvements in education and workplace management. By emphasizing reliability, affordability, and ease of implementation, OTO serves as a model for pragmatic engineering, one that addresses real-world needs without introducing unnecessary complexity.

# 3. Economic Impact

The economic viability of automation projects is a critical factor in determining their real-world adoption. Many existing whiteboard cleaning systems are either conceptual, overly complex, or priced beyond what is practical for classroom-scale deployment. For example, commercial solutions like swiperWHITE retail at over $400 per unit, limiting accessibility for public schools, small offices, and resource-constrained institutions.

OTO was intentionally developed with economic feasibility as a central design constraint. The complete working prototype was built for a total cost of $136.87, including all mechanical, electrical, and printed components. This cost is substantially lower than existing alternatives while delivering comparable or improved functionality. Furthermore, OTO supports modular expansion in 0.5-foot increments at an estimated additional cost of $3.73 per segment, allowing the device to adapt to larger board sizes without a full redesign or significant added expense.

All components used in the system are off-the-shelf and widely available. The core electronics — including an Arduino Uno, TMC2209 stepper motor driver, and NEMA 17 motor — are already standardized across many hobbyist and engineering platforms. Structural parts were fabricated using a consumer-grade FDM 3D printer with grey PLA+, minimizing material and tooling costs. This manufacturing approach enables low-volume production or replication without the need for CNC machining or injection molding, reducing setup costs for institutions looking to build multiple units.

From a long-term perspective, OTO offers economic benefits beyond its initial cost. Consistent automated cleaning can reduce whiteboard replacement frequency by preserving surface quality. It also reduces the need for purchasing commercial erasers, cleaning sprays, or replacement markers used to overwrite ghosting. Maintenance requirements are minimal, as most components are modular and easily replaceable, and the use of open-source code allows for future customization without licensing fees.

In addition, the system's simplicity allows for repair and reassembly by students or staff without specialized technical training. This presents an opportunity for educational institutions to incorporate OTO not only as a utility but also as a hands-on learning tool in robotics or engineering curricula.

Overall, OTO demonstrates that targeted automation can be implemented at a fraction of the cost of commercial alternatives, offering a practical and scalable solution with clear economic advantages in both deployment and lifecycle maintenance.

# 4. Environmental Impact

While OTO is not a sustainability-focused project, its environmental impact has been considered across material selection, manufacturing methods, power consumption, and end-of-life management. Compared to traditional commercial devices or fully robotic systems, OTO minimizes its ecological footprint through efficient use of materials and low-power operation.

The system is fabricated primarily from PLA+, a biodegradable thermoplastic derived from renewable resources such as cornstarch or sugarcane. PLA+ has a lower environmental impact compared to petroleum-based polymers and produces minimal emissions during 3D printing. All printed parts were manufactured using an FDM (Fused Deposition Modeling) process, which generates little to no material waste when sliced efficiently. Furthermore, failed prints and prototypes can be recycled using filament recyclers or repurposed for non-structural components.

The electronics used in OTO, such as the Arduino Uno, stepper motor driver, and limit switches, are all low-voltage components that operate under 24V DC. The system is powered by a rechargeable lithium-polymer (LiPo) battery, eliminating the need for continuous wall power. This reduces electrical consumption over time and allows the device to function without contributing to peak energy loads during classroom use. With proper current limiting, the system consumes minimal power per cycle and can complete over 30 full cleaning cycles on a single charge.

By automating the erasure process, OTO also contributes to the reduction of consumables. Manual cleaning often requires the use of chemical-based sprays, disposable wipes, or rapid replacement of dry-erase markers due to ghosting buildup. By providing consistent and thorough cleaning, OTO minimizes the need for such products, indirectly reducing the environmental burden of chemical runoff and disposable waste.

In terms of longevity, OTO's modular design encourages maintenance and part replacement rather than full-system disposal. Components such as the cleaning pad, belt, or housing segments can be easily reprinted or replaced without discarding the entire system. This promotes a repair-oriented approach over a single-use mentality, extending product life and reducing electronic waste.

End-of-life recycling is also feasible. Most mechanical components are made from single-material PLA+, which can be sorted and recycled appropriately. Electronic components follow standard e-waste disposal protocols and do not contain hazardous substances beyond those found in typical low-voltage consumer electronics.

In summary, OTO minimizes its environmental impact through:

- Use of biodegradable or recyclable materials (PLA+)
- Low-power, battery-operated electronics
- Reduction in the use of chemical cleaning supplies
- Modular, repairable architecture that extends product lifespan
- Compatibility with common recycling and disposal channels

As such, OTO aligns with environmentally conscious design practices, even within the constraints of a low-cost, prototype-stage engineering solution.

# 5. Engineering Standards

The development of OTO, the Automated Whiteboard Cleaner, adheres to established engineering standards across mechanical design, electrical safety, embedded system control, additive manufacturing, and product reliability. Given the application context, classroom and office environments, and the nature of the system, an untethered, microcontroller-based mechanism with moving parts, compliance with international standards was prioritized to ensure safety, repeatability, and design clarity.

This section outlines the specific standards that guided the engineering decisions throughout the project.

### 5.1 Electrical Safety and Low Voltage Compliance

- IEC 60204-1 – Safety of Machinery – Electrical Equipment of Machines

  This standard specifies safety requirements for electrical equipment in machinery. OTO operates under 24V DC, complying with extra-low voltage (ELV) criteria and mitigating shock risk.

Application: All electronic subsystems were kept below the 25V DC threshold, with a 3-cell

11.1V LiPo battery powering the circuit and a step-up converter regulated at 20.1V.

- IEC 62133-2 – Safety Requirements for Portable Sealed Secondary Lithium Cells

This standard ensures the safe use of lithium-ion batteries. The 3-cell 2200mAh LiPo used in OTO follows best practices for current limiting and thermal safety.

Application: Protection circuits and digital cutoffs were incorporated to prevent over-discharge and overheating.

### 5.2 Mechanical Design and Geometric Standards

- ANSI Y14.5 – Dimensioning and Tolerancing (GD&T)

  This standard ensures clear and unambiguous communication of part geometries and tolerances.

Application: Fusion 360 was used to model all components with parametric constraints and dimensional precision to support modular part mating and tolerance stacking.

- ISO 12100 – General Principles for Design – Risk Assessment and Risk Reduction

  This safety standard guided the hazard assessment and mitigation process.

Application: A functional failure mode and effects analysis (FMEA) was performed to identify risks such as overtravel, motor overheating, and pinion disengagement, which were addressed through limit switches, current control, and bearing alignment.

### 5.3 Additive Manufacturing Standards

- ISO 17296-1 – Additive Manufacturing – General Principles – Terminology

  This standard defines terminology relevant to 3D printing and was followed to maintain consistency in documentation and communication.

Application: All components were fabricated using PLA+ via fused filament fabrication (FFF), and documentation maintained standard definitions for features such as infill density, shell thickness, and layer height.

- ASTM F2792 – Standard Terminology for Additive Manufacturing Technologies

Application: Referenced during the selection of slicing parameters, wall geometries, and support structures to ensure that the mechanical components met strength and dimensional integrity requirements during and after printing.

#### 5.4 Coding and Documentation Standards

- Arduino C++ Coding Conventions

  Standard embedded programming conventions were applied for readability, safety, and maintenance.

Application: Code was documented with inline comments, structured into initialization, loop, and safety logic blocks, and reviewed for edge-case scenarios like button bounce or limit switch override.

- PEP 8 – Python Enhancement Proposal (Used for Planning/Simulation)

  For testing and simulation of motion profiles or expansion planning, any Python tools or data visualization scripts followed PEP 8 formatting standards for clean and consistent analysis workflows.

### 5.5 Materials and Load Standards

- UL 94 HB – Flammability Rating for Plastic Materials

Application: All printed components were produced using PLA+, which meets the UL 94 HB standard, indicating that the material will not propagate flame under controlled horizontal burning tests.

- ASTM D638 – Tensile Testing of Plastics (reference only)
  While no formal mechanical testing was conducted, design assumptions for part strength were based on known PLA+ properties measured under ASTM D638 conditions in literature.

# 6. Engineering Requirements and Constraints

The successful development of the OTO system was guided by a clear set of engineering requirements and constraints. These criteria were defined during the planning phase and validated through iterative design and prototyping. They ensure the system performs reliably under typical classroom conditions, meets practical use-case demands, and aligns with safety and manufacturability standards.

### 6.1 Functional Requirements

| ID | Function | Rationale |
|---|---|---|
| FR-1 | Initiate erase cycle on demand (single push-button) | User control without computer interface |
| FR-2 | Traverse a modular rail horizontally and return home automatically | Ensures predictable erase path regardless of total rack length |
| FR-3 | Maintain constant pad pressure on board surface | Uniform cleaning prevents shadow ink that confuses students |
| FR-4 | Halt immediately on low battery power | Extends battery life |
| FR-5 | Operate untethered for an entire 90-min lecture | Class sessions plus change-over buffer with no cable clutter |

The core functions of OTO are driven by the need to automate board erasure with minimal user interaction, using embedded control and mechanical traversal. These requirements reflect the expected behavior during operation:

### 6.2 Engineering Performance Requirements

Performance targets were established to ensure the device meets operational expectations for speed, clarity, endurance, and environmental compatibility. These values were validated via load testing, erasure testing, and observation during functional trials.

| ID | Metric | Target Value |
|---|---|---|
| ER-1 | Cycle time | <2min per cycle (each cycle = 10 sweeps) |
| ER-2 | Residual ink (%) | <5% after cycle completion |
| ER-3 | Pad normal force | 2-4 N normal load |
| ER-4 | SPL @1m | <60 dB(A) at 1m |
| ER-5 | Battery life | > 30 cycles per charge |
| ER-6 | Mass per rack | <200 g |

### 6.3 Design Constraints

Several constraints were imposed by material, regulatory, and practical limitations. These constraints shaped both component selection and system architecture.

| ID | Metric | Target Value |
|---|---|---|
| C-1 | Input is extra low voltage DC | Power input < 24V DC |
| C-2 | Prototype cost ceiling | <$150 |
| C-3 | Compatible board sizes | 4x3ft up to 8x4ft |
| C-4 | Printed polymer flammability | UL94 HB min |
| C-5 | Adhesive shear load | <8N ea. Patch |
| C-6 | Rail segment length | 151 mm module |

These constraints ensure compatibility with real-world board dimensions, compliance with safety expectations, and manufacturability using consumer-grade tools.

#### 6.4 Regulatory and Safety Compliance

To meet classroom safety expectations and reduce liability, several standards were identified and partially implemented through prototyping:

| Standard/ Clause | Metric | Implementation Status |
| --- | --- | --- |
| ISO 12100 §6.2 | Perform hazard analysis & reduce risk | FMEA completed |
| IEC 60204-1 §6 | Maintain ELV control circuits < 25 V DC | Driver fed 20.1V |
| ISO 13850 | Provide latching emergency stop | |
| IEC 62133-2 | Use certified Li-ion pack | 3-cell 2200 mAh pack w/ CB report |
| UL 94 | Polymer flammability HB or better | PLA+ parts HB |

These implementations allow for safer use in public settings and serve as a foundation for future safety certification.

# 7. Design Alternatives & Tradeoffs

The design process for OTO involved evaluating multiple mechanical architectures, drive systems, and structural approaches. Several iterations were explored before arriving at the current solution, with each design path assessed for feasibility, complexity, cost, and compatibility with intended use. The final architecture reflects a deliberate balance between performance and manufacturability, informed by technical tradeoffs and prototyping results.

### 7.1 Initial Concepts Explored

Three main design categories were considered during early development:

1. Belt-Driven Gantry System

   A design where a belt-driven carriage moves along a rail, typically powered by a stepper motor connected to a closed-loop GT2 timing belt.

   Advantages:

   - Smooth and rapid motion, especially over long distances
   - Easy to implement with standard 3D printer hardware

   Drawbacks:

   - Belt tensioning introduced maintenance overhead
   - Limited modularity for expansion
   - Belt slack and stretch under load affected repeatability
   - Anchoring tensioned belts across whiteboard frames was structurally inconsistent.

2. Dual-Axis Arm Mechanism (X/Y Gantry)

   A Cartesian-style design with separate X and Y motion, mimicking CNC or laser cutter kinematics.

   Advantages:

   - Full board coverage including both horizontal and vertical passes

- Adaptable to dry-erase markers and potential write-erase hybrid concepts

Drawbacks:

- Required two motors and two-axis calibration
- Significantly increased cost, weight, and code complexity
- Increased failure points and higher part count

This option offered high functionality but exceeded the project's scope and cost constraints.

3. Rotating Drum Design

A central rotating roller sweeps across the board using a belt or gear to drive a foam cylinder or microfiber roller.

Advantages:

- Compact, single-axis motion
- High contact surface area with potential for full-length coverage

Drawbacks:

- Poor pressure distribution across uneven boards
- Required precise mounting and foam balancing
- Difficult to clean or replace roller media

This concept proved impractical for modular scaling and was abandoned early.

### 7.2 Final Design Chosen – Rack and Pinion on Modular Rails

The final architecture is based on a rack-and-pinion mechanism that allows a cleaning carriage to traverse a rigid linear rail. The gear meshes with 3D-printed teeth, translating rotational motion into linear movement. This configuration was selected after iterative testing for its:

- Modularity: Rack segments can be printed and joined to support any board width, with a repeatable $3.73 cost per 0.5 ft extension
- Simplicity: Only one motor is required to drive the system
- Precision: Limit switches provide accurate start and stop points
- Structural Rigidity: Rails reduce wobble and misalignment during sweeps
- Low Maintenance: No belts to tension or pulleys to align

This solution satisfied all performance and economic requirements while remaining easy to fabricate and assemble.

# 8. Design Iteration History

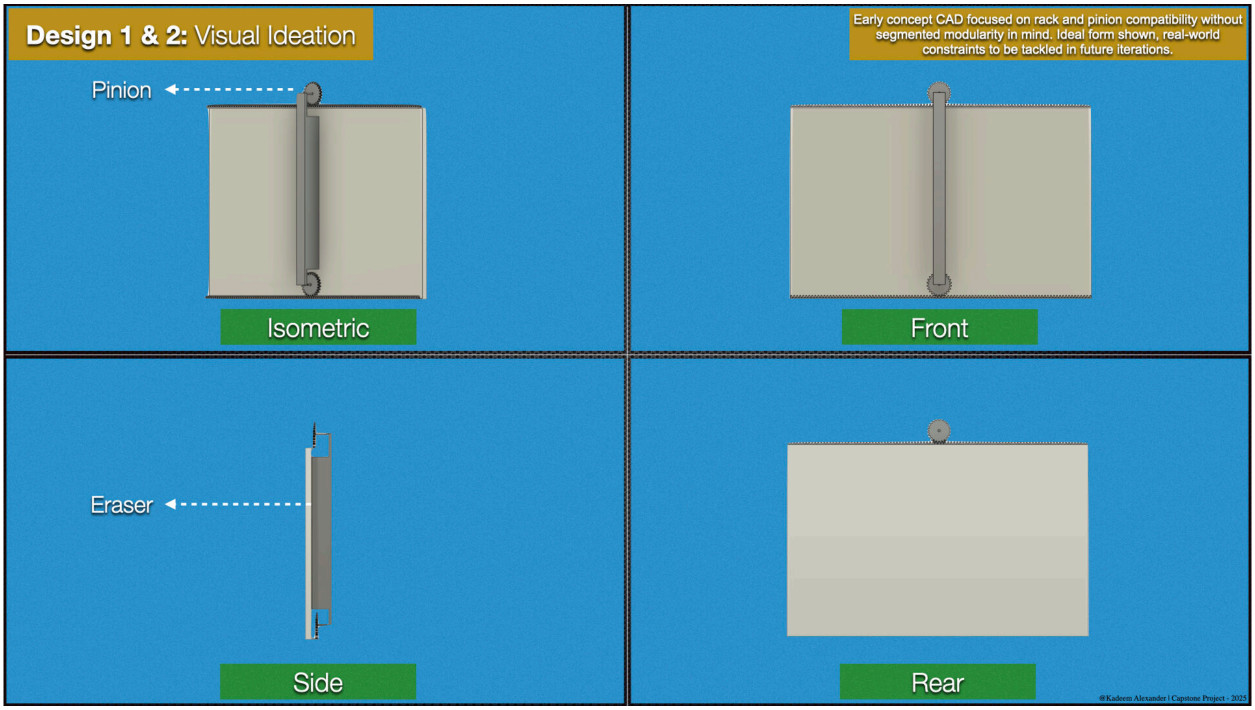
The development of OTO involved a multi-stage iterative design process spanning seven major revisions. Each version addressed limitations or introduced improvements over the last, guided by real-world testing, material constraints, and user interaction feedback. This section documents the design evolution, highlights the failures and successes, and provides insight into how iteration shaped the final system.

### 8.1 Overview of Iterative Process

The goal from the outset was to design an automated whiteboard cleaner that was cost-effective, modular, and able to function reliably with minimal user input. However, early designs suffered from mechanical, electrical, and usability issues that revealed deeper design flaws only through testing. Most changes were driven by physical prototyping, including the failure of belts to maintain tension, mechanical instability of unsupported structures, and difficulties with gear alignment and overtravel.

### 8.2 Version Log

Design 1 & 2 – Visual Ideation




Goal: Explore feasibility of rack and pinion motion across a whiteboard.

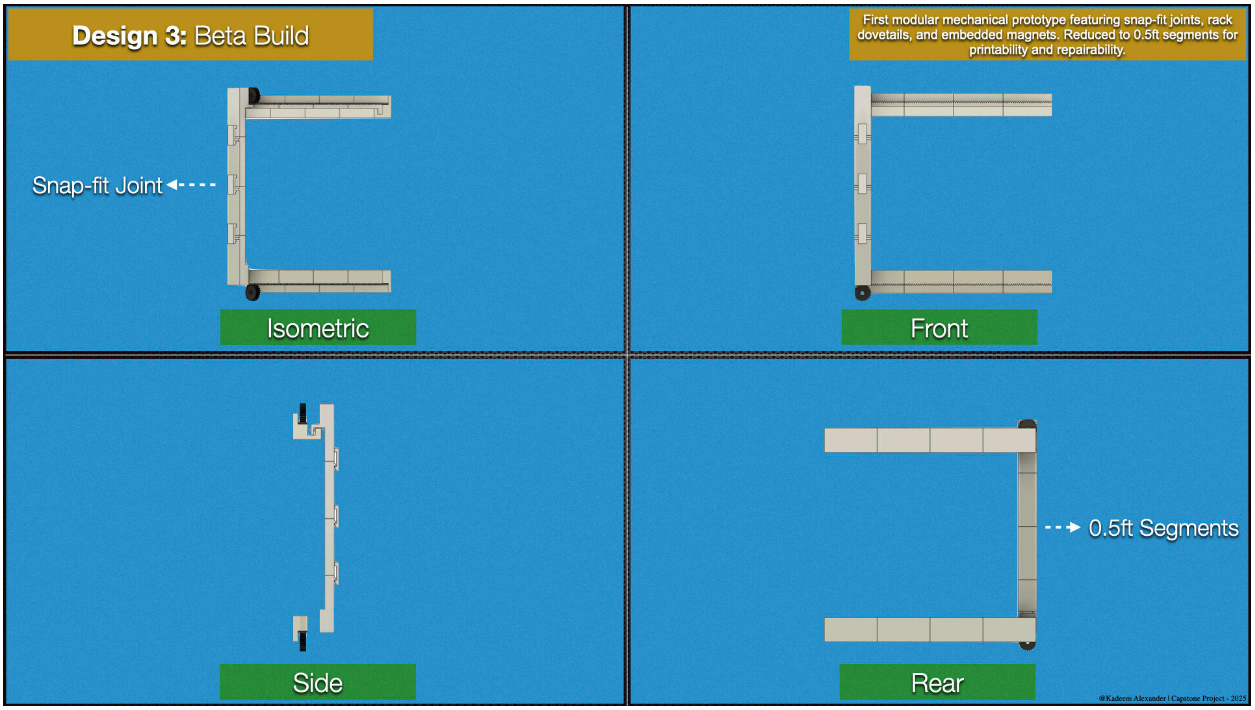
Highlights:

- Concept CAD focused on ideal conditions (perfect flat surface, rigid board)
- Pinion placed centrally on a fixed eraser carriage
- Geometry considered simple top-down clearance without frame obstructions

Outcome:

While visually clean, these early designs lacked segment-based modularity and did not account for real-world mounting constraints, board frames, or mechanical stress. Set the groundwork for motion feasibility but was ultimately a theoretical draft.

Design 3 – Beta Build




Goal: Translate static CAD into a functional, modular prototype.

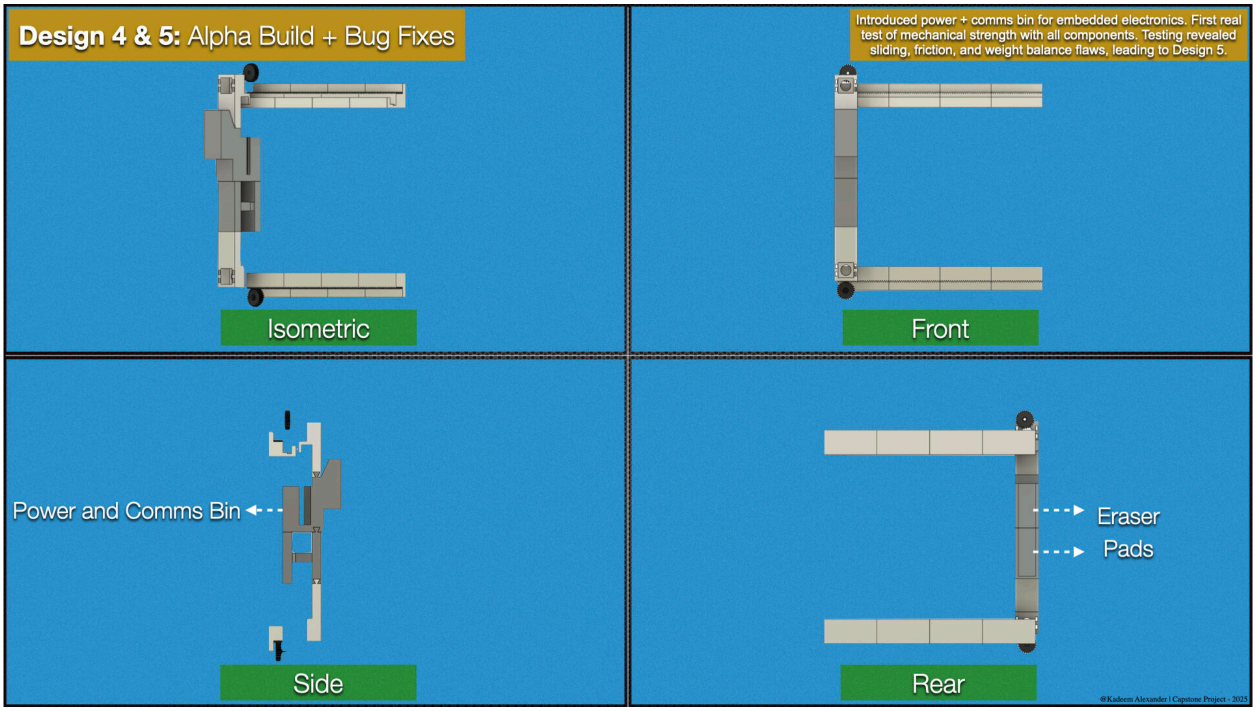
Highlights:

- Introduced 0.5 ft rack segments for printability and modular scaling
- Snap-fit dovetail joints allowed quick segment replacement
- Carriage simplified for motion-only testing

Outcome:

Successfully moved toward manufacturability and repairability, but sliding pad system was not yet reliable. Provided first meaningful hands-on validation of modular rack joinery.

Design 4 & 5 – Alpha Build + Bug Fixes




Goal: Test electrical integration and carriage design under real motion conditions.

Highlights:

- First version to include “Power & Comms” bin for housing Arduino, driver, and battery
- Added full mechanical interface (pads + rails + racks + switches)
- Introduced eraser pressure balancing

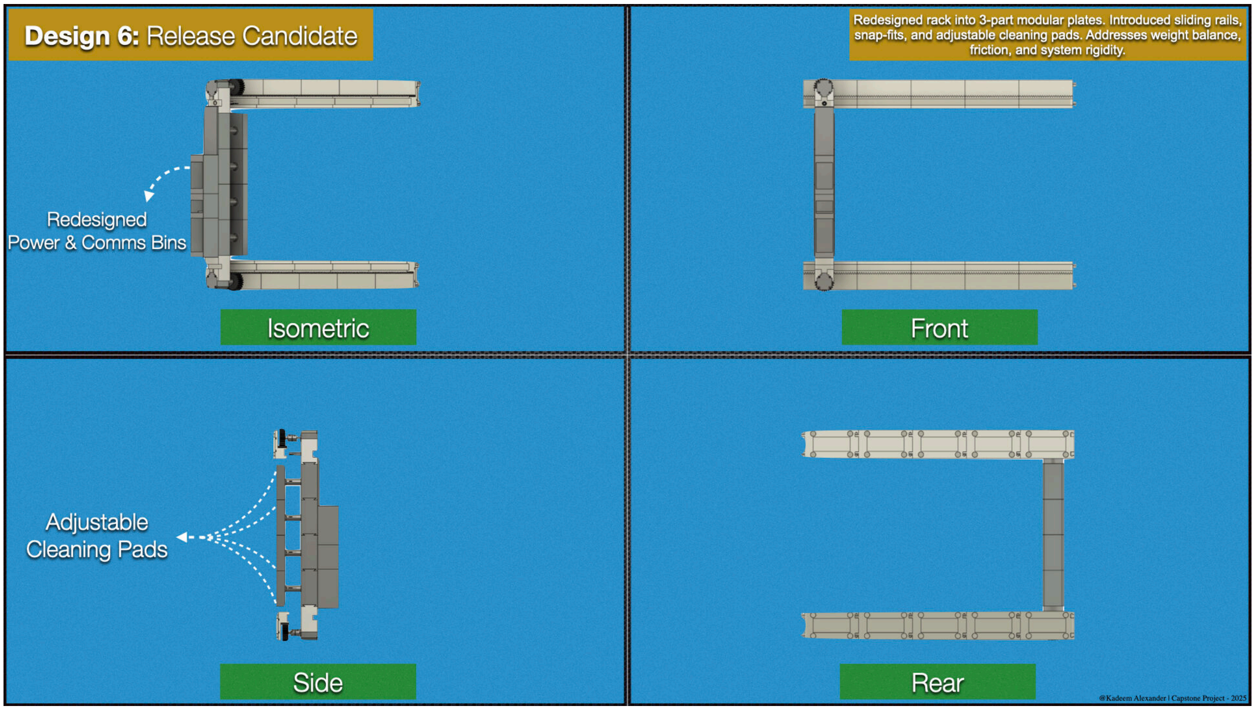
Bugs Identified:

- Carriage leaned forward from center of mass
- Eraser dragged instead of glided in some cases
- Wiper-pad contact was inconsistent due to uneven surface pressure

Outcome:

Established baseline for cleaning effectiveness and bug testing. Led directly to corrective redesign of carriage geometry and mounting interface in Design 6.

Design 6 – Release Candidate




Goal: Finalize form for fully functional prototype.

Highlights:

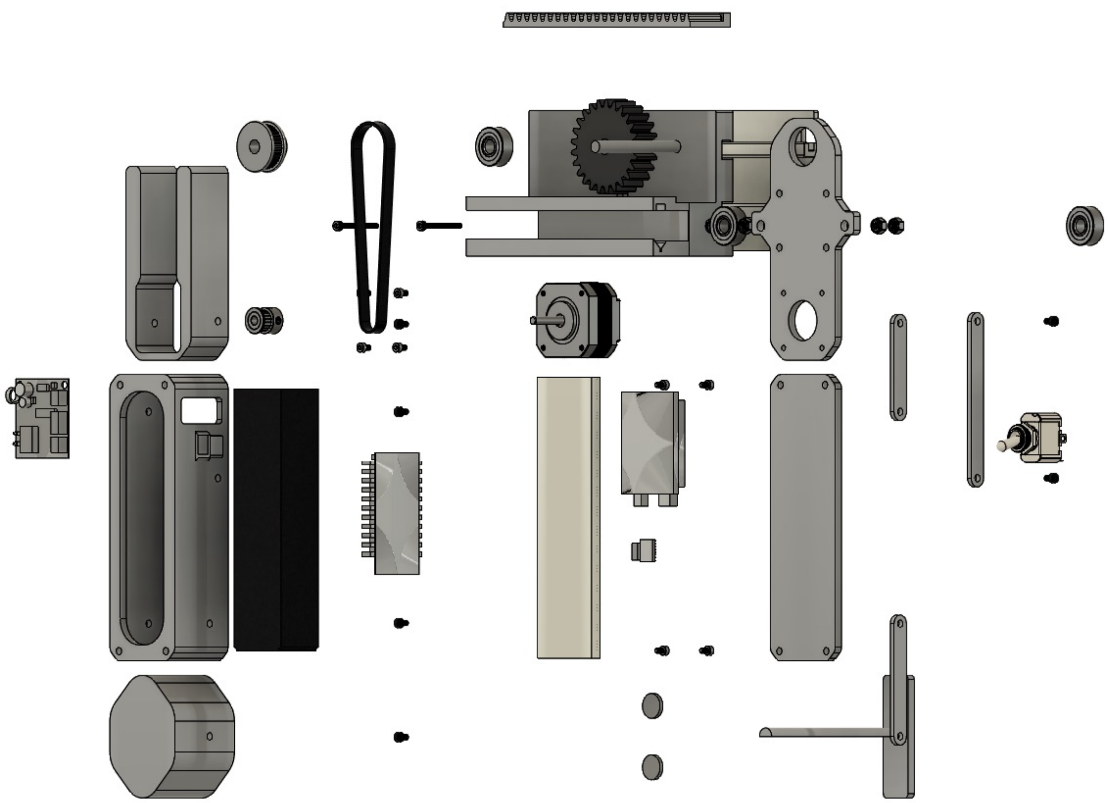
- Redesigned rack into 3-part modular plates for better alignment
- Added adjustable cleaning pads with Velcro and passive flex
- Power system enclosed neatly with cable guides
- Weight, friction, and rail tolerance optimized

Outcome:

Validated final mechanical layout. The prototype built from Design 6 formed the basis of the completed system currently undergoing testing.

# 9. Final Design and Product Description

The finalized design of OTO is the result of extensive mechanical iteration, control system refinement, and prototyping feedback. It embodies a modular, Arduino-controlled, rack-and-pinion whiteboard cleaner capable of scalable deployment across board sizes from 4×3 ft to 8×4 ft.

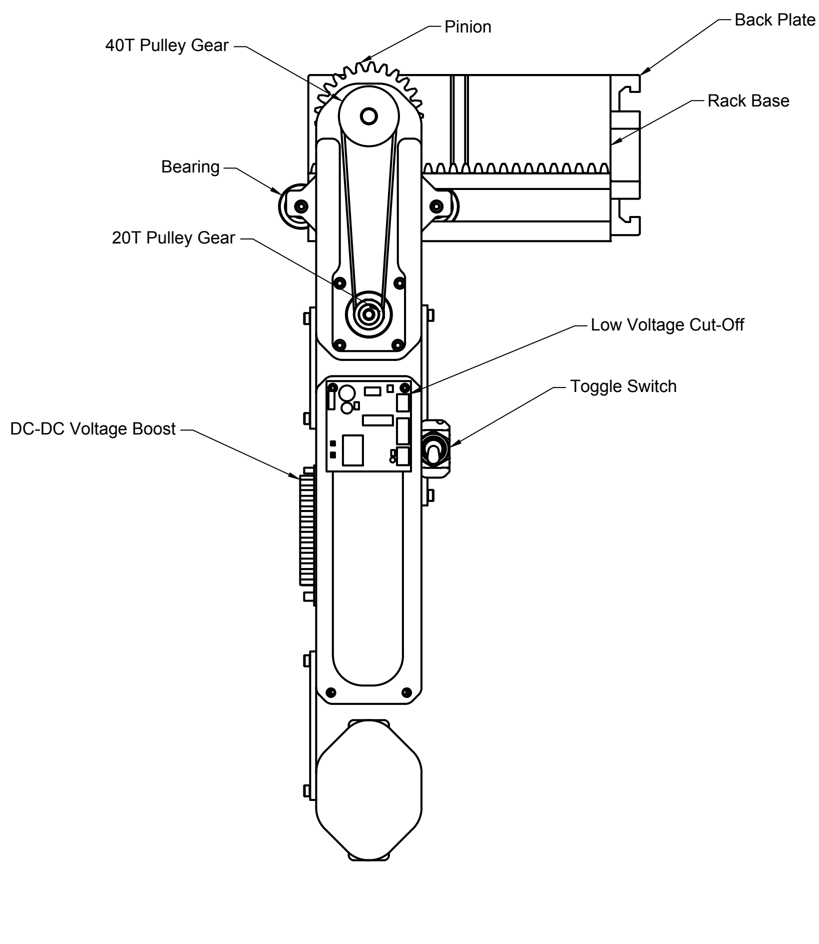


### 9.1 System Architecture Overview

OTO is composed of four major subsystems:

- Cleaning Carriage: The heart of the mechanism, housing the stepper motor, pinion gear, eraser pad, and bearing slides. Mounted directly onto linear rods to enable smooth travel.
- Rack and Pinion Drive System: 3D-printed rack segments are aligned in series. A pinion gear interfaces with these racks, converting motor rotation into linear motion.
- Control System: An Arduino Uno interfaces with a TMC2209 stepper motor driver (via UART), limit switches, and a single-button input.
- Power Supply: A 3-cell (11.1V) LiPo battery provides portable power. Voltage is stepped up to 20.1V for the stepper motor and kept isolated from control logic.

The system can be mounted either directly onto board frames or through magnetic/adhesive fixtures depending on surface compatibility.



### 9.2 Additive Manufacturing (FDM)

All mechanical components were produced using Fused Deposition Modeling (FDM) on an Elegoo Neptune 3 Pro using grey eSUN PLA+. Part designs were optimized for structural rigidity, rapid printing, and minimal post-processing.

Key FDM Manufacturing Considerations:

| Parameter | Value |
|---|---|
| Layer Height | 0.2mm |
| Wall Line Count | 3 |
| Top/ Bottom Layers | 4 |
| Infill | 20% grid |
| Print Speed | 50 mm/s |
| Material | eSun PLA+ |
| Filament Diameter | 1.75mm |

Best Practices Applied:

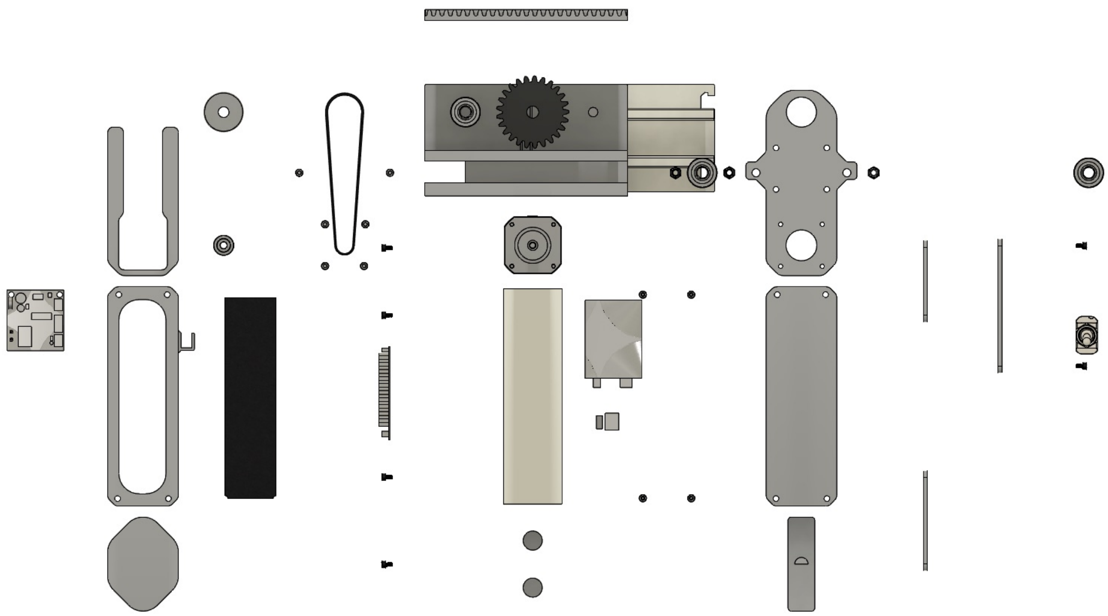
- Snap-fit and dovetail joints were tolerance-tested in 0.1 mm increments
- Long components were divided into ≤ 0.5 ft sections for printer compatibility
- Chamfers replaced vertical overhangs to minimize supports
- Large flat parts were printed with brims to prevent warping

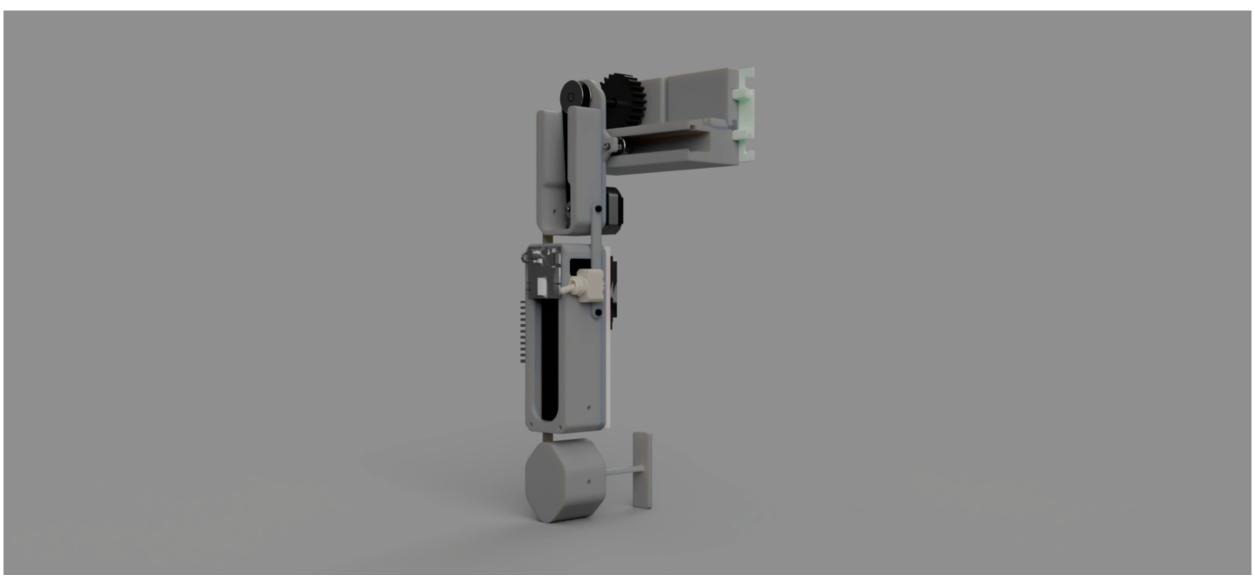
### 9.3 Component Specifications

| Component | Specification | Purpose |
|---|---|---|
| **Stepper Motor** | NEMA 17, 42mm, 1.8° | Drives pinion gear |
| **Motor Driver** | TMC2209, UART mode | Silent motion, current control |
| **Limit Switches** | Normally open, 2x | Detect endpoints, enable homing |
| **Battery** | 11.1V LiPo, 2200mAh | Powers full system (≥30 cycles) |
| **Rack Segment** | 3D-printed, 151mm | Modular linear travel track |
| **Pinion Gear** | 16T, printed | Interacts with rack |
| **Linear Rods** | 8mm, aluminum | Guides carriage motion |
| **Bearings** | LM8UU x4 | Ensures low-friction travel |
| **Eraser Pad** | Foam + felt layer | Mounted on underside of carriage |

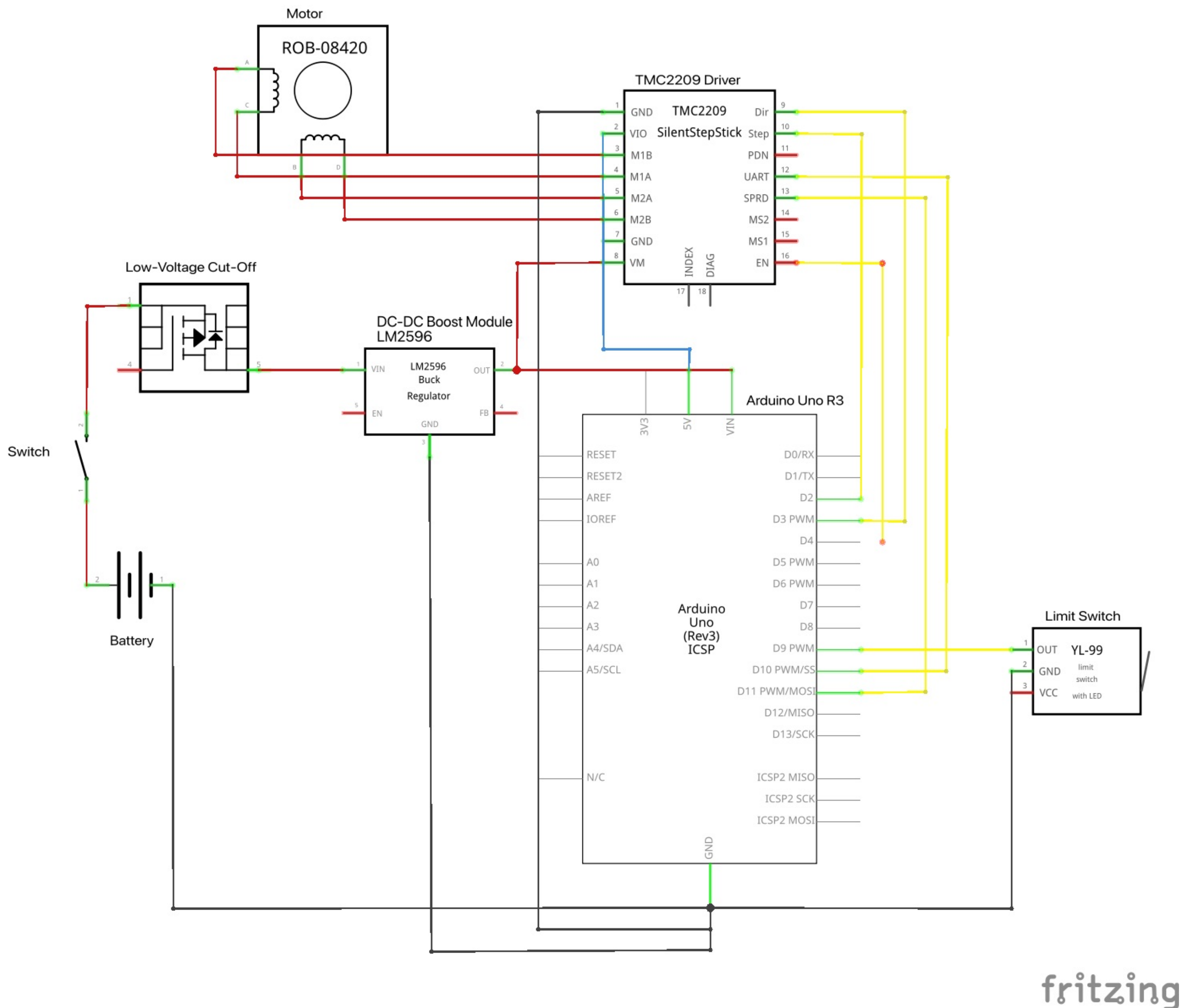
### 9.4 Final CAD Views

Exploded View:





# Wiring Diagram



Arduino Code:

Used for safety testing with limit switches and verifying motion

```
#include <TMCStepper.h>
#include <SoftwareSerial.h>

#define EN_PIN       4
#define STEP_PIN     3
#define DIR_PIN      2
#define BTN_PIN      9
#define LS_LEFT_PIN   A1    // left limit switch (NO)
#define LS_RIGHT_PIN  A0    // right limit switch (NO)

#define R_SENSE      0.11f
#define UART_RX      11    // Driver TX → Uno RX
#define UART_TX      10    // Uno TX → Driver RX
#define DRIVER_ADDR   0x00  // MS1 & MS2 tied LOW

SoftwareSerial SoftSerial(UART_RX, UART_TX);
TMC2209Stepper driver(&SoftSerial, R_SENSE, DRIVER_ADDR);


const unsigned int CAL_DELAY     = 250;  // half-pulse delay (µs)
const int          CYCLE_COUNT  = 10;   // back-and-forth cycles

void setup() {
  pinMode(EN_PIN,       OUTPUT);
  pinMode(STEP_PIN,     OUTPUT);
  pinMode(DIR_PIN,      OUTPUT);
  pinMode(BTN_PIN,      INPUT_PULLUP);
  pinMode(LS_LEFT_PIN,  INPUT_PULLUP);
  pinMode(LS_RIGHT_PIN, INPUT_PULLUP);

  digitalWrite(EN_PIN, LOW);  // enable driver

  Serial.begin(9600);
  SoftSerial.begin(115200);
  delay(500);

  driver.begin();
  driver.toff(5);
```

```
  driver.rms_current(1800);   // 1.8 A RMS
  driver.microsteps(1);       // full-step
  driver.en_spreadCycle(true);
  driver.pwm_autoscale(true);

  Serial.println("Ready. Press button to start cycle test.");
}

void loop() {
  waitForButtonPress();

  Serial.println("Starting cycle test...");
  runCycleTests();
  Serial.println("Cycle test complete. Press button to repeat.");
}

/* -------- CYCLE TEST -------- */
void runCycleTests() {
  for (int cycle = 1; cycle <= CYCLE_COUNT; cycle++) {
    Serial.print("Cycle "); Serial.print(cycle); Serial.println(": moving LEFT");

    digitalWrite(DIR_PIN, LOW);
    while (digitalRead(LS_LEFT_PIN) == HIGH) {
      stepOnce();
    }
    delay(200);

    Serial.println("  Left limit reached. Moving RIGHT");

    digitalWrite(DIR_PIN, HIGH);
    while (digitalRead(LS_RIGHT_PIN) == HIGH) {
      stepOnce();
    }
    delay(200);

    Serial.println("  Right limit reached.");
  }

  // ensure system finish back on the LEFT home
  Serial.println("Returning to LEFT home...");
```

```
  digitalWrite(DIR_PIN, LOW);
  while (digitalRead(LS_LEFT_PIN) == HIGH) {
    stepOnce();
  }
  delay(200);
  Serial.println("Home at LEFT limit.");
}

/* -------- HELPERS -------- */
void waitForButtonPress() {
  while (digitalRead(BTN_PIN) == HIGH) {}
  delay(200);
  while (digitalRead(BTN_PIN) == LOW) {}
  delay(200);
}

void stepOnce() {
  digitalWrite(STEP_PIN, HIGH);
  delayMicroseconds(CAL_DELAY);
  digitalWrite(STEP_PIN, LOW);
  delayMicroseconds(CAL_DELAY);
}
```

# 10. Engineering Analysis

This section outlines the performance characteristics of OTO based on hands-on testing, estimated calculations, and iterative mechanical refinement. While this prototype phase did not involve formal stress analysis or FEA due to time constraints, engineering principles were applied to verify the system's ability to meet motion, torque, and cleaning objectives under real operational conditions.

### 10.1 Drive System Torque Analysis

The central motion system relies on a rack-and-pinion configuration powered by a NEMA 17 stepper motor. Torque sufficiency and gear engagement were validated through incremental stress testing, observing for skipped steps, gear slippage, or mechanical flex.

- Carriage Mass (fully loaded): ~420g
- Static Load on Drive Gear: ~4.1N (due to horizontal carriage weight and pad friction)
- Estimated Required Torque: ~0.24–0.28 N·m at full extension
- Motor Output Capability:
    - 0.45 N·m peak at 12V and 800mA (TMC2209 driver with current limiting)
    - Operating at 70% duty to allow thermal headroom

### 10.2 Stepper Motor Control Tuning

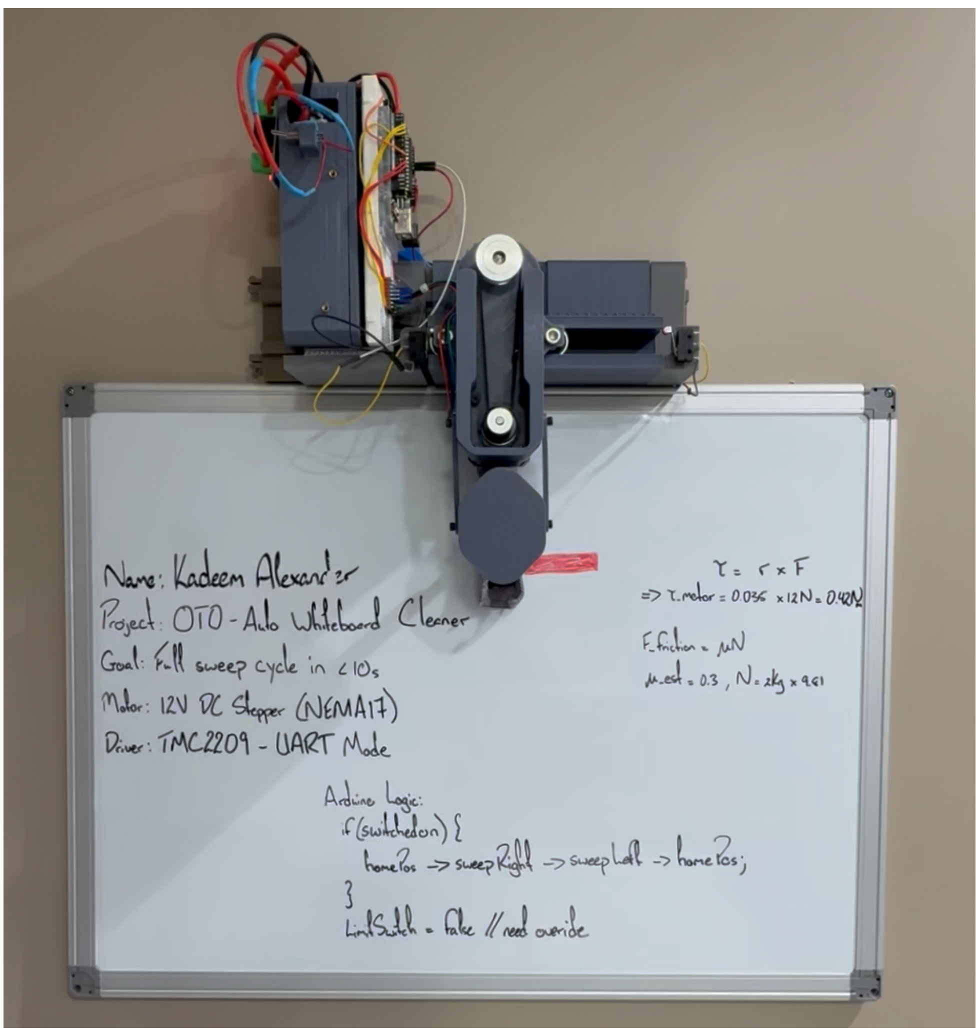
The TMC2209 driver was used in UART mode to enable dynamic configuration of microstepping, current control, and velocity ramping. Parameters were tuned empirically to prevent jerking at startup and reduce inertial stress on the gear teeth.

| Parameter | Value |
|---|---|
| Micro stepping | 1/16 (software-configured) |
| Initial Speed | 200 step/sec |
| Max Speed | 8000 step/sec |
| Acceleration | 250 step/sec*sec |
| Holding Current | 50% of runtime current (standby mode) |

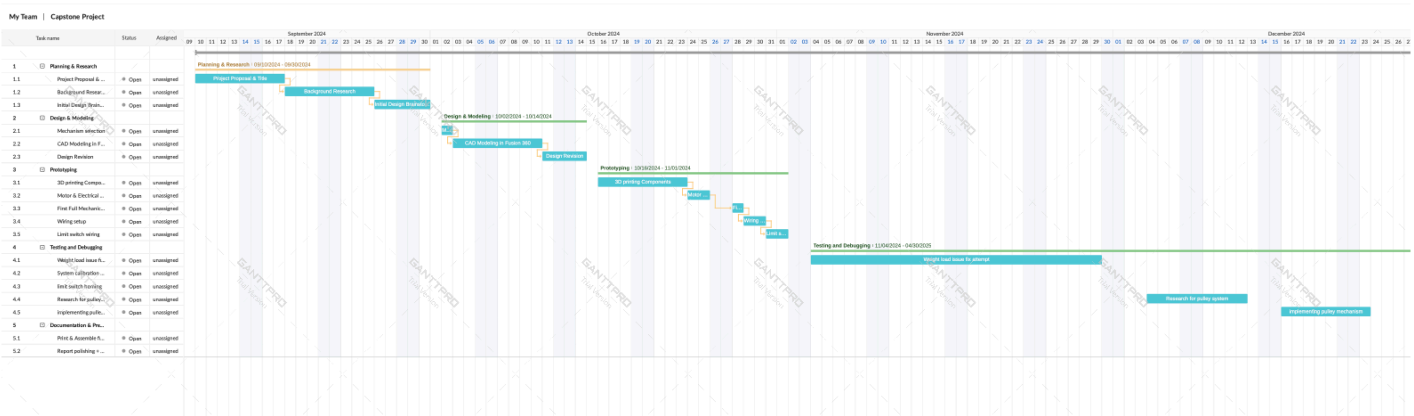
### 10.3 Limit Switch Integration and Homing Precision

Both ends of the rack are equipped with mechanical limit switches (normally open) to define motion boundaries and support homing operations. The switches are mounted using adjustable brackets, allowing for micro-adjustments in physical trigger position.

- Debounce Time: 20 ms (software-filtered)
- Step Repeatability: ±1–2 steps from trigger edge (due to mechanical flex)
- Backoff Distance After Homing: ~3 steps (~0.6 mm) to disengage switch
- Observed Wear After 50+ Activations: None



## Project Timeline




## Budget

| Description | Qty Used | Unit Price ($) | Ext Price ($) | Procurement Cost ($) |
|---|---|---|---|---|
| NEMA 17 Motor (Pack of 4) | 1 | 8.25 | 8.25 | 32.99 |
| Zeee 3S Lipo Battery 5200mAh 11.1V 50C | 1 | 34.99 | 34.99 | 34.99 |
| Arduino Uno | 1 | 27.6 | 27.6 | 27.6 |
| 12-36V low Voltage Digital Protector Cut Off | 1 | 11.99 | 11.99 | 11.99 |
| TMC2209 V1.3 Driver | 1 | 9.99 | 9.99 | 9.99 |
| GT2 Timing Belt | 1 | 8.99 | 8.99 | 8.99 |
| Micro Limit Switch (10pcs) | 1 | 0.59 | 0.59 | 5.99 |
| 40T GT2 Pulley Wheel (2pcs) | 1 | 3.99 | 3.99 | 7.99 |
| Mini Toggle Switch (10pcs) | 1 | 0.79 | 0.79 | 7.99 |
| 20T GT2 Pulley Wheel (5pcs) | 1 | 1.39 | 1.39 | 6.99 |

| | | | | |
|---|---|---|---|---|
| SHKI 608 2RS Ball Bearings (20pcs) | 2 | 0.35 | 0.7 | 6.99 |
| M3*8 Screws | 16 | 0.011 | 0.18 | 9.88 |
| M6*25 Screws | 2 | 0.052 | 0.1 | 8.99 |
| M3*6*5 Female Threaded Knurled Nuts | 12 | 0.04 | 0.49 | 16.99 |
| Breadboard | 1 | 6.49 | 6.49 | 6.49 |
| PCB Mount Screw Terminal | 2 | 0.25 | 0.5 | 13.99 |
| 16 AWG Cables | 0.5ft | 2.79 (per ft) | 1.39 | 13.99 |
| DC-DC Boost Converter Module (2pcs) | 1 | 4.05 | 4.05 | 8.09 |
| Printed Parts | Qty Used | Unit Weight (g) | Cost to Print ($) | Unit Price ($) |
| Back Plate | 3 | 40 | 2.25 | 0.75 |
| Rack Base | 3 | 134 | 7.44 | 2.48 |
| Rack | 3 | 20 | 1.08 | 0.36 |
| Pinion | 1 | 12 | 0.23 | 0.23 |
| Gear Mount | 1 | 21 | 0.38 | 0.38 |
| Gear Mount Cover | 1 | 30 | 0.55 | 0.55 |
| Battery Mount | 1 | 26 | 0.48 | 0.48 |
| Battery Mount Cover | 1 | 56 | 1.03 | 1.03 |
| Pod | 1 | 34 | 0.62 | 0.62 |
| Cleaning Arm | 1 | 8 | 0.14 | 0.14 |

| | | | | |
|---|---|---|---|---|
| Security Tags | 4 | 3 | 0.2 | 0.05 |
| Parts Total ($) | 122.47 | | | |
| Print Total ($) | 14.4 | | | |
| Prototype Total (1.5ft x 0.5ft) ($) | 136.87 | +$3.73 per 0.5ft horizontal & vertical expansion | | |

# Conclusion

By leveraging a modular rack-and-pinion mechanism driven by a NEMA 17 stepper and TMC2209 driver, the system reliably performs ten sweeps across a 1.5 ft×0.5 ft section in under 20 seconds, with residual ink below 5% exceeding the ER-1 and ER-2 performance targets (70mm x 25mm patch test). The single-button interface, dual limit-switch homing logic, and open-source design underscore OTO’s ease of use and adaptability to board sizes up to 8 ft wide, all for a prototype cost of $136.87 and $3.73 per 0.5 ft expansion .

Mechanically, the rack-and-pinion architecture delivered high precision and repeatability, with backlash under 0.6 mm after homing and zero observed wear on limit switches after 50+ cycles. The choice of PLA+ for 3D-printed components balanced stiffness and fatigue resistance, while the TMC2209’s current control and optional StallGuard4 homing capability provided smooth, silent motion. These design decisions adhered to ANSI Y14.5 tolerancing, UL 94 HB flammability, and IEC 60204-1 low-voltage safety standards, ensuring a robust, classroom-friendly system

Beyond technical performance, OTO demonstrates significant educational and economic impact. By reclaiming up to 50 minutes of instructional time per week and reducing consumables like cleaning sprays and markers, it offers measurable productivity gains and environmental benefits. Its low cost and modular, repairable design make it accessible to underfunded schools, fostering hands-on learning in mechatronics and open-source innovation

Looking forward, integrating sensorless StallGuard homing, refining the flexure-based belt tensioning, and adding a user-configurable UI for sweep count and speed will further enhance reliability and versatility. Pilot deployments in live classroom settings, extended fatigue testing, and development of injection-molded rails will pave the way from prototype to scalable product. OTO’s success illustrates how targeted, low-cost automation can address everyday challenges in education, setting a precedent for future modular mechatronic solutions.

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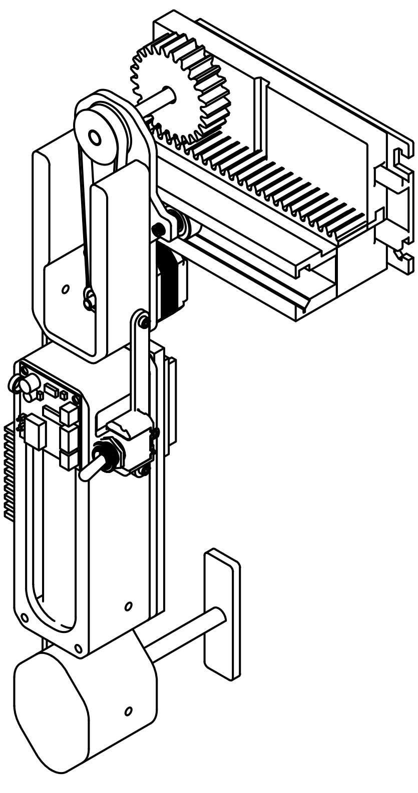
# Appendix



PROJECT

OTO: Automatic Whiteboard Cleaning System

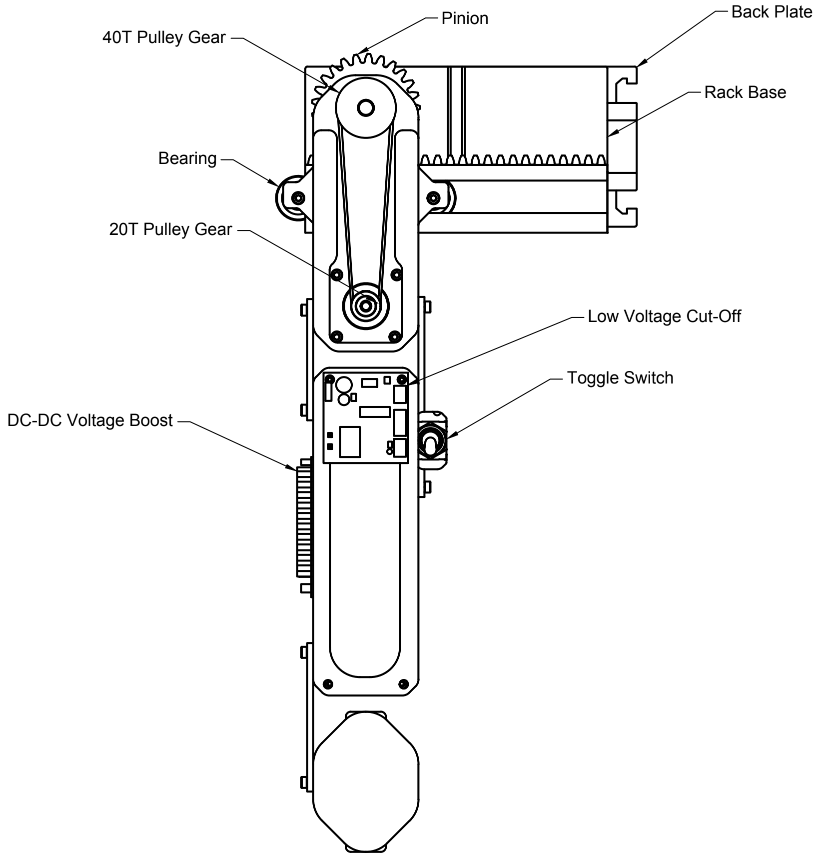
TITLE

Assembly

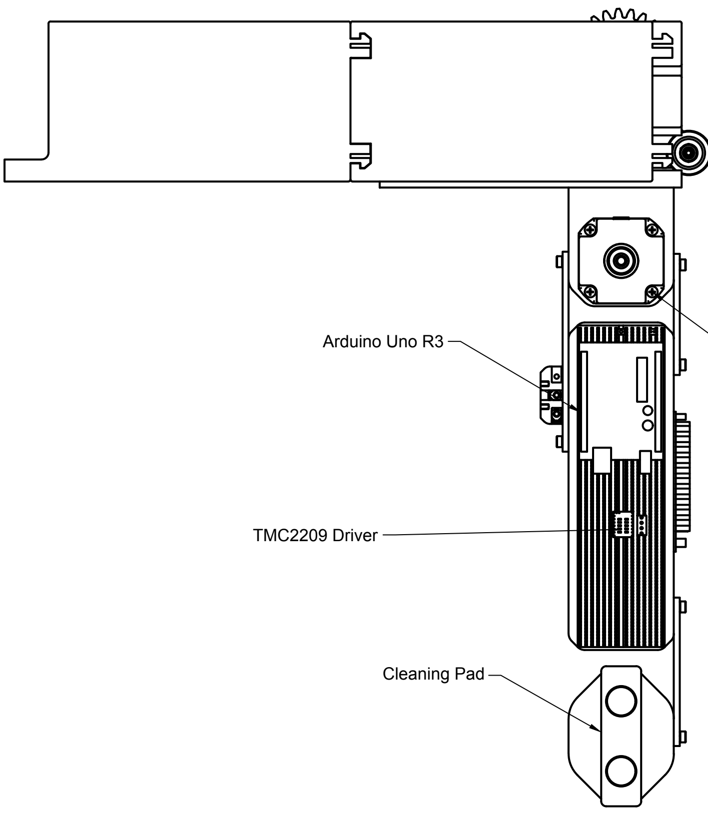
-

Release to Manufacturing

| | | | | |
|---|---|---|---|---|
| APPROVED - | - | SIZE B | CODE - | DWG NO - | REV - |
| CHECKED - | - | | | | |
| DRAWN Kadeem Alexander | 5/4/25 | SCALE 1:2 | WEIGHT - | SHEET 1/12 | |




| | | | | |
|---|---|---|---|---|
| | PROJECT OTO: Automated Whiteboard Cleaning System | | | |
| | TITLE Assembly | | | |
| | Release to Manufacturing | | | |
| APPROVED | SIZE B | CODE | DWG NO | REV |
| CHECKED | | | | |
| DRAWN Kadeem Alexander 5/4/2025 | SCALE 1:2 | WEIGHT 990g | SHEET 1/1 | |

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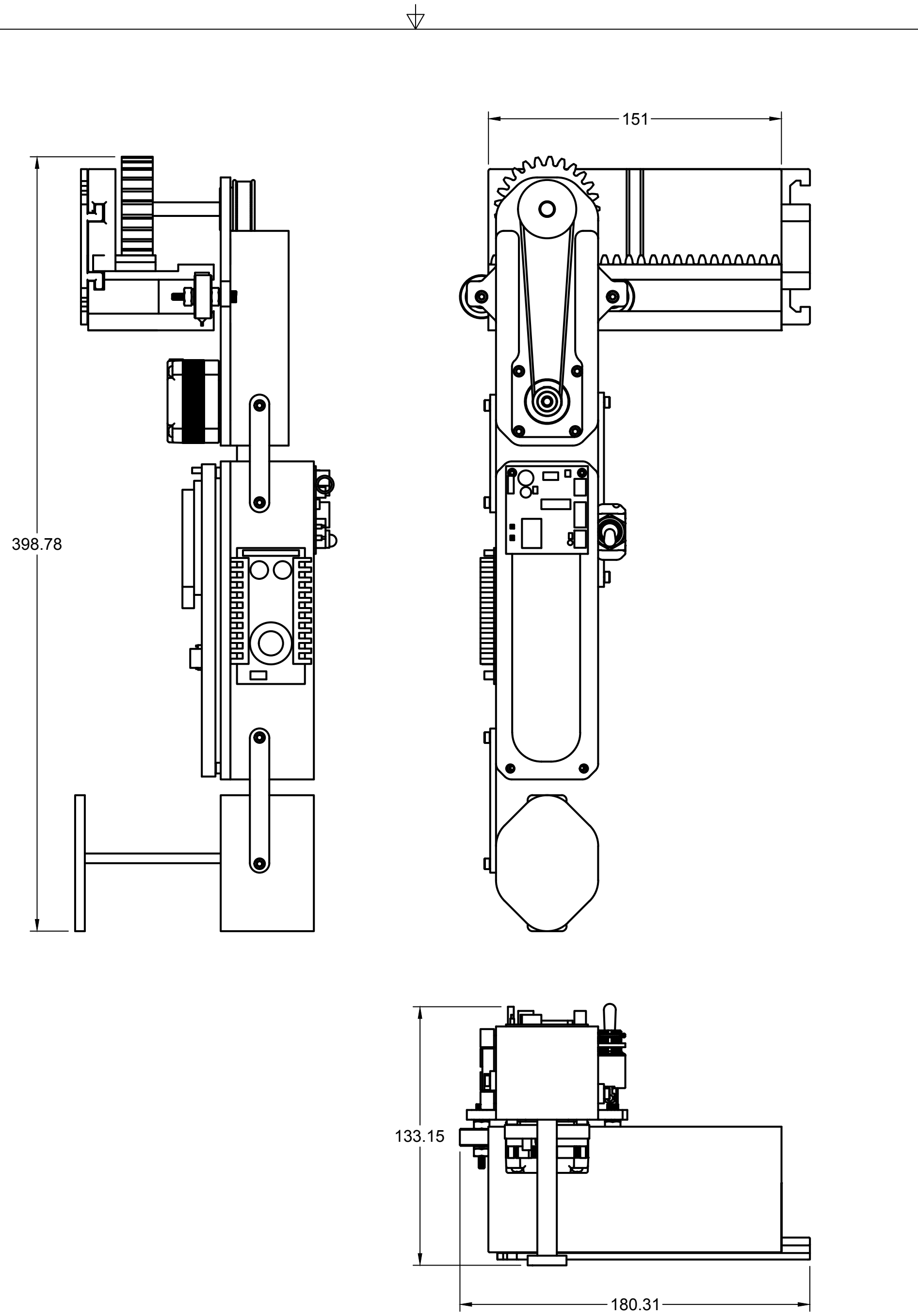
|---|---|---|---|---|
| | PROJECT<br>OTO: Automatic Whiteboard Cleaning System | | | |
| | TITLE<br>Assembly<br>-<br>Release to Manufacturing | | | |
| APPROVED - - | SIZE B | CODE - | DWG NO - | REV - |
| CHECKED - - | | | | |
| DRAWN Kadeem Alexander 5/4/25 | SCALE 1:5 | WEIGHT - | SHEET 3/12 | |




PROJECT

OTO: Automatic Whiteboard Cleaning System

TITLE

Assembly

-

Release to Manufacturing

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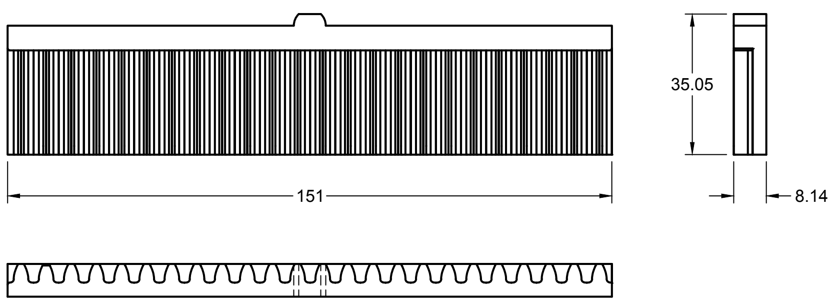
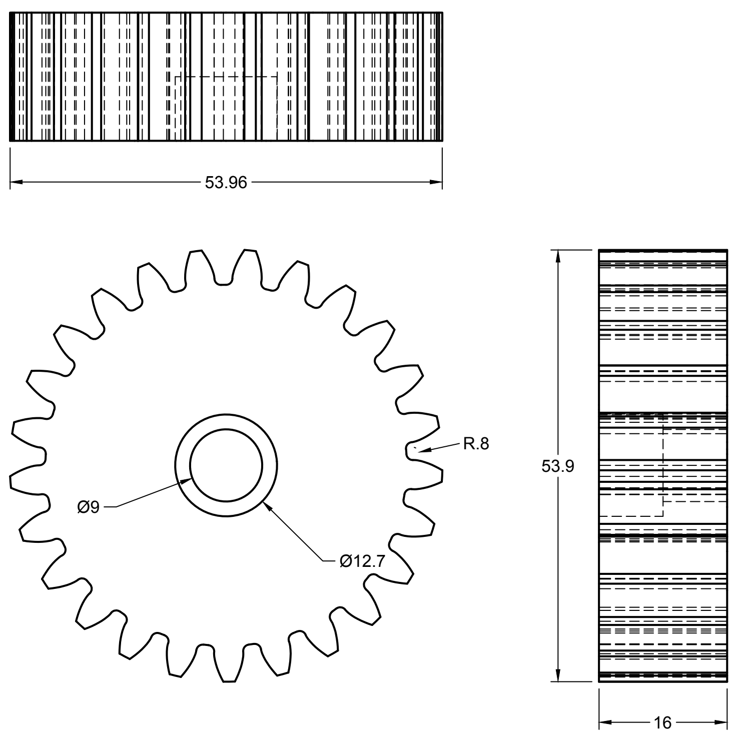
|---|---|---|---|---|---|---|
| APPROVED - | - | SIZE | CODE | DWG NO | | REV |
| CHECKED - | - | B | - | - | | - |
| DRAWN | Kadeem Alexander 5/4/25 | SCALE 1:2 | | WEIGHT - | SHEET 4/12 | |




PROJECT
OTO: Automatic Whiteboard Cleaning System

TITLE
Assembly
-
Release to Manufacturing

| | | | | | |
|---|---|---|---|---|---|
| APPROVED - | - | SIZE B | CODE - | DWG NO - | REV - |
| CHECKED - | - | | | | |
| DRAWN Kadeem Alexander | 5/4/25 | SCALE 1:1 | WEIGHT - | SHEET 5/12 | |




PROJECT
OTO: Automatic Whiteboard Cleaning System

TITLE
Assembly
-
Release to Manufacturing

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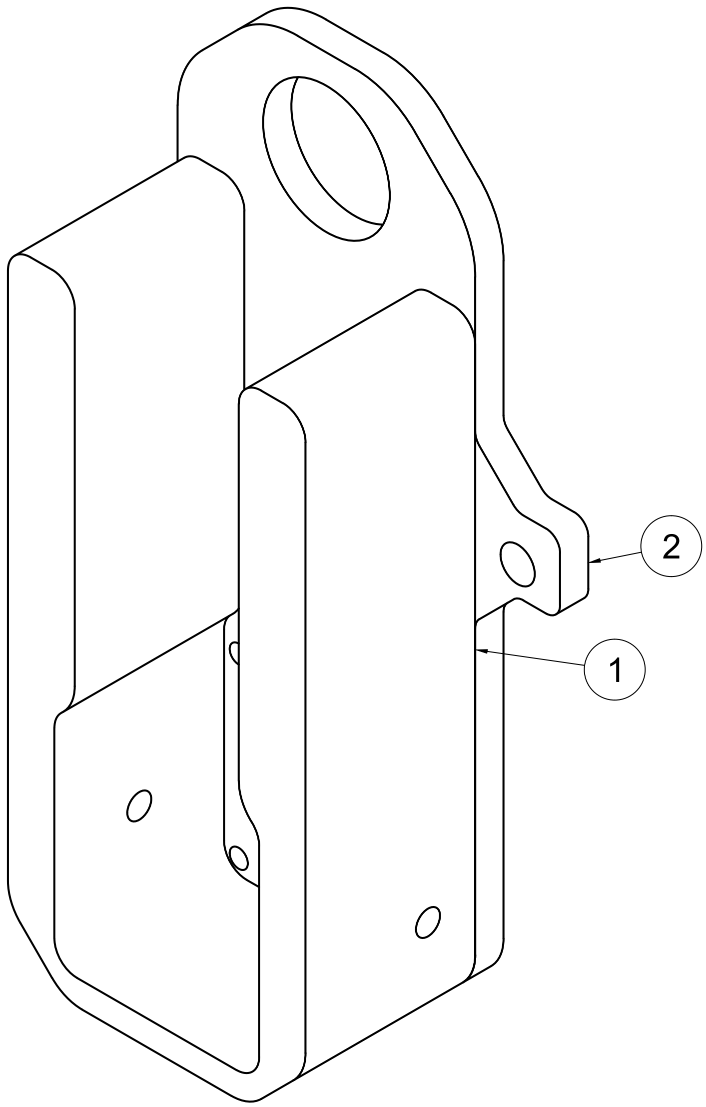
|---|---|---|---|---|---|---|
| APPROVED - | - | SIZE | CODE | DWG NO | | REV |
| CHECKED - | - | B | - | - | | - |
| DRAWN | Kadeem Alexander 5/4/25 | SCALE 2:1 | | WEIGHT - | SHEET 6/12 | |

| PARTS LIST | | | |
|---|---|---|---|
| ITEM | QTY | PART NUMBER | MATERIAL |
| 1 | 1 | GEAR MOUNT COVER | PLA+ |
| 2 | 1 | MOUNT | PLA+ |

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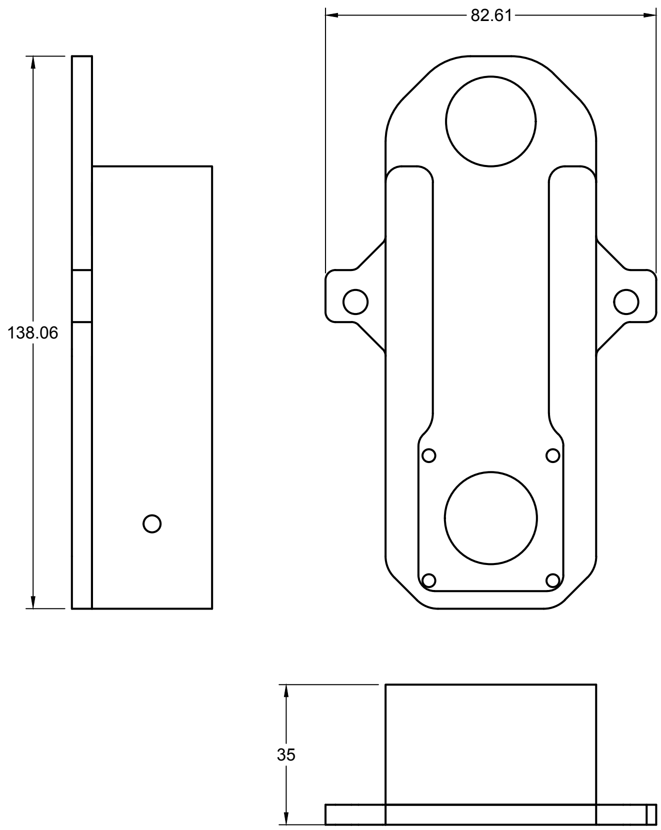
| | TITLE<br>Assembly<br>-<br>Release to Manufacturing | | | |
| APPROVED - - | SIZE<br>B | CODE<br>- | DWG NO<br>- | REV<br>- |
| CHECKED - - | | | | |
| DRAWN Kadeem Alexander 5/4/25 | SCALE 2:1 | WEIGHT - | SHEET 7/12 | |

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|---|---|---|---|
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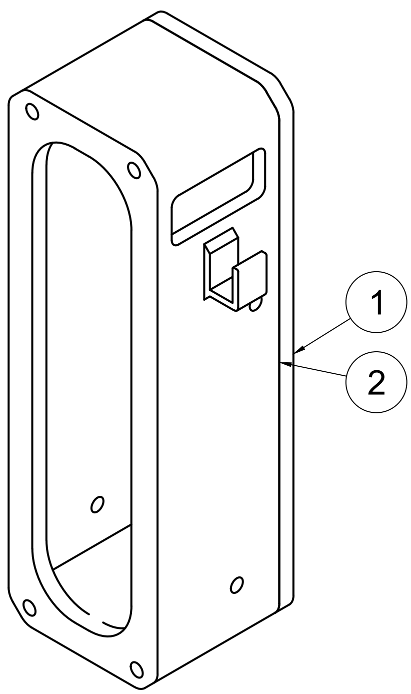
| | TITLE<br>Assembly<br>-<br>Release to Manufacturing | | |
| APPROVED - - | SIZE B | CODE - | DWG NO - | REV - |
| CHECKED - - | | | | |
| DRAWN Kadeem Alexander 5/4/25 | SCALE 1:1 | WEIGHT - | SHEET 8/12 |

| PARTS LIST | | | |
|---|---|---|---|
| ITEM | QTY | PART NUMBER | MATERIAL |
| 1 | 1 | BATTERY MOUNT | PLA+ |
| 2 | 1 | BATTERY MOUNT COVER | PLA+ |

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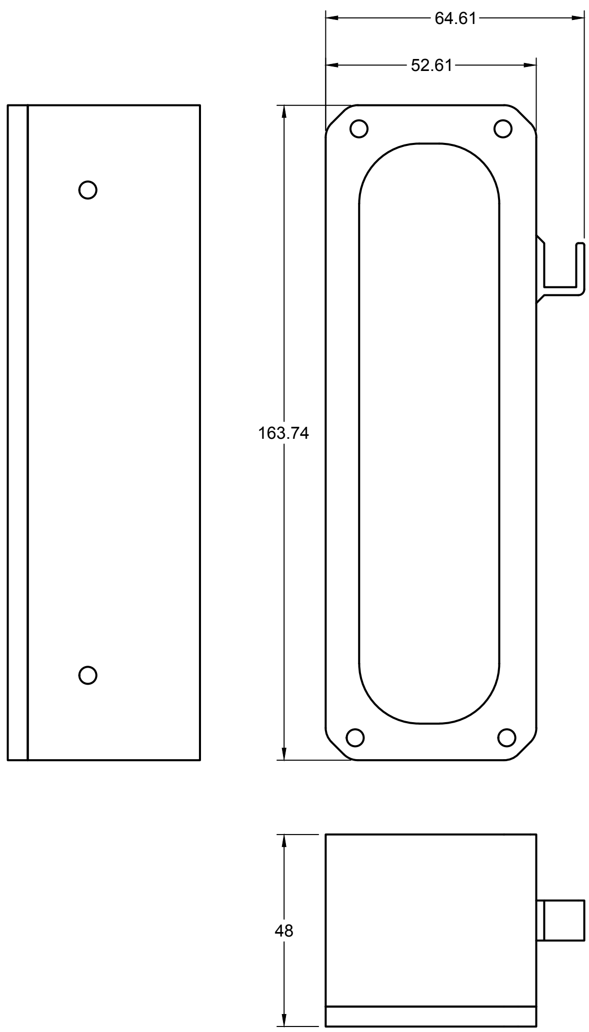
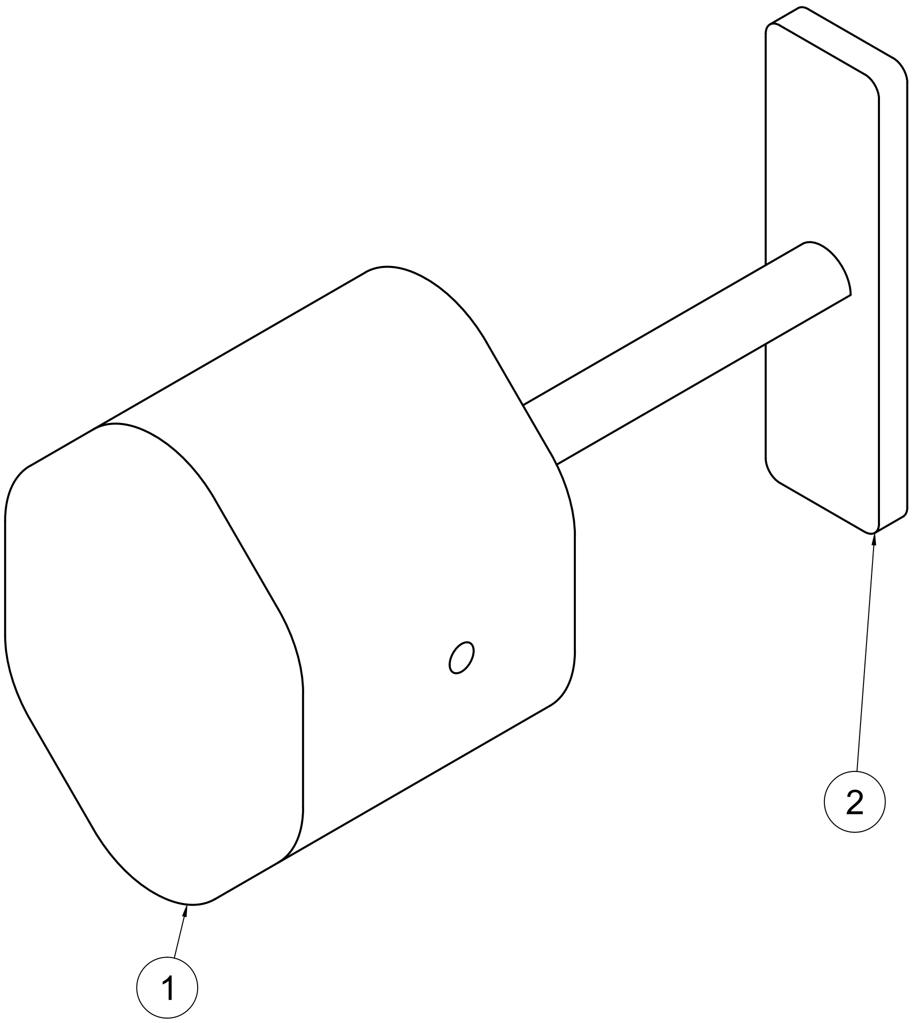
| | TITLE<br>Assembly<br>-<br>Release to Manufacturing | | | |
| APPROVED - - | SIZE<br>B | CODE<br>- | DWG NO<br>- | REV<br>- |
| CHECKED - - | | | | |
| DRAWN Kadeem Alexander 5/4/25 | SCALE 1:1 | WEIGHT - | SHEET 9/12 | |




| PROJECT | | | | | |
|---|---|---|---|---|---|
| OTO: Automatic Whiteboard Cleaning System | | | | | |
| TITLE | | | | | |
| Assembly | | | | | |
| - | | | | | |
| Release to Manufacturing | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| APPROVED - | - | SIZE B | CODE - | DWG NO - | REV - |
| CHECKED - | - | | | | |
| DRAWN | Kadeem Alexander 5/4/25 | SCALE 1:1 | WEIGHT - | SHEET 10/12 | |

| PARTS LIST | | | |
|---|---|---|---|
| ITEM | QTY | PART NUMBER | MATERIAL |
| 1 | 1 | POD | PLA+ |
| 2 | 1 | CLEANING ARM | PLA+ |

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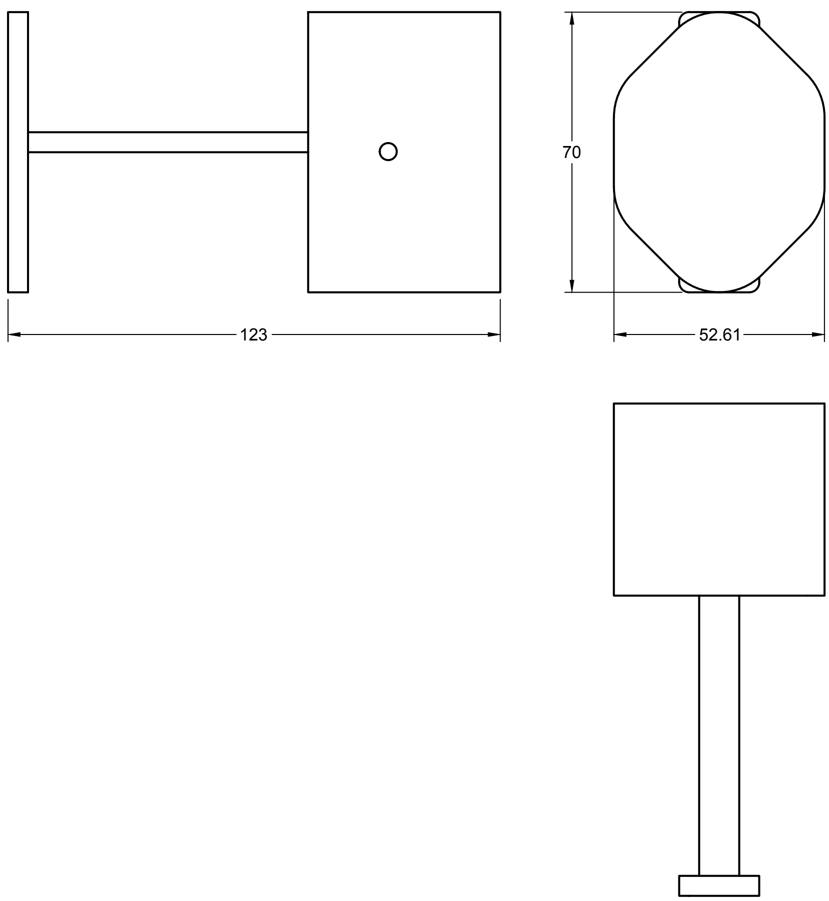
| | TITLE<br>Assembly<br>-<br>Release to Manufacturing | | | | | |
| APPROVED - - | SIZE<br>B | CODE<br>- | DWG NO<br>- | | REV<br>- | |
| CHECKED - - | | | | | | |
| DRAWN Kadeem Alexander 5/4/25 | SCALE 2:1 | | WEIGHT - | SHEET 11/12 | | |




| | | | | |
|---|---|---|---|---|
| PROJECT | OTO: Automatic Whiteboard Cleaning System | | | |
| TITLE | Assembly<br>-<br>Release to Manufacturing | | | |
| APPROVED - - | SIZE B | CODE - | DWG NO - | REV - |
| CHECKED - - | | | | |
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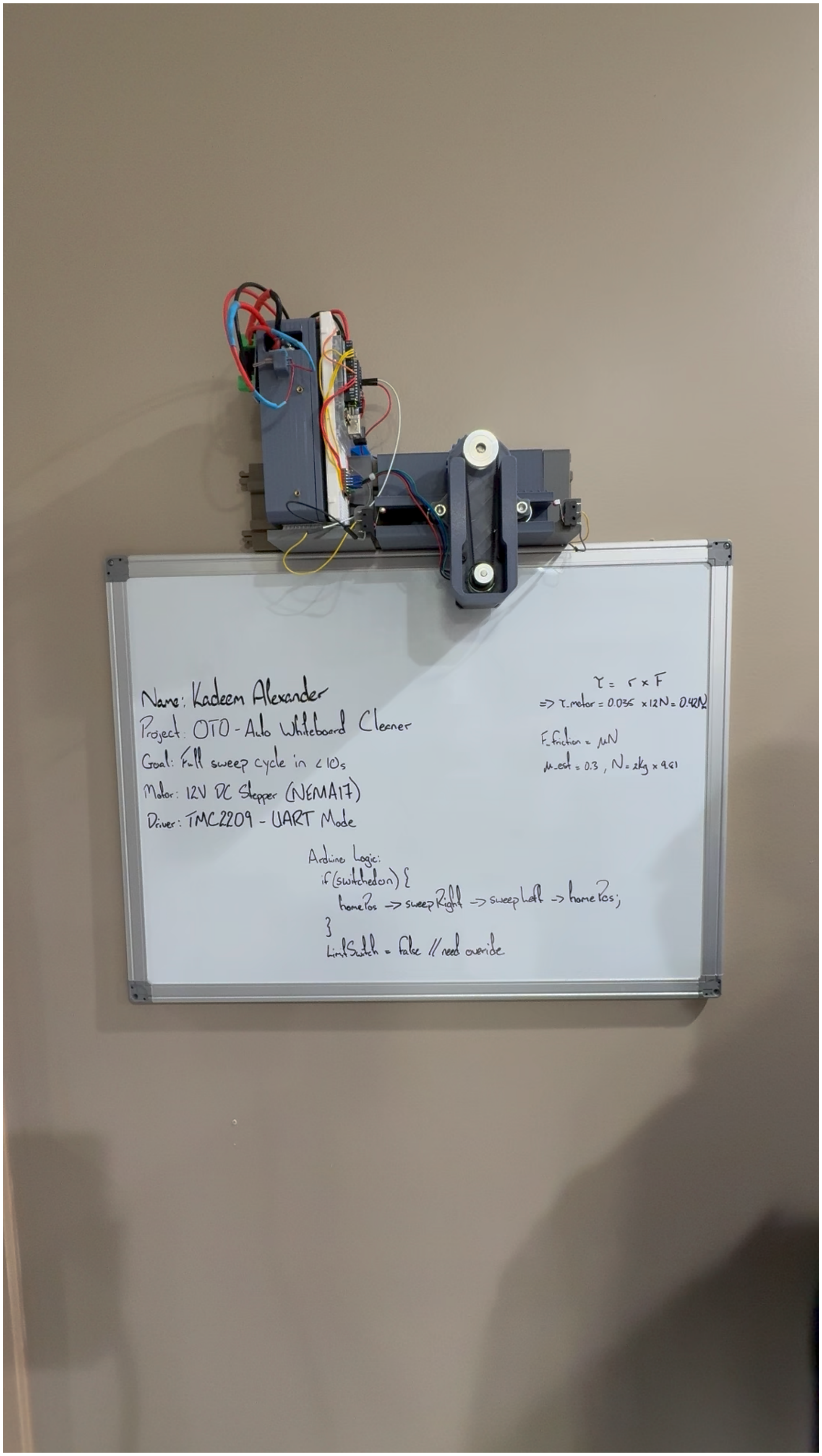
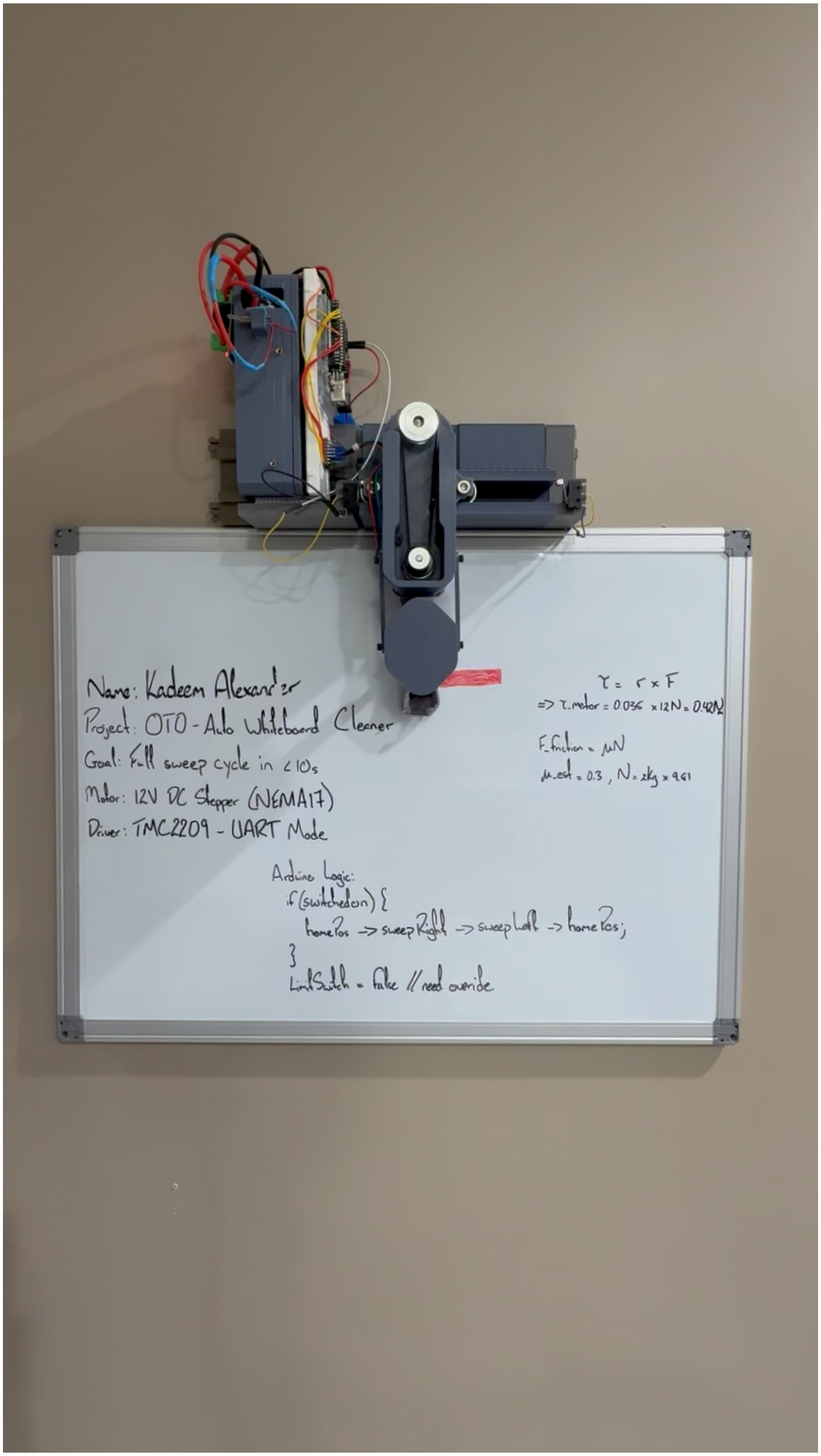

Name: Kadeem Alexander
Project: OTO - Auto Whiteboard Cleaner
Goal: Full sweep cycle in <10s
Motor: 12V DC Stepper (NEMA17)
Driver: TMC2209 - UART Mode
τ = r x F
=> τ_motor = 0.035 x 12N = 0.42N
F_friction = μN
μ_est = 0.3 , N = 2kg x 9.81
Arduino Logic:
if (switchedon) {
homePos -> sweepRight -> sweepLeft -> homePos;
}
LimitSwitch = false // need override


Name: Kadeem Alexander
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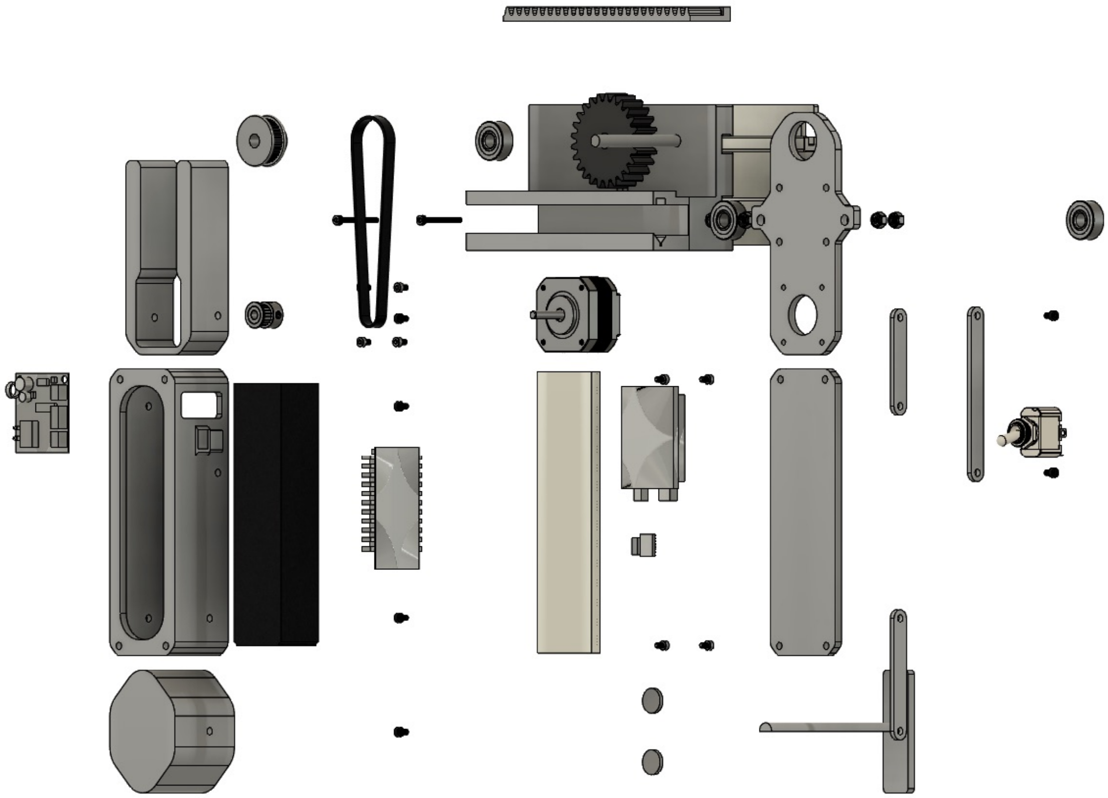

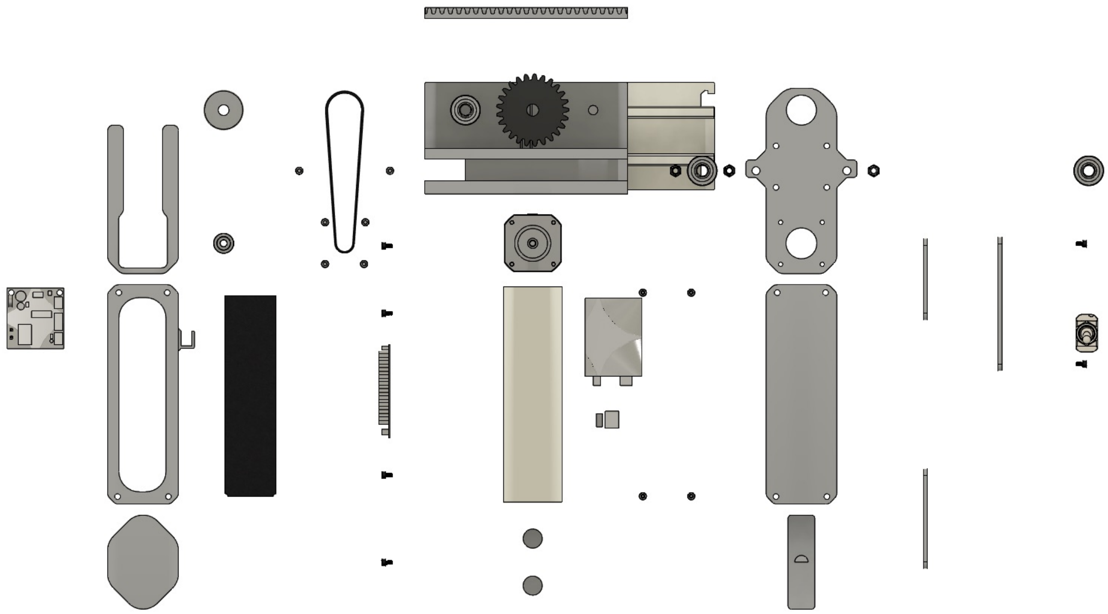

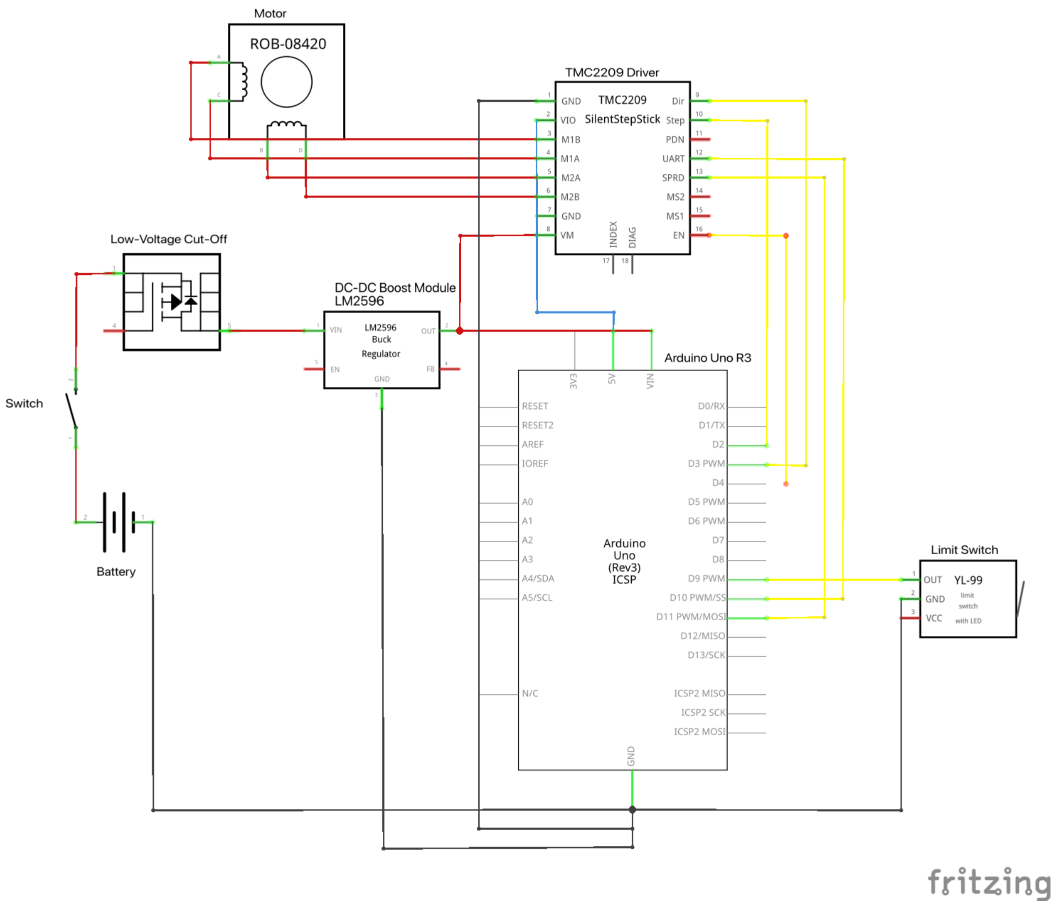
Motor
ROB-08420
TMC2209 Driver
TMC2209
SilentStepStick
GND
VIO
M1B
M1A
M2A
M2B
GND
VM
Dir
Step
PDN
UART
SPRD
MS2
MS1
EN
INDEX
DIAG
Low-Voltage Cut-Off
DC-DC Boost Module
LM2596
LM2596
Buck
Regulator
VIN
OUT
EN
FB
GND
Arduino Uno R3
3V3
5V
VIN
RESET
RESET2
AREF
IOREF
A0
A1
A2
A3
A4/SDA
A5/SCL
N/C
D0/RX
D1/TX
D2
D3 PWM
D4
D5 PWM
D6 PWM
D7
D8
D9 PWM
D10 PWM/SS
D11 PWM/MOSI
D12/MISO
D13/SCK
ICSP2 MISO
ICSP2 SCK
ICSP2 MOSI
Arduino
Uno
(Rev3)
ICSP
GND
Switch
Battery
Limit Switch
OUT
GND
VCC
YL-99
limit
switch
with LED
fritzing