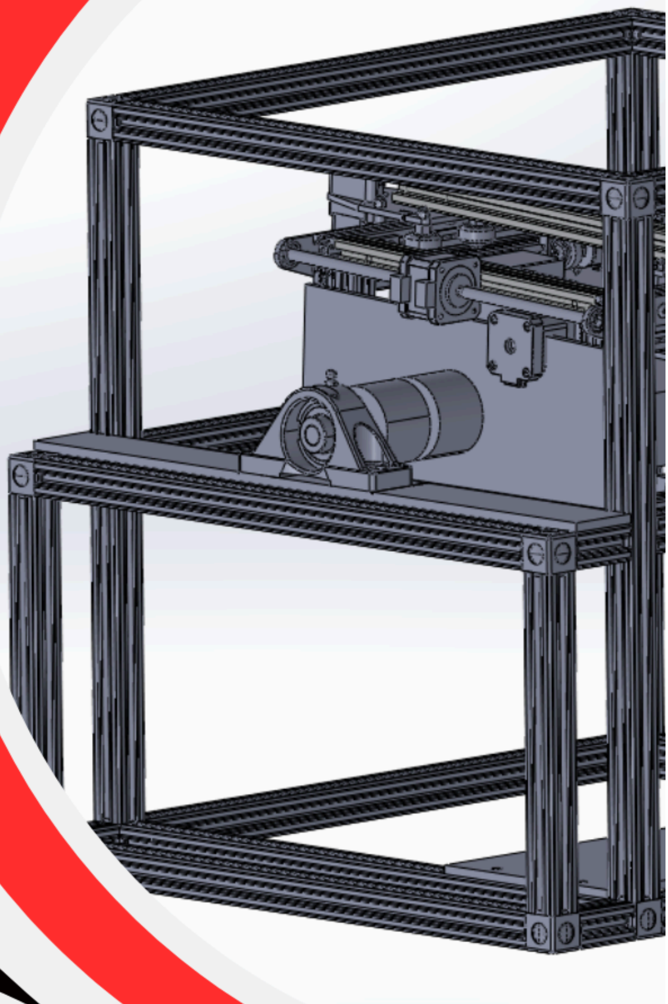
ENG 4000

FINAL CAPSTONE REPORT



Group 36: D.I.C.E.

Exploring Manufacturing In The Stars

April 21st , 2025

DYNAMIC INERTIAL CLINOSTAT EXPERIMENTAL SYSTEM

Exploring Manufacturing in the Stars

CAPSTONE PROJECT

Submitted to

LASSONDE SCHOOL OF ENGINEERING

In Fulfillment of the Requirements for the Degree

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Team Member	Designation/Major	Student ID	Signature	Date
Al-Adwan, Gaith	*Mechanical Engineer*	*218604066*	*G.A.*	*4/21/25*
Almufleh, Omar	*Mechanical Engineer*	*218318840*	*O.M.*	*4/21/25*
Balagan, Herman	*Mechanical Engineer*	*217136490*	*H.B.*	*4/21/25*
Bir, Navroz	*Electrical Engineer*	*217322967*	*N.B.*	*4/21/25*
El Zamzamy, Ibrahim	*Mechanical Engineer*	*214496657*	*I.E.*	*4/21/25*
Tawil, Omar	*Mechanical Engineer*	*217692351*	*O.T.*	*4/21/25*

Supervisor	Signature	Date
Czekanski, Aleksander	*A.C.*	*4/21/2025*

Project Teaching Team

The following esteemed faculty members comprised the teaching team for THE D.I.C.E system, providing academic guidance, support and supervision where required throughout the duration of the project.

Lead Supervisor

Prof. Aleksander Czekanski
Department of Mechanical Engineering, York University
Director of Manufacturing Technology Entrepreneurship Research Centre

Capstone Management Team

Prof. Edris M. Hassan
Department of Mechanical Engineering, York University

Prof. Costas Armenaski
Department of Earth & Space Science & Engineering, York University

Prof. Gerd Grau
Department of Electrical Engineering & Computer Science, York University

Ms. Claudia Bennett
Engineering Capstone Course Coordinator, York University

Executive Summary

This report presents the design, development, and validation strategy of the Dynamic Inertial Clinostat Experiment System (D.I.C.E.), a single-axis rotational device engineered to simulate hypergravity conditions for additive manufacturing research. Developed in response to the growing need for accessible gravity simulation platforms, THE D.I.C.E. enables the controlled testing of 3D printing processes under dynamic forces up to 4g, all within a compact 2 ft × 2 ft laboratory footprint. The project focuses on balancing mechanical performance, user accessibility, and affordability, with a strict budget cap of $1,000 CAD and compatibility requirements for a 12 kg, 1 ft^3 printer payload.

D.I.C.E. was developed using Agile project management principles, which allowed the team to iterate through five structured sprints. Each sprint focused on distinct development goals, including frame assembly, motor integration, environmental monitoring, vibration mitigation, and full-system calibration. The final system includes integrated temperature, humidity, and acceleration sensors, as well as a high-resolution camera for live monitoring of the printing process. These features ensure that performance under simulated gravitational conditions can be observed, analyzed, and refined in real time.

Key engineering challenges included ensuring rotational stability, reducing mechanical deflection, and maintaining system safety during high-speed operation. These were addressed through strategic design decisions such as torque-optimized motor selection, enclosure reinforcement, and vibration isolation.

Project execution was supported by comprehensive planning tools, including a Gantt chart, RACI matrix, and story point-based prioritization. Task delegation was organized to maintain clear responsibilities, improve internal coordination, and ensure progress across mechanical, electrical, and software components. Periodic reviews and feedback cycles allowed the team to assess trade-offs and pivots quickly when challenges emerged.

D.I.C.E. represents a meaningful step forward in democratizing hypergravity experimentation. Its modular design, low cost, and research-focused capabilities make it a scalable solution for academic and industrial labs alike. The system is now fully operational, with RPM precision, vibration damping, torque delivery, and sensor reliability fully evaluated. These outcomes confirm THE D.I.C.E.'s readiness for future use in simulated-gravity manufacturing studies and aerospace-oriented research.

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1.0 Introduction

1.1 Motivation and Problem Statement

The demand for simulating extraterrestrial conditions on Earth has grown significantly as space exploration, bioprinting, and advanced manufacturing technologies continue to evolve. A major challenge in this domain is the ability to replicate variable gravity environments such as hypergravity for research and testing purposes. Traditional gravity simulation systems are often large, expensive, and inaccessible to smaller institutions or iterative design teams. In response, this project introduces the Dynamic Inertial Clinostat Experimental system, also known as D.I.C.E., a compact, cost-effective clinostat system capable of simulating gravitational forces through controlled single-axis rotation.

1.2 Primary Objectives

The clinostat is engineered to rotate a 1 ft^3 3D printer payload weighing up to 12 kilograms at speeds of up to 120 RPM, enabling simulation of forces up to 4g. This allows researchers to assess the performance of additive manufacturing systems in environments analogous to those encountered in space. The system integrates environmental sensors to monitor temperature, humidity, and acceleration, as well as a high-resolution camera for real-time monitoring of printing operations. The design prioritizes portability, safety, and modularity by incorporating features like vibration-damping mounts, controlled acceleration and a protective plexiglass enclosure.

The core engineering challenge addressed by this project is the development of a stable, safe, and affordable platform that allows for precise and repeatable gravity simulations while supporting the operation of delicate systems such as bioprinters. Built under strict constraints including a maximum system footprint of 2 ft × 2 ft and a total budget of under $1,000 CAD, the clinostat provides an accessible solution for ground-based space research. Through Agile development and iterative testing, THE D.I.C.E aims to serve as a foundational tool for future research in aerospace, biomedical applications, and off-world manufacturing.

2.0 Stakeholder Analysis

2.1 Lassonde School of Engineering

A comprehensive stakeholder analysis is essential to guiding system development in a manner that satisfies both technical specifications and application-driven requirements. Stakeholders exert varying degrees of influence over design priorities, performance criteria, and long-term applicability, and their expectations must be systematically addressed to ensure successful implementation. This section evaluates the interests, influence, and roles of relevant academic, industrial, and research-based stakeholders associated with the Gravity Gizmo clinostat. By identifying and categorizing these groups based on their strategic importance, the design process can remain focused, informed, and aligned with broader objectives in aerospace research, additive manufacturing, and experimental material testing under altered gravity conditions.

2.2 Space Agencies (CSA, NASA and Blue Origin)

These organizations represent long-term end users and thought leaders in gravity-simulated experimentation. While not directly involved in the design cycle, their standards and innovation goals have heavily influenced the functional criteria of the clinostat. With high interest and influence (9/10), their role is crucial in aligning the project with the broader goals of space-based research and manufacturing validation.

2.3 3D Printing Industry

As technology providers and potential collaborators, the 3D printing sector holds strong influence over hardware integration, compatibility standards, and scalability. Their interest lies in testing new solutions under gravity variations to improve reliability in aerospace and field-based manufacturing. Their input has helped define parameters such as structural tolerances, rotational stability, and payload adaptability.

2.4 Biomedical Research (Regenerative Technology)

This stakeholder group is particularly invested in the clinostat's potential for biofabrication under variable gravity conditions. Although they have moderate influence, their interest level is high due to the relevance of this system in experimental cell printing and tissue engineering research. Their feedback guided the environmental monitoring and camera integration features of the device.

2.5 Investors

Investors, both hypothetical and actual, are represented in the stakeholder analysis due to their potential role in funding future developments or commercialization of the clinostat system. Their influence is significant, particularly regarding cost management, scalability, and proof-of-concept demonstration. They were key drivers behind the <$1,000 budget requirement and modular design principles.

2.6 Future Research and Graduate Students

Graduate students and future researchers represent a growing user base for compact gravity simulators. Their feedback emphasized ease of use, clear documentation, and remote operation features. While their influence is limited, their high level of interest reinforces the importance of intuitive interface design and accessible functionality.

2.7 Government and Defense Sector

These institutions have a peripheral yet strategic interest in gravity simulation technology for applications such as material testing, aerospace prototyping, and defense-related manufacturing. Their influence is moderate, though current engagement is low. However, maintaining awareness of their potential regulatory and funding roles is important for long-term system evolution.

2.8 Material Science Companies

These stakeholders are interested in using the clinostat as a platform to test materials under simulated stress conditions. Their mid-level placement in both interest and influence suggests that while their feedback is valued, it may be more relevant in future iterations of the project involving more rigorous stress/strain testing and material lifecycle analysis.

2.9 Students and Universities

This group includes broader educational users, such as undergraduate students and universities not directly involved in the project. While their current influence is minimal, their presence in the stakeholder map underscores the potential educational value of the clinostat. As the system matures, its scalability and low cost may make it a valuable teaching tool for engineering curricula.

2.10 Stakeholder Prioritization

As shown in both the figure and table below, the most influential and interested stakeholders, such as Professor Czekanski, space agencies, and industry partners are categorized in the "Manage Closely" quadrant. These stakeholders were actively engaged throughout the project and had the greatest impact on system requirements. Others, such as material science companies and graduate students, were placed in the "Keep Informed" quadrant, allowing for updates without direct involvement. The "Keep Satisfied" and "Monitor" quadrants represent lower-priority stakeholders whose long-term roles may evolve as the project transitions from prototype to potential deployment.

Table 1. Stakeholder prioritization and influence.

Stakeholder	***Interest Level (1-10)***	***Influence Level (1-10)***
Professor Czekanski & Lassonde School of Engineering	*10*	*10*
Space Agencies (CSA, NASA, Blue Origin)	*9*	*9*
3D Printing Industry	*8*	*8*
Biomedical Research & Cell Printing Community	*8*	*6*
Investors	*7*	*8*
Future Research & Graduate Students	*7*	*4*
Government & Defense Organizations	*2*	*4*
Material Science Companies	*6*	*6*
Students & Universities	*4*	*1*

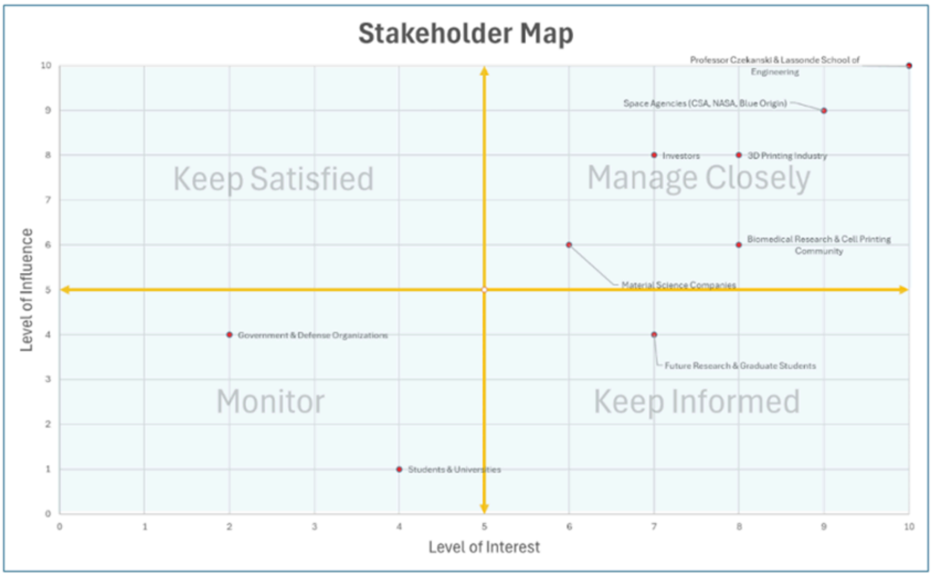

Figure 1. Stakeholder influence map.

3.0 Updated Requirements

Simulating gravity effects on Earth to study manufacturing processes presents significant challenges. Therefore, before initializing the design stage of the clinostat hyper gravity simulator, it is essential the needs, requirements and goals of the project are well defined to ensure design success. Adequately defining these aspects of the project creates a strong foundation for final design modelling and ensures that all stakeholders have a clear understanding of the objectives, scope, and expected outcomes. By addressing ambiguities and setting measurable success criteria, the team can focus on creating a reliable and functional prototype that meets both technical and usability requirements, paving the way for successful implementation and future scalability. These requirements are outlined below.

1. **Rotational Speed:** The clinostat device must be capable of operating at speeds capable of simulating hypergravity. To remove ambiguity, this would be up to 120 +/- 1 RPM, as required by key stakeholders. This speed should allow for consistent and reliable rotation, ensuring accurate testing and observation of materials for simulations up to 4 times the force of gravity.
2. **Environmental Monitoring:** The clinostat device must be equipped with systems capable of monitoring both temperature and humidity. To remove ambiguity, this would be up to no less than 60 and no more than 90 degrees Celsius and humidity up to 90%, as outlined by key stakeholders. This will allow for better monitoring over environmental conditions to minimize the risk of failures while providing optimal results by outlining current operating conditions.
3. **Physical Dimensions:** The clinostat device must have a compact and functional design. In specifics this would mean having physical dimensions not exceeding 2 ft by 2 ft in base size as requested by the key stakeholders. This would ensure ease of integration into various laboratory setups. The design should also prioritize portability, allowing for easy transportation and relocation between different research environments.
4. **Design Cost:** The total cost of the clinostat device, including all components, materials, and assembly, must be affordable. This means that the budget must not exceed $1,000, as specified by key stakeholders. This budget should cover the development of the device, including any necessary software and hardware integrations, while maintaining the quality and functionality needed for accurate and reliable gravity simulation. A small budget should allow for design replication if successful.
5. **Camera Integration:** The clinostat device must include a high-quality camera system capable of capturing clear, real-time images and video of the materials and device during experimentation. The camera should have a minimum resolution of 1080p and be able to record at a frame rate of at least 30 frames per second. The angle in which the camera is installed must allow for clear visual recordings for testing. The system must be integrated seamlessly with the device’s control interface, allowing for remote operation and real-time monitoring.
6. **Ease of Usage:** The clinostat device must be designed to be intuitive and user-friendly, requiring minimal training for operation. To remove ambiguity, this means the user interface should allow for simple control of rotational speed, environmental settings (temperature and humidity), and camera integration. The system must feature a straightforward, interactive control panel or software application, accessible remotely, enabling users to adjust settings and monitor the device in real time.
7. **3D Printer Compatibility:** The clinostat device must be fully compatible with the provided 3D printer. In specifics, this applied to the printer created by capstone group 35. The design should accommodate the specifications of the printer, ensuring that parts can

be printed without requiring significant modifications to the device. The system must also support the printer's material capabilities, including but not limited to PLA, ABS, and other common 3D printing materials, while ensuring that printed components meet the structural and functional requirements for operation under simulated gravity conditions.

3.1 Needs and Requirements Scope Analysis

Staying within the defined scope of a project is essential to maintaining focus, manageability, and alignment with the project's goals and objectives. The scope acts as a roadmap, clearly defining what will and will not be delivered, which helps prevent unnecessary complexity, delays, or resource wastage. Avoiding scope creep is critical for ensuring smooth and efficient design and development stages. In the case of the ENG4000 Clinostat project, the scope is well-defined, with a comprehensive set of requirements that outline the deliverables and delineate what falls outside the scope of this specific project. The primary goal is to develop a fully functional clinostat device capable of simulating hypergravity for material testing, incorporating key requirements such as rotational speed, environmental controls, data logging, and camera integration. To ensure these requirements are met efficiently, the engineering team will be split into cross-functional groups, each focusing on specific aspects of the project. One group will focus on analytical modeling and simulations for temperature, humidity, and rotational speed controls. Another group will handle physical modeling, ensuring compliance with ease of use, camera integration, and physical dimensioning. The entire team will collaborate to ensure the project remains within budget and that the final design integrates all elements seamlessly. This approach fosters streamlined coordination, clear responsibility, and efficient integration of all requirements into the final product. Each team should track their progress using Gantt charts and other scheduling tools, with performance assessed during weekly team meetings. This approach ensures that tasks are completed on time and allows for early identification of any issues, promoting accountability and keeping the project on track. Regular check-ins provide an opportunity to evaluate progress, adjust timelines if necessary, and ensure the team is meeting performance expectations.

It was determined that requirements related to 3D printer modifications, while important to the overall system, fall outside the scope of this project and are managed by a separate team. This clear separation allows the project team to maintain focus on the development and testing of the clinostat device itself, ensuring both efficiency and clarity in execution. By defining these boundaries, the team can prioritize its resources and efforts on the critical components of the project, avoiding distractions and promoting a streamlined workflow.

3.2 Needs and Requirements Compliance Analysis

To ensure the successful completion of the ENG4000 Clinostat project, it is essential to regularly assess and verify compliance with the defined requirements throughout the design and development phases. This section outlines the key requirements of the project, potential areas where non-compliance could occur, and the steps planned to address these issues. By identifying potential compliance risks early, the team can take corrective actions to stay on track and ensure that the final product meets all specified standards. The below table provides an overview of how potential non-compliances may be mitigated.

Table 2. General system objectives.

Requirement	***Potential Non-Compliance***	***Plan to address Non-Compliance***	***Verification***
Rotational Speed	*Motor does not achieve 120 RPM rotational speed*	*1.) Switch provided motor* *2.) NEMA-34, capable of rotating at speeds up to 150 RPM, well above the requirement*[1]	*Systematic testing on the motor using a tachometer during prototyping.*
Environmental Control	*Temperature and Humidity cannot be maintained within the provided ranges.*	*1.) Switch materials to that of high insulation, minimizing energy consumption and mitigating heat loss*	*Verification of temperature and humidity through the usage if sensors not integrated into the system*
Physical Dimensions	*The final design exceeds 2ft by 2ft*	*1.) Refining the final design using a material reduction analysis to ensure all components fit comfortably*	*Measure the final prototype to confirm that the constraint is met*
Design Cost	*The project exceeds budget constraints*	*1.) Review design to eliminate unnecessary features, negotiate with suppliers for cost savings.*	*Track costs throughout the design and testing phases through the usage of a bill of materials*
Camera Integration	*Camera resolution does not meet criteria or integration failure*	*1.) Re-evaluate camera selection and ensure compatibility with control systems.*	*Conduct integration testing to confirm functionality and image quality during design phase.*
Ease of Usage	*Device interface is not user-friendly.*	*1.) Simplify the user interface, using simplistic design principles including a touch screen or dial control option*	*Conduct usability tests with potential users such as Tas to gather feedback and identify areas of improvement.*

The sprint review process is crucial for ensuring the project remains on track and meets its requirements. At the end of each sprint, the project team should assess whether the objectives for each requirement have been achieved and identify any issues or gaps. This includes evaluating the progress of each specific requirement, such as rotational speed, environmental controls, camera integration, and others. If any non-compliance or delays are identified, the team can make necessary adjustments to stay aligned with project goals. Regular sprint reviews promote continuous improvement, ensuring that the design and development process is efficient and effective throughout the project.[2]

3.3 Needs and Requirements Final Acceptance Criteria Status

The following table provides a comprehensive overview of each finalized requirement, incorporating user-driven goals, measurable acceptance criteria, assigned priority levels, and implementation status. These requirements were developed and refined iteratively through Agile sprint cycles and stakeholder feedback, ensuring alignment with both functional expectations and project constraints. Each entry reflects a clear and unambiguous statement of need, supported by validation strategies described earlier in this report. By consolidating these requirements into a structured format, the project team can efficiently track completion, demonstrate compliance, and ensure that all critical system capabilities are delivered in the final clinostat prototype.

Table 3. User requirements.

Requirement ID	***User Requirement***	***Acceptance Criteria***	***Priority***	***Status***
REQ-01	*The device must rotate at speeds high enough to establish hypergravity conditions*	*- Rotational speed adjustable to 120 ±1 RPM* *- Simulates up to 4g* *- Consistent and stable operation*	*Must Have*	*Implemented*
REQ-02	*As a material scientist, I want to be able to monitor the environment to ensure printed materials are up to standard and under optimal printing conditions.*	*- Temperature monitoring between up to 90°C* *- Humidity monitoring up to 90%* *- Room for Manual control for future improvements*	*Must Have*	*Implemented*
REQ-03	*As a lab technician, I want the device to be compact and portable for flexible lab integration, while being safe for long term usage.*	*- Base dimensions not exceeding 2 ft x 2 ft* *- Lightweight and portable design* *- Fully encased system for failure protection*	*Must Have*	*Implemented*
REQ-04	*As a project lead, I want the total design cost to be low for budgeting and replication purposes.*	*- Total cost ≤ $1,000 including all components* *- Includes both hardware and software integration*	*Must Have*	*Implemented*

REQ-05	*As an experimenter, I want a high-quality camera system to capture tests in real-time.*	*- Camera resolution ≥ 1080p* *- 30 fps minimum* *- Integrated with device control for remote monitoring*	*Must Have*	*Implemented*
REQ-06	*As a user, I want the device interface to be easy to use for adjusting settings and monitoring.*	*- Simple and intuitive interface* *- Remote access to controls* *- Minimal training required*	*Should Have*	*Implemented*
REQ-07	*As a developer, I want the device to be compatible with our existing 3D printer for easy part replacement.*	*- Compatible with Capstone Group 35's 3D printer* *- Supports PLA, ABS, and other common materials*	*Must Have*	*Implemented*

Throughout the development process, several requirements emerged as particularly influential in driving the design. REQ-01, which focuses on achieving specific rotational speeds to simulate hypergravity, served as a foundation for mechanical and control system development. REQ-02, relating to environmental control, shaped material compatibility and thermal management considerations, while REQ-07 defined interface requirements necessary to ensure compatibility with the Capstone Group 35 3D printer. These requirements had significant technical implications and were prioritized early in the iterative design process. Through robust planning methods, all needs and requirements were able to be implemented into the final design with ease.[3][4][5]

4.0 Design Choice Rationale - A Trade-Off Study

4.1 Identifying Design Criteria

Several design options were assessed using five main criteria to make sure the clinostat design satisfies the requirements of all stakeholders and project limitations. Each criteria was prioritized and justified based upon stakeholders needs and requirements:

1. **Safety (1-5):** Safety was prioritized by adding protective enclosures and emergency mechanisms to prevent injuries.
2. **Effectiveness (1-5):** The system achieves its desired goal of simulating a gravitational pull through precise and calibrated rotational controls.
3. **Maintainability (1-5):** The design focused on using readily available parts for easy and quick component replacements.
4. **Cost (1-5):** The design meets budget constraints through effective material and component selection without compromising the systems overall functionality.
5. **Longevity (1-5):** Durability was ensured through the use of robust materials and thus maintaining structural integrity at high speeds and under extended use.

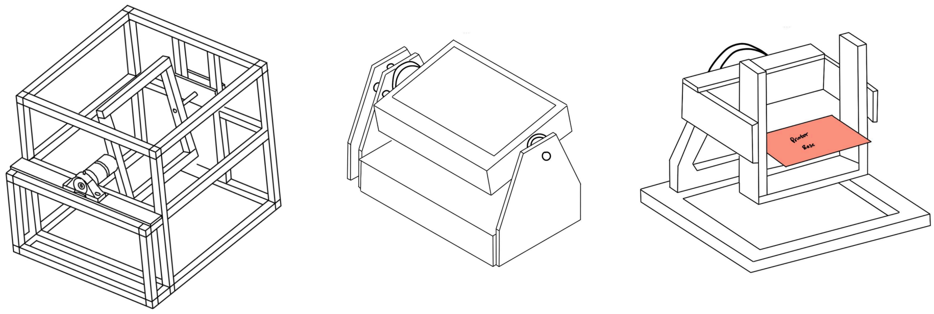

Figure 2. Initial Designs A, B and C

The following results are based upon discussions and calculations:

Table 4. Design score from group 36 team members.

Criteria	***Design A***	***Design B***	***Design C***
Safety	*5*	*4*	*2*
Effectiveness	*5*	*3*	*1*
Maintainability	*4*	*4*	*2*
Cost	*4*	*3*	*4*
Longevity	*5*	*3*	*1*
Total (assuming a design with a perfect score of 25)	***23***	***17***	***10***

4.2 Design Evaluation

After identifying the criteria to compare and evaluate various design solutions/options, A number of meetings and discussions were carried out with some stakeholders to get their opinions on the three design options, particularly in regards to the established criteria of cost, effectiveness, longevity, safety and maintainability. The discussions provided insightful information about their objectives and issues, which were eventually turned into scores.

For instance, Professor Czekanski of the Lassonde School of Engineering, who received a high interest and influence score of 10, underlined the importance of effectiveness and safety in the design, particularly in high-risk settings like space missions and engineering labs. In our weekly meetings, Professor Czekanski gave Design A the highest rating for all criteria due to exceeding durability and safety requirements. This resulted in an average score of 10 for this stakeholder, as shown in the table.

Similarly, the effectiveness and safety of the designs were the main concerns of officials from the Space Agencies (primarily CSA), who similarly had high interest and influence scores (9 each). They emphasized the need of making sure the design complied with strict space mission standards during a brief chat we had with one of their representatives. Each stakeholder's input was weighted as seen by the following table:

Table 5. Stakeholder scoring criteria.

Stakeholder	***Interest Score***	***Influence Score***	***Average***
Professor Czekanski & Lassonde School of Engineering	*10*	*10*	*10*
Space Agencies (CSA, NASA, Blue Origin)	*9*	*9*	*9*
3D Printing Industry	*8*	*8*	*8*
Biomedical Research & Cell Printing Industry	*8*	*6*	*7*
Investors	*7*	*8*	*7.5*
Future Research & Graduate Students	*7*	*4*	*5.5*
Government & Defense Organizations	*2*	*4*	*3*
Material Science Companies/Professors	*6*	*6*	*6*
Students & Universities	*4*	*1*	*2.5*
Maximum Score			***1462.5***

Each stakeholder's input was weighted based on their interest in and influence over the project. These discussions and meetings were intended to ensure that all perspectives were taken into account. The final stakeholder ratings were determined by averaging out their impact and interest scores.

Table 6. Final design scores (based on discussion between team members and stakeholders).[6][7][8]

Stakeholder	***Design A***	***Design B***	***Design C***
Professor Czekanski & Lassonde School of Engineering	*230*	*170*	*100*
Space Agencies (CSA, NASA, Blue Origin)	*207*	*153*	*90*
3D Printing Industry	*184*	*136*	*80*
Biomedical Research & Cell Printing Industry	*161*	*119*	*70*
Investors	*172.5*	*127.5*	*75*

Future Research & Graduate Students	*126.5*	*93.5*	*55*
Government & Defense Organizations	*69*	*51*	*30*
Material Science Companies/Professors	*138*	*102*	*60*
Students & Universities	*57.5*	*42.5*	*25*
Score (out of 1462.5)	***1345.5***	***994.5***	***585***
Percentage Score (out of 100%)	***92%***	***68%***	***40%***

The design evaluation process involved comparing three design options, Design A, B, and C, across five critical criteria: safety, effectiveness, maintainability, cost, and longevity. Design A consistently outperformed the other two, achieving the highest scores across all categories and earning a total of 23 out of 25. This strong performance is attributed to its superior safety and effectiveness, which were particularly emphasized by stakeholders with high influence and interest, such as Professor Czekanski and representatives from space agencies. Their feedback helped reinforce the importance of durability and compliance with high-risk operational standards, giving Design A a distinct edge in environments like engineering labs and space missions.

Stakeholder input was carefully weighted based on their influence and interest levels, providing a comprehensive and balanced assessment of each design's potential. Design A received a final weighted score of 1345.5 out of a possible 1462.5, representing 92% of the total score. In comparison, Design B and C scored significantly lower, with 994.5 (68%) and 585 (40%) respectively. These results clearly position Design A as the most viable and well-rounded solution, offering strong performance in critical areas while aligning with stakeholder expectations and requirements.

5.0 As Built-Design

The As-Built Design phase marks a significant milestone in the development of the Gravity Gizmo project, transitioning from conceptual models and initial prototypes to a fully assembled and functional Minimum Viable Product. This phase ensures that all design elements, from structural integrity to performance metrics, align with the defined project requirements. Through an iterative approach, the team has refined the system's mechanical framework, motor integration, and environmental monitoring capabilities to enhance overall functionality. The as-built design reflects careful engineering considerations, balancing stability, usability, and scientific accuracy. This section details the final constructed design, its core features, and its compliance with key performance benchmarks, ensuring that it meets the needs of stakeholders and fulfils the project's broader objectives.[9]

5.1 Solution Overview

Simulating hyper gravity environments on Earth presents a significant challenge for research and manufacturing applications, particularly in the field of additive manufacturing and bioprinting. Current hyper gravity simulation solutions are often costly, large-scale, and inaccessible to smaller research institutions. The need for a compact, cost-effective, and adaptable solution that can replicate high-gravity conditions reliably is crucial for advancements in space-related research and material sciences. To address this need, the Clinostat for the Gravity Gizmo project was initiated to develop a single-axis clinostat capable of achieving controlled hyper gravity conditions while integrating real-time monitoring and environmental control mechanisms. The device must sustain rotational speeds sufficient to simulate gravity variations while maintaining system stability, structural integrity, and ease of use for researchers. The design must also adhere to budget constraints and allow for adaptability in future iterations. The SolidWorks model is shown below.

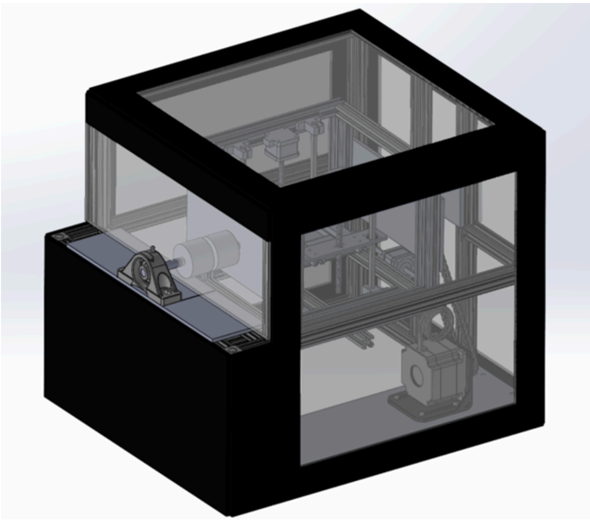

Figure 3. Final CAD model with 3D printer fully integrated.

The Gravity Gizmo project effectively tackles the challenge of simulating hypergravity environments on Earth by implementing a creative and innovative design approach that balances functionality, cost-effectiveness, and accessibility. The problem definition and requirements analysis were structured to identify key limitations in existing solutions—high costs, large-scale setups, and limited availability for smaller research institutions. By focusing on a compact, portable, and adaptable clinostat, the team proposed a groundbreaking solution that enables controlled hypergravity conditions while integrating real-time monitoring capabilities, ensuring that research institutions with limited resources can access high-quality experimental setups.

To meet stakeholder needs, the project explored unique engineering approaches that prioritize modularity and cost-efficiency. Traditional hypergravity simulation devices are often stationary and cumbersome, limiting their usability across multiple research settings. The clinostat's lightweight aluminum frame, coupled with a NEMA 34 stepper motor, allows for high rotational speeds (up to 120 RPM) while maintaining stability and structural integrity. The design also incorporates real-time environmental monitoring using integrated temperature, humidity, and rotational speed sensors, ensuring that researchers can capture precise experimental data without external disturbances. A high-resolution camera system further enhances usability by providing continuous documentation of 3D printing processes under hypergravity conditions, an innovative addition that sets this system apart from traditional clinostats. To better categorize stakeholder needs and priority, a stakeholder analysis was conducted as shown below.

The Gravity Gizmo project embodies originality by merging mechanical, electrical, and software engineering principles to create a scalable and adaptable solution that outperforms traditional hypergravity simulators in accessibility and cost. By maintaining a budget under $1,000, the team has demonstrated that high-performance hypergravity simulation can be achieved without excessive financial investment. The result is a versatile, robust, and cutting-edge system that expands the possibilities for hypergravity research in additive manufacturing, bioprinting, and material science applications. This prototype is shown below.

This system operates using a plug-in power supply that provides energy to the sensors and the NEMA 34 motor. Additionally, a slip ring system enables direct power delivery to the printer, which is centrally housed within the clinostat. The compact printer system, developed by Group 35, is supported by two rotating shafts driven by the motor's electromechanical output. For structural integrity, aluminum extrusions were used to ensure adequate support, while Plexiglass serves as a protective barrier in case of critical failures. Insulation was incorporated to regulate internal temperature variations detected by the temperature sensor. These sensors are mounted directly on the printer to monitor specimen temperature and track any overheating incidents that could lead to system failure.

5.2 Decomposition and Prioritization of Features

To ensure the Gravity Gizmo project was developed efficiently and met all stakeholder expectations, the team employed an Agile methodology that decomposed the system into structured, manageable product increments. This decomposition allowed for a systematic approach to tackling each critical component while maintaining flexibility for iterative refinements based on testing feedback. The sprints were designed to sequentially build upon one another, ensuring the most essential features were addressed first while allowing adjustments as needed. Each sprint focused on a distinct aspect of the system's development, prioritizing core functionalities before refining the user experience and ensuring compliance with performance metrics.

Sprint 1: BOM Finalization and Procurement

The first sprint was dedicated to finalizing the Bill of Materials (BOM) to ensure all required components were accounted for, including the NEMA 34 motor, aluminum frame extrusions, environmental sensors, and control electronics. This phase was crucial as it established the foundation for subsequent development stages by securing necessary materials within budget constraints. Procurement of long-lead items was prioritized to prevent delays in later sprints. This sprint ensured that all core elements of the clinostat were ready for assembly, avoiding last-minute sourcing challenges.

Sprint 2: Frame Assembly and Motor Integration

With all materials procured, the second sprint focused on assembling the structural framework and integrating the motor system. The aluminum extrusion frame was designed for durability while maintaining the required 2ft × 2ft footprint. The NEMA 34 motor was mounted and connected using a chain and sprocket system, ensuring it could achieve and sustain the required 120 RPM rotational speed. Vibration control measures, including dampening materials and secure fastening techniques, were introduced in this phase to improve stability. Addressing structural integrity early in the development process allowed subsequent sprints to focus on refining performance and system optimization.

Sprint 3: Sensor Integration and Calibration
The third sprint focused on integrating environmental sensors, a key feature for researchers who needed precise monitoring over experimental conditions. Sensors for temperature, humidity, and rotational velocity were installed and calibrated to ensure accurate data acquisition. Power management strategies were also implemented to ensure that all sensors operated efficiently without overloading the system. This sprint was particularly critical for meeting stakeholder expectations, as research teams relied on real-time data to validate their experimental findings. Proper calibration and validation of sensor accuracy were prioritized to ensure reliable readings under varying operational conditions.

Sprint 4: Camera Installation and Real-Time Data Acquisition
In response to stakeholder needs for process visualization, the fourth sprint integrated a high-resolution camera to capture real-time observations of experimental materials. This feature was essential for research applications, allowing for detailed analysis of material behavior under hypergravity conditions. The enclosure was refined to reduce vibrations that could distort image quality, ensuring clear documentation. The implementation of real-time data acquisition ensured that researchers could monitor and analyze the system's effects on various materials without requiring physical access to the device during operation. This sprint aligned with industry and research priorities, supporting the broader adoption of the clinostat in scientific studies.

Sprint 5: Calibration, Testing, and System Optimization
The final sprint was dedicated to full-system testing, calibration, and final refinements. The motor’s performance was validated to ensure it could sustain stable rotation at 120 RPM, while additional vibration analysis was conducted to further reduce any inconsistencies. The entire system was tested under operational conditions to confirm that all components functioned cohesively. Any remaining performance issues, such as inconsistencies in sensor readings or mechanical misalignments, were addressed during this phase. The final validation ensured that the system met all functional, safety, and usability requirements before stakeholder review and deployment.

Each of these product increments was strategically planned to align with the needs of different stakeholder groups. Researchers required precise environmental monitoring, which was prioritized in early sprints through sensor integration and calibration. Engineers needed a robust rotational system, addressed in the frame and motor assembly phases. Industry adopters required real-time monitoring capabilities, which were incorporated in later sprints to facilitate process documentation and analysis.

The backlog roadmap was continuously updated based on sprint progress and testing results, ensuring a clear and adaptable development path. Adjustments were made as necessary to refine system performance and address unforeseen challenges. By structuring the development into focused, incremental releases, the team effectively balanced innovation with reliability, ensuring that the clinostat met its design objectives while adhering to project timelines and budget constraints.

5.3 Overview of Applied Engineering Practices

The goal of this analysis is to assess the structural integrity and mechanical performance of a rotating aluminum frame used in the Gravity Gizmo device. The rotating system holds a 12 kg component, and we analyze:

- Torque required for angular acceleration,
- Bending moments and stresses,
- Angular and linear deflection,
- Safety factors,
- Torsional performance,
- Heat dissipation for insulation,
- Gravitational effects.

To simplify and reasonably model the system:

- The frame is a 24" × 24" × 24" cube, with structural components on the outer frame.
- The load is evenly distributed, centered on the rotating section.
- Shaft diameter: d = 12 mm
- Material properties for case hardened, heat-treated shaft::
  - Core Yield strength σ_y = 700 MPa [11]
  - Young's modulus E = 210 GPa [11]
  - Modulus of Rigidity G = 80 GPa [11]
- The system accelerates from 0 to 120 RPM in 10 seconds.
- The force acts at a radius of half the diagonal of a 14" × 14" inner housing square..

5.3.1 Load and Geometry Calculation

- Weight of Component:
  W = 12 kg, F = W · g = 120 N
- Frame Width:
  14″ = 0.3556 m
- Distance to Load (Half Diagonal of 14" × 14" Frame):

$$d = \sqrt{14^2 + 14^2} = 19.8" = 0.503m$$

$$r = d/2 = 0.2515m$$

5.3.2 Rotational Mass Inertia

$$I = mr^2 = 12 \cdot 0.2515^2 = 0.759\ kg.m^2$$

5.3.3 Torque

- Angular Velocity

$$\omega = \frac{2\pi(120)}{60} = 4\pi = 12.56\ rad/s$$

- Angular Acceleration

$$\alpha = \frac{\omega}{t} = \frac{12.56}{10} = 1.256\, rad/s^2$$

- Estimated Torque

$$T_{acceleration} = I\alpha = 0.759 \cdot 1.256 = 0.954\, N.m$$

$$T_{bearing, friction} = 0.16196\, N.m$$

$$T_{total} = 0.954 + 0.16196 = 1.116\, N.m$$

5.3.4 Bending Moment, Section Modulus, Bending Stress and Factor of Safety

$$M = Fd = 120 \cdot 0.0978 = 11.74\, Nm$$

$$Z = \frac{\pi d^3}{32} = \frac{\pi(0.012)^3}{32} = 1.7 \times 10^{-7}\, m^3$$

$$\sigma = \frac{M}{Z} = \frac{11.74}{1.7\times10^{-7}} = 69.2\, MPa$$

$$FOS_{shaft, driving\ side} = \frac{Yield\ Strength}{\sigma} = \frac{700}{69.2} = 10.1$$

5.3.5 Deflection

$$I = \frac{\pi}{64}d^4 = \frac{\pi}{64}(0.0127)^4 = 1.018 \times 10^{-9}\, m^4$$

$$\Theta_{deflection} = \frac{FL^2}{2EI} = \frac{120(0.2032)^2}{2(210\times10^9)(1.018\times10^{-9})} = 0.016^{\circ}$$

$$\delta = \frac{FL^3}{3EI} = \frac{120(0.2032)^3}{3(210\times10^9)(1.018\times10^{-9})} = 0.0016\, mm$$

5.3.6 Torsion

$$J = \frac{\pi}{632}d^4 = \frac{\pi}{632}(0.0127)^4 = 2.55 \times 10^{-9}\, m^4$$

$$\Theta_{twist} = \frac{TL}{JG} = \frac{1.1(0.2032)}{(2.55\times10^{-9})(80\times10^9)} = 0.0011^{\circ}$$

5.3.7 Heat Transfer[12][13][14]

Table 7. Design assumptions and materials.

Section	***Details***
Objective	*Maintain 60°C using only the 75W heated bed (≈48 W effective), with ≤50W heat loss*
Enclosure Size	*20" × 20" × 20" (0.508 m³ cube)*
Surface Area	*1.548 m²*
Temperature (ΔT)	*35°C (60°C internal – 25°C ambient)*
Materials Evaluated	*Polyurethane Foam (3 cm & 5 cm), Acrylic Window (5×5 cm)*

Table 8. Heat loss for 3 different configurations.

Configuration	***Total Heat Loss (W)***	***Status***
3 cm Polyurethane Foam (all sides)	*45.2 W*	*Acceptable*
3 cm PU + 5×5 cm Acrylic Window	*48.6 W*	*Near limit*
5 cm PU + 5×5 cm Acrylic Window	*30.5 W*	*Recommended*

Table 9. Heat transfer analysis results.

Property	***Value***
Air Mass	*0.157 kg*
Energy Required (Q)	*5523 J*
Heating Time (48 W)	*~115 seconds (~1.9 min)*

5.3.8 Gravitational Pull

To rotate at 120 revolutions per minute:

1. Angular Velocity

$$\omega = \frac{2\pi \cdot \text{RPM}}{60} = \frac{2\pi \cdot 120}{60} = 12.56\,\text{rad/s}$$

2. Angular Acceleration

$$a_c = (12.57)^2 \cdot 0.25 = 39.48\,\text{m/s}^2$$

3. Gravitational Force

$$g_f = \frac{39.48}{9.81} = 4.02\,g$$

5.4 Engineering Principles Review

The development of the clinostat required the application of various engineering principles and theoretical foundations to address the challenges associated with creating a functional and reliable hyper gravity simulation device. By integrating mechanical and electrical engineering concepts, the team systematically designed, optimized, and validated the system to meet both functional and performance criteria. Each engineering discipline contributed critical insights to solving complex design challenges, ensuring the device's robustness, efficiency, and accuracy in replicating controlled gravitational conditions.

From a mechanical engineering standpoint, fundamental principles of rotational dynamics, structural analysis, and material selection played a crucial role in the system's development. The frame was designed using static and dynamic load analysis to ensure it could withstand operational forces while remaining lightweight and compact. The NEMA 34 stepper motor and chain-sprocket system were selected based on torque and power calculations to achieve the required rotational speed of 120 RPM, balancing force efficiency and power consumption. Additionally, vibration control strategies were implemented by incorporating damping materials and micro stepping techniques, reducing mechanical oscillations that could interfere with experimental outcomes. The team also leveraged computational simulations and analytical modelling to refine system design before physical prototyping. Finite Element Analysis (FEA) simulations were conducted to assess the frame's structural integrity and the effects of temperature fluctuations within the enclosure. These simulations allowed for proactive identification of design inefficiencies, reducing the need for extensive physical iterations and ensuring optimal performance.

In terms of electrical and control engineering, the integration of sensor networks and power management systems was critical in maintaining operational stability. Temperature, humidity, and rotational speed sensors were implemented following signal processing techniques, ensuring high-precision data collection. PID (Proportional-Integral-Derivative) control algorithms were applied to fine-tune the rotational stability of the motor, maintaining consistent speeds under varying operational loads. Electrical safety measures, such as overcurrent protection and thermal management, were employed to safeguard components from overheating and electrical faults.

By synthesizing these engineering concepts, theories, and practices, the Gravity Gizmo was developed as a robust, and functional system. The application of advanced engineering methodologies not only solved key technical challenges but also ensured the device met stakeholder requirements for accuracy, durability, and ease of use. The combination of theoretical modelling, experimental validation, and iterative refinement demonstrates the project's strong foundation in applied engineering principles, positioning the Gravity Gizmo as a viable tool for hyper gravity research and manufacturing applications.

6.0 As Built-Design Compliance Analysis

6.1 Manufacturing and Machining

As part of the fabrication process, aluminum extrusions and plates were precisely machined to specified dimensions to meet the structural and functional requirements of the design.

6.1.1 Aluminum Extrusions

Two distinct lengths of aluminum extrusion were prepared:

- 14 pieces of 1.5 feet length
- 12 pieces of 3 inches length

Each extrusion, regardless of length, required ¼-20 (quarter-twenty) threaded holes tapped on both ends. The tapping was done to a depth of 1 inch to allow for strong mechanical fastening using standard bolts. This operation ensures that all extrusions can be securely connected to other components or structures using threaded fasteners.

6.1.2 Aluminum Plates

Three square/rectangular aluminum plates were used in the assembly:

- 2 plates measuring 4 inches × 4 inches
- 1 plate measuring 4 inches × 8 inches

All three plates were drilled through at the edges using M5 holes, allowing them to be mounted or attached to the extrusions using M5 bolts. The evenly spaced through-holes along the edges ensure compatibility with standard fastener sizes and provide modularity in assembly.

6.1.3 Motor Mounting Plates

Two motor mounting plates measuring 5 inches × 8 inches were fabricated. These plates were machined with M5-sized slots running along the 8-inch length. These slots allow for adjustable positioning of motors or other mechanical components, making alignment and tensioning easier during final assembly.

6.1.4 Loctite

To ensure secure fastening and prevent loosening due to vibration, Loctite threadlocker was applied to the nuts during assembly. This adhesive compound helps lock the threads in place, providing resistance to shock and vibration while still allowing for disassembly with tools if needed. Using Loctite enhances the reliability of mechanical joints, especially in dynamic applications like motor mounts and structural frames.

6.2 Performance Evaluation

This section presents a case study focused on evaluating the mechanical integrity of PLA samples fabricated with a custom-built mini 3D printer. The primary goal was to analyze how rotational motion during printing influences the mechanical performance of the final parts. Standardized tensile testing methods were employed to provide quantitative insights into the effects of rotational printing, particularly in applications such as clinostat-based research.

6.2.1 Tensile Strength Test

To assess the mechanical properties of the printed PLA samples, tensile strength testing was performed. The study compared samples produced under two conditions: conventional static printing and rotational spinning during printing. This test was essential for determining each sample's ability to resist tensile forces applied along a single axis, a key factor for evaluating their structural integrity under dynamic conditions.

Stress values were calculated in megapascals (MPa) by dividing the applied tensile force by the original cross-sectional area of each specimen. The results provided a clear indication of each sample's mechanical robustness and print quality, offering insight into their potential use in motion-intensive environments like a clinostat.

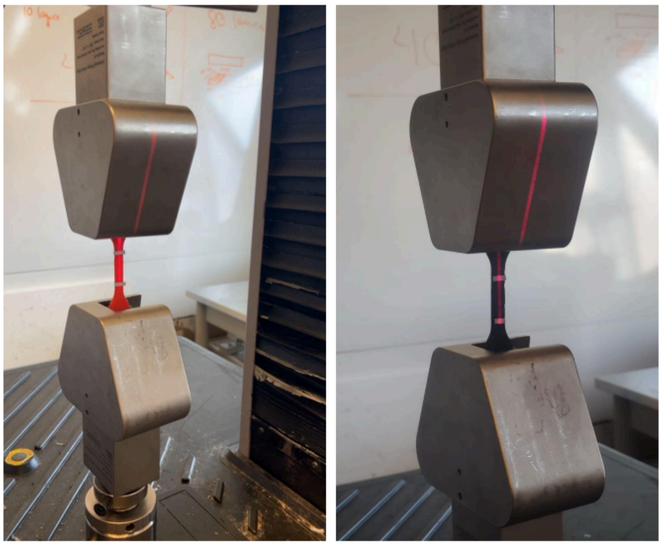

Figure 4. Tensile testing performed on the printed coupon printed by PrintaGo.

As seen in the figure above, tensile testing was conducted using a universal testing machine in a controlled laboratory setting. The specimens, which followed the Type IV geometry specified in ASTM D638 standards, were carefully clamped and subjected to a steady uniaxial tensile load.

Real-time measurements of force and displacement were recorded throughout the test until the samples fractured. Stress was computed as the applied force divided by the original cross-sectional area, while Young's modulus was derived from the initial linear portion of the stress–strain curve. This modulus served as an indicator of the material's stiffness and elasticity, further highlighting the mechanical impact of rotational versus static printing techniques.

6.2.2 Requirements Compliance

The following tables correspond to a specific user requirement (REQ-01 to REQ-07) and include:

- Acceptance Criteria: Detailed conditions for the requirement to be met.
- Validation Method: How the criteria were tested or verified.
- Results: Confirmation of compliance (all passed).

Table 10. Summary of results.

Req. ID	*Acceptance Criteria*	*Validation Method*	*Results*
REQ-011	*Rotational speed adjustable to 120 ± 1 RPM*	*Measured RPM using a tachometer during operation at maximum speed.*	*Pass*
REQ-012	*Simulates up to 4g*	*Calculated g-force using RPM and radius measurements; verified with speed sensor.*	*Pass*
REQ-013	*Consistent and stable operation*	*Monitored RPM fluctuations over 1 hour of continuous operation.*	*Pass*

Table 11. Summary of results.

Req. ID	*Acceptance Criteria*	*Validation Method*	*Results*
REQ-021	*Temperature monitoring up to 90°C*	*Used a calibrated thermometer to compare with device readings.*	*Pass*
REQ-022	*Humidity monitoring up to 90%*	*Used a hygrometer to verify device humidity readings.*	*Pass*
REQ-023	*Room for manual control*	*Confirmed unused I/O ports and documentation for future integration.*	*Pass*

Table 12. Summary of results.

Req. ID	*Acceptance Criteria*	*Validation Method*	*Results*
REQ-031	*Base dimensions ≤ 2 ft×2 ft*	*Measured dimensions with a tape measure.*	*Pass*
REQ-032	*Lightweight and portable design*	*Verified weight (<20 kg) and tested transport between lab spaces.*	*Pass*
REQ-033	*Fully encased system*	*Inspected enclosure for gaps and tested emergency stop functionality.*	*Pass*

Table 13. Summary of results.

Req. ID	*Acceptance Criteria*	*Validation Method*	*Results*
REQ-041	*Total cost ≤ $1,000*	*Reviewed itemized receipts and compared with budget.*	*Pass*
REQ-042	*Includes hardware/software*	*Audited component list and software licenses.*	*Pass*

Table 14. Summary of results.

Req. ID	*Acceptance Criteria*	*Validation Method*	*Results*
REQ-051	*Camera resolution ≥ 1080p*	*Recorded test footage and verified resolution in video metadata.*	*Pass*
REQ-052	*30 fps minimum*	*Analyzed frame rate using video editing software.*	*Pass*
REQ-053	*Remote monitoring integration*	*Tested live feed access via device control interface.*	*Pass*

Table 15. Summary of results.

Req. ID	*Acceptance Criteria*	*Validation Method*	*Results*
REQ-061	*Simple and intuitive interface*	*Conducted usability tests with 5 first-time users; all completed tasks successfully.*	*Pass*
REQ-062	*Remote access to controls*	*Verified remote login and control functionality from a secondary device.*	*Pass*
REQ-063	*Minimal training required*	*Observed users operating the device after a 5-minute demonstration.*	*Pass*

Table 16. Summary of results.

Req. ID	*Acceptance Criteria*	*Validation Method*	*Results*
REQ-071	*Compatible with Group 35's printer*	*Tested mounting and communication with the target 3D printer.*	*Pass*
REQ-072	*Supports PLA, ABS, etc.*	*Verified material compatibility in documentation and tested prints.*	*Pass*

1. Core Functional Requirements (REQ-01, REQ-05)

REQ-01: Hypergravity Simulation via Rotation

Objective:
The system must simulate hypergravity conditions of up to 4g using precise rotational control.

Key Features:

- RPM Stability (±1 RPM): Maintains tight rotational tolerance to ensure experimental consistency and reproducibility.
- g-Force Verification: Achieved using a dual approach—accelerometer readings corroborated with theoretical calculations.
- Long-Term Operation: Successfully completed a 1-hour continuous test under load, confirming stable performance without degradation.

Implications:

- Demonstrates the system's reliability for advanced material science and biological research where gravity-dependent phenomena are studied.
- Future improvements may include support for higher g-forces or automated feedback control systems for real-time dynamic adjustments.

REQ-05: High-Quality Real-Time Camera System

Objective:
Deliver clear, real-time video for effective monitoring and post-analysis of experiments.

Key Features:

- 1080p at 30fps Performance: Validated through metadata analysis, ensuring sufficient resolution for detailed review.
- Remote Viewing Capability: Fully integrated with the control interface, enabling remote observation and documentation.

Implications:

- Enables precise visual analysis of experimental behaviors under hypergravity.
- Future upgrades could include 60fps for slow-motion analysis or AI-enhanced tracking to automatically highlight key motions or anomalies.

2. User Experience & Safety (REQ-02, REQ-03, REQ-06)

REQ-02: Environmental Monitoring for Material Integrity

Objective:
Ensure real-time tracking of temperature and humidity to preserve optimal printing and experimental conditions.

Key Features:

- High Sensor Accuracy: Cross-checked with calibrated tools for data reliability.
- Expandable Design: Spare I/O ports allow easy addition of extra sensors (e.g., CO_2, vibration).

Implications:

- Essential for maintaining the quality of printed materials and experimental results.
- Could be enhanced with automated alerts for out-of-range conditions or data logging for trend analysis.

REQ-03: Portability and Safety

Objective:
Design a compact, lightweight, and safe system for flexible deployment in lab environments.

Key Features:

- Verified Size & Weight Constraints: Confirmed via physical inspection and transport tests.
- Full Safety Enclosure: Prevents contact with moving parts; tested successfully with emergency stop features.

Implications:

- Safe and practical for use in shared labs without the need for specialized infrastructure.
- Future iterations could include built-in handles, locking wheels, or stackable modules for increased convenience.

REQ-06: Intuitive User Interface

Objective:
Provide a user-friendly control system that requires minimal training and supports remote operation.

Key Features:

- Ease of Use: First-time users operated the system successfully with only brief guidance.
- Remote Accessibility: Interface supports off-site control and monitoring, enhancing workflow flexibility.

Implications:

- Lowers the barrier to entry for new researchers and accelerates adoption.
- Future developments may include voice command support, mobile app integration, or custom user profiles.

3. Cost Efficiency & Compatibility (REQ-04, REQ-07)

REQ-04: Budget Compliance (≤ $1,000)

Objective:
Maintain cost-effectiveness to support scalability and broader accessibility.

Key Features:

- Component Cost Validation: Audited with receipts to ensure all expenses remain within the $1,000 limit.
- All-Inclusive Budgeting: Covers both hardware and software components, with no hidden costs.

Implications:

- Makes the system viable for small labs, student projects, or educational institutions.
- Cost could be further reduced through bulk sourcing, component optimization, or open-source software adoption.

REQ-07: 3D Printer Compatibility

Objective:
Enable seamless integration with standard lab 3D printers, supporting materials like PLA and ABS.

Key Features:

- Mechanical & Software Compatibility: Confirmed through mounting and communication interface tests.
- Material Compatibility Testing: Successfully produced prints with commonly used filaments.

Implications:

- Simplifies setup, maintenance, and replacement, reducing downtime.
- Future iterations could support advanced materials such as carbon fiber composites or flexible filaments.

Summary
All requirements were successfully met, confirming the device's technical performance, user-friendliness, and cost-effectiveness. Core functions like hypergravity simulation and environmental monitoring are robust, while safety and interface features enhance usability.

Future Improvements:

- Tighter RPM Tolerance (REQ-01) for higher precision experiments.
- AI-Driven Monitoring (REQ-02) to detect anomalies like unexpected vibrations.
- Modular Add-ons (REQ-03/REQ-07) for easy sensor and accessory upgrades.

6.3 Results and Discussion

Testing was carried out until each PLA coupon fully fractured. As illustrated in the figure below, the fractures consistently occurred near the grip area, suggesting localized stress concentrations and effective load transmission through the specimen. To ensure the validity of the results, initial observations were reviewed in collaboration with Ragab Etiwa, a PhD candidate at IdeaLab. The collected data were then processed and used to generate stress–strain curves, providing a clear representation of the mechanical response under uniaxial tension.

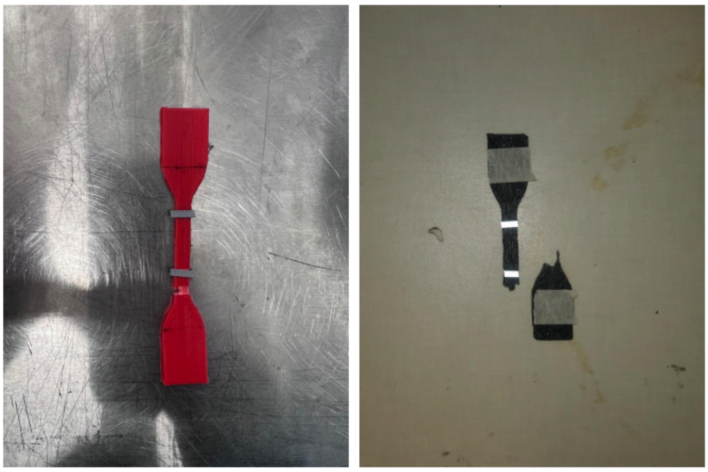

Figure 5. Coupon post-testing failure (Static, Rotational).

To quantify these failures, fundamental material engineering principles are utilized to further understand the relation between an increased gravitational pull and material mechanical properties.

To evaluate the stress:

$$\sigma = \frac{F}{A}$$

where σ is the engineering stress, F is the applied force and A is the original cross-sectional area at which the failure is expected to occur at.

As for the strain,

$$\epsilon = \frac{\Delta L}{L_0}$$

where ϵ is the engineering strain, ΔL is the elongation doe to the applied force and L_0 is the initial specimen length.

From these mechanical properties, the Young's is then obtained as follows:

$$E = \frac{\Delta \sigma}{\Delta \epsilon}$$

The data for the stress-strain graph was obtained from an Excel spreadsheet containing the experimental results of a tensile test. From the dataset, only the gage strain and stress values were selected. To focus on the elastic behavior and initial yielding of the material, data points were included only up to the maximum stress and corresponding strain.

Using the linear portion of the stress-strain curve, the slope was calculated to determine the Young's modulus (E) of the material. A linear regression was then applied to this elastic region to obtain the slope equation, representing the relationship between stress and strain in the elastic regime. The same procedure was followed for the rotational sample to enable a comparative analysis between static and dynamic loading conditions.

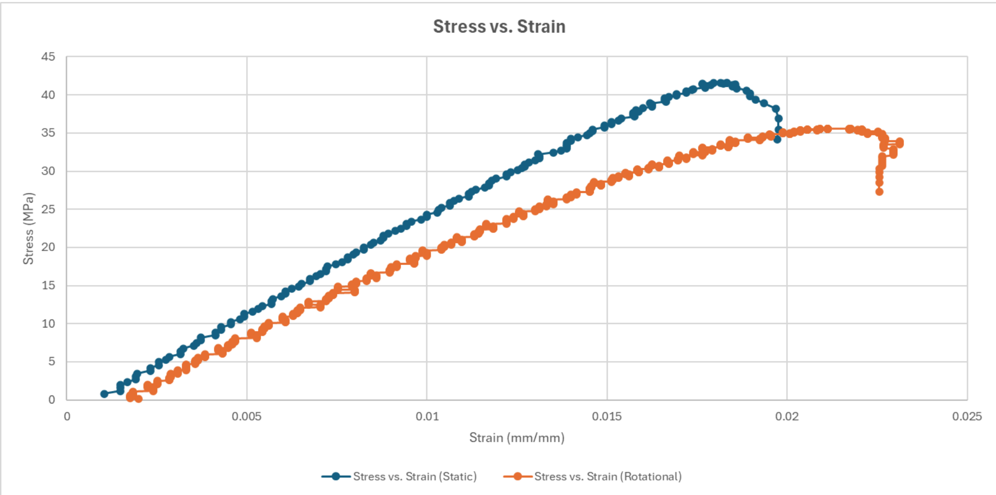

Figure 6. Stress vs. Strain curves for both static and rotational coupon specimens.

The stress vs. strain graph compares the mechanical response of a material under static and rotational loading conditions. The static sample exhibits a steeper initial slope, indicating a higher Young's modulus and greater stiffness. It also reaches a higher maximum stress of approximately 42 MPa, suggesting superior strength when subjected to purely axial tension. The curve follows a typical pattern with a distinct elastic region, yielding point, and subsequent strain softening, which implies necking or failure. This behavior reflects a more stable and predictable response under static loading.

In contrast, the rotational sample displays a lower initial slope and reduced maximum stress around 33 MPa, indicating decreased stiffness and strength. The transition from elastic to plastic deformation appears more gradual, and the curve shows more fluctuations after yielding. This could be due to added complexities from rotational or torsional stresses, which may introduce localized defects or premature yielding. Despite both samples reaching similar strain values at failure, the rotational sample demonstrates inferior mechanical performance, likely influenced by non-uniform stress distribution or dynamic loading effects.

Table 17. Summary of results.

Measured Mechanical Property	***Static***	***Rotational***
Tensile Strength (MPa)	*42*	*33*
Young's Modulus (MPa)	*2.6*	*2.3*

7.0 Project Management Updates

7.1 Project Task Management Status

The given schedule, which breaks down work into manageable chunks in accordance with Agile principles, describes the project's timetable, milestones and deliverables.

Task allocations, progress reports and due dates are all clearly indicated in the roadmap. Validation of the design, sourcing of materials, assembly, testing and reporting are key milestones.

Key Updates:

- Now-Next-Later Framework:
  - Now:
    - Ongoing completion of assembly.
    - Finalization of the insulation and integration of sensors.
  - Next:
    - Preparing for wiring setup.
  - Later:
    - System verification and testing phases.

- Backlog Management:
  - Pending tasks related to system testing and adjustments include:
    - Verifying sensor data collection by running the clinostat for extended durations to assess performance.

- Task Completion Summary:
  - Completed:
    - Initial design phases, including stakeholder analysis, charter development and preliminary design calculations.
    - Material sourcing.
    - Assembly.
  - Remaining:
    - Final system-level testing and verification.

- Increment Prioritization and MVP Definition:
  - Each sprint focuses on delivering specific features of the MVP.

Essential Deliverables:

- Storyboard/Design Board:
  A timeline-based breakdown of tasks, demonstrating progress through Gantt charts. Evidence of task completion includes CAD models, simulations and finalized BOMs.
- Completion of Materials:
  Documentation, including design iterations, feedback reviews and risk management plans, ensures appropriate progress tracking.
- Assigned Story Points:
  Tasks are assigned points based on their size and complexity, further ensuring logical prioritization.

Milestone Highlights:

- BOM Finalization: Completed by 20 November, 2024, ensuring materials are ready for assembly.
- Assembly: Key components like frames, brackets and motor integrations to be completed by March 2025.
- Testing Phase: System-level checks (torque, stability and vibration) to validate MVP features commenced in April 2025.

7.2 Work Breakdown Structure (WBS)

Table 18. Project WBS.

WBS Code	***Category***	***Task Name***	***Subtasks***
PM-010	*Project Management*	*Project Management*	*Project Administration (PM-011), Project Coordination (PM-012), Project Review (PM-013), Stakeholder Coordination (PM-014)*
RA-020	*Research & Analysis*	*Research & Analysis*	*3D Printers Tech Research (RA-021), Printer Selection (RA-022), Heating Tech Research (RA-023), Design Selection (RA-024), Build Plate Research (RA-025), Extrusion Camera Research (RA-026)*
CM-030	*CAD Modelling*	*CAD Modelling*	*Initial CAD Model (CM-031), Modified CAD Model (CM-032), Model Assessment (CM-033), Theoretical Calculations (CM-034)*
MP-040	*Model Prototyping*	*Prototyping & Procurement*	*Material Procurement (MP-041), Assembly of Initial Printer (MP-042), Component Machining (MP-043)*
FB-050	*Final Build Assembly*	*Final Build Assembly*	*Modified Frame Assembly (FB-051), Heating Bed Assembly (FB-052), Camera Module Assembly (FB-053), Final Modified Printer Assembly (FB-054)*
FT-060	*Final Testing*	*Final Testing*	*Simulation Testing (FT-061), Software Testing (FT-062), Rotational Testing (FT-063), Printing Capability Testing (FT-064), Heating Bed Testing (FT-065), Rotational Printing Testing (FT-066), Extrusion Camera Testing (FT-067)*

The above table outlines a Work Breakdown Structure (WBS) for a 3D printer project, divided into six main phases: Project Management, Research & Analysis, CAD Modelling, Prototyping, Final Assembly, and Final Testing. Each phase includes specific subtasks to guide the development, from planning and research to design, assembly and testing.

7.3 Resource Allocation Matrix (RAM) and RACI

To ensure effective job execution and accountability, the Resource Allocation Matrix (RAM) and RACI framework establish team roles, responsibilities and progress. The project schedule, which is broken down into sprints, helps in work setting priorities, progress monitoring and constant adaptation, maintaining alignment with Agile principles and project milestones.

Testing and Reporting				
Check system power supply.	All members	100%	3/27/25	4/25/25
Verify sensor data collection.	All members	100%	3/27/25	4/25/25
Ensure the clinostat achieves the minimum RPM (120 revs/min).	All members	100%	3/27/25	4/25/25
Ensure the balance and stability of the inner box housing the 3D printer.	All members	100%	3/27/25	4/25/25
Record initial system response (e.g., torque, rotational speed) under different load conditions.	All members	100%	3/27/25	4/25/25
Introduce vibrations to see how the motor compensate.	All members	100%	3/27/25	4/25/25
Run the clinostat for an extended duration to ensure it maintains stable rotation without losing speed.	All members	100%	3/27/25	4/25/25

Figure 7. Final stage of the Gantt Chart (Project Schedule).

Table 19. RAM

Task	***Assigned Team Member(s)***	***Progress (%)***	***Comments***
Define Goals	*All Members*	*100*	*Completed during the initial planning phase.*
Conduct Research	*All Members*	*100*	*Used to define the problem statement.*
Problem Statement Definition	*Ibrahim*	*100*	*Finalized for the team.*
Develop Charter	*Herman*	*100*	*Included objectives and stakeholder inputs*
Design Calculations	*Gaith*	*100*	*Basis for early design concepts.*
Finalized BOM	*All Members*	*100*	*Ensures materials and components are sourced efficiently.*
Assembly	*Gaith, Omar A. & Omar T.*	*100*	*Fully assembled.*
Motor and Sensor Integration	*Navroz & Ibrahim*	*100*	*Fully integrated.*
Testing and Verification	*All Members*	*85*	*Scheduled to start March 2025*

Table 20. RACI

Task	*Responsible*	*Accountable*	*Consulted*	*Informed*
Define Goals	*All Members*	*Team Lead*	*Project Supervisor*	*Stakeholder*
Conduct Research	*All Members*	*Team Lead*	*Project Supervisor*	*Stakeholder*
Material Sourcing	*Gaith & Omar A.*	*Team Lead*	*Vendors*	*Project Supervisor*
Design Validation	*All Members*	*Team Lead*	*Project Supervisor*	*Project Supervisor*
Assembly	*Gaith & Omar A.*	*Team Lead*	*Project Supervisor*	*Project Supervisor*
System Integration	*All Members*	*Navroz & Ibrahim*	*Project Supervisor*	*Project Supervisor*
Testing and Reporting	*All Members*	*Project Supervisor*	*Project Supervisor*	*Stakeholder*

7.4 Project Schedule/Sprints

- **Sprint 1: BOM Finalization and Initial Setup**
  - Objective: Finalize and organize resources for assembly.
  - Timeline: September 16, 2024 – November 22, 2024
  - Key Activities:
    - Finalize the Bill of Materials (BOM).
    - Purchase key components.
    - Organize and label parts for efficient assembly.
  - Deliverables: Complete BOM and all materials ready for assembly.
  - Storyline: Laying the foundation for the clinostat assembly.
  - Story Points: 5
  - Progress: 100%
  - Comments: Done as scheduled.

- **Sprint 2: Frame Construction and Motor Integration**
  - Objective: Build the structural framework of the clinostat.
  - Timeline: November 25, 2024 – March 14, 2025
  - Key Activities:
    - Assemble the frame using aluminum extrusions.
    - Mount the motor and connect it to hollow shafts with a bicycle chain.
    - Add vibration reduction padding.
  - Deliverables: Sturdy frame and motor securely integrated.
  - Storyline: Constructing the clinostat's framework and integrating the motor.
  - Story Points: 8
  - Progress: 100%
  - Comments: Frame assembly done, motor alignment requires adjustments.

- **Sprint 3: Sensor Integration and Safety Features**
    - Objective: Ensure precision monitoring and operational safety.
    - Timeline: March 17, 2025 – April 4, 2025
    - Key Activities:
        - Integrate sensors for temperature, humidity, gravity and rotational speed.
        - Calibrate sensors for accurate data collection.
        - Secure the frame with a plexiglass enclosure.
        - Implement failsafe systems (emergency stop).
    - Deliverables: Calibrated sensors and operational safety features.
    - Storyline: Ensuring precision and safety in the operational setup.
    - Story Points: 10
    - Progress: 100%
    - Comments: Sensors ordered, plexiglass enclosure design being finalized.

- **Sprint 4: Real-Time Camera Integration and Refinement**
    - Objective: Enable real-time monitoring and optimize stability.
    - Timeline: April 7, 2025 – April 18, 2025
    - Key Activities:
        - Install a camera for monitoring.
        - Refine the enclosure to minimize vibrations.
        - Ensure all components function in harmony.
    - Deliverables: Integrated camera and optimized enclosure.
    - Storyline: Enhancing usability and monitoring for stakeholders.
    - Story Points: 7
    - Progress: 100%
    - Comments: Camera integrated and real time monitoring was successfully achieved.

- **Sprint 5: Calibration, Testing and Iteration**
    - Objective: Achieve final functionality and optimization.
    - Timeline: April 11, 2025 – April 23, 2025
    - Key Activities:
        - Calibrate motor to achieve stable 120 RPM.
        - Test clinostat for functionality and resolve any issues.
        - Make final adjustments to ensure performance, safety and reliability.
    - Deliverables: Fully operational clinostat meeting design specifications.
    - Storyline: Finalizing and optimizing the clinostat for use.
    - Story Points: 12
    - Progress: 85%
    - Comments: Adjustments will be based on feedback from initial testing phases.

7.5 Project Procurement/Equipement/Travel List

Table 21. Available Components.

		Avaliable Parts			
1	Keyed Rotary Shafts	1	Available	Fall	**NA**
2	Bearings	2	Available	Fall	**NA**
3	Steel Plates (Sourced)	5	Not Available	Fall	**NA**
4	Loctite	1	Available	Fall	**NA**
5	WD-40	1	Available	Fall	**NA**

Table 22. Design A cost analysis.

ITEM NO.	PART NUMBER	QTY./Length (ft)	STATUS	ORDER PRIORITY	PRICE	PRICE (Including TAX, delivary, and adjustments)
1	T-Slotted Aluminum Extrusions	30ft	Available	Fall	$36	$36
2	Outside Corner Brackets for Single Rails	12	Available	Fall	$200	$305
3	Sprocket (12 teeth)	2	Available	Fall	$50	
4	Surface Brackets for Single Rails	16	Available	Fall	$48	$79
5	Roller Chain	1	Available	Fall	$24	
6	Bushings	4	Available	Winter	$14	$111
7	Slip Rings	2	Available	Winter	$84	
8	Screws (M3, M4 and M5)	1	Available	Fall	$23	
9	NEMA 34	1	Available	Fall	$72	
10	Driver	1	Available	Fall	$32	$217
11	Motor Power Supply	1	Available	Fall	$33	
12	Motor mount	1	Available	Fall	$32	
13	Chain Tool	1	Available	Winter	$5	$10
14	Insulation Foam	1	Available	Winter	$52	$79
15	Printer Side Plates	1	Available	Winter	$18	
16	Top Plate	1	Available	Winter	$34	$39
17	Compartment Covers	1	Available	Winter	$16	$72
18	Nails	1	Available	Winter	$34	$38
		Total Cost				**$987**

Table 23. Design B cost analysis.

ITEM NO.	PART	QTY./Length (ft)	STATUS	ORDER PRIORITY	PRICE (Including Tax, Delivery, Adjustments)
1	Steel Plates (1/2-inch thick, base)	2 ft x 1 ft x 1.5 ft	Not Bought	Fall	$250.00
2	Triangular Steel Side Plates	2	Not Bought	Fall	$120.00
3	Shafts (Steel, 20mm diameter)	2	Not Bought	Fall	$150.00
4	Bushings	4	Not Bought	Fall	$50.00
5	Bearings	2	Not Bought	Fall	$40.00
6	Slip Rings	2	Not Bought	Winter	$90.00
7	NEMA 34 Motor	1	Not Bought	Fall	$72.00
8	Motor Driver	1	Not Bought	Fall	$32.00
9	Motor Power Supply	1	Not Bought	Fall	$33.00
10	Screws and Bolts	1 set	Not Bought	Fall	$20.00
11	Small Steel Housing (for 3D printer)	12"x12"x12"	Not Bought	Fall	$120.00
	Total Cost				**$937.00**

Table 24. Design C cost analysis.

ITEM NO.	PART	QTY./Length (ft)	STATUS	ORDER PRIORITY	PRICE (Including Tax, Delivery, Adjustments)
1	Steel Base (1-inch thick)	2 ft x 2 ft x 2 ft	Not Bought	Fall	$200.00
2	Side Plate (Thick Steel)	1	Not Bought	Fall	$80.00
3	Shafts (Steel, 20mm diameter)	2	Not Bought	Fall	$140.00
4	Bushings	4	Not Bought	Fall	$50.00
5	Bearings	2	Not Bought	Fall	$40.00
6	Slip Rings	2	Not Bought	Winter	$90.00
7	NEMA 34 Motor	1	Not Bought	Fall	$72.00
8	Motor Driver	1	Not Bought	Fall	$32.00
9	Motor Power Supply	1	Not Bought	Fall	$33.00
10	Screws and Bolts	1 set	Not Bought	Fall	$20.00
		Total Cost			**$757.00**

The cost analysis compares three designs to support budget-conscious decision-making. **Design A ($987)** is the top choice, balancing affordability, effectiveness, and safety. Its use of standard aluminum extrusions simplifies assembly and ensures reliability, justifying the slightly higher cost. **Design B ($937)** uses thicker steel and custom parts, boosting strength but adding complexity and weight. **Design C ($757)** is the cheapest but may lack durability due to its simpler structure. All designs share key components like motors, shafts, and slip rings. Design A’s locally sourced aluminum slightly raised costs but improved procurement. Overall, Design A offers the best value within budget.

7.6 Risk Register

Table 25. Risk Register.

ID	*Risk Event*	*Stage*	*Likelihood (1–5)*	*Impact (1–5)*	*Combined Score*	*Contingency Plan & Response*	*Trigger Condition*
PM-R1	*Team supervisor unavailable for meetings*	*Project Management*	*2*	*3*	*5*	*Pre-schedule meetings and maintain async communication via Slack/Teams.*	*Supervisor misses 2+ planned meetings or feedback windows.*
PM-R2	*Team members unavailable for coordination*	*Project Management*	*2*	*3*	*5*	*Assign backup members and adjust deadlines to accommodate unavailability.*	*Team fails to meet synchronous milestone deliverables.*
PM-R3	*Lack of expertise for key tasks*	*Project Management*	*2*	*4*	*6*	*Assign research tasks early, enable peer learning, consult external experts if needed.*	*Errors or delays due to misunderstandings or lack of technical knowledge.*

PM-R4	*Delays in meeting deliverables*	*Project Management*	*3*	*5*	*8*	*Use updated Gantt charts with realistic time buffers.*	*Client milestone dates are missed repeatedly.*
PM-R5	*Project budget overrun*	*Project Management*	*2*	*4*	*6*	*Track weekly expenses; explore cost-saving options or seek additional funding.*	*Purchases exceed budget or unexpected costs arise.*
PD-R1	*Loss or corruption of design files*	*Preliminary Design*	*1*	*3*	*4*	*Use version-controlled storage systems (e.g., Google Drive, GitHub).*	*Files are missing or corrupted during reviews.*
PD-R2	*Incorrect printer model selected*	*Preliminary Design*	*2*	*3*	*5*	*Compare printer specifications through trade studies.*	*Selected printer cannot interface with the chosen software.*
PD-R3	*Inaccurate simulations*	*Preliminary Design*	*2*	*4*	*6*	*Validate with manual calculations and sensitivity analysis before testing.*	*Results deviate significantly from test data.*
TST-R1	*Motor overheats at 120 RPM*	*Testing*	*3*	*5*	*8*	*Install active cooling and monitor temperature continuously.*	*Motor housing exceeds 95°C or emits noticeable heat.*
TST-R2	*Sensor fluctuations due to EMI*	*Testing*	*3*	*4*	*7*	*Use grounded/shielded cables; test sensors in isolation pre-integration.*	*Sensor readings show unexpected spikes/drops during testing.*
TST-R3	*Camera misalignment during rotation*	*Testing*	*2*	*5*	*7*	*Use vibration-resistant mounting; verify alignment after setup.*	*Camera appears loose or shifts during operation.*
ASM-R1	*Misalignment during frame assembly*	*Assembly*	*3*	*4*	*7*	*Use alignment jigs/guides and verify accuracy with calipers.*	*Frame is off-axis or doesn't meet specs.*

ASM-R2	*Late delivery of critical components*	*Assembly*	*3*	*5*	*8*	*Confirm lead times in advance; expedite shipping when necessary.*	*Critical parts arrive after the needed date.*
INT-R1	*Printer and chassis incompatibility*	*Integration*	*3*	*5*	*8*	*Perform prototype fitting before final assembly.*	*Printer collides with chassis during integration.*
INT-R1	*Software-hardware mismatch*	*Integration*	*2*	*4*	*6*	*Keep firmware backups; run integration tests prior to the demo.*	*Services or UI fail to sync during trials.*

The project risk register outlines 16 potential risks categorized across five key stages: Project Management, Preliminary Design, Testing, Assembly, and Integration. Within Project Management, risks include the unavailability of the supervisor and team members, lack of expertise for complex tasks, delays in meeting deliverables, and budget overruns. These are managed through scheduling strategies, backup assignments, early skill development, progress tracking, and expense monitoring.

In the Preliminary Design stage, concerns like file loss, incorrect 3D printer selection, and inaccurate simulations are mitigated with version control, thorough trade studies, and validation methods such as manual calculations. Testing risks focus on hardware reliability and measurement accuracy, including motor overheating, sensor fluctuations due to electromagnetic interference (EMI), and camera misalignment during rotation—each addressed with cooling systems, shielding techniques, and secure mounting practices.

During Assembly, potential issues include frame misalignment and late delivery of critical components, controlled using jigs for precision and advanced procurement planning. Finally, in the Integration phase, high-impact risks such as printer-chassis incompatibility and software-hardware mismatches are anticipated, with fitting sessions and integration tests ensuring smooth system functionality. Each risk includes a detailed contingency plan and clearly defined trigger conditions to facilitate early detection and responsive action.

8.0 Preliminary Business Case

8.1 Value Proposition

Understanding the value a project delivers is just as important as understanding how it was built. A value proposition is essential as it demonstrates the broader impact of THE D.I.C.E. system, not just as a technical solution, but as a system that creates long-term academic, financial and research value. By clearly outlining how the design fulfills stakeholder needs and contributes to future innovation at Lassonde, the value proposition ensures that the work done has meaning beyond just being a prototype.

A Low-Cost Gravity Simulation Platform for Research and Education

Based on the final BOM, the total system cost of THE D.I.C.E. is under $1000 CAD, thus meeting the strict cost ceiling set during beforehand.Commercial clinostats capable of simulating hypergravity typically cost well over a couple of thousand dollars, making them inaccessible to student-led research or small scale-labs. By designing a custom-built, modular system using both off-the-shelf components as well as in-lab sourcing, the team has delivered a gravity simulation solution at a fraction of typical industry like systems. This makes THE D.I.C.E. system a viable solution and platform for research and development trams at Lassonde and other academic institutions working within similar budget constraints.

Innovation Design Tailored for High-Precision Experimentation

While gravity simulators have been created for alternative means before, THE D.I.C.E system introduces innovation through its compact size, single axis 120 RPM rotation capability, and integration of real-time sensor and camera systems. These features enable not only high-fidelity simulation of up to 4 times the Earth's gravitational pull *($4G_s$)*, but also real-time diagnostics which are critical for applications in bioprinting and material testing where precision printing is of the utmost significance. With a clear mechanical focus in minimizing vibration and thermal instability, the design advances the clinostat concept in both functionality and usability. These innovations offer value to the future of space infrastructure and research here at Lassonde.

A Learning Platform for Future Student Research and Prototyping

D.I.C.E. is not just a prototype, but rather represents a framework on which future tema can build upon. The mechanical, electrical and software documentation produced by the team provides a foundation for student projects and lab integration efforts. By contributing a fully documented, validated test platform, the project aims to guide Lassonde in areas such as space manufacturing and biomedical device testing. Moreover, the project strengthens interdisciplinary collaboration by bridging the gap between mechanical design, embedded systems and material science.

8.2 SWOT Analysis

To evaluate the viability of THE D.I.C.E., as a functional product and future research tool, a preliminary business case was developed using a SWOT analysis. This analysis helps assess the internal strengths, weaknesses, opportunities and threats on a per stakeholder basis. The SWOT framework provides strategic insight into how well D.I.C.E. addresses identified stakeholder needs. It also outlines potential risks and areas for improvement. By incorporating feedback from academic advisors, technical collaborators, industry professionals, and potential end-users, the business case offers a grounded view of the system's practical value and growth potential.

Table 26. SWOT analysis.

Stakeholder	***Strengths***	***Weaknesses***	***Opportunities***	***Threats***
Professor Czekanski & Lassonde Faculty	*Compact size, low cost, educational value; Agile process aligns with academic timelines.*	*Limited scalability and long-term support beyond the capstone team; no wireless UI.*	*Adoption into senior design projects and research labs; integration into course-based learning.*	*Project continuity post-capstone; institutional support may lapse without dedicated funding.*
Space Agencies (CSA, NASA, Blue Origin)	*Supports hypergravity simulation up to 4g; live environmental monitoring enables analog ground testing.*	*Single-axis systems may not simulate microgravity or multi-axis conditions for advanced missions.*	*Expansion to multi-axis simulation; incorporation into CubeSat payload validation programs.*	*Commercial simulators may outperform D.I.C.E. in automation and force complexity.*
3D Printing Industry	*Modular design, compatibility with existing hardware (Group 35 printer); low barrier for integration.*	*Payload capacity capped at 12kg; not optimized for industrial-scale or automated workflows.*	*Adaptation for plug-and-play hardware kits or printer testing environments under dynamic forces.*	*Market saturation with higher-end simulation rigs may outcompete low-cost solutions.*
Biomedical Researchers	*Integrated sensors and stable enclosure suitable for cell printing and stress-sensitive biotesting.*	*Potential thermal buildup; may require better vibration mitigation under sensitive printing conditions.*	*Broader applications in tissue engineering and bioprinting under varying force environments.*	*Tissue integrity risks if thermal or vibrational conditions are unstable in extended use.*
Graduate Students & Researchers	*Simple UI, real-time feedback, supports research under faculty supervision; low-cost experimentation.*	*Lack of touch interface or remote-control tools; wired sensor setup can limit flexibility.*	*Use in thesis-based projects and graduate research with additional software/data support.*	*Obsolescence due to tech advances in UI/UX and gravity simulation frameworks.*
Investors	*Cost-effective prototype with clear application potential; scalable platform with proof of feasibility.*	*No existing commercialization path; limited documentation for handoff or IP development.*	*Pitch for seed funding or university commercialization grants; develop a full research kit.*	*Component inflation or supply chain issues could challenge the budget-replication model.*
Material Science Labs	*Supports temperature/humidity control under rotational loads; viable for advanced materials testing.*	*Lacks in-depth post-processing analysis tools; not ready for lifecycle fatigue testing.*	*Collaborate on material deformation studies under simulated g-forces; publish comparative data.*	*Safety requirements for higher-energy tests may exceed D.I.C.E. structural limitations.*
Government & Defense Organizations	*Enclosed, torque-tested design allows safe operation; early-stage prototype for regulated applications.*	*Not yet certified for use in government or defense environments; regulatory compliance unverified.*	*Prototype standardization for government R&D testing platforms; defense-aligned stress testing.*	*Regulatory hurdles for operation in controlled facilities; limitations in scalability or IP.*

9.0 Deviations From Initial Plan

9.1 Base Dimensional Expansion

The original design was predicated on a compact base of 1.5ft x 1.5ft. This dimension was chosen to optimize for portability, minimize material usage and ensure easy placement within conventional lab setups or small research stations. However, as the project progressed and physical components arrived, it became increasingly clear that the original footprint was insufficient.

During Sprint 1 and early parts of Sprint 2, several challenges emerged:

- **Component Clearance Issues**: The NEMA 34 motor and carbon steel shafts required more lateral spacing than anticipated. With the 3D printer enclosure, chain drive, slip rings and environmental sensors, the original frame width caused overlap and mechanical interference.
- **Poor Shaft Alignment**: With a restricted base, aligning the rotating shafts at the correct center of mass and at a consistent parallel angle was difficult. This led to skewed rotation and increased vibration in testing.
- **Inaccessible Wiring Channels**: The wiring layout, which involved routing cables to sensors, the camera and power systems through the rotating axis, became too congested in the limited footprint. Risk of cable entanglement increased.
- **Sensor and Heat Distribution Challenges**: Proper placement of the humidity and temperature sensors required additional internal spacing to avoid cross-interference and overheating.

As a result, the decision was made to expand the base to 2ft x 2ft, which remained within the upper limit of stakeholder specifications. The benefits of this change included:

Table 27. Dimensional expansion effects.

Factor	*Before (1.5ft x 1.5ft)*	*After (2ft x 2ft)*
Mechanical Clearance	*Overlapping parts, shaft misalignment.*	*Adequate room for components and cabling.*
Shaft Placement Accuracy	*Difficult to center and stabilize.*	*Precise alignment, better balance.*
Wiring and Sensor Layout	*Congested, high risk of tangling.*	*Clean layout, reduced EMI and heat buildup.*
Assembly and Complexity	*High due to spatial constraints.*	*Reduced complexity and assembly errors.*
Portability	*Very compact and lightweight.*	*Slightly bulkier, still manageable.*

While the base expansion added marginally to weight and size, these drawbacks were offset by improvements in operational stability, structural durability and ease of assembly. The update also provided future-proofing for potential add-ons, such as a second axis of rotation or upgraded environmental sensors.

9.2 Exterior Frame Redesign

The original enclosure concept for the clinostat was a simple cuboid structure meant solely to encase the 3D printer and a few sensors. However, during Sprint 2, multiple issues arose during stakeholder feedback and internal testing that necessitated a substantial redesign. Supervisors emphasized the need for increased usability, accessibility for debugging and enhanced visual access to support demonstrations and educational outreach. Key shortcomings of the initial enclosure design included:

- **Lack of Electronics Access**: Inconvenient access to mounted sensors like the TMP36, ADXL345 and DHT22 hindered calibration and maintenance.
- **Heat Buildup Around Electronics**: All electronics were placed in close proximity to the heat-generating 3D printer, leading to potential signal drift and thermal instability.
- **No Real-Time Visual Feedback**: The fully opaque enclosure meant no on-the-fly assessment of print quality or system behavior was possible without halting operation.
- **Difficult Troubleshooting and Maintenance**: Crammed layout with no separation of electrical components from mechanical ones complicated repair or reconfiguration.

Table 28. Redesign overall enhancements.

Feature	*Original Design*	*Revised Design Enhancements*
Enclosure Structure	*Simple opaque cuboid.*	*Modular compartments for electronics and sensor access.*
Safe Viewing Accessibility	*None.*	*Plexiglass viewing window with wide-angle visibility.*
Electronics Integration	*Embedded with mechanical parts.*	*Isolated electronics to reduce heat/signal interference.*
Debugging Ease	*Difficult.*	*Quick access panels for testing/calibration.*
Presentation Usability	*Minimal.*	*Suitable for demonstrations and stakeholder walkthroughs.*

Notable additions to the redesigned enclosure include:

- **Two Dedicated Compartments**: One for housing the motor driver, microcontroller and wiring (with heat shielding) and another for accessing calibration interfaces for sensors and the slip ring.
- **Plexiglass Viewing Platform**: Installed on one side of the clinostat to allow real-time visual monitoring of the 3D printing process and internal motion without opening the system.
- **Sliding/Removable Panels**: Designed to allow faster repairs and modular testing of new components.

9.3 Bearing Configuration

Initially, the clinostat was designed with two bearings: one linear ball bearing and one rotary bearing. This configuration was expected to be sufficient based on static load assumptions and idealized shaft dynamics. However, early dynamic testing at rotational speeds near 120 RPM revealed unexpected instability and noise.

Key problems identified during testing included:

- **Shaft Wobble**: The minimal support length caused the shaft to deflect during rotation, introducing imbalanced forces and leading to cyclical vibration.
- **Alignment Challenges**: Manual assembly of only two bearings resulted in angular misalignments that exacerbated vibrations.
- **Inconsistent Sensor Data**: The accelerometer registered erratic spikes due to oscillating movements, affecting the reliability of gravity simulation data.
- **Structural Stress Concentration**: Load was disproportionately carried by the limited support points, creating localized stress zones in the frame.

To resolve these issues and improve overall system stability, the bearing setup was expanded to include:

- **2 Linear Ball Bearings**: Placed symmetrically at the shaft entry/exit points to reduce radial displacement.
- **2 Self-Aligning Rotary Bearings**: Added to compensate for minor angular errors and self-correct during high-speed rotation.

The changes led to measurable improvements in performance and usability, as outlined below:

Table 29. 2 bearing configuration vs. 4 bearing configuration.

Parameter	***Original Configuration (2 Bearings)***	***Updated Configuration (4 Bearings)***
Rotational Stability	*Moderate vibration and shaft wobble.*	*Significantly reduced oscillation and deflection.*
Bearing Load Distribution	*Concentrated on two points.*	*Evenly distributed across four support points.*
Assembly Precision Requirements	*High (tight tolerances).*	*Lowered due to self-aligning correction capability.*
Sensor Reading Reliability	*Inconsistent due to mechanical jitter.*	*Stable data with minimal noise.*
Maintenance Frequency	*High (risk of wear and misalignment).*	*Lower due to better load management.*

9.4 Slip Rings

The original electrical design of the clinostat included two slip rings: one dedicated to power transmission and the other for data signals. This configuration was driven by the initial assumption that the 3D printer's heatbed would require 240W (drawing up to 10A at 24V), thereby demanding a separate, high-capacity slip ring to handle the load.

However, during Sprint 3, the printer setup was revised to incorporate a more energy-efficient heatbed. This reduced the power requirement to 60W (2.5A), well within the 10A rating of the signal-compatible slip ring already sourced for the project. As a result, the team made the decision to consolidate both power and data lines into a single slip ring.

Primary reasons for this deviation included:

- **Reduced Current Demand**: Lower power draw allowed safe current transmission within the limits of the existing slip ring.
- **Simplified Wiring Architecture**: Consolidating into one slip ring reduced internal cable routing, minimizing clutter and potential signal interference.
- **Improved Rotational Balance**: Removing the second slip ring reduced any friction die to wiring mismanagement (exterior slip ring wires going underneath the interior slip ring).
- **Component Availability**: Delays in procuring a second high-current slip ring would have hindered assembly progress.

Table 30. Slip ring count system level comparison.

Factor	***Two Slip Rings (Original Plan)***	***One Slip Ring (Final Implementation)***
Power Transmission	*Split across two rings.*	*Combined through a single 10A-rated slip ring.*
System Complexity	*Higher – more wires, larger enclosure size.*	*Reduced – simplified internal layout.*
Cost	*Double the slip ring expense.*	*Savings on components and mounting.*
Rotational Drag and Inertia	*Slightly increased.*	*Lower rotational resistance.*
Signal Integrity	*Physically separated paths.*	*Maintained through data validation.*

Prior to finalizing this change, the team validated the consolidated setup through:

- **Thermal Load Testing**: Confirmed that heat buildup stayed well below critical thresholds.
- **Signal Interference Checks**: Tests showed no data corruption on sensor outputs or camera feeds.
- **Mechanical Trials**: Verified that balance and smooth rotation improved post-consolidation.

9.5 Machining Delays and Precision Challenges

The original project timeline assumed that all custom components, such as motor brackets, sensor mounts and shaft couplers, would be machined by the Lassonde machine shop. This approach was expected to ensure high precision, minimize risk of human error and allow the team to focus on design and integration. However, during Sprint 2 and 3, unforeseen backlogs and limited technician availability caused significant delays in machining schedules, prompting a critical change.

To avoid stalling progress, the team decided to fabricate several parts in-lab using available portable CNC tools, manual drilling and handheld cutting equipment. This deviation required not only a shift in responsibility but also rapid skill development and creative problem solving.

Challenges encountered due to this deviation included:

- **Limited Tolerance Control**: Hand-fabricated parts had dimensional variations that affected alignment.
- **Increased Vibration**: Imperfect fits in shaft couplers and motor mounts led to wobble during initial trials.
- **Time-Consuming Fabrication**: Manual machining increased build time and required multiple iterations.
- **Tool Limitations**: Equipment available in the lab lacked the precision and rigidity of professional-grade CNC machines.

To address these, the team implemented the following mitigation strategies:

- **3D Printed Jigs**: Used to guide drilling and hole placements, improving alignment.
- **Adjustable Mounting Designs**: Tolerances were relaxed in the CAD models to accommodate imperfect holes and part variations.
- **Post-Fabrication Testing**: Each component underwent validation before integration into the system.
- **Padding and Damping Materials**: Used at mounting interfaces to absorb mechanical inconsistencies and reduce resonance.

Table 31. Machine shop vs. In-lab machining comparison.

Aspect	***Planned (Central Machine Shop)***	***Actual (In-Lab Machining)***
Precision	*High (sub-millimeter tolerances).*	*Moderate (dependent on tool and user skill).*
Turnaround Time	*Delayed by external queue.*	*Controlled but slower than expected.*
Cost	*Included in university support.*	*Minor increase due to tooling and material waste.*
Design Adaptability	*Fixed once submitted.*	*High – allowed iterative adjustments.*
Team Skill Development	*Minimal.*	*Significant hands-on machining and troubleshooting.*

9.6 Material Procurement Bottlenecks

At the start of the project, one of the core planning assumptions was to rely heavily on off-the-shelf components and readily available materials to streamline the assembly process. This included sourcing standard plexiglass panels, bushings, sprockets, slip rings and mounting hardware from common suppliers. However, during Sprints 2 and 3, the team encountered substantial procurement issues.

Multiple factors contributed to material delays:

- **Supplier Backlogs**: Local distributors experienced shipping delays, particularly for specialty mechanical components like precision bushings and slip rings.
- **Stock Shortages**: Popular items such as plexiglass sheets and certain aluminum profiles were on backorder or completely unavailable.
- **Budget Constraints**: Prices for some off-the-shelf components exceeded the initial estimates, pushing the team to reconsider their selection.
- **Delivery Lead Times**: Standard delivery times ranged from 2 to 4 weeks, threatening sprint timelines.

In response, the team pivoted to an in-lab substitution and adaptation strategy:

- **Manual Plexiglass Cutting**: Instead of pre-cut sheets, raw plexiglass was cut using laser cutters and drills available in the fabrication lab.
- **Alternate Bushings and Sprockets**: Slightly larger components were sourced and accommodated through redesign of housing mounts.
- **Redesigned Motor Mounts**: Created new motor plates to fit different bolt patterns after planned components became unavailable.
- **On-the-Fly Hardware Adjustments**: Used adjustable fasteners, oversized washers and 3D printed spacers to maintain compatibility.

Table 32. Off-the -shelf sourcing vs. In-Lab Substitutions.

Factor	***Planned (Off-the-Shelf Sourcing)***	***Actual (In-Lab Substitutions)***
Component Availability	*High (assumed readily accessible).*	*Moderate – some delays and shortages.*
Design Flexibility	*Low – fixed dimensions.*	*High – allowed for real-time iteration.*
Fabrication Requirements	*Minimal.*	*Increased due to custom modifications.*
Cost Implications	*Predictable.*	*Slight overages on raw materials/tools.*
Timeline Impact	*Subject to external delays.*	*Managed internally with rapid prototyping.*

Though this deviation required increased manual labor and frequent redesigns of mounts and interfaces, it ultimately helped the team maintain progress and meet critical sprint milestones. The flexibility to adapt quickly to what materials were available locally and the willingness to modify designs accordingly, highlighted the importance of agility in project management.

10.0 Failure Report

One of the most encouraging aspects of this project was the absence of any major system-wide failures. While the team encountered numerous engineering challenges and had to deviate from the initial plan multiple times, none of these issues escalated to the point of jeopardizing the core functionality of the clinostat or causing sprint-wide delays. Instead, the project featured a series of minor failures and setbacks, all of which were addressed promptly through agile responsiveness and collaborative problem-solving.

One such minor failure occurred during early rotational testing. The original two-bearing configuration led to significant shaft instability, which was not anticipated during static design evaluations. This manifested as rotational wobble and noisy sensor outputs, briefly halting further mechanical integration. However, the team quickly iterated on the design and resolved the issue by doubling the number of bearings and introducing self-aligning supports. This highlighted the importance of testing under real operational conditions and the limitations of over-reliance on CAD models.

Another minor issue arose from the slip ring integration. The original wiring setup lacked proper internal strain relief, leading to intermittent signal loss during rotation tests. Upon identifying the problem, the team modified the mounting approach by adding cable management clips, which successfully restored signal stability and enhanced long-term reliability. This experience highlighted the critical role of mechanical design in ensuring robust electrical integration, especially in systems involving rotational motion.

A further example includes the use of misaligned, hand-drilled brackets during in-lab machining. These minor errors led to uneven motor mounts and elevated vibration during high-speed operation. The team responded by creating 3D printed jigs and templates to standardize drilling patterns and implemented padding to absorb excess vibration. This small failure emphasized the importance of precision, even when relying on manual fabrication techniques and showed how simple tools can enhance repeatability.

Lastly, the team encountered a miscommunication regarding available plexiglass stock, which temporarily halted enclosure assembly. This was resolved immediately through sourcing and redesign of mounting holes to fit a different sheet thickness. Though minor, this failure reinforced the need for real-time inventory checks and material flexibility.

In summary, while the project had no catastrophic failures, these small but significant moments of friction offered valuable learning experiences. Each incident reinforced the importance of iterative testing, cross-functional awareness and adaptability, cornerstones of Agile development. The team's ability to identify, address and resolve failures quickly was a major contributor to the overall success of the MVP and will inform best practices in future engineering work.

11.0 Lessons Learned

11.1 Team Member Statements

Table 33. Team Reflections

Team Member	***Role***	***Key Contributions***	***Areas for Improvement***	***Strengths***
Gaith Al-Adwan	*Mechanical Engineer*	*- CAD Modeling - Calculations - Machining - Assembly - BOM - Report Writing & Formatting*	*Electrical modeling.*	*Leading the team and keeping team members up to date. Design, calculations and machining. Report writing and formatting.*
Omar Almufleh	*Mechanical Engineer*	*- Assembly - Machining - CAD Modeling - BOM - Report Writing*	*Being more active during scheduled meetings and electrical circuitry.*	*Material mechanics, stress analysis, CAD modeling and simulations.*
Herman Balagan	*Mechanical Engineer*	*- Vibration Analysis - Led mini-capstone day presentation. - Coding - Report Writing*	*Expressing ideas more often.*	*Skilled in vibration control and stakeholder communication.*
Navroz Bir	*Electrical Engineer*	*- Wiring Schematics - PSU Selection - Motor Selection - Coding - Wiring - Report Writing*	*Ensure effective communication of electrical aspects to mechanical engineers.*	*Knowledge of circuit design and programming.*
Ibrahim El Zamzamy	*Mechanical Engineer*	*- Sensor Selection - Power Calculations - Coding - Wiring - Report Writing*	*Time organization and keeping up with deadlines*	*Sensors and motors.*
Omar Tawil	*Mechanical Engineer*	*- Power Delivery - Torque Calculations - BOM - Cad Modeling - Report Writing*	*- Get involved more. - Listen to peer's needs more often.*	*Design calculations and CAD modeling.*

11.2 Individual and Team ITPMetrics Review Statements

11.2.1 Al-Adwan, Gaith

- **Role:** Mechanical Engineer – CAD design, RPM calculations, Structural Integrity/Vibrations calculations, Assembly and Machining.
- **Responsibilities:**
    - Oversee project planning, execution and team coordination.
    - Perform CAD modeling, including detailed designs for clinostat components and layout.
    - Conduct RPM calculations and structural/vibration analysis through hand calculations and simulation software.
    - Lead assembly and machining of components.
    - Maintain clear documentation of progress, designs and calculations.
- **Skills & Qualifications:**
    - Strong proficiency in CAD software (SolidWorks) and FEA (Star-CCM).
    - Strong proficiency in Microsoft (word and excel).
    - Excel in report writing, effectively conveying complex technical information in a clear, organized and professional manner.
    - Practical machining and assembly skills for hands-on implementation.
    - Research experience in engineering design (mechanical systems).
    - Effective communication and leadership abilities for managing a project team.
- **Motivation:**
    - Desire to lead innovative engineering projects and contribute to research.
    - Interest in applying mechanical engineering skills to real-world challenges.
- **Fulfilling Team Gaps:**
    - Provides technical expertise and leadership, filling gaps in mechanical design, simulation and hands-on assembly knowledge.
    - Bridges theoretical research and practical application.
    - Ensures continuity and depth in the project through prior experience.

Based on the ITPMetrics peer feedback, strengths were identified in five key competencies: Commitment, Communication, Capabilities, Standards and Focus, all rated as outstanding by my fellow peers. This reflects a high level of engagement, skill and alignment with team goals. Maintaining this consistency involves continuing to meet deadlines, support teammates, share information openly and sustain high standards of work. From my perspective, one challenge for the team could be evenly distributing responsibilities to ensure that everyone has opportunities for meaningful contributions. Additionally, maintaining seamless communication across all members can be challenging in complex projects, so regularly checking in and exchanging feedback will be crucial.

11.2.2 Almufleh, Omar

- **Role:** Mechanical Engineer – Focused on designing and CAD modelling.
- **Responsibilities:** My responsibility as a team member is creating the ideal design based on the calculations done by my team, also creating the CAD model for our team selected design with all the required materials and doing the necessary assembly for the CAD Model.
- **Skills & Qualifications:** Proficiency in CAD Modelling, strong understanding of material loading and stress analysis, strong understanding in material properties.
- **Motivation:** A genuine interest in advanced manufacturing technologies.
- **Fulfilling Team Gaps:** Designing for our team is considered a big gap as our whole project needs designing and CAD models so fulfilling the CAD modeling and designing gap is a crucial part for our team, and a very important part for our project to succeed and be a hundred percent functional, and I believe I will be able to make significant contributions to fulfil this gap.

A summary of my ITPMetrics results shows that I've made significant contributions to the team, especially in preliminary design and the initial Bill of Materials (BOM). I take pride in generating and sharing innovative ideas, which I believe fosters collaboration. While I'll continue this practice, I recognize the need to refine my ideas further and engage more deeply in discussions to enhance our collective output. My contributions during the planning phase and my CAD design expertise have been key, and I always strive to respond promptly to stay updated on project details. I also focus on motivating my colleagues, which helps create unity within the team and build trust. By supporting my team members, we can overcome the challenges we may face during our project. I aim to strengthen our overall dynamics and elevate our performance together.

11.2.3 Balagan, Herman

- **Role:** Mechanical Engineer – Focus on Vibrations and Electrical System.
- **Responsibilities:**
    - Perform design-based calculations around vibrations which would ensure design stability during operation. This would include calculations to be computed on factors such as dampening and design oscillation.
    - Assist Electrical engineer in creation of electrical systems required for design clinostat usage. This would include circuit design and creation of circuitry. This would allow for the implementation of failsafe systems.
    - Collaboration with other teammates to ensure final design is up to standard. Communication with stakeholders involved to provide updates on the project status.
- **Skills & Qualifications:**
    - Strong understanding of mechanical vibrations, including damping, resonance, and frequency response.
    - Proficiency in electrical circuit design through systems such as LabVIEW, MATLAB and Python.
    - Knowledge of vibration control methods and electrical safety standards.
    - Experience in project management demonstrating firsthand experience in stakeholder communication.
- **Motivation:** Strong interest in electrical systems and vibration control. Fulfilment of associated engineering courses has developed strong analytical skills in these various areas of study. Among the only individuals within the team that has completed the vibrations engineering course.
- **Fulfilling Team Gaps:** By focusing on both vibrations and electrical systems, this team member addresses crucial gaps in the project, ensuring that the clinostat operates stably without vibration-induced interference and that its electrical components are safely and efficiently managed. Additionally, communication with the stakeholders involved would bridge the communication gap between the design team and the various groups of stakeholders involved.

The provided IPT metrics results show that my commitments, communication, capabilities, focus and standards are at an exceptional standard. It was noted that my immense contribution to team meetings allowed for strong idea generation and motivation amongst the team. The promotion of early work has also been a strong suit in order to achieve the desired goals at a much more efficient rate. One thing that I could work on is allowing others input into my own ideas. Though conflicting ideas within a group are required to create optimal designs, it is important to compromise between ideas to ensure everyone has some kind of input within the design. Overall, the team has been a pleasure to work with and have shown great attitude and interest.. One thing that the team should improve on is questioning each other's opinions. I feel that it is too easy to come to a consensus with this team. It is important that we challenge each other's ideas to further optimize the design in question.

11.2.4 Bir, Navroz

- **Role:** Electrical Engineer - Focused on Electrical circuit design and wiring. Integration of microcontroller and camera.
- **Responsibilities:**
  1. Develop and draw the wiring schematic for the clinostat device, including power supply, sensors, motors, and control systems. Doing power calculation to determine the power draw of each device.
  2. Integrate temperature and humidity sensors into the device, positioning them to provide accurate and reliable data without interfering with the rotation.
  3. Help with installing and wiring the NEMA motors, ensuring proper connections to the microcontroller and feedback systems.
  4. Help team with overall assembly of device
  5. Develop and implement the user interface for monitoring the clinostat's temperature and humidity.
- **Skills & Qualifications:**
  - I am proficient in programming languages including MATLAB, Python, C, and C++. I completed 16 months of professional experience as a Senior Technical Student at Toronto Hydro, where I worked on various electrical systems and technical projects, gaining practical industry experience. I have 4 years of academic experience in Electrical Engineering , where I developed a foundation in electrical systems, circuit analysis, and programming.
- **Motivation:** I am motivated by the challenge of applying my electrical engineering skills to develop innovative and impactful solutions. I also have a genuine interest in space technology as well promoting efficiency and sustainability in engineering.
- **Fulfilling Team Gaps:** With a background in electrical engineering, I bring a critical skill set that complements my team's mechanical engineering expertise. I am responsible for the electrical system design, wiring, and integration of control systems, which are essential for the device's functionality. My proficiency in programming and circuit design allows me to bridge the gap between mechanical components and electrical control, ensuring seamless integration and operation of the clinostat.

The ITPMetrics results highlight my strengths in commitment, communication, capabilities, focus, and standards. My contributions to electrical design and integration, particularly in selecting components and completing tasks reliably, have been valuable. My attention to detail has supported the team's progress and high standards. However, I could improve by fostering balanced task distribution and encouraging more critical discussions to incorporate diverse ideas. The team's dedication and collaboration have been excellent, but challenging each other's ideas more rigorously could further refine our designs and improve outcomes.

11.2.5 El Zamzamy, Ibrahim

- **Role:** My role in this project is to lead the technical design and assembly of the clinostat system. This involves performing critical design and power calculations, ensuring smooth integration of mechanical components, and coordinating closely with Group 35 on the 3D printer modifications. My primary focus is to ensure that the mechanical system is robust, functional, and aligned with project objectives.
- **Responsibilities:**
  - A key aspect of my responsibilities is conducting technical design calculations to determine the system's power requirements, torque, and center of gravity. Specifically, I calculate the torque demands for the motor to handle variable load distributions caused by the shifting weight of the 3D printer enclosure. These calculations are instrumental in selecting the appropriate motor and ensuring the clinostat operates stably under diverse conditions.
- **Skills & Qualifications:**
  - With four years of mechanical engineering coursework, I have developed strong skills in mechanical design, analysis, and hands-on assembly. My experience includes excelling in design project courses that emphasized teamwork, problem-solving, prototyping, and manufacturing.
- **Motivation:** My passion for advancing space technology drives my involvement in this project. I am motivated by the opportunity to develop innovative engineering solutions that enable material manufacturing and bioprinting in microgravity environments.
- **Fulfilling Team Gaps:** I bring specialized knowledge in mechanical design and power system optimization, filling key gaps in our team's expertise. My previous experience working with clinostat systems allows me to provide informed guidance on assembly, stability, and performance, which are critical to the project's success.

The ITP Metrics results highlight my contributions to the project's planning and technical execution. Team members have noted my respectful and responsive communication, as well as my diligence in addressing technical challenges. My prior experience with clinostat systems has also been recognized as a valuable asset, enhancing the team's understanding of key design aspects. However, one challenge identified is our team's difficulty in scheduling regular collaborative meetings due to conflicting individual commitments. This dynamic often leads to independent work and delayed feedback on critical tasks, potentially slowing iterative improvements. To address this, I aim to facilitate better time management by encouraging consistent scheduling and improving communication to ensure more frequent and productive collaborative sessions.

11.2.6 Tawil, Omar

- **Role:** As a mechanical Engineer my role in this project is to help with the technicalities and functions of the project, i.e. CAD modeling and design, material selections and assembly.
- **Responsibilities:**
  - Provide the team with innovative designs and creative solutions.
  - Apply feasibility studies and team calculations to re-design systems with reinforced parts and improved functional mechanisms.
  - Design parts, including motor brackets, power transmission systems, body supports, and printer platforms.
  - Conduct simulations to test system behavior and identify imperfections or potential errors.
  - Friction calculations and assembly.
- **Skills & Qualifications:**
  - 4th-year mechanical engineering student with a foundation in mechanical systems and design.
  - Proficient in CAD modeling using SolidWorks and Fusion360.
  - Skilled in simulation software, including Ansys, Star CCM, and SolidWorks Simulation.
  - Experience in assembly work, such as assembling electric motorbikes and construction projects.
- **Motivation:**
  - Driven by the challenge of fully designing a system to mimic micro-gravitational effects on 3D printing and manufacturing.
  - Seeking engineering excellence and striving for an executive role as a mechanical engineer.
- **Fulfilling Team Gaps:**
  - Provides expertise in CAD modeling, honed through multiple design projects as an engineering student.
  - Brings an analytical and visual understanding of mechanical systems to support the team.

Based on the ITP Metrics feedback, results show an exceptional rating for the five factors of a team member. This rating indicates that my performance is excellent and that I play an important role within this team helping the success of the team. I'm keen to stay on track and to always deliver quality work and to always have a positive influence for my team members.

11.3 Self Evaluation

Table 34. Team self evaluation.

Criterion	***Self-Evaluation Ranking***	***Justification***
Stakeholder Communication and Feedback Integration	*Exceeding*	*Regular stakeholder feedback (e.g., Professor Czekanski, space agencies) was incorporated into design iterations. Demonstrated in sprint reviews and trade studies.*
Cost Management and Budget Adherence	*Exceeding*	*Achieved 60% cost reduction ($2500 → $987) through material optimization and component selection. Budget tracked via BOM and procurement lists .*
Agile Methodology Compliance	*Exceeding*	*Sprints were executed as planned, with iterative improvements (e.g., vibration mitigation, sensor calibration). Backlog management and MVP prioritization were effective.*
Cross-Team Collaboration	*Meeting*	*Coordinated with Group 35 for 3D printer compatibility. Roles were clearly defined via RACI, though scheduling conflicts occasionally delayed feedback.*
Innovation in Design Solutions	*Exceeding*	*Unique integration of a 3D printer with gravity simulation, real-time monitoring and modular components. Addressed space constraints and safety creatively.*
Risk Mitigation Implementation	*Meeting*	*Identified and addressed high-priority risks (e.g., vibration, safety) with contingency plans. Failsafe mechanisms and spare parts were incorporated.*
Documentation and Reporting	*Exceeding*	*Comprehensive report with clear sections, figures and appendices (e.g., meeting minutes, BOM, CAD models). Critical analysis evident in compliance and trade studies.*
Technical Problem-Solving	*Exceeding*	*Resolved torque, vibration and structural challenges using engineering fundamentals. Calculations validated motor and shaft selections.*

12.0 Conclusions

The Gravity Gizmo, now renamed The CUBE, project was a comprehensive engineering effort that successfully delivered a functional prototype capable of simulating gravitational force effects in a controlled system. Through iterative design, multidisciplinary collaboration and strategic problem-solving, the team overcame numerous technical and logistical challenges to meet project goals.

12.1 Technical Summary

From a technical standpoint, the project required integration of mechanical, electrical and software subsystems. The team's primary objective was to construct a rotating platform supported by a robust structural frame, incorporating dynamic torque and power delivery systems. Several design iterations led to improvements, including:

- **Structural Enhancements**: The original 1.5 ft x 1.5 ft base was expanded to a 2 ft x 2 ft footprint to improve system stability and accommodate new structural features.

- **Subsystem Additions**: The exterior frame was redesigned to include a viewing platform and two compartments, optimizing usability and equipment organization.

- **Component Integration**: The bearing system evolved from an initial two-bearing design to four (two linear ball and two rotary self-aligning), improving load distribution and operational smoothness.

- **Power System Optimization**: Power requirements were reduced with a new heatbed configuration, which allowed the use of a single slip ring (instead of two), simplifying electrical routing and improving reliability.

Machining delays and material procurement bottlenecks added complexity, but the team adapted through in-lab fabrication and design pivots. The final system demonstrated reliable mechanical performance and effective interfacing between mechanical and electrical elements. Engineering standards such as safety, modularity and sustainability were considered, particularly in material selection and energy efficiency.

12.2 Project Management Summary

The project followed Agile-inspired management, with regular sprint reviews, iterative prototyping and role delegation. Key decisions and changes were tracked via structured documentation and continuous team feedback. The team adhered to a flexible but disciplined workflow, emphasizing the following practices:

- **Task Ownership and Specialization**: Roles were assigned based on technical strengths, with clear accountability for BOM, CAD design, circuitry and testing.

- **Communication and Documentation**: Weekly meetings, peer reviews and design logs ensured that design changes were communicated effectively across subteams.

- **Risk Mitigation**: The team adjusted timelines and responsibilities to address machining and supply chain delays. Critical tasks were prioritized and parallel workstreams helped maintain progress.

Though minor hiccups arose, such as tolerance misalignments and sensor calibration issues, these were quickly resolved. There were no major failures and most setbacks were mitigated within short timeframes through team coordination and design flexibility.

12.3 Team Review Summary

The project team comprised six members with mechanical and electrical engineering backgrounds. Reflections from the team revealed strong individual contributions in CAD modeling, power systems, structural design, vibration analysis and motor control. Each member leveraged their strengths and recognized opportunities for growth:

- **Collaboration and Role Definition**: Some Members set the technical tone for the mechanical and electrical systems, respectively, while others contributed in stakeholder communication and sensor integration.

- **Adaptability**: Several members improved time management, communication and technical confidence through peer feedback and hands-on challenges.

- **Leadership and Team Culture**: The team fostered an environment of openness and iterative learning. Final reflections emphasized the value of early engagement, formal documentation of pivots and better integration across subsystems.

13.0 Acknowledgements

Table 35. Acknowledgements.

Name(s)	***Title/Role***	***Contribution***
Prof. Aleksander Czekanski	*Capstone Supervisor*	*Provided academic supervision, project oversight, and critical feedback throughout the design and development process.*
Prof. Elli Gkouti	*Advisor*	*Provided insights in regards to design improvements.*
Group 35 (PrintaGo)	*Direct Stakeholders*	*Integration of the two systems made possible through constant collaboration and communication.*
Prof. Edris Hassan	*Capstone Director*	*Provided valuable feedback and insights in regards to manufacturing and assembly.*
Ms. Claudia Bennett	*Capstone Coordinator*	*Provided guidance in regards to material procurement and helped haste crucial tasks that required approval (machining and concur).*
Usman, MSc	*Lab Mentor*	*Shared industry knowledge, guided project direction with practical insights, and helped align outcomes with real-world applications.*
Ragab, PhD	*PhD Student Mentor*	*Offered in-depth technical advice, helped troubleshoot design and testing challenges, and supported the research approach.*
Florin, Armando and Norman	*Lassonde Mechanical Engineering Technicians*	*Assisted with access to equipment, lab setup, safety procedures, and general technical support in the mechanical engineering facilities.*
Thomas, Gurjit and Ian	*Lassonde Machine Shop Technicians*	*Provided hands-on fabrication assistance, expert machining, and valuable advice on material selection and manufacturing techniques.*

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15.0 Appendices

15.1 Links to External Resources

The following are links to important aspects to the project that were not included in the main body of the report due to page limitations.

Gantt Chart

Detailed Gantt chart detailing the project timeline (September - April).

BOM

Part lists including the final cost of the entire project.

Live Recording of the System

A live recording of the system rotating at 120 rpms.

Tensile Testing Results

Spreadsheet including the tensile strength test results in regards to the coupon printed.

SolidWorks Model

Finalized CAD model.

Assembly Tips & Tricks

Tips and tricks as to how to assemble ***THE D.I.C.E.*** *without any hassle.*

Testing Logbook

Records of milestone testing done throughout the winter semester.

Project Video

A cool cinematic trailer of ***THE D.I.C.E.*** *(3 min).*

Arduino Codes

Arduino codes for the both master and slave configurations.

15.2 List of Meeting Minutes

ENG 4000
Weekly Meeting Minutes

Every week, this document should be presented to the supervisor, as this will be the basis for grading.

Project Name	Gravity Gizmo
Date & Time of Meeting	October 31, 2024

Attendees			
#	Name	Student ID	Username (email)
1	Gaith Al-Adwan	218604066	gaith03@my.yorku.ca
2	Omar Almufleh	218318840	omartmufleh@gmail.com
3	Herman Balagan	217136490	herman04@my.yorku.ca
4	Navroz Bir	217322967	navrozbir@gmail.com
5	Ibrahim El Zamzamy	214496657	izzy1998@my.yorku.ca
6	Omar Tawil	217692351	omar01@my.yorku.ca

Decision Made / Agenda / Objectives / Plan for the Coming Week
Critical Requirements: Motor & Weight, Vibrations, Driver and Safety. Requirements divided between team members. **Requirements Done:** Power transmission and RPM.

Team Responsibilities for the Coming Week		
#	Name	Responsibility
1	Gaith Al-Adwan	Motor & Weight
2	Omar Almufleh	Safety
3	Herman Balagan	Vibrations
4	Navroz Bir	Motor Driver
5	Ibrahim El Zamzamy	Vibrations
6	Omar Tawil	Motor & Weight

Progress Report on Last Week's Activities			
#	Name	% Completed	Comment (provide the reasoning only if 100% is not completed)
1	Gaith Al-Adwan	100%	
2	Omar Almufleh	50%	Safety design is conducted after the technical design is done
3	Herman Balagan	100%	
4	Navroz Bir	100%	
5	Ibrahim El Zamzamy	100%	
6	Omar Tawil	100%	

ENG 4000
Weekly Meeting Minutes

Every week, this document should be presented to the supervisor, as this will be the basis for grading.

Project Name	Gravity Gizmo
Date & Time of Meeting	Nov 7^{th} , 2024

Attendees			
#	Name	Student ID	Username (email)
1	Gaith Al-Adwan	218604066	gaith03@my.yorku.ca
2	Omar Almufleh	218318840	omartmufleh@gmail.com
3	Herman Balagan	217136490	herman04@my.yorku.ca
4	Navroz Bir	217322967	navrozbir@gmail.com
5	Ibrahim El Zamzamy	214496657	izzy1998@my.yorku.ca
6	Omar Tawil	217692351	omar01@my.yorku.ca

Decision Made / Agenda / Objectives / Plan for the Coming Week
In 2 weeks: Have a design and a finalized BOM. Chain transmission calculation and CAD. Inertia and center of mass calculations. Sensor integration. Assemble the frame.

Team Responsibilities for the Coming Week		
#	Name	Responsibility
1	Gaith Al-Adwan	Bill of materials, Inertia calculation.
2	Omar Almufleh	Frame
3	Herman Balagan	Center of mass calculation
4	Navroz Bir	Sensor integration
5	Ibrahim El Zamzamy	Center of mass calculation
6	Omar Tawil	Chain calculation and CAD

Progress Report on Last Week's Activities			
#	Name	% Completed	Comment (provide the reasoning only if 100% is not completed)
1	Gaith Al-Adwan	100%	
2	Omar Almufleh	100%	
3	Herman Balagan	50%	Waiting for printer team to send printer information.
4	Navroz Bir	100%	
5	Ibrahim El Zamzamy	50%	Waiting for printer team to send printer information.
6	Omar Tawil	100%	

ENG 4000
Weekly Meeting Minutes

Every week, this document should be presented to the supervisor, as this will be the basis for grading.

Project Name	Gravity Gizmo
Date & Time of Meeting	Nov 21st , 2024

Attendees			
#	Name	Student ID	Username (email)
1	Gaith Al-Adwan	218604066	gaith03@my.yorku.ca
2	Omar Almufleh	218318840	omartmufleh@gmail.com
3	Herman Balagan	217136490	herman04@my.yorku.ca
4	Navroz Bir	217322967	navrozbir@gmail.com
5	Ibrahim El Zamzamy	214496657	izzy1998@my.yorku.ca
6	Omar Tawil	217692351	omar01@my.yorku.ca

Decision Made / Agenda / Objectives / Plan for the Coming Week
Make a prototype/proof of concept. Decide whether to use bushings or weld the shaft. Purchase the majority of the parts, make value out of time. Engineering Validation: Engineering, Design and Production validation testing (EV,DV and PV).

Team Responsibilities for the Coming Week		
#	Name	Responsibility
1	Gaith Al-Adwan	Proof of Concept, EV and PV
2	Omar Almufleh	Proof of Concept, DV and PV
3	Herman Balagan	EV (Vibrations)
4	Navroz Bir	EV (Electrical components)
5	Ibrahim El Zamzamy	EV (Vibrations)
6	Omar Tawil	Purchase part, Proof of Concept DV and PV

Progress Report on Last Week's Activities			
#	Name	% Completed	Comment (provide the reasoning only if 100% is not completed)
1	Gaith Al-Adwan	90%	PV, Completion of the design is pending due to some part and printer team.
2	Omar Almufleh	90%	PV, Completion of the design is pending due to some part and printer team.
3	Herman Balagan	100%	
4	Navroz Bir	100%	
5	Ibrahim El Zamzamy	100%	
6	Omar Tawil	90%	PV, Design is pending due to some part and printer team.

ENG 4000
Weekly Meeting Minutes

Every week, this document should be presented to the supervisor, as this will be the basis for grading.

Project Name	Gravity Gizmo
Date & Time of Meeting	January 9, 2025

Attendees			
#	Name	Student ID	Username (email)
1	Gaith Al-Adwan	218604066	gaith03@my.yorku.ca
2	Omar Almufleh	218318840	omartmufleh@gmail.com
3	Herman Balagan	217136490	herman04@my.yorku.ca
4	Navroz Bir	217322967	navrozbir@gmail.com
5	Ibrahim El Zamzamy	214496657	izzy1998@my.yorku.ca
6	Omar Tawil	217692351	omar01@my.yorku.ca

Decision Made / Agenda / Objectives / Plan for the Coming Week
Integrate driving system (motor and chain). Purchase sliprings. Mount Bearings. Machine Extrusions for extension.

Team Responsibilities for the Coming Week		
#	Name	Responsibility
1	Gaith Al-Adwan	Machining
2	Omar Almufleh	Assembly
3	Herman Balagan	Driving System
4	Navroz Bir	Electrical Wiring
5	Ibrahim El Zamzamy	Coding
6	Omar Tawil	Driving System

Progress Report on Last Week's Activities			
#	Name	% Completed	Comment (provide the reasoning only if 100% is not completed)
1	Gaith Al-Adwan	100%	
2	Omar Almufleh	100%	
3	Herman Balagan	100%	
4	Navroz Bir	100%	
5	Ibrahim El Zamzamy	100%	
6	Omar Tawil	100%	

ENG 4000
Weekly Meeting Minutes

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Project Name	Gravity Gizmo
Date & Time of Meeting	January 9, 2025

Attendees			
#	Name	Student ID	Username (email)
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2	Omar Almufleh	218318840	omartmufleh@gmail.com
3	Herman Balagan	217136490	herman04@my.yorku.ca
4	Navroz Bir	217322967	navrozbir@gmail.com
5	Ibrahim El Zamzamy	214496657	izzy1998@my.yorku.ca
6	Omar Tawil	217692351	omar01@my.yorku.ca

Decision Made / Agenda / Objectives / Plan for the Coming Week
Integrate driving system (motor and chain). Purchase sliprings. Mount Bearings. Machine Extrusions for extension.

Team Responsibilities for the Coming Week		
#	Name	Responsibility
1	Gaith Al-Adwan	Machining
2	Omar Almufleh	Assembly
3	Herman Balagan	Driving System
4	Navroz Bir	Electrical Wiring
5	Ibrahim El Zamzamy	Coding
6	Omar Tawil	Driving System

Progress Report on Last Week's Activities			
#	Name	% Completed	Comment (provide the reasoning only if 100% is not completed)
1	Gaith Al-Adwan	100%	
2	Omar Almufleh	100%	
3	Herman Balagan	100%	
4	Navroz Bir	100%	
5	Ibrahim El Zamzamy	100%	
6	Omar Tawil	100%	

ENG 4000
Weekly Meeting Minutes

Every week, this document should be presented to the supervisor, as this will be the basis for grading.

Project Name	Gravity Gizmo
Date & Time of Meeting	February 20, 2025

Attendees			
#	Name	Student ID	Username (email)
1	Gaith Al-Adwan	218604066	gaith03@my.yorku.ca
2	Omar Almufleh	218318840	omartmufleh@gmail.com
3	Herman Balagan	217136490	herman04@my.yorku.ca
4	Navroz Bir	217322967	navrozbir@gmail.com
5	Ibrahim El Zamzamy	214496657	izzy1998@my.yorku.ca
6	Omar Tawil	217692351	omar01@my.yorku.ca

Decision Made / Agenda / Objectives / Plan for the Coming Week
Add compartments. Machine plexiglass (viewing platform). Add 2 more bearings. Mount bearing and machine plates. Code and wire sensors. Readjust chain and sprocket due to the addition of the compartmets.

Team Responsibilities for the Coming Week		
#	Name	Responsibility
1	Gaith Al-Adwan	Machining
2	Omar Almufleh	Assembly
3	Herman Balagan	Driving System
4	Navroz Bir	Electrical Wiring
5	Ibrahim El Zamzamy	Coding
6	Omar Tawil	Driving System

Progress Report on Last Week's Activities			
#	Name	% Completed	Comment (provide the reasoning only if 100% is not completed)
1	Gaith Al-Adwan	100%	
2	Omar Almufleh	100%	
3	Herman Balagan	100%	
4	Navroz Bir	100%	
5	Ibrahim El Zamzamy	100%	
6	Omar Tawil	100%	

ENG 4000
Weekly Meeting Minutes

Every week, this document should be presented to the supervisor, as this will be the basis for grading.

Project Name	Gravity Gizmo
Date & Time of Meeting	March 20, 2025

Attendees			
#	Name	Student ID	Username (email)
1	Gaith Al-Adwan	218604066	gaith03@my.yorku.ca
2	Omar Almufleh	218318840	omartmufleh@gmail.com
3	Herman Balagan	217136490	herman04@my.yorku.ca
4	Navroz Bir	217322967	navrozbir@gmail.com
5	Ibrahim El Zamzamy	214496657	izzy1998@my.yorku.ca
6	Omar Tawil	217692351	omar01@my.yorku.ca

Decision Made / Agenda / Objectives / Plan for the Coming Week
Begin vibration and structural integrity testing. Make a flat on the shaft. Drill through holes to ensure tight connections between the sprocket and chain (no slippage). Adjust sprocket to ensure a common ceterline with the motors shaft. Test again at different rpms. Re-evalaute the code to ensure exponential acceleration and deceleration.

Team Responsibilities for the Coming Week		
#	Name	Responsibility
1	Gaith Al-Adwan	Machining
2	Omar Almufleh	Assembly
3	Herman Balagan	Driving System
4	Navroz Bir	Electrical Wiring
5	Ibrahim El Zamzamy	Coding
6	Omar Tawil	Driving System

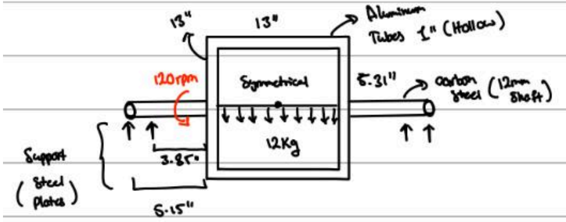
Progress Report on Last Week's Activities			
#	Name	% Completed	Comment (provide the reasoning only if 100% is not completed)
1	Gaith Al-Adwan	100%	
2	Omar Almufleh	100%	
3	Herman Balagan	100%	
4	Navroz Bir	100%	
5	Ibrahim El Zamzamy	100%	
6	Omar Tawil	100%	

15.3 Updated Product Vision Boards

Table 36. Updated product vision boards.

Target Group	Problem Solved by Product	Product Description, Uniqueness and Feasibility	Product Societal Benefits
Universities and research institutions studying gravity-dependent material sciences.	Limited tools available for affordable and precise gravity simulation.	Integrates user-friendly interfaces for programming and data collection. Affordable setup with off-the-shelf components and widely available materials.	Facilitates hands-on STEM education and training for students and researchers.
Companies conducting experiments in tissue engineering, bioprinting, and drug development (i.e. nerve cells, implants, etc.).	Need for controlled environments to study microgravity's effects on biological and material processes. Current implants don't meet proper design standards which means implants are not as effective.	Sensors monitor temperature and humidity to ensure reliable experimental data for different circumstances.	Supports healthcare innovation, enabling breakthroughs in drug discovery, tissue engineering, and bioprinting under simulated gravitational conditions. Better implants for individuals who may need them (i.e. dental implants lasting longer).
Organizations like NASA, ESA, SpaceX.	Expensive space-based research. Limited access to simulate hypergravity conditions.	One rotation enables precise gravity simulations. Compact, modular design fits into existing lab setups. Real-time environmental monitoring.	Advances space research by providing cost-effective, Earth-based alternatives for experiments (i.e. simulating mars gravity without the need for travel).
Individuals in materials science and advanced manufacturing exploring new methods to achieve stronger designs (less deformities through increased gravity).	Current 3D printers cannot make adequate designs without some kind of deformity. Adding hypergravity allows for more compact prints which would increase durability and longevity.	Current methods for hypergravity simulations are costly and often lack precision.	Stronger products created by manufacturing companies allow for stronger models and less material wasted over time caused by faulty prints.

15.4 Hand Calculations



Weight = 12Kg

Force = 12x10 = 120N

Frame width = 14" = 0.3556 m

Circular Motion ⇒ $\text{radius} = \frac{\text{diagonal}}{2}$ ⇒ $\text{diagonal} = \sqrt{14^2+14^2} = 19.8" = 0.503\,m$

∴ $\text{radius} = \frac{0.503}{2} = 0.2515\,m$

Moment of Inertia ⇒ $I = m \times r^2 = 12(0.2515)^2 = 0.759\ Kg.m^2$

$\omega = \frac{2\pi N}{60} = \frac{2\pi(120)}{60} = 4\pi \approx 12.56\ rad/s$

Torque ⇒ $T = I\alpha$, $\alpha = \omega/t$, assume 10 seconds to reach 120rpms ⇒ $\alpha = \frac{12.56}{10} = 1.256\ rad/s^2$

$T = 0.759 \times 1.256 = 0.954\ N.m$ (Required torque to reach 120 rpms in 10 seconds with a 12Kg load) [1.1 N.m taking into account friction]

Bending Moment ⇒ $M = F \times d = 120 \times 0.0978 = 11.74\ Nm$ (d: 3.85")

Section Modulus ⇒ $Z = \frac{\pi d^3}{32} = \frac{\pi(0.012)^3}{32} = 1.7 \times 10^{-7}\ m^3$

Bending Stress ⇒ $\sigma = \frac{M}{Z} = \frac{11.74}{1.7\times10^{-7}} = 69.2\ MPa$

$FoS = \frac{\text{yield strength}}{\text{bending stress}} = \frac{300}{69.2} = 4.34$

Angle of Deflection ⇒ $\theta = \frac{FL^2}{2EI} = \frac{120(0.2032)^2}{2(210\times10^9)(1.3\times10^{-9})} = 0.52°$

Max Deflection ⇒ $\delta = \frac{FL^3}{3EI} = \frac{120(0.2032)^3}{3(210\times10^9)(1.3\times10^{-9})} = 0.4\,mm$

Modulus of Rigidity for carbon steel ⇒ $G = 80GPa$, $J = \frac{\pi d^4}{32} = \frac{\pi(0.0127)^4}{32} = 2.55\times10^{-9}\ m^4$

Angle of Twist ⇒ $\theta = \frac{TL}{JG} = \frac{(0.2032)}{2.55\times10^{-9}(80\times10^9)} \times \frac{180}{\pi} \approx 1.4°$

find the Torque required to rotate the shaft

shaft $m \approx 1$ kg $d = 0.5'' = 0.0127$ m

Box $m = 12$ kg $d = 0.503$ m

$$w = \frac{120 \times 2\pi}{60} = 12.57 \text{ rad/s}$$ accelerates in 10 s

$$\alpha = \frac{12.57}{10} = 1.257 \text{ rad/s}^2$$

Moment of inertia of the encloser $\text{radius} = \frac{\text{diagonal}}{2} \longrightarrow \sqrt{14^2+14^2} = 19.8 = 0.503$ m

$$\text{radius} = \frac{0.503}{2} = 0.2515$$

$$I_{box} = m \times r^2 = 12\,(0.2515)^2 = 0.759 \text{ kg.m}^2$$

$$I_{shaft} = \tfrac{1}{2} m r^2 = \tfrac{1}{2} \cdot 1 \times 0.127^2 = 8.0645 \times 10^{-5} \text{ kg.m}^2$$

for Two shafts $2 \times I_{shaft}$

$$I_{tot} = I_{box} + 2 I_{shaft} = 0.7592 \text{ kg.m}^2$$

$$T_{acceleration} = I_{total} \cdot \alpha = 0.7592 \cdot 1.257 \approx 0.954$$

$$F_{bearing} = \frac{m_{box} + m_{shaft}}{2} \cdot g = \frac{12 + 0.25}{2} \cdot 9.81 = 63.765 \text{ N}$$

assume a coefficient of friction $\mu = 0.1$

$$T_{friction} = 2 \cdot F_b \cdot r_{shaft} \cdot \mu_b = 2 \times 63.765 \times 0.0127 \times 0.1 = 0.16196 \text{ N.m}$$

$$T_{tot} = T_{acc} + T_f = 0.954 + 0.16196 = 1.116 \text{ N.m}$$

chain length

distance beteen shafts axis (sprockets): 0.29 m

$N_1 = 12$

$N_2 = 24$

Pitch = 9.53 mm

$$\text{Number of links} = \frac{N_1 + N_2}{2} + 2c$$

Average teeth count

# of links between sprockets Multiplied by 2 to account top and botoom

first find the center distance between sprockets c measured in links

$$c = \frac{d}{p} = \frac{0.29\ m}{0.00953\ m} = 30.43 \text{ links}$$

* $2c = 60.86$ links

* $\frac{12+24}{2} = 18$ links

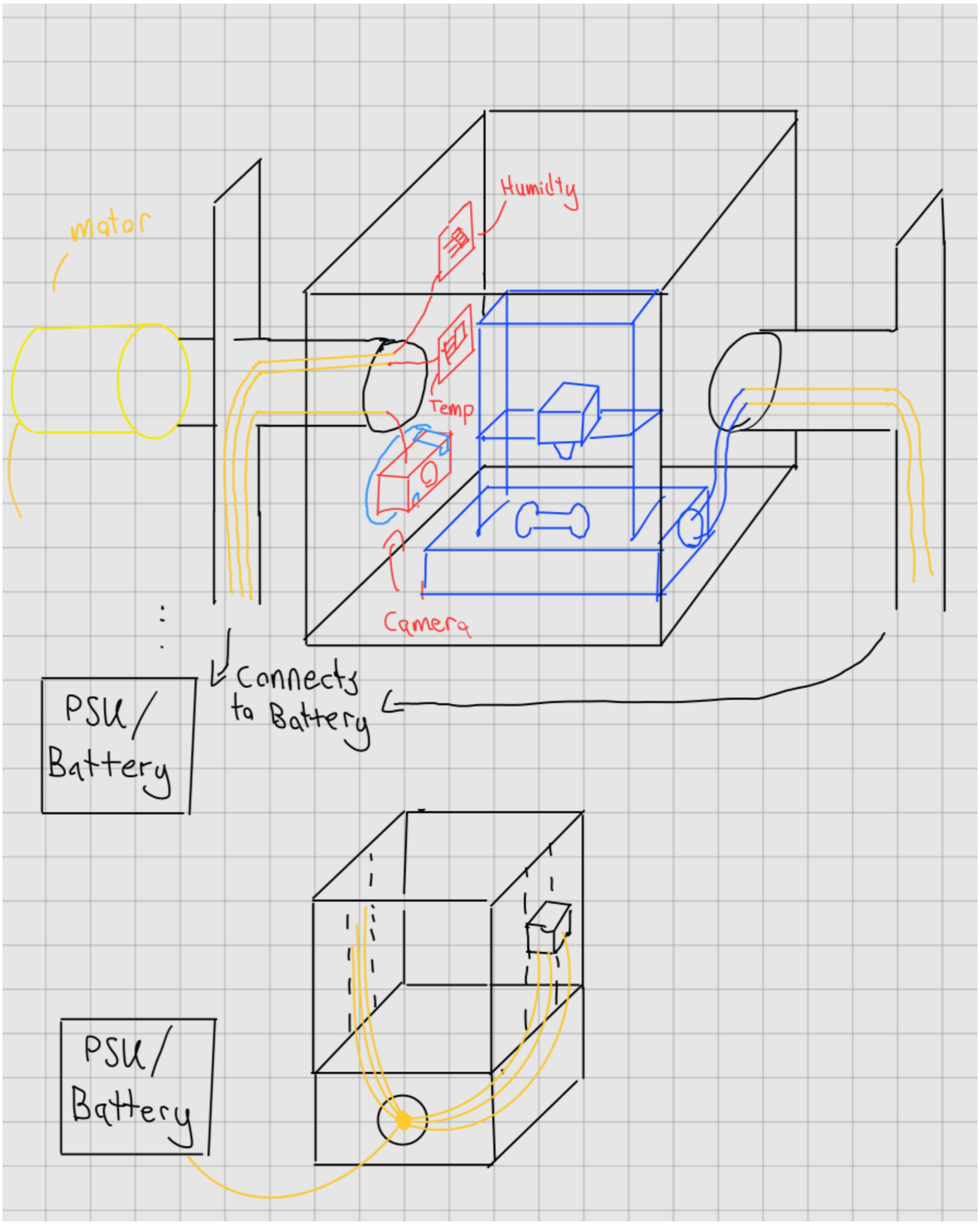
$$\text{Number of links} = \frac{N_1 + N_2}{2} + 2c = 18 + 60.86 = 78.86 \text{ links}$$

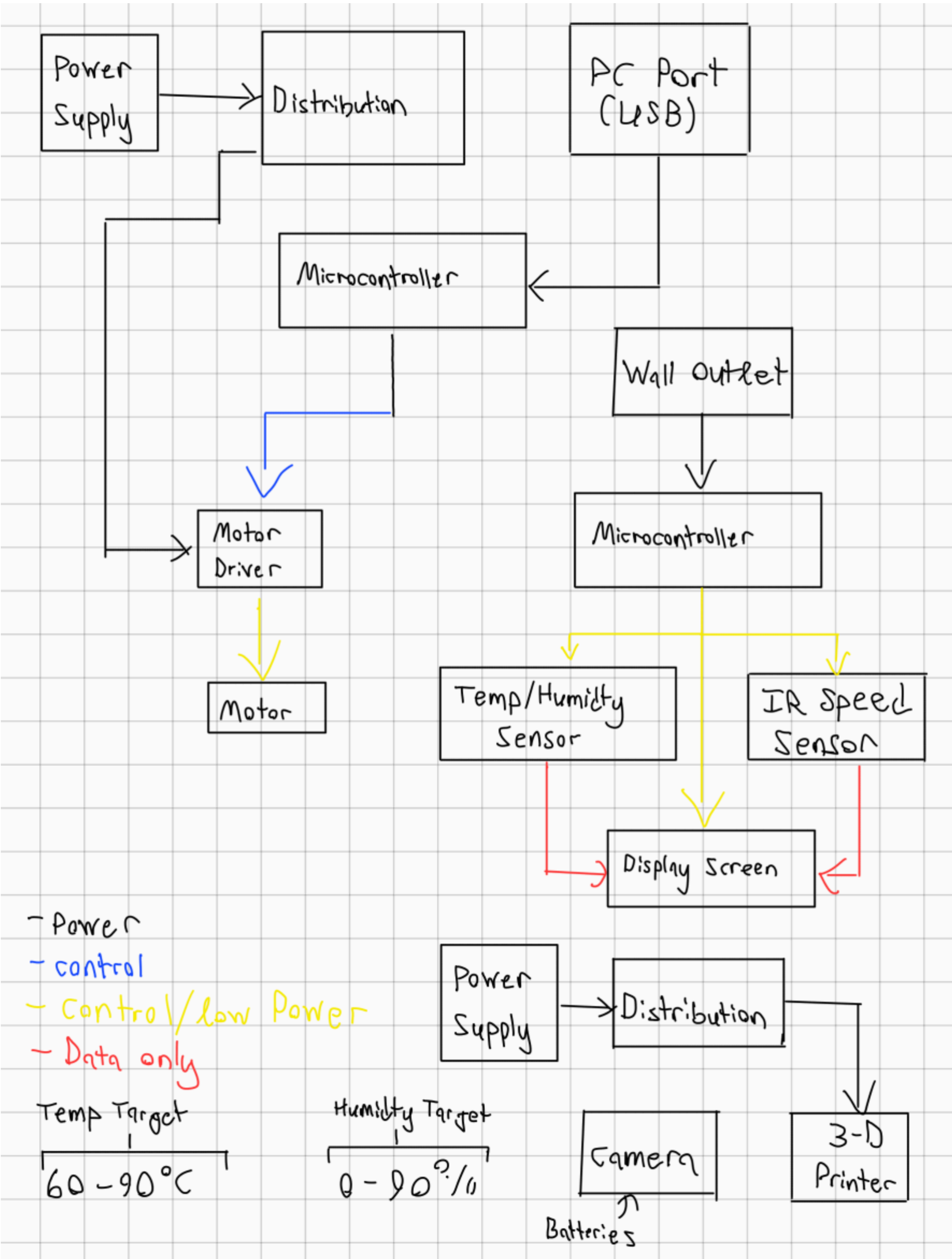
to occount for sag add one pitch (79.86)

or add 2% $(78.86 \times 2\%) + 78.86 = 80.44$ links

$$\boxed{79.86 \times 0.00953 = 0.761\ m}$$

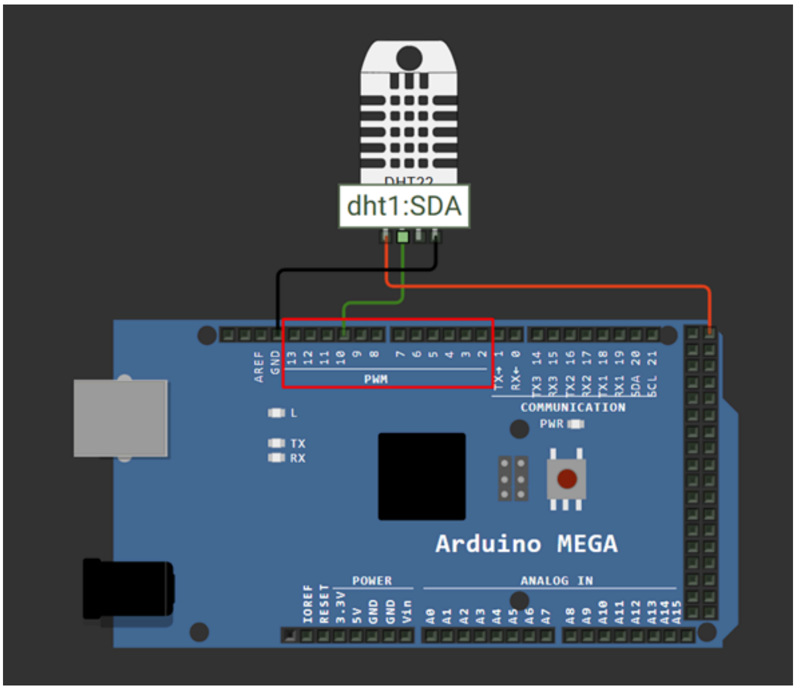
15.5 Wiring Setup/Schematics





Power Supply
Distribution
PC Port (USB)
Microcontroller
Wall Outlet
Motor Driver
Microcontroller
Motor
Temp/Humidity Sensor
IR Speed Sensor
Display Screen
Power
control
Control/low Power
Data only
Power Supply
Distribution
Temp Target
60-90°C
Humidity Target
0-90%
Camera
Batteries
3-D Printer

DHT DATA



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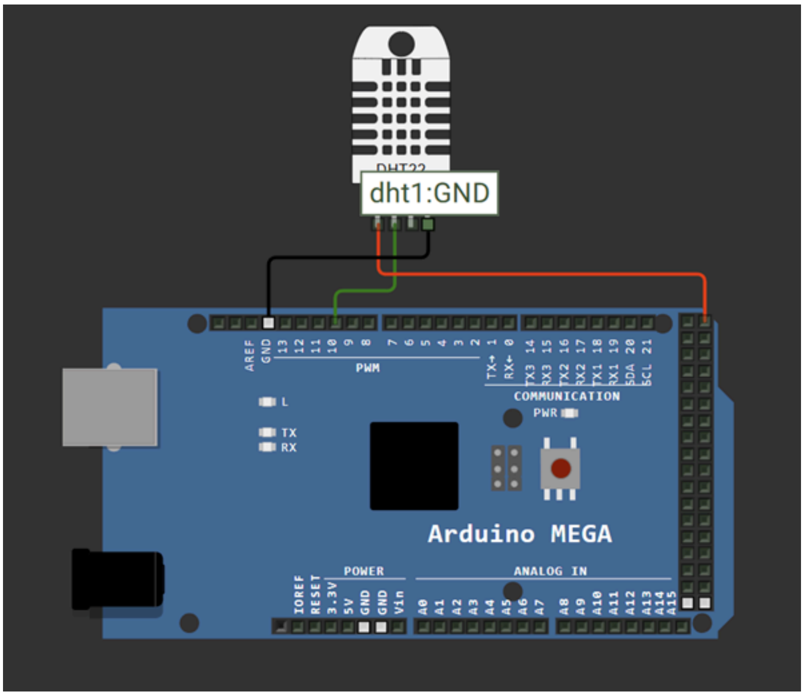

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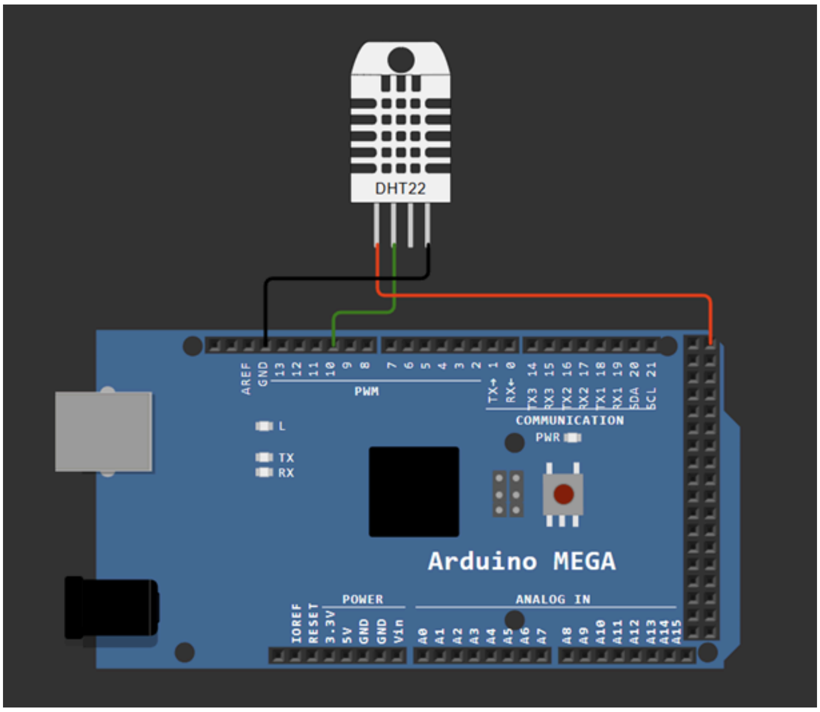
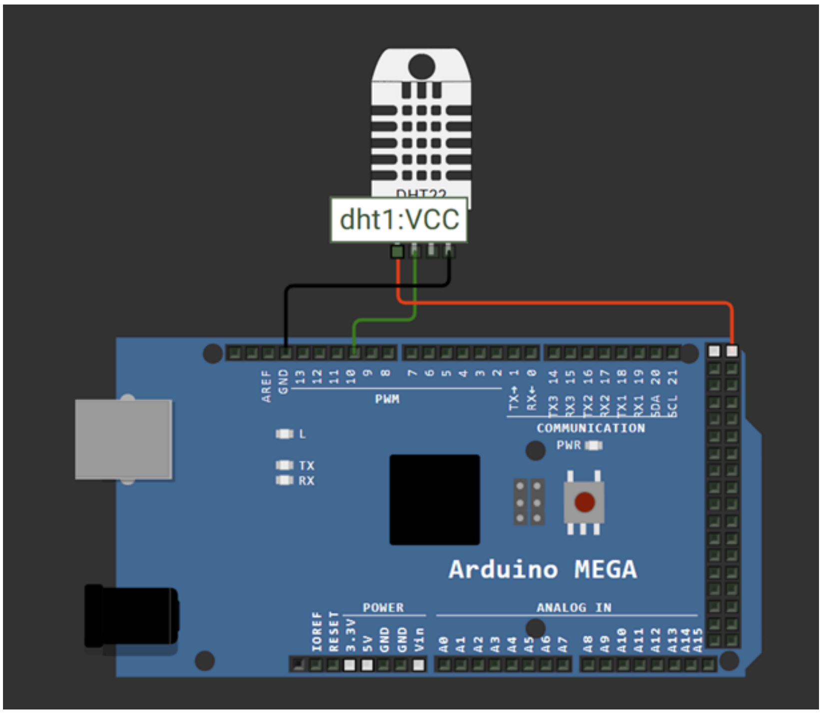
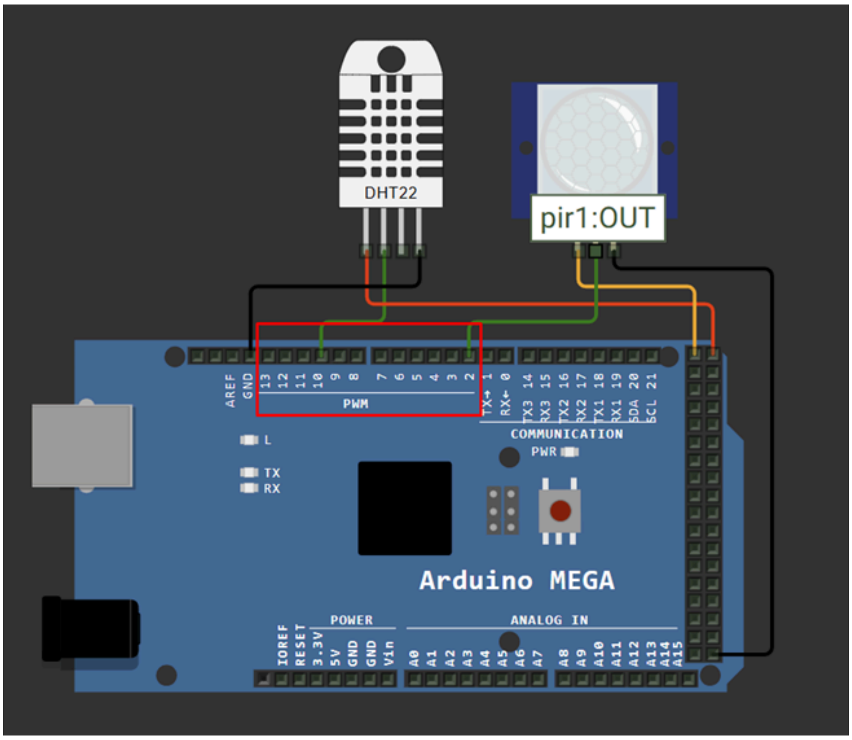


DHT VCC



IR D0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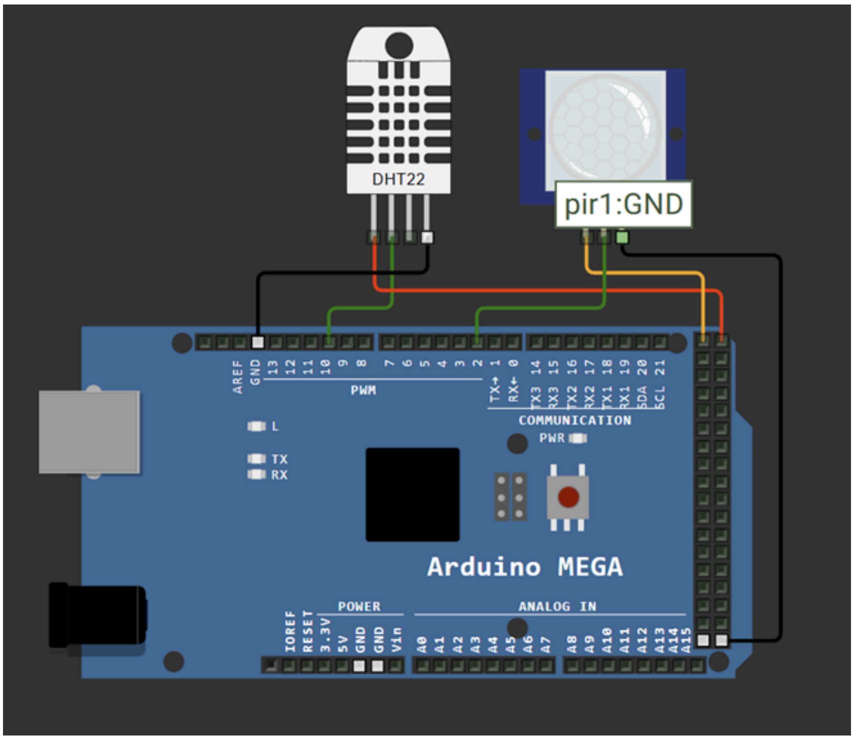
PWM
COMMUNICATION
PWR
Arduino MEGA
POWER
ANALOG IN

IR GND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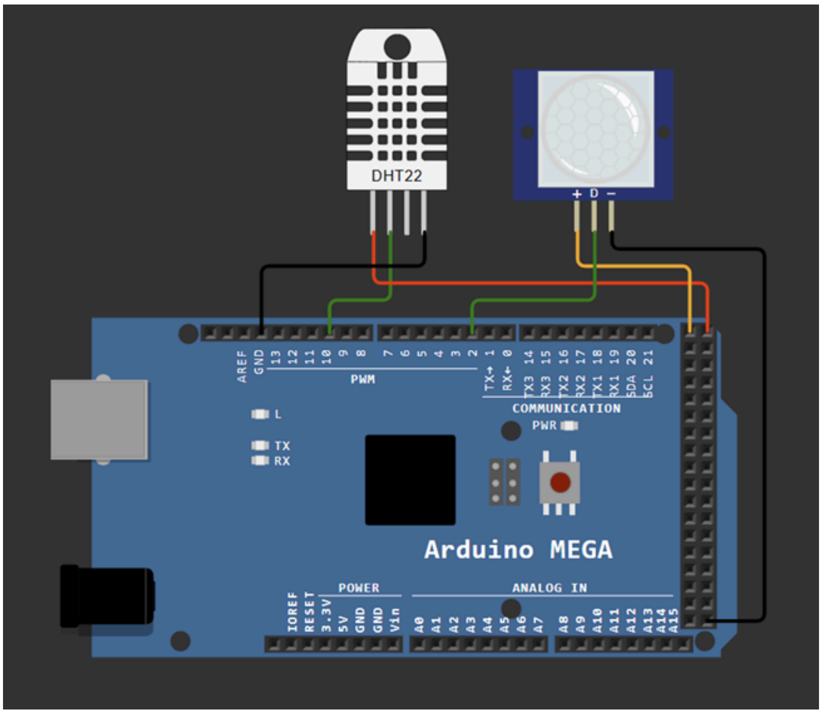
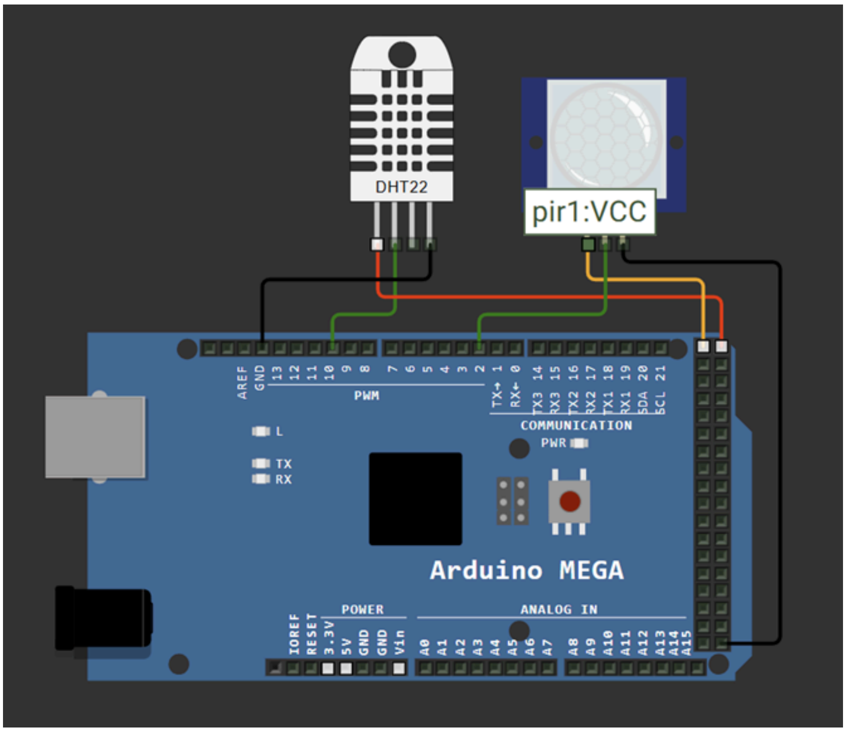
PWR
Arduino MEGA
POWER
ANALOG IN

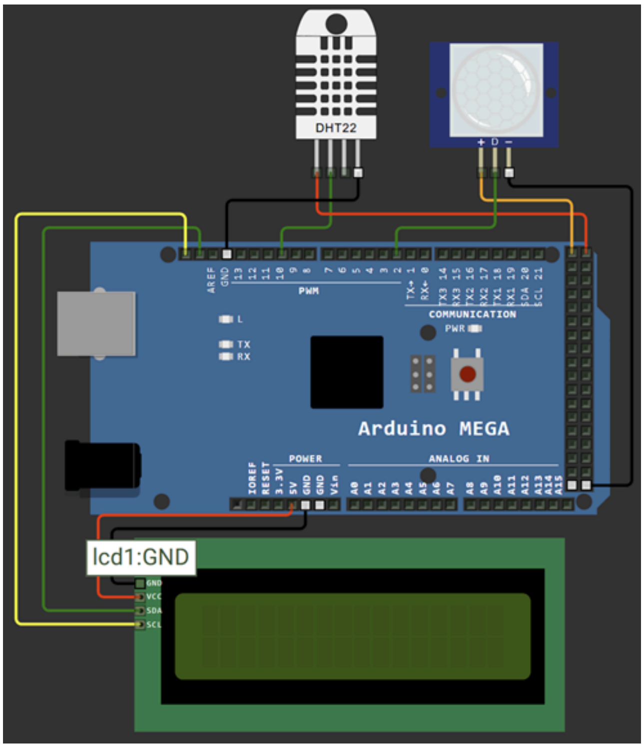
IR SETUP



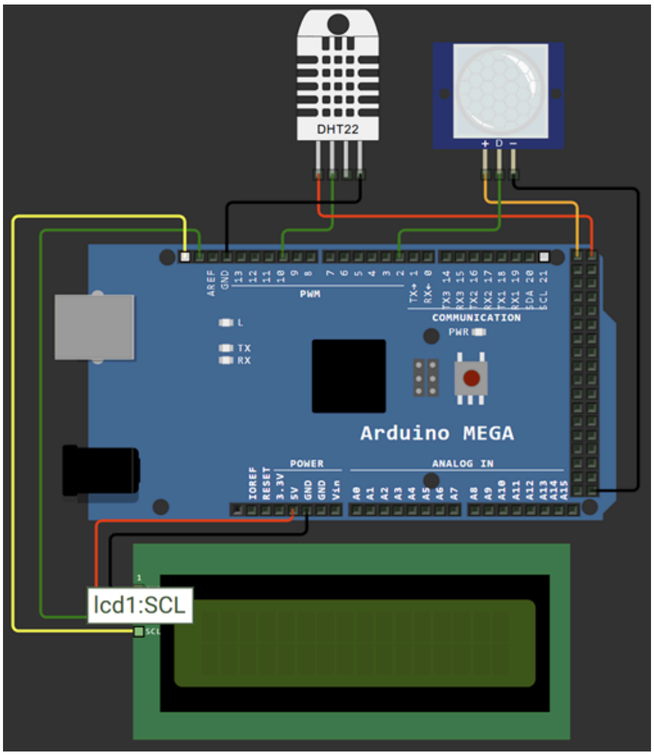
IR VCC



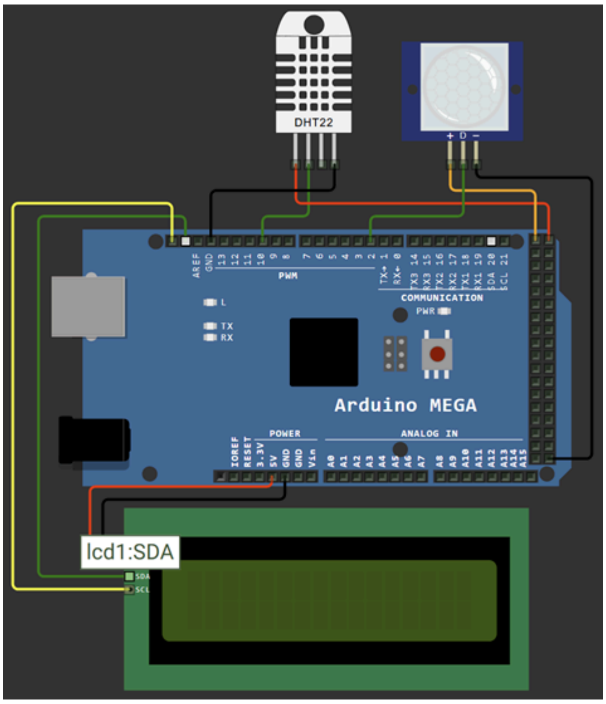
LCD GND



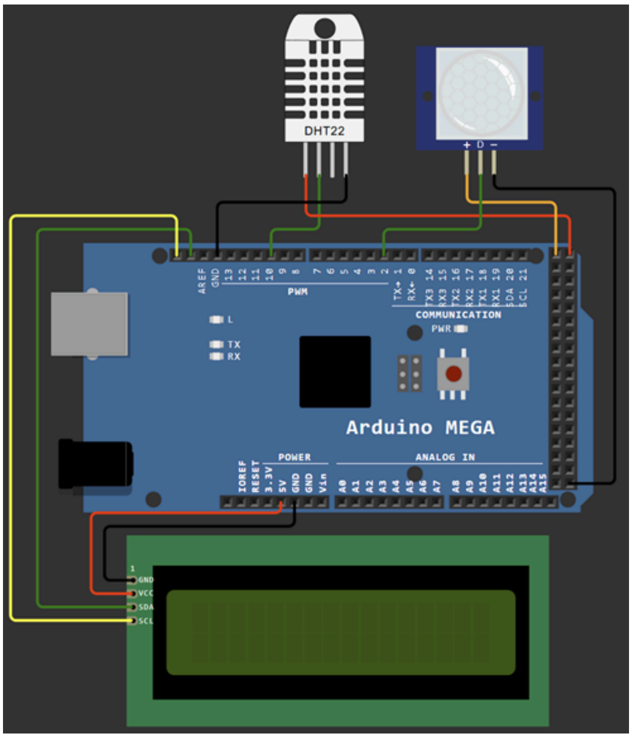
LCD SCL



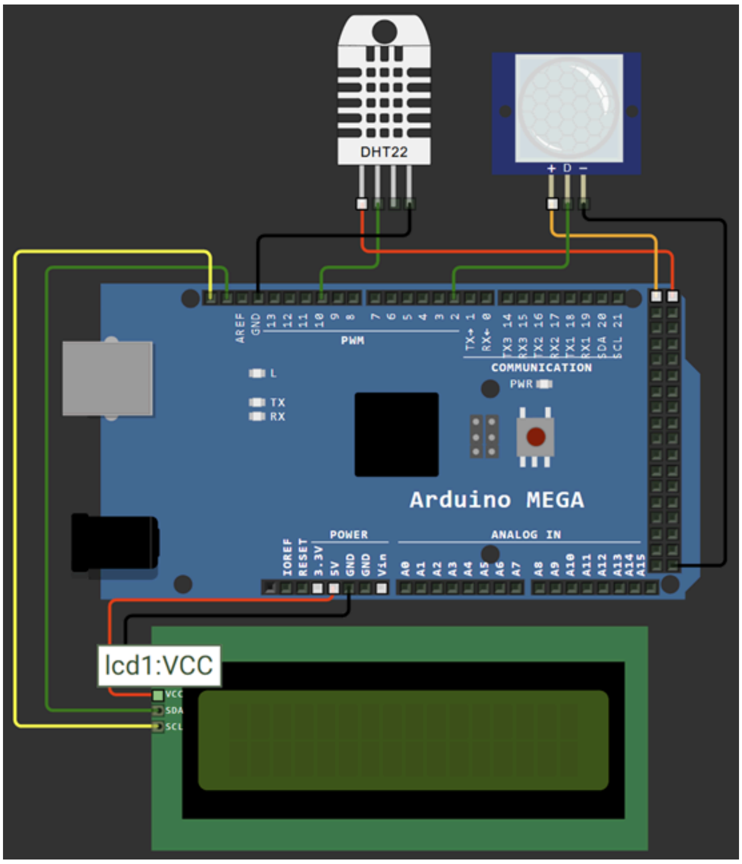
LCD SDA



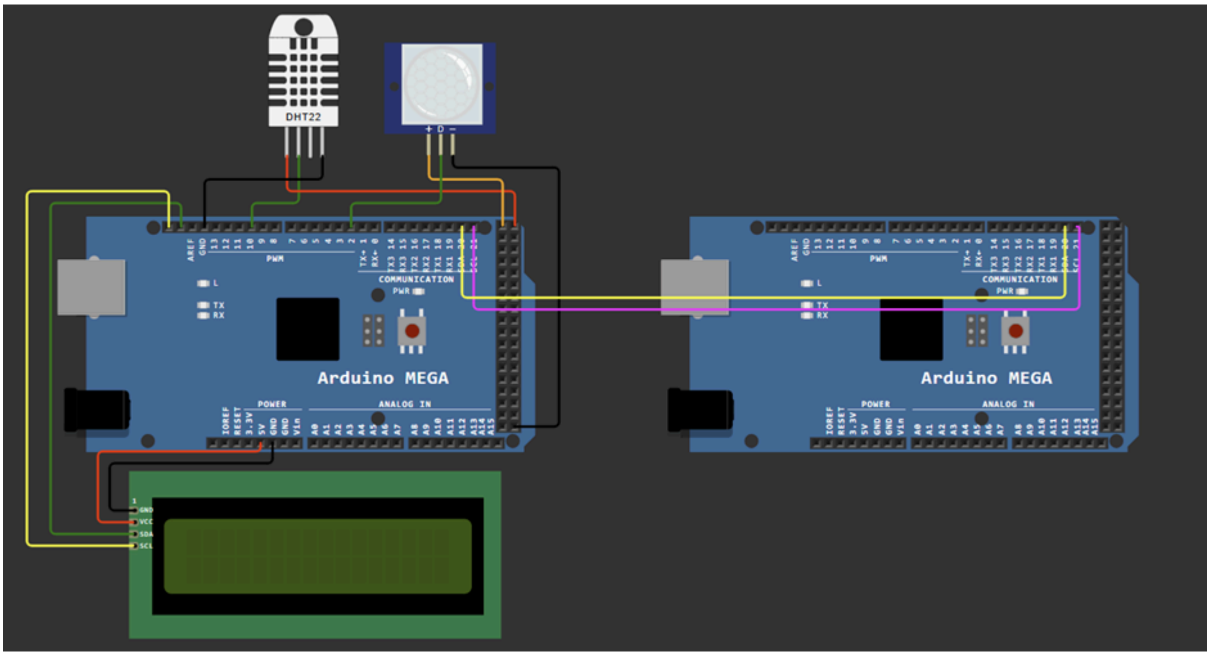
LCD SETUP



LCD VCC



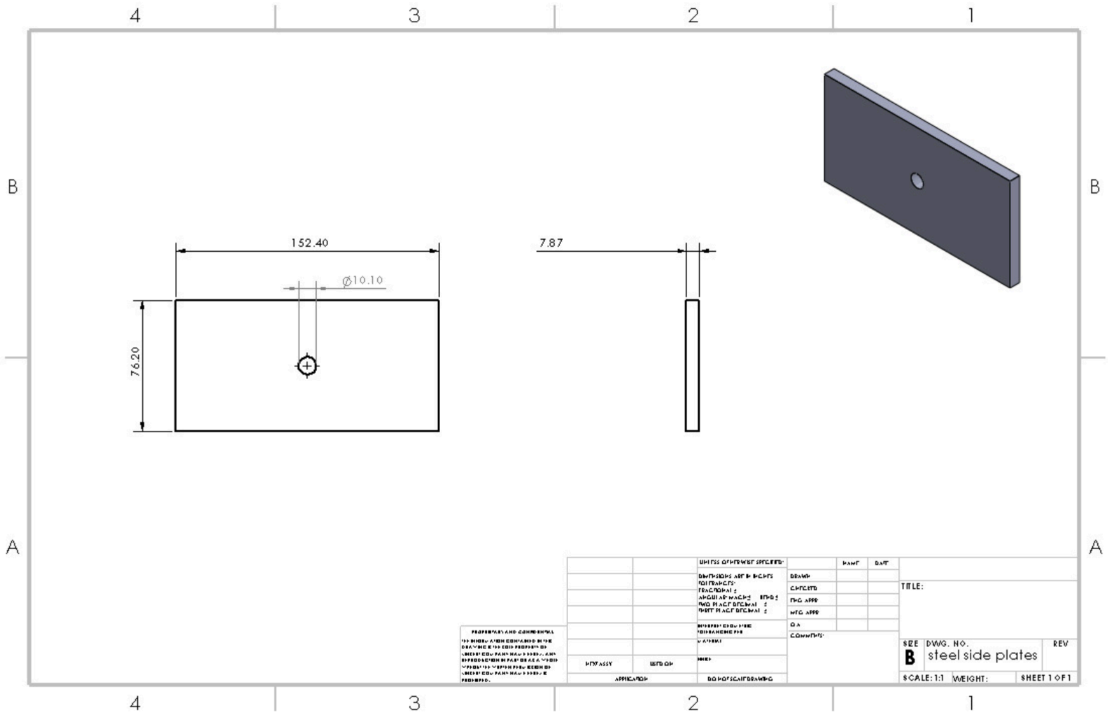
MASTER & SLAVE

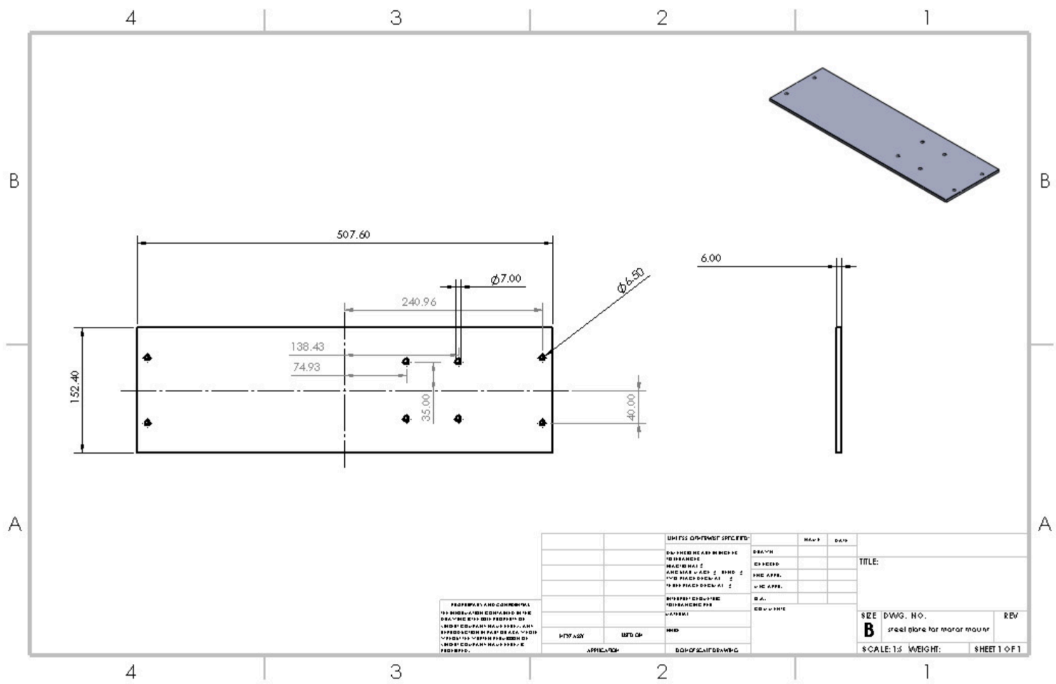


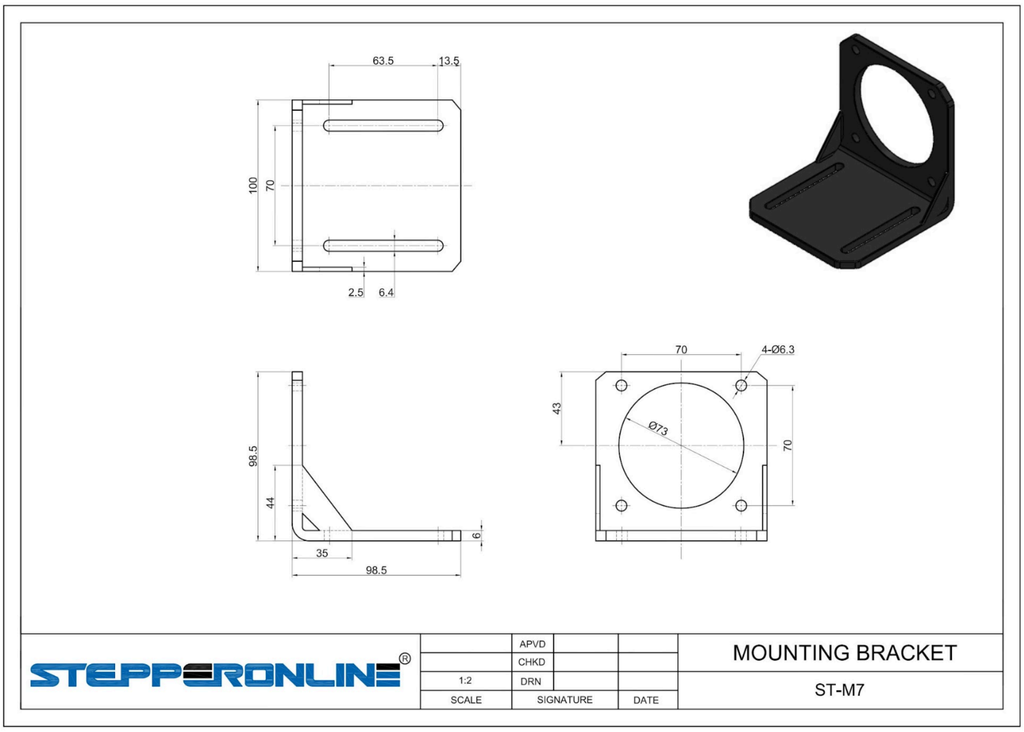
MASTER GND

MASTER PINS

15.6 CAD Drawings



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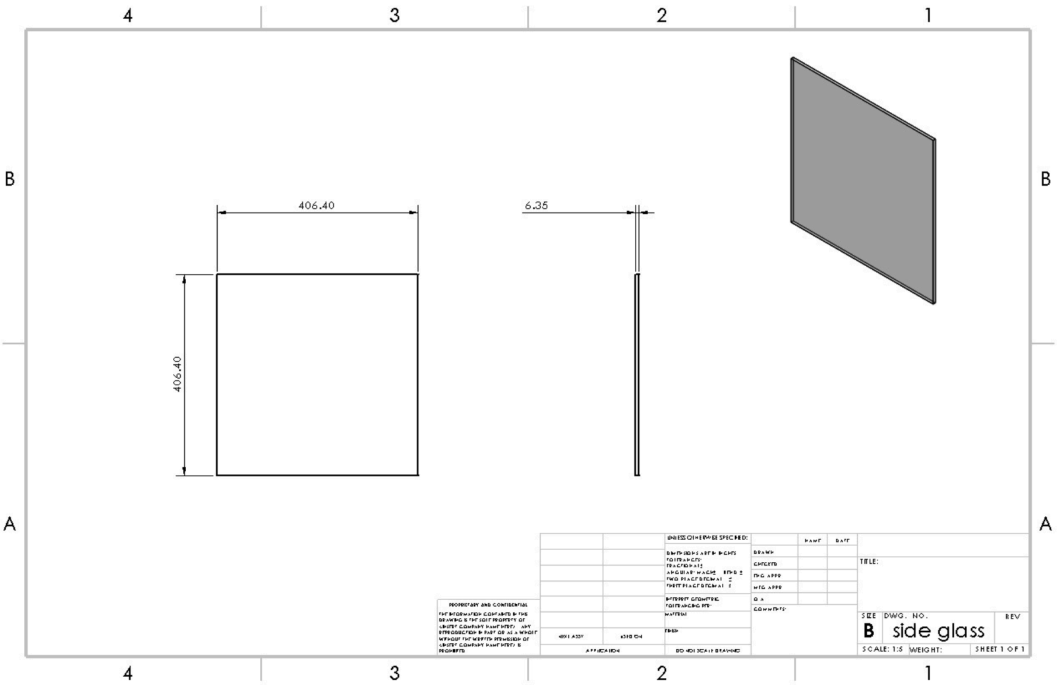
13.5
100
70
2.5
6.4
70
4-Ø6.3
43
Ø73
70
98.5
44
6
35
98.5
APVD
CHKD
DRN
1:2
SCALE
SIGNATURE
DATE
MOUNTING BRACKET
ST-M7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406.40
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REV
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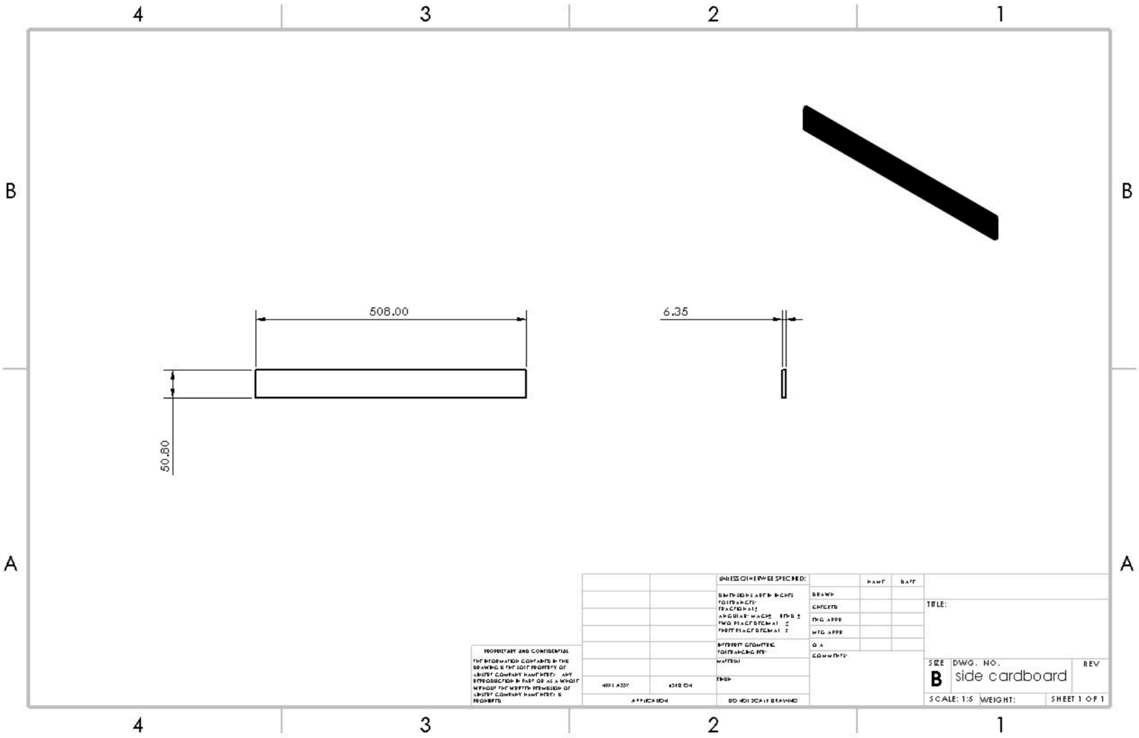
WEIGHT:
SHEET 1 OF 1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6.35
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B
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REV
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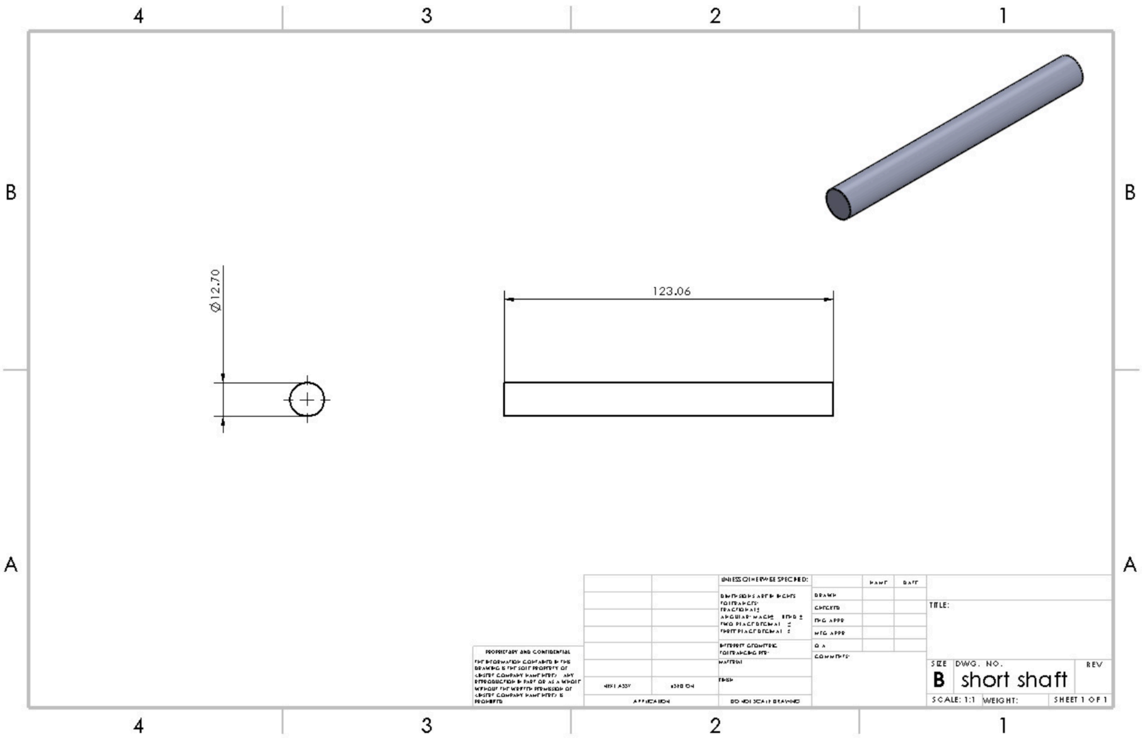
SHEET 1 OF 1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123.06
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B
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REV
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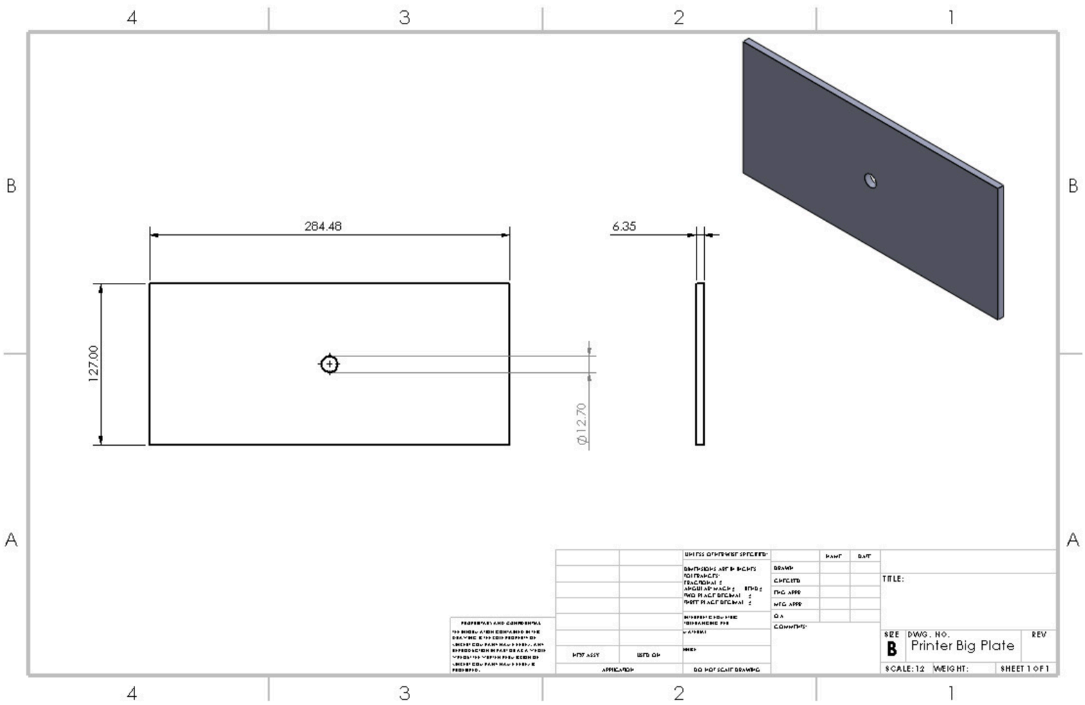
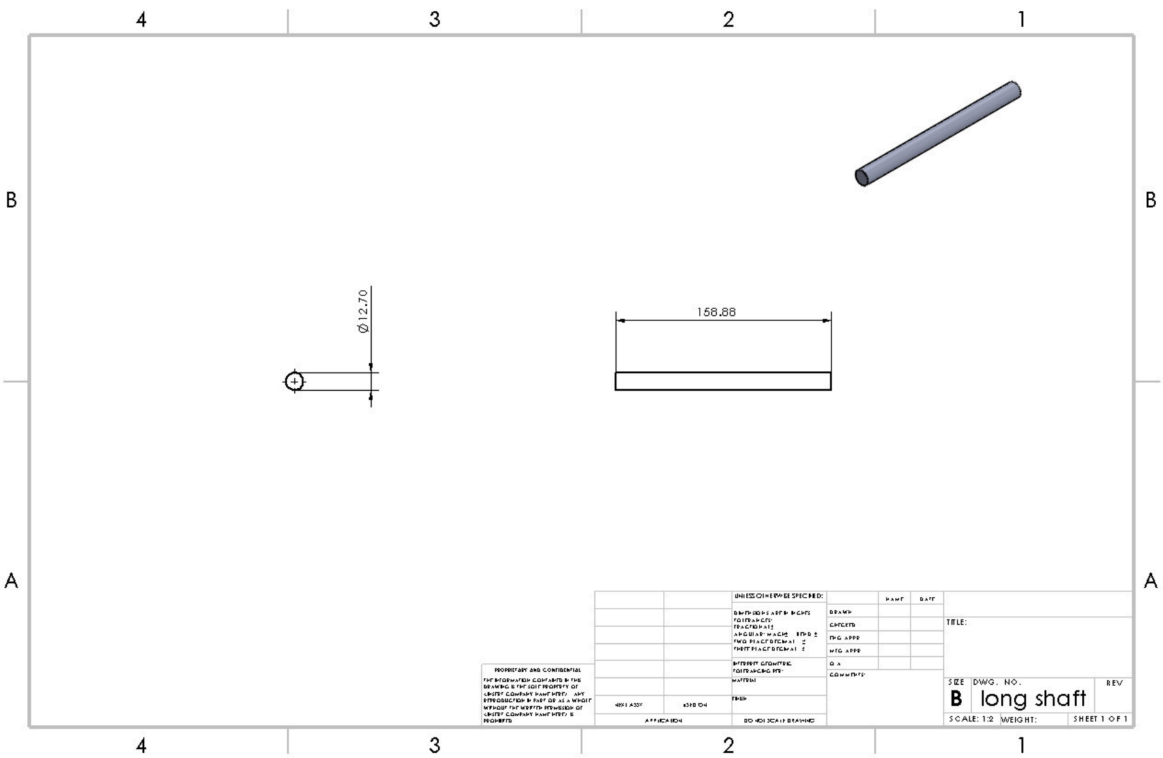
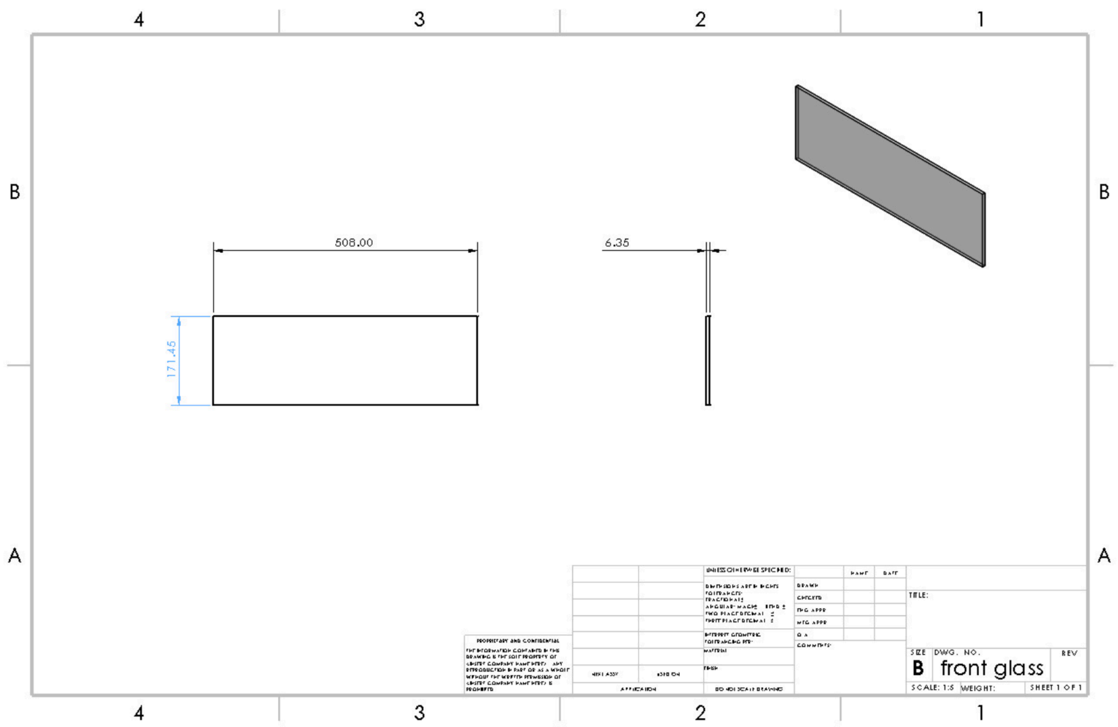
WEIGHT:
SHEET 1 OF 1


284.48
6.35
127.00
Ø12.70
TITLE:
SIZE
DWG. NO.
REV
B
Printer Big Plate
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
DO NOT SCALE DRAWING


Ø12.70
158.88
UNLESS OTHERWISE SPECIFIED:
TITLE:
SIZE
DWG. NO.
REV
B
long shaft
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
DO NOT SCALE DRAWING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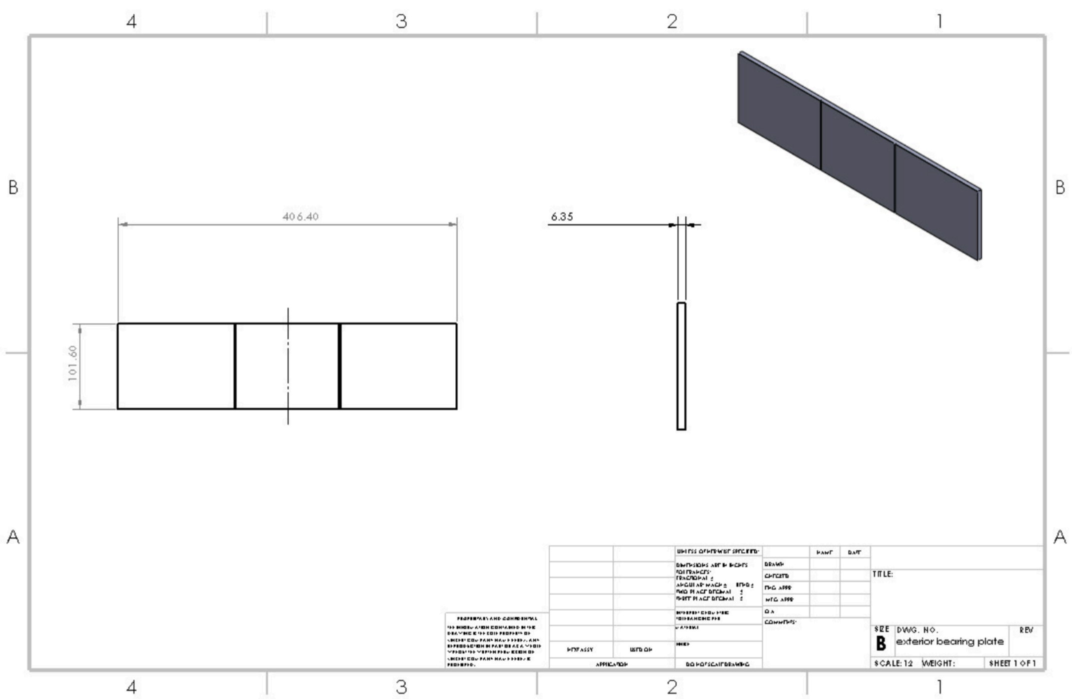
SHEET 1 OF 1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6.35
TITLE:
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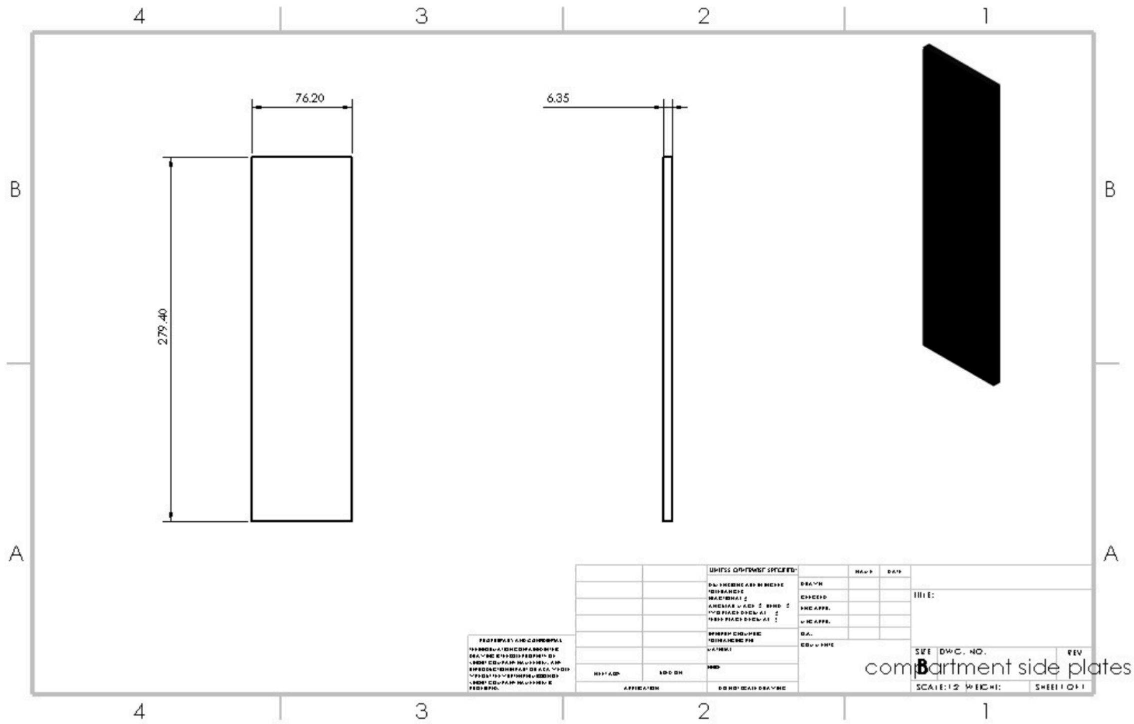
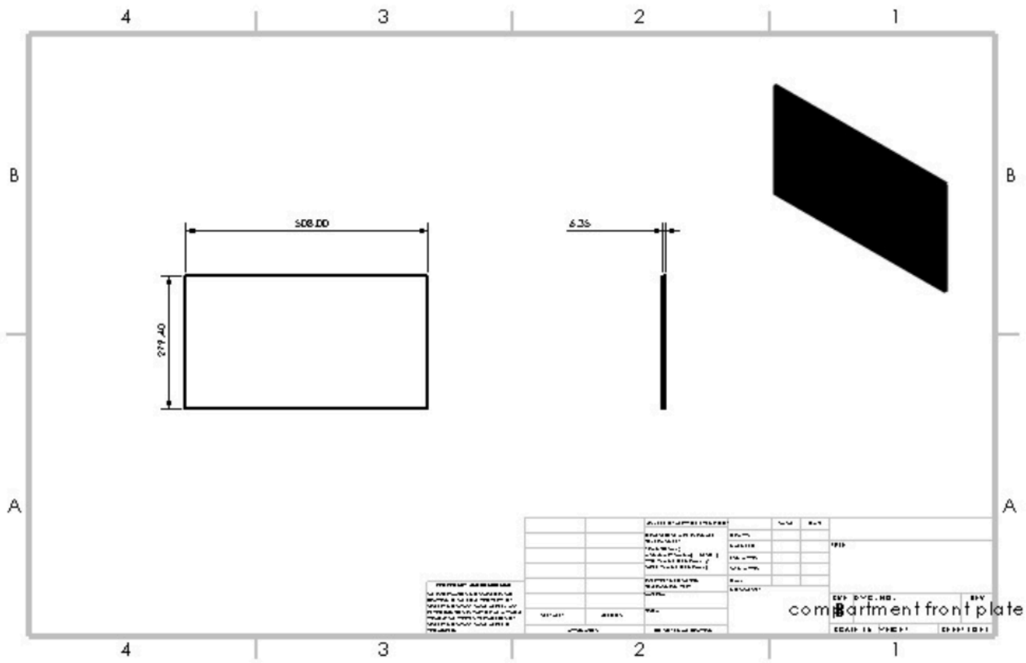
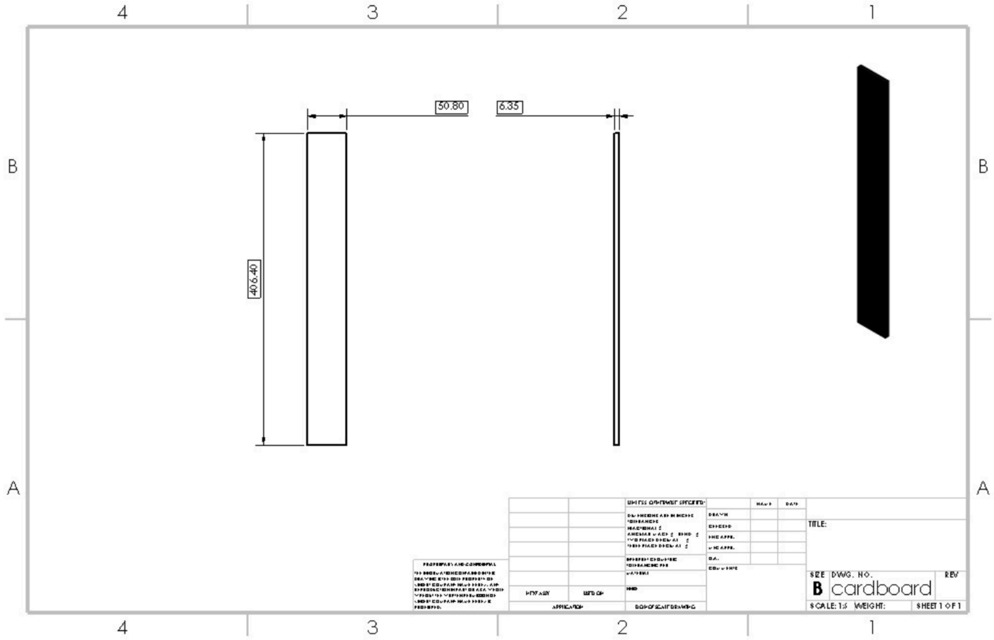
SHEET 1 OF 1



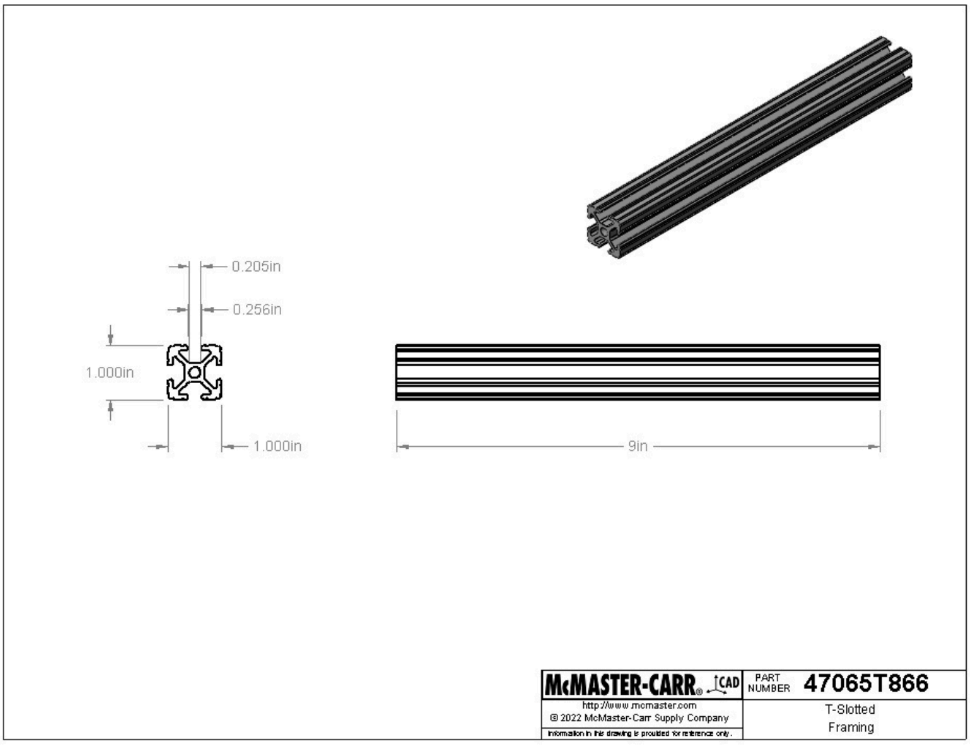
76.20
6.35
279.40
compartment side plates



508.00
6.35
279.40
compartment front plate



4
3
2
1
B
A
50.80
6.35
406.40
TITLE:
SIZE DWG. NO.
REV
B cardboard
SCALE: 1:5 WEIGHT:
SHEET 1 OF 1



0.205in
0.256in
1.000in
1.000in
9in
McMASTER-CARR
CAD
PART NUMBER
47065T866
http://www.mcmaster.com
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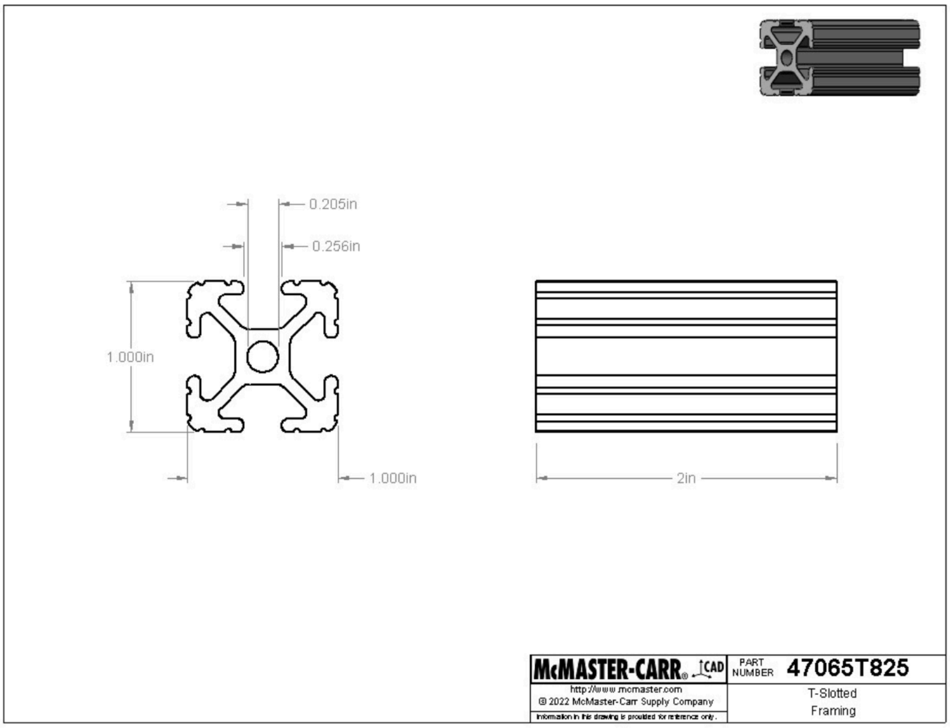
T-Slotted
Framing


0.205in
0.256in
1.000in
1.000in
2in
McMASTER-CARR
CAD
PART NUMBER
47065T825
http://www.mcmaster.com
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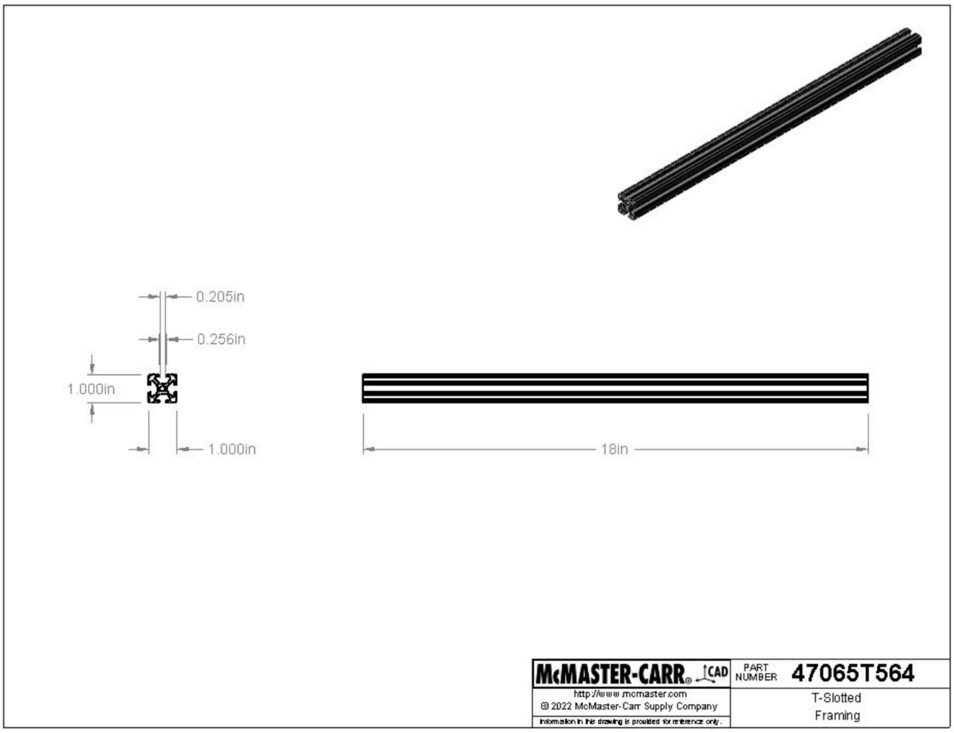
T-Slotted Framing


0.205in
0.256in
1.000in
1.000in
18in
McMASTER-CARR
CAD
PART NUMBER
47065T564
http://www.mcmaster.com
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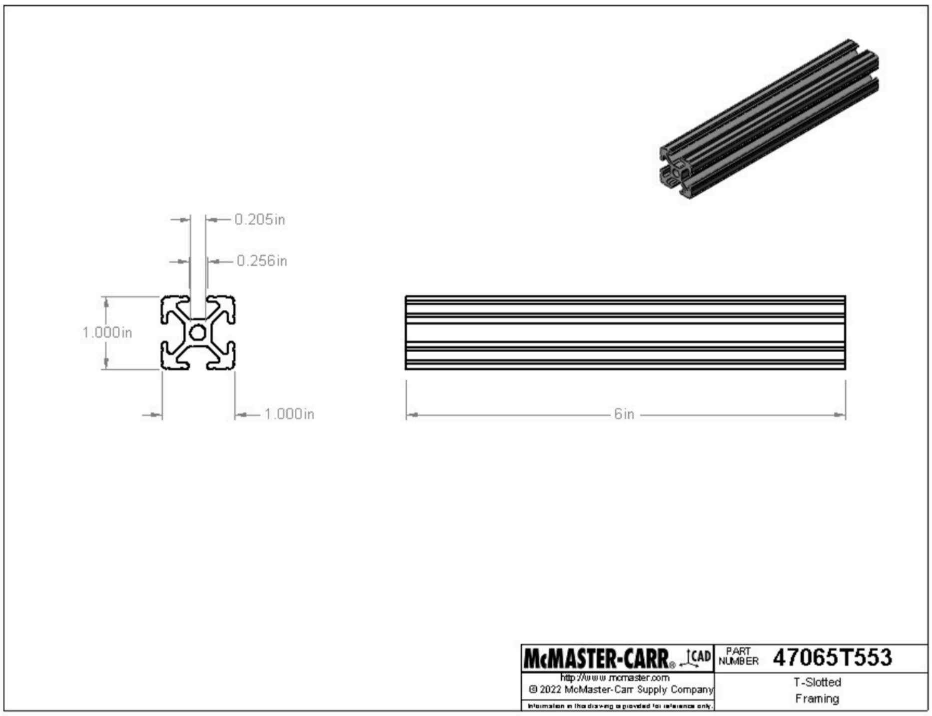
T-Slotted Framing


0.205in
0.256in
1.000in
1.000in
6in
McMASTER-CARR
CAD
http://www.mcmaster.com
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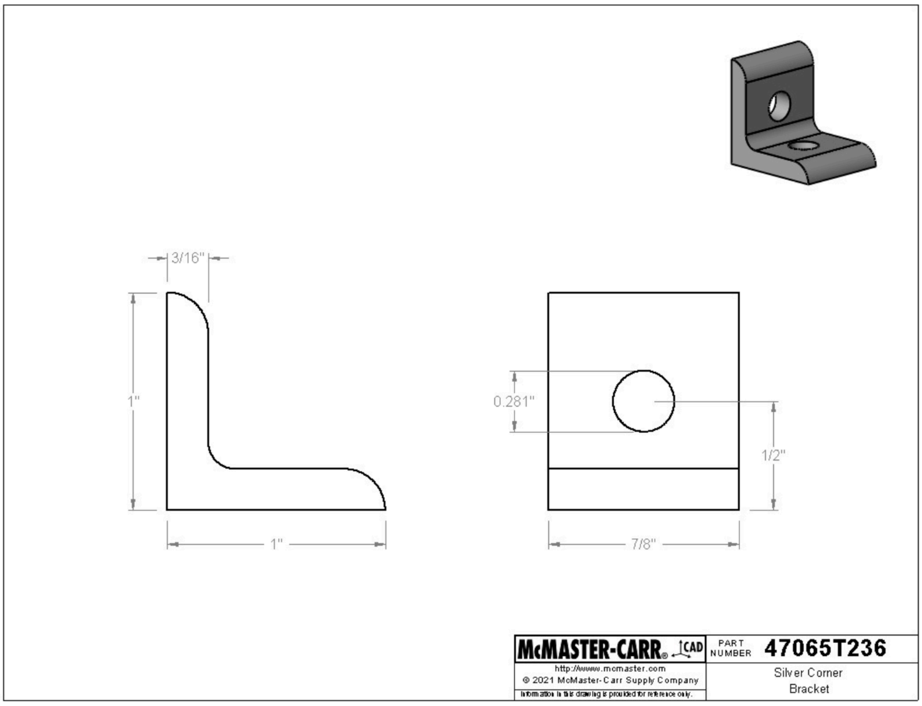
PART NUMBER
47065T553
T-Slotted Framing


3/16"
1"
1"
0.281"
1/2"
7/8"
McMASTER-CARR
CAD
http://www.mcmaster.com
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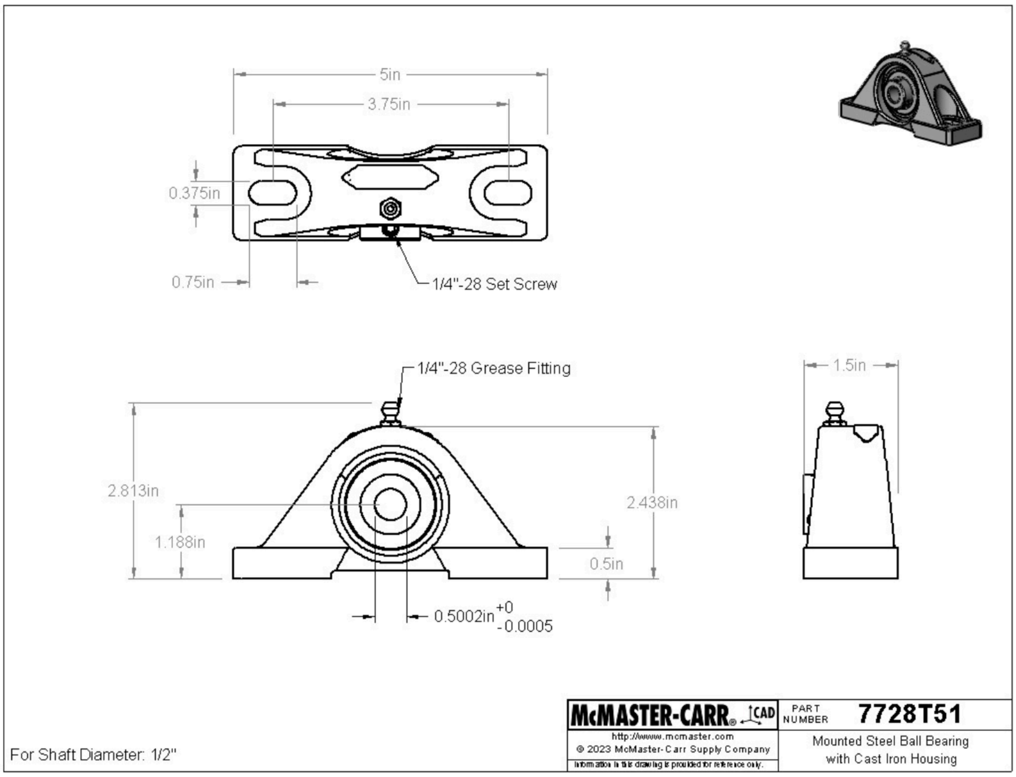
PART NUMBER
47065T236
Silver Corner Bracket


5in
3.75in
0.375in
0.75in
1/4"-28 Set Screw
1/4"-28 Grease Fitting
1.5in
2.813in
1.188in
2.438in
0.5in
0.5002in +0 -0.0005
McMASTER-CARR CAD
PART NUMBER 7728T51
http://www.mcmaster.com
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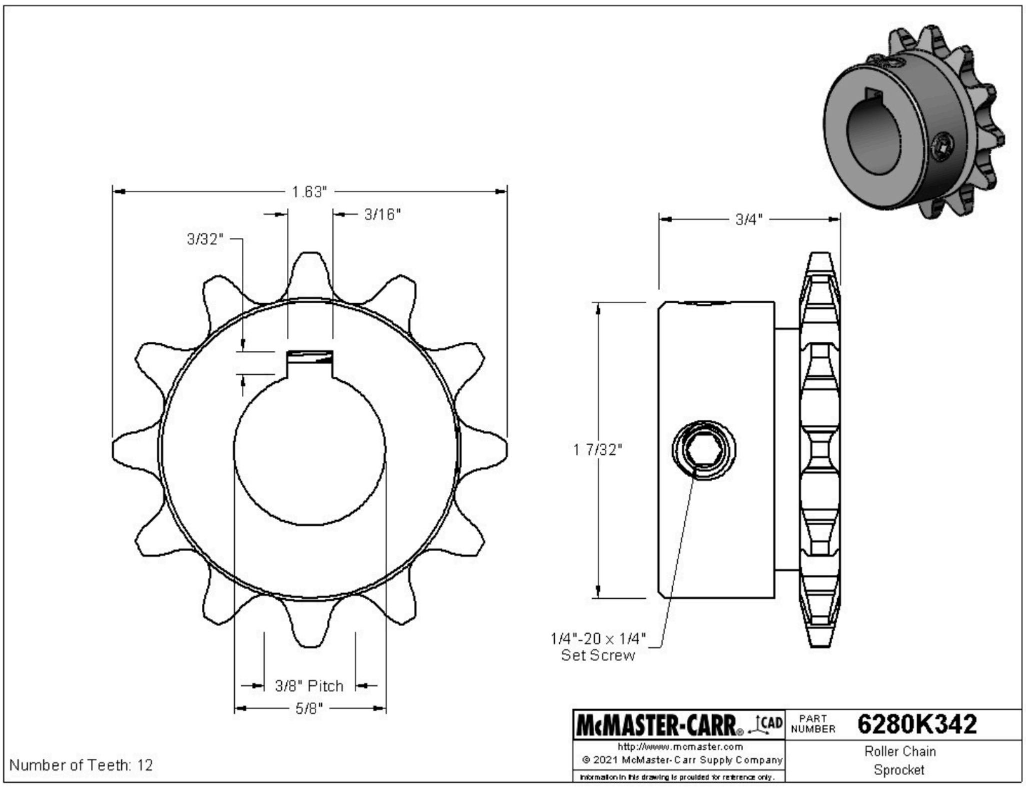
Information in this drawing is provided for reference only.
Mounted Steel Ball Bearing with Cast Iron Housing
For Shaft Diameter: 1/2"


1.63"
3/16"
3/32"
3/4"
1 7/32"
1/4"-20 x 1/4" Set Screw
3/8" Pitch
5/8"
McMASTER-CARR CAD
PART NUMBER 6280K342
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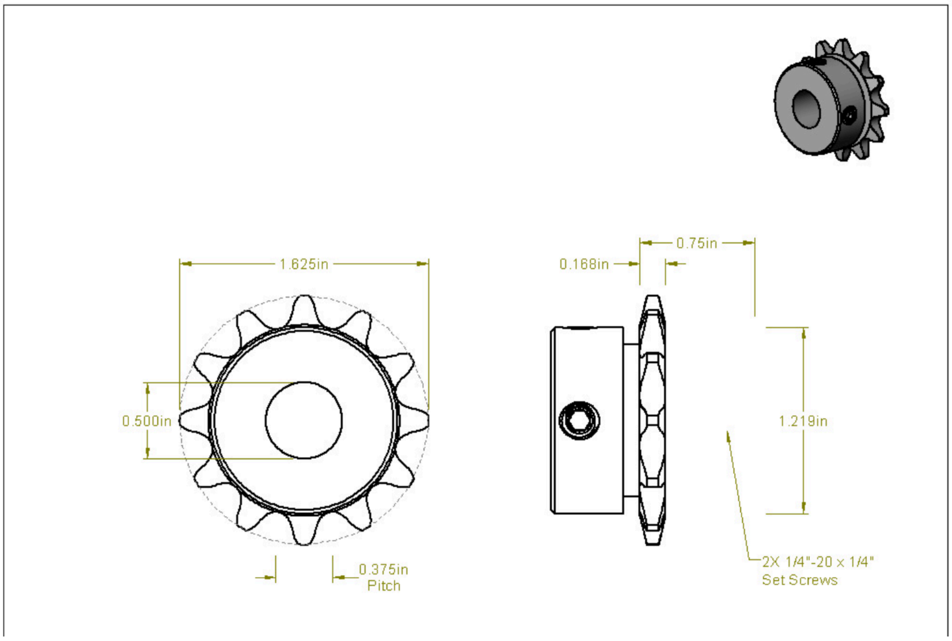
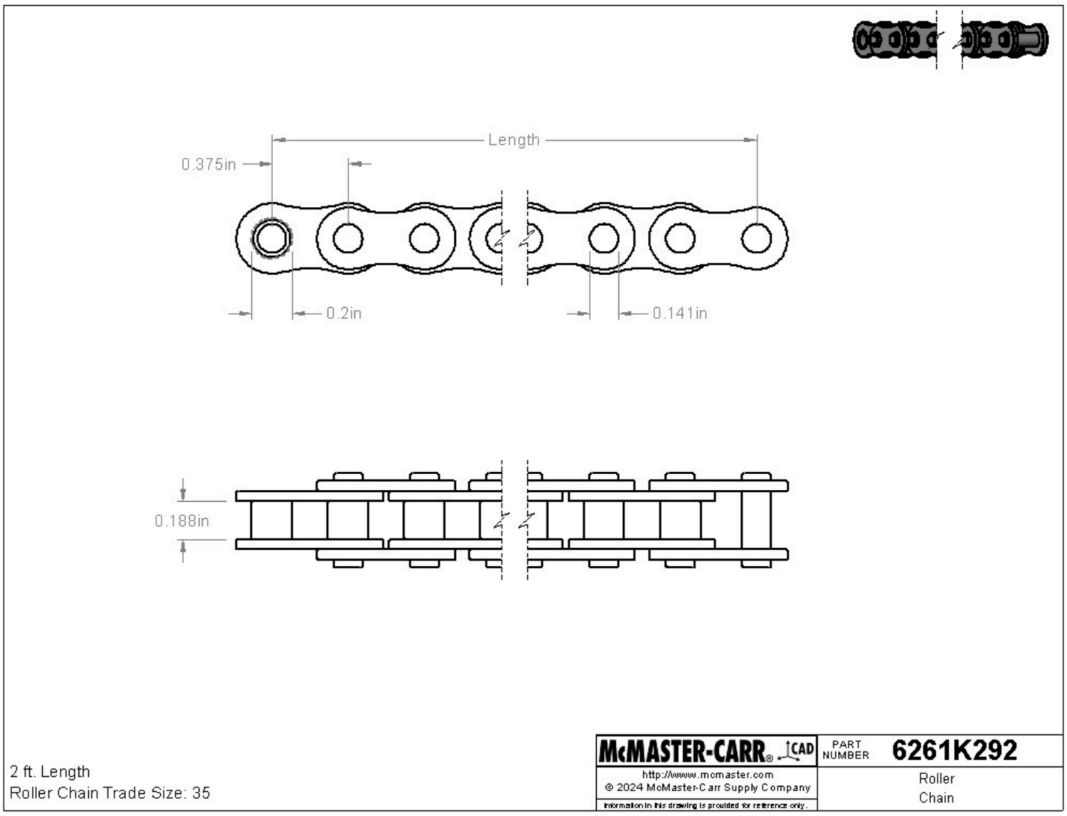
Information in this drawing is provided for reference only.
Roller Chain Sprocket
Number of Teeth: 12


1.625in
0.168in
0.75in
0.500in
1.219in
0.375in
Pitch
2X 1/4"-20 x 1/4"
Set Screws


Length
0.375in
0.2in
0.141in
0.188in
2 ft. Length
Roller Chain Trade Size: 35
McMASTER-CARR
PART NUMBER
6261K292
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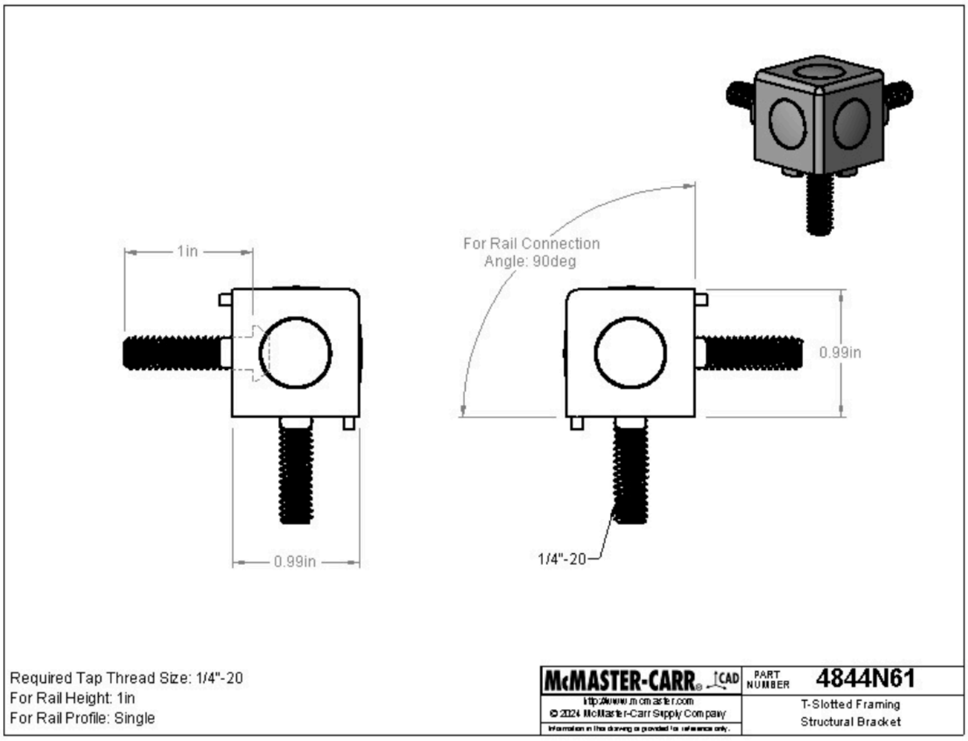
Roller
Chain


For Rail Connection
Angle: 90deg
1in
0.99in
0.99in
1/4"-20
Required Tap Thread Size: 1/4"-20
For Rail Height: 1in
For Rail Profile: Single
McMASTER-CARR
CAD
PART NUMBER
4844N61
http://www.mcmaster.com
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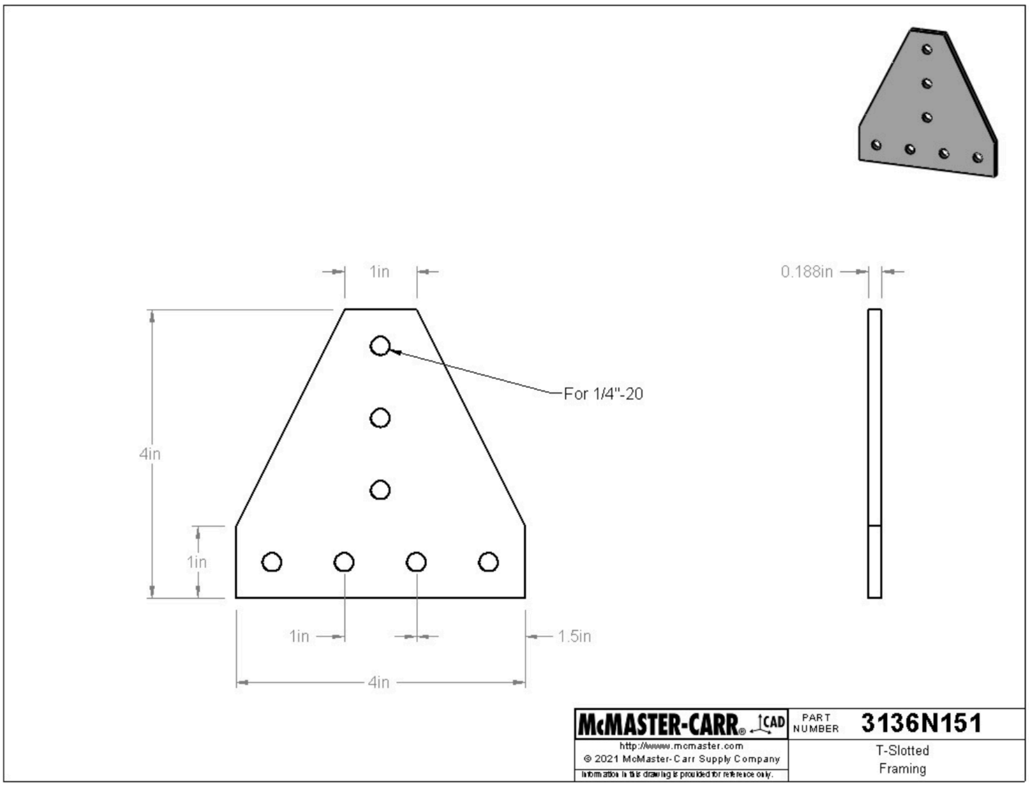
Information in this drawing is provided for reference only.
T-Slotted Framing
Structural Bracket


1in
0.188in
For 1/4"-20
4in
1in
1in
1.5in
4in
McMASTER-CARR
CAD
PART NUMBER
3136N151
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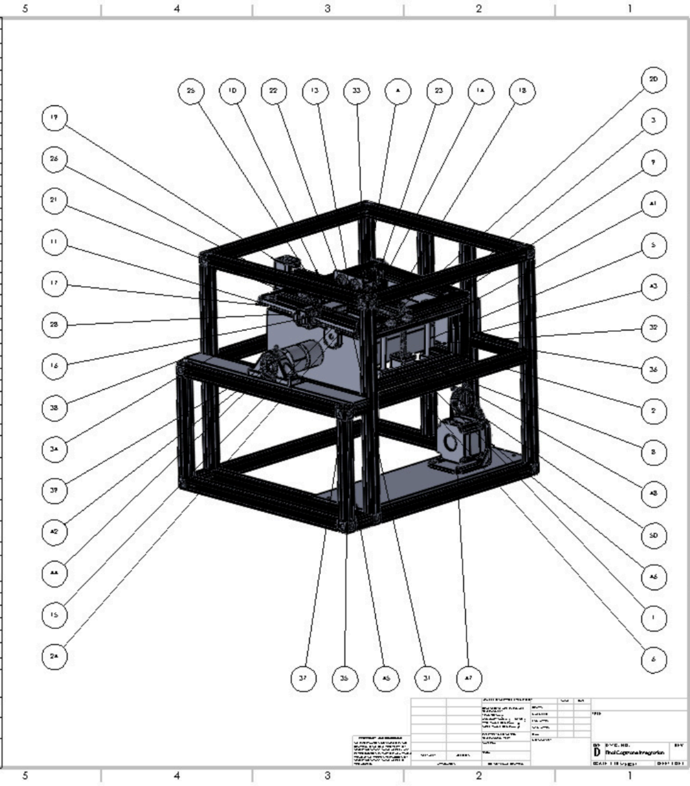
Information in this drawing is provided for reference only.
T-Slotted
Framing

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	EXS-001-003-004_Y-axis half.STEP		2
2	EXS-001-003-004_X-axis half.STEP		4
3	EXS-002_Join Y half.STEP		2
4	EXS-001-003-004_Z strut half.STEP		4
5	CPP-005-QTY4_Guide half.STEP		4
6	CPH-025-QTY8.STEP		8
7	HBS-013-QTY2_shaft.STEP		2
8	42-34 motor_Standard.STEP		4
9	SS-006-QTY2_lead shaft.STEP		2
10	EXS-001-003-004_X rail mod.STEP		1
11	DS-007_Shaft.STEP		2
12	TBP-022-QTY2_strut.STEP		2
13	BPP-009-QTY1.STEP		1
14	HPP-010-QTY1.STEP		1
15	HCS-014-QTY2.STEP		2
16	BPC-015-QTY2.STEP		2
17	BracketforYaxisDS.STEP.STEP		1
18	BracketforYaxisDS_Mirror.step.STEP		1
19	x1.STEP.STEP		1
20	x2.STEP.STEP		1
21	corner.STEP.STEP		4
22	hat.STEP.STEP		1
23	y1.STEP.STEP		1
24	ex.STEP.STEP		1
25	camera case v13.step.STEP		1
26	cover v4.step.STEP		1
27	camera v1 step.STEP		1
28	front_cover.STEP		1
29	back_cover.STEP		1
30	bracket for screen case.STEP		2
31	EXS-002MODIFIED HOLY HECK_f reduced.STEP		4
32	cover.STEP		1
33	4844N51_T-Slotted Framing Structural Bracket_4844N51.STEP		12
34	47065T564_T-Slotted Framing_47065T564.STEP		19
35	47065T866_T-Slotted Framing_47065T866.STEP		2
36	47065T553_T-Slotted Framing_47065T553.STEP		2
37	47065T825_T-Slotted Framing_47065T825.STEP		4
38	exterior bearing plate.STEP		1
39	7728T51_Mounted Steel Ball Bearing with Cast Iron Housing_7728T51.STEP		1
40	short shaft.STEP		1
41	steel side plates.STEP		2
42	spring.STEP		2
43	Printer Big Plate.STEP		2
44	long shaft.STEP		1
45	steel plate for motor mount.STEP		1
46	SHW7.STEP		1
47	formed hex screw_am_B18.2.3.2M - Formed hex screw, M6 x 0.8 x 8 --8WN.STEP		8
48	6627T651_Stepper Motor_6627T651.STEP		1
49	6280K341_Roller Chain Sprocket_6280K341.STEP		2
50	6261K261_Add Connect link for ANSI 35 Single Strand Roller Chain_6261K261.STEP		71



15.7 System User Manual

D.I.C.E
System User Manual

Dynamic Inertial Clinostat Experimental System

Capstone Design Project – 2024/2025

This user manual provides guidance on the operation and maintenance of the DICE System — a custom-built clinostat integrated with a 3D printer, designed to simulate hyper gravity conditions at variable rotational speeds. The system was developed to evaluate the effects of altered gravitational forces on 3D-printed materials, supporting advancements in microgravity simulation research.

DICE Developed By:

Gaith Al-Adwan
Omar Almufleh
Herman Balagan
Navroz Bir
Ibrahim El Zamzamy
Omar Tawil

Capstone students in the Department of Electrical and Mechanical Engineering

Lassonde School of Engineering, York University

Introduction

Overview of Dice System and its purpose

The Dynamic Inertial Clinostat Experimental (DICE) System is a custom-built rotational platform designed to simulate hyper gravity conditions by rotating samples at controlled speeds. The system enables experimental observation of how varying gravitational forces affect the quality and structure of 3D-printed materials during the printing process.

At the heart of the system is a dual-Arduino architecture, where a master Arduino controls the rotational speed of the motor, and a slave Arduino monitors environmental conditions — including temperature, humidity, and real-time rotational speed (RPM). The system communicates internally over the I²C protocol to synchronize sensor readings and motor feedback.

The DICE System was developed in collaboration with Capstone Group 35, who designed and provided a miniature 3D printer specifically for this project. The printer was customized to fit securely within the DICE platform, allowing it to operate under rotational stress. Close coordination between both groups ensured mechanical compatibility, electrical integration, and safe operation during testing phases.

Highlights

The DICE System combines precision control and environmental monitoring to create a versatile platform for rotational experimentation. At its core is a dual-Arduino architecture: a master Arduino responsible for motor control and user interaction, and a slave Arduino dedicated to sensor monitoring and system feedback. This division of responsibility not only simplifies development and debugging but also allows each microcontroller to perform its tasks efficiently without interference or processing lag.

What sets DICE apart is its smooth and intelligent motor control system. Instead of abruptly changing speeds, the system employs a soft-ramping algorithm that dynamically adjusts the motor's pulse rate using an exponential curve. This ensures that acceleration and deceleration occur gradually, reducing mechanical stress on the rotating components and any payload, such as a 3D printer or printed sample.

Communication between the master and slave Arduinos takes place over the I²C protocol, enabling fast and reliable data exchange. The slave continuously collects and processes data from an onboard DHT11 temperature and humidity sensor, as well as an IR sensor that tracks the rotational speed in real time. This information is displayed on an I²C-connected LCD screen and is also made available to the master controller for live monitoring. Users can view current temperature, humidity, and RPM without needing to pause or stop the system.

One of the standout features of the DICE System is its user interface simplicity. Through the Arduino Serial Monitor, users can input a desired RPM value, and the system automatically computes the necessary motor pulse timing to match. A simple text command such as "s" initiates a controlled deceleration and stops the system without causing sudden jolts. This streamlined interaction design means the DICE System can be operated by users with minimal training, while still offering the precision and responsiveness required for more advanced experimentation.

Beyond its control and feedback mechanisms, the DICE System was also developed with modularity and compatibility in mind. It was built in close collaboration with Capstone Group 35, who designed a miniature 3D printer tailored to fit within the DICE frame. This allowed for seamless mechanical integration and the ability to observe 3D printing processes under rotational stress conditions — a use case with significant implications for space-based manufacturing research. Together, these features make the DICE System a robust and adaptable platform for simulating inertial and hyper gravity environments in a controlled, measurable, and user-friendly way.

Safety and Usage Guidelines

General Handling

The DICE System is primarily constructed from aluminum extrusion framing, which provides both structural integrity and secure grip points for safe handling. BEFORE ATTEMPTING TO MOVE THE SYSTEM, ALL POWER MUST BE DISCONNECTED, INCLUDING UNPLUGGING THE POWER SUPPLY AND REMOVING ANY CONNECTED USB OR EXTERNAL CABLES. Never attempt to move the DICE while the printer is operating or while the system is in motion, as this could cause mechanical damage or pose a serious safety risk. Once fully powered down and disconnected, two people should lift the system, each gripping the aluminum extrusion from opposite sides of the frame. Lifting should never be done by a single person due to the weight distribution and potential for instability.

A key safety feature of DICE is the inclusion of transparent plexiglass panels. These panels serve two primary purposes: first, they create a protective barrier between the moving internal components and observers; second, they allow users to safely observe the motion of the system during testing without being exposed to any rotating parts. Users should always remain on the side of the clear plexiglass when monitoring the DICE in operation, as this is the designated safe viewing zone.

The rear plexiglass panel is also transparent but is designed for cess rather than observation. It is magnetically secured and can be carefully removed or opened for maintenance purposes. This panel provides access to the interior compartment, where the miniature 3D printer is housed, as well as the lower electronics bay that contains the Arduinos, microstep driver, and power supply unit (PSU). Only trained personnel should perform maintenance inside the compartment, and the device must be powered off and unplugged before accessing any internal components.

Power Connection Caution

The DICE System operates using a 24V, 15A industrial power supply unit (PSU) (Model: S-360-24), capable of delivering up to 360W of power. This unit receives input from a standard 110V AC wall outlet via a power adapter mounted on the lower wall inside the DICE's frame. The PSU directly powers the DM556 microstep driver, which in turn drives the high-torque NEMA 34 stepper motor responsible for rotating the printer.

Extreme caution must be taken when handling or connecting power to the system. The internal PSU deals with high current at 24V DC, and its input is live 110V AC. Users must never attempt to access or adjust the PSU while the system is plugged in, as improper contact may lead to electric shock or component damage.

To fully power down the system, the external power plug must be physically disconnected from the wall socket. There are no built-in switches, fuses, or isolation relays in the DICE enclosure, so unplugging the power cable is the only safe method of ensuring the system is de-energized. Users should never rely on just powering down the PC connected to the Arduinos as this does not interrupt the motor's power circuit.

The PSU must remain fixed in its installed position, mounted securely and oriented upside down, as designed. This orientation is critical to maintaining proper airflow through its vented chassis, preventing overheating. Never attempt to move or relocate the PSU within the DICE. Although the unit includes internal fuses for short-circuit protection, it is not a substitute for external safety hardware.

Arduinos can be powered either via USB connections to a PC or through their own power cables. When connected via USB, users can actively monitor system behavior, upload code, and adjust motor speed through the Serial Monitor. When running from external power, the Arduinos will operate using the last uploaded code. In both scenarios, users should avoid plugging or unplugging cables while the system is powered to prevent accidental shorts or data corruption.

Finally, do not touch exposed wires, terminals, or electronic components inside the DICE while powered on. All internal access — especially for maintenance in the electronics compartment — must be done with the system completely unplugged.

Sensor Interference Warning

The DICE System relies on real-time data from multiple sensors to monitor performance during operation. These include a DHT11 temperature and humidity sensor, an infrared (IR) sensor for RPM measurement, and a 16x2 I²C LCD display to visualize sensor data. Ensuring accurate readings from these components is critical to reliable system operation, and users should follow the guidelines below to minimize the risk of interference or sensor-related faults.

The DHT11 sensor is mounted at the top of the frame, positioned away from any fans or heat-generating components. However, the rotational motion of the 3D printer and internal air circulation may still cause fluctuations in temperature and humidity readings. It is not uncommon for the DHT11 to output occasional incorrect or inconsistent values. These readings typically self-correct after a brief period as the sensor refreshes. If the issue persists or if the LCD screen freezes or displays blank or incorrect data, users should disconnect and reconnect the Slave Arduino's power to reset the system. Do not attempt to unplug or reconnect sensor wires while the system is powered on.

The IR sensor Is positioned near a rotary encoder wheel mounted on the rotating shaft that drives the printer. This configuration ensures the system reads the actual physical RPM of the rotation, not just a theoretical output. It is extremely important that the encoder wheel does not come into direct contact with the IR sensor. Contact may damage the sensor's fragile internal IC, potentially resulting in a system crash or incorrect RPM feedback. If physical contact is observed or suspected, immediately disconnect power to the system and gently adjust the spacing before resuming operation.

The DICE enclosure includes foam padding throughout the frame to minimize external vibration, and cable management is enforced using clips and zip ties to secure all connections along the aluminum extrusions. However, small issues may still arise. If any female-to-male jumper wires appear loose, gently push them back together without excessive force, as these connectors can break easily under stress.

To prevent interference:

- Do not block the IR sensor's line of sight during operation.
- Do not touch or reposition sensors or wires while the DICE is powered.
- Keep any external wireless or electrical devices away from the electronics compartment while in use.
- Allow the system a few seconds after startup to stabilize sensor readings before beginning observation.

Note: By following these precautions, users can ensure consistent sensor performance and prevent potential damage to critical components.