LE/ENG 4000 A – Capstone Project

Group 36: Gravity Gizmo – Exploring Manufacturing in the Stars

Capstone Project Mid-Year Report


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**Abstract**

This report outlines the progress of a single-axis clinostat that can replicate gravity conditions to facilitate space-like manufacturing experimentation. Designed to house a 1ft x 1ft x 1ft 3D printer weighing 12 kg, the system is capable of achieving a rotational speed of up to 120 RPM, enabling simulations of microgravity and hypergravity environments depending on common centre of mass between the printer and the rotating axis. To ensure stability and accuracy, the clinostat uses efficient rotational mechanics and a lightweight, sturdy frame.

To support the printer while preserving load balance and reducing vibrations during high-speed operation, the design incorporates a unique mounting mechanism. To maximize performance, structural analysis, vibration tests and motor torque calculations were carried out. A high-resolution camera is incorporated to observe the printing process and environmental monitoring tools such as temperature, humidity and pressure sensors are integrated to gather data in real-time. These elements guarantee a regulated and visible setting for testing additive manufacturing under varying gravitational conditions.

With an emphasis on sprint planning, thorough testing and integrating stakeholder feedback to improve design aspects and address identified setbacks, the project has advanced through iterative Agile development phases. This semester's major accomplishments include the successful calibration of rotational controls, the assembly of the prototype and the preliminary validation of environmental monitoring systems. To guarantee steady operation at maximum capacity, the next stages entail completing system testing, including sophisticated control features and resolving vibration-related problems.

This clinostat is a big step toward allowing study in bioprinting and additive manufacturing under space-like conditions, which could have uses in material sciences, medical improvements and space exploration.

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## 1.0 Executive Summary

Our project follows Agile methodology for project management to ensure the development of a high-performance, cost-effective clinostat while maintaining flexibility and responsiveness to our stakeholder's needs, The project’s timelines use a structured framework that organizes the tasks into manageable phases and ensures a steady progress to achieve key milestones, current tasks include material purchasing, BOM finalization and assembly of the exterior and interior frames, all scheduled for completion by March 2025. Following this, system-level testing focuses on critical performance metrics like rotational stability, torque and vibration control, validating the design’s readiness for practical applications.

The development of the clinostat is structured into five focused sprints. Sprint 1 involves finalizing the Bill of Materials (BOM) and organizing all necessary components for assembly. Sprint 2 centers on constructing the aluminum frame and integrating the NEMA 34 motor for rotational functionality. Sprint 3 prioritizes sensor integration for environmental monitoring and safety features like plexiglass/aluminum enclosures. Sprint 4 incorporates a camera for real-time monitoring while refining the enclosure to minimize vibrations. Finally, Sprint 5 focuses on calibration, testing and iterations to ensure the clinostat operates efficiently, safely and within the desired specifications.

Successful management of resources is achieved by following a Resource Allocation Matrix (RAM) and RACI framework to define clear roles and responsibilities, to prioritize the tasks a story point system is used to clearly define which tasks are considered a priority. A Gantt chart was used to keep track of progress for the tasks assigned and prioritized, providing a detailed visualization of our project's advancements. Thus, by combining resource management, a detailed Gantt chart, foundational research and regular communication with our supervisor, the clinostat design is developed step-by-step to ensure maximum efficiency, cost-effectiveness and reliability, meeting all requirements and expectations.

## 2.0 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 modeling 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 Controls: The clinostat device must be equipped with systems capable of regulating both temperature and humidity. To remove ambiguity, this would be between 60 and 90 degrees Celsius and humidity up to 90%, as outlined by key stakeholders. This will allow for simulated controlled environmental conditions for material testing. The system should also allow for manual adjustments to accommodate a variety of experimental 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.

### *2.1 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.

### *2.2 Needs and Requirements Compliance Analysis*

In order 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 1: Means of Compliance for in-scope requirements.

| Requirement | Potential Non-Compliance | Plan to address Non-Compliance | Verification |
|---|---|---|---|
| Rotational Speed | Motor does not achieve 120 RPM rotational speed | Switch provided motor with 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. | 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 | 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 | 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 | Reevaluate 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. | 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]

## 3.0 Baseline Design

### *3.1 Design Articulation*

The primary design problem our project addresses is the need for a cost-effective, compact, and versatile system that simulates microgravity and hypergravity environments to facilitate 3D printing, particularly of biological materials. We aim to develop a two-axis clinostat that can rotate a 3D printer to simulate these gravity conditions at speeds of up to 120 RPM. The clinostat's rotation allows the samples being printed to experience simulated gravity, such as zero-gravity or hypergravity environments, which is crucial for experiments like 3D bioprinting in space. By replicating gravity-like environments in a compact system, our project will provide valuable insights into the feasibility of 3D printing in space and its potential applications for medical and scientific purposes. The goal is to create a design that can be built by anyone with the necessary resources, at a fraction of the cost compared to highly specialized and large-scale systems used by organizations like NASA. The clinostat's design is constrained by the need to fit within a 2ft x 2ft footprint to ensure it remains compact and accessible for users. The space constraints apply not only to the structure itself but also to all internal components, such as the motors, chains, and any necessary wiring. Additionally, safety is a major consideration. To ensure that the clinostat is both safe to operate and reliable over extended periods, we have planned for several safety features. The frame will be padded to minimize vibration, a critical factor when working with high-precision 3D printers. The clinostat's enclosure will be made from plexiglass to prevent any potential hazardous components from being ejected in case of a catastrophic failure. Furthermore, a failsafe mechanism will ensure that the clinostat never exceeds the target rotational speed of 120 RPM. The motor will be microstepped to gradually accelerate the system, minimizing the risk of sudden jerks or mechanical failure.

This design aims to balance the goals of affordability, safety, and performance. In addition to these considerations, the feedback and needs of various stakeholders will be integral to the ongoing development. Space agencies, biomedical researchers, and the 3D printing industry, among others, will benefit from a system capable of simulating gravity in a controlled, repeatable manner. Our ongoing outreach to these groups is designed to ensure their needs and requirements are reflected in our design decisions, further underscoring the relevance and impact of the project.

### *3.2 Feasibility*

The technical feasibility of the clinostat design is ensured through the careful selection of components, such as the NEMA 34 stepper motor, which provides a torque of 8 N.m. This motor is capable of driving the system at the required rotational speed, enabling the simulation of microgravity and hypergravity conditions for the 3D printing process. The motor is connected to one of the clinostat's carbon steel hollow shafts via a bicycle chain, providing the necessary rotational movement to simulate gravity conditions for the 3D printer. Our integration of the motor, shaft, and chain system ensures that the rotational speed is stable and smooth, meeting the project's key performance targets.

The design also carefully considers the load-bearing requirements, ensuring that the motor's torque is sufficient to rotate the full system, including the 3D printer housed within the clinostat. These components work in tandem to meet the specific rotational speed targets while maintaining the structural integrity and stability of the clinostat's design.

The design remains within the allocated budget of 1,000 CAD. As of now, the project has spent 828 CAD on key components, including the motor (180 CAD), motor mount (37 CAD), sprockets and corner brackets (305 CAD), and aluminum extrusions (36 CAD). Additional costs include screws and bushings. This budget has been managed effectively, and the remaining funds will be allocated to finalizing the assembly, including wiring and final testing. These components have been selected with both cost-effectiveness and performance in mind. The aluminum extrusions, for example, are used for the frame assembly and offer a lightweight yet durable solution that ensures stability while keeping material costs low. The motor and motor mount were chosen for their balance between price and capability, offering sufficient torque for the rotational requirements without exceeding the budget.

In terms of legal feasibility, the project adheres to relevant safety and engineering standards to ensure that it complies with regulations, particularly in biomedical and space applications. We are consulting ISO standards such as ISO 10218-1:2011 (Robots and Robotic Devices - Safety Requirements for Industrial Robots - Part 1: Robots)[3] and ISO 9001:2015 (Quality management systems - Requirements)[4], which provide guidelines for the design and development of systems that could be used in sensitive environments like space or automated environment settings. These standards ensure that the clinostat design will meet necessary safety, performance, and quality requirements. The design will follow strict safety protocols and include vibration-damping padding, protective plexiglass enclosures, and a failsafe to prevent excessive rotational speeds, ensuring compliance with said safety regulations.

The clinostat's modular design allows for straightforward assembly, with clear component connections and minimal complexity in the system setup. The selected materials and components have been chosen for their durability, with aluminum extrusions providing a strong yet lightweight frame. Maintenance is simplified through the use of common materials and components, ensuring that replacements and repairs can be made easily and cost-effectively. The system's design also facilitates smooth operation, with minimal need for continuous adjustments once it is assembled and calibrated.

### *3.3 Strategy Formulation*

The selection of the NEMA 34 motor, capable of providing 8 N.m of torque ensures the clinostat can achieve the required rotational speeds to simulate both microgravity and hypergravity environments. The motor is coupled with a bicycle chain system, which will transmit the necessary power to the carbon steel hollow shafts holding the 3D printer enclosure. This integration ensures that the rotational speed remains stable while minimizing vibration, crucial for maintaining precision in printing experiments.

The use of the NEMA 34 motor was driven by its high torque capabilities, providing sufficient power to rotate the 3D printer at the required speeds without overloading the system. The bicycle chain, a reliable and affordable power transmission method, was selected to maintain rotational consistency and reduce maintenance complexity compared to more advanced options. These choices ensure the design meets the technical requirements while adhering to the budget. Other potential designs were considered during the initial stages of the project, including the use of smaller motors with lower torque ratings and alternative power transmission systems such as gears or belts. However, the alternatives posed several challenges. Smaller motors would have required a more complex system to achieve the desired torque, leading to an increase in complexity. Gears, although efficient in transmitting power, were ruled out due to their higher cost and potential for requiring frequent maintenance. The belt system, while more common in some motion designs, was dismissed due to concerns over reliability and the need for tenuous tension adjustments.

Given these considerations, the decision to use the NEMA 34 motor and bicycle chain system was made because it offered the best balance between performance, cost, and ease of maintenance. The NEMA 34 motor is robust enough to handle the dynamic forces involved in simulating microgravity conditions, while the chain system provides a straightforward and durable means of translating motor power into rotational movement without introducing significant complexity or cost.

### *3.4 Decomposition and Prioritization of Product Features*

To manage the development of the two-axis clinostat effectively, we’ve broken down the overall design into manageable parts, following the Agile methodology. Each part, or product increment, is focused on a specific task that builds towards the completion of the final design. The process begins with simpler tasks and gradually progresses to more complex ones, ensuring that critical components are addressed early and effectively.

- **Sprint 1: BOM Finalization and Initial Setup** - The first sprint involves finalizing the Bill of Materials to ensure all components are accounted for, including the NEMA 34 motor, aluminum extrusions, and sensors. This is followed by the procurement of all necessary materials and preliminary assembly steps, including organizing and labeling the parts. This is crucial for ensuring that the team has everything required for the next stages.

- **Sprint 2: Frame Construction and Motor Integration** - The next sprint focuses on constructing the clinostat’s frame from aluminum extrusions and integrating the motor. Given that the clinostat’s size is constrained to 2ft x 2ft, this sprint prioritizes building the frame to fit all components within the space limit. The motor, crucial for achieving the required rotational speed of 120 RPM, will be mounted and connected to the carbon steel hollow shafts using a bicycle chain. Safety measures, such as vibration reduction padding and securing the motor, will also be incorporated at this stage.

- **Sprint 3: Sensor Integration and Safety Features** - Sensor integration is crucial, as stakeholders have emphasized the importance of tracking environmental factors like temperature, humidity, and rotational speed. This sprint ensures that all sensors are properly integrated and calibrated to ensure the accurate collection of data during experimentation. Additionally, safety is a top priority; therefore, this sprint focuses on ensuring that the clinostat's frame is securely enclosed in plexiglass to prevent potential risks from chain breakage, as well as implementing a failsafe mechanism.

- **Sprint 4: Real-Time Camera Integration and Enclosure Refinements** - To facilitate real-time monitoring of the 3D printing process, a high-resolution camera will be integrated inside the clinostat, allowing stakeholders to observe and study the print behavior as the printer rotates. This sprint will focus on finalizing the camera installation, refining the enclosure to minimize vibration, and ensuring that all components function in harmony.

- **Sprint 5: Calibration, Testing, and Iteration** - In the final sprint, we will focus on the calibration of the motor, ensuring that it reaches the desired speed and remains stable at 120 RPM. This will also involve testing the clinostat in its entirety, making necessary adjustments based on feedback and real-time data collection. Any issues identified, such as vibrations or discrepancies in rotational speed, will be addressed promptly. This sprint also includes ensuring that the design meets safety, functionality, and performance targets.

The prioritization of features is guided by stakeholder needs. Safety, sensor accuracy, and real-time monitoring are essential features that must be developed and validated early to ensure the clinostat operates not only efficiently, but safely as well. The sensor verification process is particularly important for enabling data collection, which will provide insights into the feasibility of using the clinostat for future bioprinting applications. This backlog management process ensures that tasks are completed in the most logical order, with each sprint building on the previous one. The flexibility inherent in the Agile approach allows for adaptation as the project evolves, particularly during testing and validation. By keeping the team's roles clearly defined and allowing for real-time feedback, we ensure that each feature is delivered on time and to specification.

### *3.5 Application of Engineering Fundamentals*

The design of the clinostat leverages core mechanical and structural engineering principles to ensure functionality and reliability. For example, torque calculations were used to select the NEMA 34 motor, which delivers 8 N.m of torque, ensuring the shaft can rotate the 12 kg 3D printer enclosure at 120 RPM without strain. Calculations for rotational inertia and angular acceleration guided the determination of acceleration and friction torque, culminating in a total torque requirement of 1.116 N.m. This ensures that the selected motor operates well within its capacity, enhancing system longevity. Vibrational analysis, using the calculated natural frequency of 30.43 Hz, demonstrates that the system avoids resonance during operation at 2 Hz, which is critical for stability. However, the presence of the bike chain introduces noise and additional vibrations that will need mitigation.

The hollow shafts, constructed from carbon steel, were chosen for their high modulus of rigidity (3.55E-09 $m^4$), ensuring they can withstand operational stresses with a Factor of Safety of 4.34. Hollow shafts also reduce overall weight while providing a conduit for electrical cables, ensuring functionality and ease of integration. Alternative steels were considered, but their lower rigidity or higher costs made them less suitable. The aluminum extrusions for the frame were selected due to their lightweight nature, ease of assembly, and high durability, ensuring structural stability without exceeding weight constraints. Plexiglass was chosen for its transparency and ability to contain failures, providing both safety and visibility for real-time monitoring.

The project faces constraints in terms of size, weight, and system dynamics. The compact dimensions of the 3D printer (1 $ft^3$) and its weight of 12 kg dictated the clinostat's base dimensions (2 ft x 2 ft) and motor torque requirements. Vibrations remain a critical challenge due to the heavy NEMA 34 motor and the use of a bicycle chain for power transmission, which introduces inconsistencies in motion and additional vibrational forces. While the calculated imbalance force of 23.715 N is manageable, it necessitates careful balancing measures, including padding and microstepping, to reduce vibrations and noise during operation.

Although the clinostat avoids resonance due to its operational frequency being far below the system's natural frequency, significant vibrations are still expected from the chain and motor. To address this, damping materials and secure mounting systems are being incorporated to minimize vibrational transmission. Additionally, gradual acceleration via microstepping minimizes abrupt forces that could exacerbate these issues. Despite these measures, the engineering team anticipates some level of vibration, which will be closely monitored during testing to ensure it does not compromise functionality or safety.

### *3.6 Solution Development*

Our design demonstrates innovation through its unique integration of a compact 3D printer into a clinostat capable of simulating both microgravity and hypergravity environments. Unlike traditional single-purpose clinostats, which often require external systems for environmental monitoring, this system houses real-time sensors to monitor and log critical parameters such as gravity, humidity, and temperature. The inclusion of a camera for live visual feedback of the printing process within the rotating system further enhances its utility, making it a versatile tool for research in bioprinting and material sciences. Additionally, the adaptation of existing technologies, such as slip rings for power transfer and vibration-dampening methods, addresses key engineering challenges.

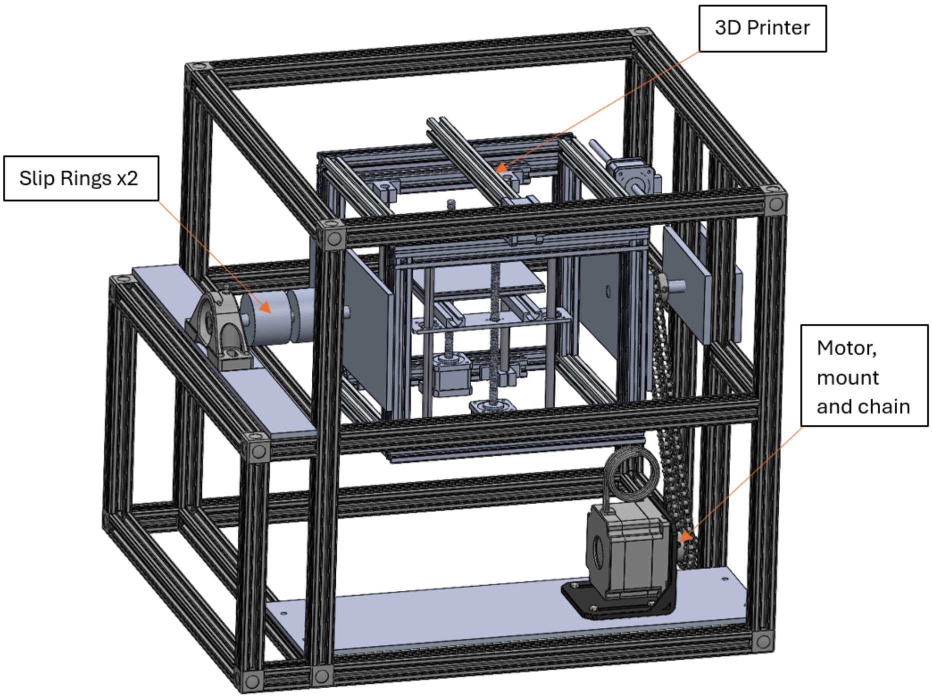



Figure 1. Clinostat CAD

The CAD image seen above highlights the overall structure, motor placement, shaft mounting, and enclosure integration. Key design aspects are explicitly labeled for clarity.

Our design incorporates valuable feedback from professors and mentors who emphasized safety and real-time monitoring. To address these concerns, additional safety measures, such as plexiglass panels to enclose the structure and padding to minimize vibrations, were implemented. Real-time monitoring needs were addressed by integrating sensors for environmental variables (e.g., humidity, temperature) and a rotational speed sensor to display the clinostat's RPM. Stakeholders also expressed the need for the system to be scalable, which was considered by ensuring that key components like the shafts and frame can support future upgrades for bioprinting.

**Sensor Selection**

1. **Gravity Sensor / Accelerometer**
   - **Option 1: ADXL345 Accelerometer (3-Axis)**
     - *Working Principle*: The ADXL345 measures acceleration on three axes and outputs data in G-units. By aligning one axis with the direction of rotation, it can effectively monitor G-forces experienced by the 3D printer's nozzle during clinostat operation.
     - *Pros*: Compact, accurate, and widely used for similar applications. Can log data for further analysis.
     - *Cons*: Requires calibration to ensure alignment and accurate readings in a dynamic environment.
     - *Availability*: Found available on platforms like DigiKey and Amazon.
   - **Option 2: MMA8451Q Accelerometer (3-Axis)**
     - *Working Principle*: Similar to the ADXL345 but optimized for

low-power operations and higher sensitivity.
    - *Pros*: Offers advanced motion detection capabilities.
    - *Cons*: Slightly higher cost compared to the ADXL345.

**Preferred Choice**: The ADXL345 is preferred due to its reliability, ease of integration with microcontrollers, and extensive documentation.

2. **Humidity Sensor**
    - **Option: DHT22 (AM2302)**
        - *Working Principle*: The DHT22 uses a capacitive humidity sensor and a thermistor to measure environmental conditions. It outputs data digitally, which can be logged for analysis.
        - *Pros*: Accurate (±2–5% RH), supports temperature monitoring, easy integration.
        - *Cons*: Slower response time compared to higher-end industrial sensors.
        - *Availability*: Available on platforms like Adafruit and SparkFun.
3. **Temperature Sensor**
    - **Option: TMP36**
        - *Working Principle*: Analog temperature sensor that provides a linear output proportional to the surrounding air temperature.
        - *Pros*: Simple, reliable, and well-documented.
        - *Cons*: Requires an ADC (analog-to-digital converter) if interfaced with a digital microcontroller.
4. **Rotational Speed Sensor**
    - **Option: TCRT5000 Reflective Optical Sensor**
        - *Working Principle*: Measures RPM by detecting reflections from a marked section on the rotating shaft.
        - *Pros*: Cost-effective and precise for rotational speed monitoring.
        - *Cons*: Requires calibration and periodic cleaning for optimal performance.

The clinostat system's mechanical design is centered around a robust yet lightweight frame constructed from aluminum extrusions. These extrusions provide the necessary rigidity to support the entire structure while maintaining a portable and modular design. The frame dimensions are carefully constrained to a 2 ft × 2 ft footprint, meeting the project's size requirements. Central to the rotation mechanism are the carbon steel hollow shafts, with a 12 mm diameter, chosen for their strength and durability. These shafts are securely held in place by custom-fabricated steel mounting brackets, ensuring precise alignment and structural integrity during high-speed operation. The rotating shafts also support the enclosure that houses the 3D printer, which is the focal point of the system.

Power transmission within the system is achieved using a NEMA 34 stepper motor, capable of delivering 8 N.m of torque, a critical requirement for rotating the load of the 3D printer and its enclosure. The motor is mounted to the base of the clinostat via a robust steel motor plate, ensuring stability and minimizing unwanted vibrations. A chain mechanism connects the motor to the rotating shafts through a sprocket system enabling efficient power transfer, allowing precise rotational control, critical for simulating various gravitational conditions.

Electrically, the clinostat system incorporates slip rings to manage the transfer of power and signals to the rotating enclosure. Two slip rings, each rated for 6A of current, are mounted on the shafts. These components ensure a seamless connection between the stationary frame and the rotating enclosure, providing continuous power to the sensors, the microcontroller, and the 3D printer. The integration of slip rings ensures reliable operation without the risk of tangled wires or signal interruptions during rotation.

Environmental monitoring within the clinostat is achieved through a suite of carefully selected sensors. A gravity sensor, specifically the ADXL345 accelerometer, is positioned near the 3D printer nozzle to measure G-forces and verify the accuracy of simulated gravity conditions. A DHT22 humidity sensor monitors and displays the enclosure's humidity levels, ensuring stable printing conditions. Additionally, it provides logged data for analyzing the impact of environmental variables on print quality over time. To track temperature fluctuations, a TMP36 sensor is incorporated to record and monitor the internal temperature of the enclosure. Finally, a TCRT5000 reflective optical sensor is used to measure the rotational speed of the enclosure. This sensor detects markings on the rotating shaft to determine the RPM of the clinostat, allowing precise monitoring of the enclosure's motion rather than just the motor's speed. Below is an example of a code snippet for the TCRT5000 to calculate RPM:

```
const int pulsePin = 2;
volatile int pulseCount = 0;

void setup() {
  pinMode(pulsePin, INPUT);
  attachInterrupt(digitalPinToInterrupt(pulsePin), countPulses, RISING);
}

void loop() {
  float rpm = (pulseCount / 1.0) * 60.0; // Assuming 1-second intervals
  pulseCount = 0; // Reset counter
  Serial.println(rpm);
  delay(1000);
}

void countPulses() {
  pulseCount++;
}
```

The 3D printer is housed within a specially designed enclosure that has been optimized for this project. Modifications to the printer include a 25% reduction in weight and a 50% reduction in volume, achieved by reengineering its components while maintaining core functionalities. The enclosure itself is constructed from lightweight materials to minimize the load on the rotation mechanism. To address potential vibrations caused by the motor and power transmission system, vibration-dampening mounts are integrated into the enclosure design. These mounts help stabilize the printer during operation, reducing disturbances that could compromise the quality of the prints or the integrity of the experimental results.[5]

## 4.0 Baseline Design Compliance Analysis

### *4.1 Strengths of the Design*

The improved clinostat exhibits great rotational performance and structural integrity. In order to maintain stability under a 120 N load and run at the necessary rotational speed of 120 RPM, the inner box is designed to support a 12 kilogram payload (1ft x 1ft x 1ft). The system operates smoothly and consistently with minimal strain on the motor and structural components given the 0.76 kg.m$^2$ moment of inertia.

The decrease in deflection and deformation under dynamic loads is one of the main enhancements. An angle of deflection of 0.5 degrees and a maximum deflection of 0.4 mm guarantee accurate operation without compromising structural rigidity. Furthermore, the shaft's bending moment of 11.74 N.m and factor of safety (FOS) of 4.3 provides durability and resistance to mechanical failure over time due to cyclical loading.

The system delivers 1.1 N·m of torque in terms of rotational efficiency, including frictional losses, guaranteeing dependable operation under load. This, along with improved vibration mitigation, makes it possible for the clinostat to function smoothly, which is essential for high-precision applications like additive printing in environments of simulated gravity.

With integrated sensors for humidity, temperature and gravity monitoring, functionality has also been improved and testing conditions can now be precisely controlled. Additionally, the integration of a high-resolution camera allowing for instantaneous monitoring offers valuable insights on the manufacturing process, enabling immediate analysis and troubleshooting. Such features, along with the clinostat's small size and effective design, make it a good choice for restricted laboratory conditions and space applications.

### *4.2 Limitations and Opportunities for Design Improvements*

Considering its advantages, the design has a few limitations that offer room for future improvements. Even though operational stability has been much enhanced by incorporating vibration mitigation features, dynamic impacts can be amplified by extended operation at max RPM. The stability and endurance of the system could be further improved by using better vibration-damping materials at key connection points, like the motor mounts and shafts.

Another area that needs focus is thermal/environmental control. Long-term use can lead to heat accumulation within the systems' parameters which might hinder performance even. This risk could be reduced by using cooling systems like ventilation fans.

### *4.3 Cost Analysis/Breakdown*

**Previous Design (Old BOM ~ $1,200):**
The previous design utilized off the shelf components and excessive materials.

- **Material Costs:**
  - Over-priced aluminum extrusions and corner brackets contributed heavily to high costs.
- **Components:**
  - Motors and power supplies were selected with higher-than-required specifications and from expensive vendors/suppliers.
  - Excessive structural support increased total expenses.

**Current Design (New BOM ~ $830):**
Material usage has been reduced and optimized (focus on essential components).

- Key cost components of the updated design:
  - **T-Slotted Aluminum Extrusions:** $36
  - **Corner and Surface Brackets:** $305.35
  - **Motor and Electronics:** $223.49
  - **Bushings, Slip Rings and Miscellaneous Components:** $122

The updated design achieves a cost reduction of roughly **$370**, or **31%**, compared to the old design.

**Key Contributors to Cost Reduction:**

1. Material Efficiency
2. Component Selection
3. Design Optimization

By choosing components that meet performance requirements, simplifying assembly and minimizing material usage, the improved clinostat design lowers costs significantly. This simplified method maintains practicality and cost effectiveness while achieving complete capability.

### *4.4 Comparison to Previous Iterations & Agile Methodology Compliance*

The current design is significantly better than the initial design as seen by the evaluated parameters regarding efficiency and cost. Although functioning, the initial design had more deflection, more vibration and used excessive material. Thus, an Agile approach was used to address these constraints, enabling iterative testing and component optimization.

Key improvements included:

- Structural Integrity: Accurate load placement is ensured in the new and improved design, which reduces deflection and the angle of deflection.
- Performance Optimization: The clinostat maintains torque requirements (without going beyond motor torque standards), thus, achieving uniform rotation. Compared to the initial design, this suggests a more effective alignment of the motor and bearing components, minimizing energy/power consumption in the long run.

- Vibration Control: Rotational stability was impacted by initial designs' motor setup and gear system. The new design incorporates a far more suitable and efficient powering and mounting system ultimately reducing the effects of vibration.

Each phase of the iterative design process ensured that all functional and technical requirements were satisfied. MVP testing verified complete fulfillment to project requirements, including mass, rotational speed and environmental monitoring capabilities, using Agile sprints. Each sprint cycle included continuous feedback from stakeholders to guarantee the design fit user needs and requirements.

## 5.0 Trade Study Identification

### *5.1 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)**
   - **Rationale**: Safety was prioritized by adding protective enclosures and emergency mechanisms to prevent injuries.
2. **Effectiveness (1-5)**
   - **Rationale**: The system achieves its desired goal of simulating a gravitational pull through precise and calibrated rotational controls.
3. **Maintainability (1-5)**
   - **Rationale**: The design focused on using readily available parts for easy and quick component replacements.
4. **Cost (1-5)**
   - **Rationale**: The design meets budget constraints through effective material and component selection without compromising the systems overall functionality.
5. **Longevity (1-5)**
   - **Rationale**: Durability was ensured through the use of robust materials and thus maintaining structural integrity at high speeds and under extended use.

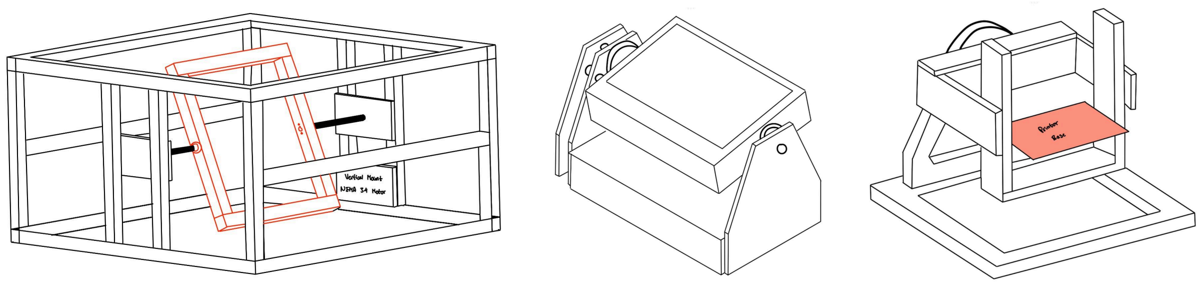


Figure 2. Initial Designs A, B and C

The following results are based upon discussions and calculations:

Table 2. 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 | 23 | 17 | 10 |

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 3. 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** (assuming a design with a perfect score of 25) | | | **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. These scores were then used to evaluate Design A, Design B and Design C's rankings across the five criteria.

Table 4. 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%** |

### *5.2 Independent Component Selection*

**Supporting the Design Decision**

During the initial design phase, trade study was subjected to us as one of the criterias that we need to address, decision making activities used to identify most logical and sensible technical solutions among a set of various alternatives.

All solutions are subject to trade offs and are subject to change since we've chosen agile as our methodology, the potential solutions of this kind of study are judged based on their benefit, trade off and risk. [9]

**Motor Selection**

Table 5. Motor Selection

| Nema 34 Motor Selection | |
|---|---|
| Price | Torque (N.m) |
| $137.00 | 13.0 |
| $72.45 | 8.0 |
| $66.00 | 4.8 |

The motor selection was evaluated based on cost and performance, while the cost difference of the various motor options we had was small, Nema 34s were chosen as our motor type as recommended per our supervisor, the trade off of the cost was negligible, this due to the fact that we care about the reliability and longevity of the motor, while also avoiding overcompensating for the motor performance. To do that, torque calculations (provided in the appendix) were performed to help us choose the best option. Based on the conducted calculations, the torque required to rotate the system at 120 rpm was 1.1 N.m.

Nema 34, providing torque 8 N.m, was chosen, due to the cost trade off being very minimal between the next best option. In addition, avoiding over saturating the motor helps increase the efficiency and thus increase its longevity.

**Power Transmission Selection**

Power transmission is another design criteria where we had to do trade study on. The design team had 3 power transmission options to choose from, gear, chain and belt systems. Thorough study and research on the optimal choice was conducted, gear systems are mechanically strong and are ideal for heavy load requirements, can deliver high transmission efficiency and they are more compact compared to belts and chains. Belt technology has its own advantages, belts are simple to use and cost-effective, they are unique for delivering energy with low noise and vibrations. A Chain is good for power transmission, has low maintenance cost with high transmission efficiency and can bear high speeds. [8]

We have chosen chain and sprockets as our power delivery method, while having the trade off of noise, but the benefit of a chain and sprocket system outweighs the trade offs and is more suitable for our design. While the gear system can be lighter, the configuration of a gear system did not fit well with the chosen design. Maintaining some distance between the rotating platform and motor (see figure below) is desired to avoid possible collisions or entanglements. A belt system is great for lightweight and simple configuration, ideal in that sense, but a belt system is spatially inefficient and is prone to wear and tear. [10]

## 6.0 Sustainability and Unintended Consequence Analysis

Our clinostat system design demonstrates sustainability and considers the potential for unintended consequences that may arise during its implementation and long-term operation. This analysis evaluates the impact of the project on stakeholders, the environment, and society, while identifying strategies to mitigate adverse effects and uphold ethical standards.
From an environmental perspective, the design minimizes resource consumption by employing lightweight, recyclable materials such as aluminum extrusions for the frame and carbon steel for the shafts. Aluminum is widely recognized for its high recyclability and strength-to-weight ratio, reducing the overall carbon footprint of the manufacturing and assembly processes. The decision to use a single NEMA 34 stepper motor and a compact power transmission system helps to lower energy consumption compared to alternative designs that may require multiple motors or more complex mechanisms. The modified 3D printer further enhances sustainability by reducing the enclosure's weight and volume, decreasing the load on the rotation mechanism and subsequently minimizing energy use during operation.

A critical aspect of sustainability lies in the operational life cycle of the system. The use of high-quality components, including the carbon steel shafts and the steel brackets, ensures durability and reduces the likelihood of frequent replacements, thereby decreasing waste over time. The integration of slip rings and vibration-dampening measures supports system reliability, further extending the device's functional life. However, one potential unintended consequence is the wear and tear of the bicycle chain and sprocket system, which may require regular maintenance or even replacements. This could result in additional material waste and maintenance costs over time. To mitigate this, we will be investigating if the design can be adapted in future iterations to incorporate a more robust timing belt or direct-drive system that eliminates the need for a chain altogether.

The clinostat's impact on stakeholders is largely positive, providing a novel platform for space research, printing, and material science experimentation. For researchers, the system offers a compact and versatile tool for simulating microgravity and hypergravity conditions, contributing to advancements in space exploration. The integration of environmental monitoring sensors, such as the ADXL345 accelerometer and DHT22 humidity sensor, ensures accurate data collection during experiments. However, unintended consequences may arise in terms of accessibility for smaller research institutions or organizations with limited budgets. The initial cost of the system, despite efforts to stay within a 1,000 CAD budget, may still be prohibitive for some stakeholders. Therefore, we will focus future iterations on cost optimization through the use of more affordable materials or simplified designs, without compromising performance.

Ethical considerations are central to the project, particularly in the context of data privacy and security. As the system incorporates sensors that log experimental data, there is a potential risk of data breaches or misuse. This is especially significant if the clinostat is used for sensitive research, such as proprietary biomedical experiments – which is what this project is intended to serve as a spiritual predecessor to. To mitigate this concern, we will look into whether our system can incorporate secure data storage and transfer protocols, such as encrypted communication between sensors and data loggers. Additionally, we will consider providing stakeholders using the system with clear guidelines on data handling and storage to prevent unauthorized access or misuse.

We also acknowledge the potential for unforeseen societal impacts. For example, the success of our clinostat in advancing bioprinting technologies could inadvertently lead to debates over the ethical implications of printing biological tissues or organs. And while we understand that this consequence lies outside the immediate control of our team, it emphasizes the importance of maintaining transparency in the intended use and limitations of the system.

Our clinostat system is designed with sustainability and ethical considerations in mind, leveraging durable materials, energy-efficient components, and robust operational mechanisms to minimize its environmental footprint. While potential unintended consequences, such as material wear or data security risks, are acknowledged, our project will incorporate tangible mitigation strategies to address these challenges.

## 7.0 Project Management Updates

### *7.1 Project Task Management*

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 material purchasing.
    - Finalization of the BOM and integration of motor and sensors.
    - Assembling of the Exterior Frame, Interior Frame and Internal Box.
  - Next:
    - Preparing for Printer Frame Assembly and Wiring Setup.
  - Later:
    - System verification and testing phases, focusing on rotational speed, stability and response under various conditions.

- 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 tasks.
    - In Progress:
        - Assembly-related tasks are underway.
    - Remaining:
        - Final integration and system-level testing.

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

**Essential Deliverables:**

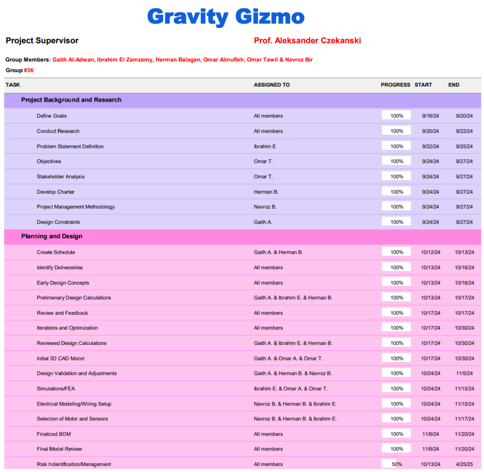
- Storyboard/Design Board:
  A timeline-based breakdown of tasks, demonstrating progress through Gantt charts. Evidence of task completion includes CAD models, simulations and finalized BOMs.
- Completion of Materials:
  Documentation, including design iterations, feedback reviews and risk management 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.
- Material 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 starting in March 2025.

### *7.2 Resource Allocation Matrix (RAM) & RACI*

In order 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.



Gravity Gizmo

Project Supervisor Prof. Aleksander Czekanski

Group Members: Gaith Al-Adwan, Ibrahim El Zamzamy, Herman Balagan, Omar Almufleh, Omar Tawil & Navroz Bir

Group #36

| TASK | ASSIGNED TO | PROGRESS | START | END |
|---|---|---|---|---|
| Project Background and Research | | | | |
| Define Goals | All members | 100% | 9/16/24 | 9/20/24 |
| Conduct Research | All members | 100% | 9/20/24 | 9/22/24 |
| Problem Statement Definition | Ibrahim E | 100% | 9/22/24 | 9/25/24 |
| Objectives | Omar T. | 100% | 9/24/24 | 9/27/24 |
| Stakeholder Analysis | Omar T. | 100% | 9/24/24 | 9/27/24 |
| Develop Charter | Herman B. | 100% | 9/24/24 | 9/27/24 |
| Project Management Methodology | Navroz B. | 100% | 9/24/24 | 9/27/24 |
| Design Constraints | Gaith A. | 100% | 9/24/24 | 9/27/24 |
| Planning and Design | | | | |
| Create Schedule | Gaith A. & Herman B. | 100% | 10/12/24 | 10/13/24 |
| Identify Deliverables | All members | 100% | 10/13/24 | 10/16/24 |
| Early Design Concepts | All members | 100% | 10/13/24 | 10/16/24 |
| Prelimenary Design Calculations | Gaith A. & Ibrahim E. & Herman B. | 100% | 10/13/24 | 10/17/24 |
| Review and Feedback | All members | 100% | 10/17/24 | 10/17/24 |
| Iterations and Optimization | All members | 100% | 10/17/24 | 10/30/24 |
| Reviewed Design Calculations | Gaith A. & Ibrahim E. & Herman B. | 100% | 10/17/24 | 10/30/24 |
| Initial 3D CAD Model | Gaith A. & Omar A. & Omar T. | 100% | 10/17/24 | 10/30/24 |
| Design Validation and Adjustments | Gaith A. & Herman B. & Navroz B. | 100% | 10/24/24 | 11/5/24 |
| Simulations/FEA | Ibrahim E. & Omar A. & Omar T. | 100% | 10/24/24 | 11/15/24 |
| Electrical Modeling/Wiring Setup | Navroz B. & Herman B. & Ibrahim E. | 100% | 10/24/24 | 11/15/24 |
| Selection of Motor and Sensors | Navroz B. & Herman B. & Ibrahim E. | 100% | 10/24/24 | 11/17/24 |
| Finalized BOM | All members | 100% | 11/6/24 | 11/20/24 |
| Final Model Review | All members | 100% | 11/6/24 | 11/20/24 |
| Risk Indentification/Management | All members | 50% | 10/13/24 | 4/25/25 |

Figure 3. Initial stage of the Gantt Chart (Project Schedule).

Table 6. 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 team |
| Develop Charter | Herman | 100 | Included objectives and stakeholder inputs |
| Preliminary 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 | Scheduled to start November 2024 |
| Motor and Sensor Integration | Navroz | 25 | Scheduled to start January 2025 |
| Testing and Verification | All Members | 0 | Scheduled to start March 2025 |

Table 7. RACI

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

### *7.3 Project Schedule*

- 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: 60%
    - 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 braking) to limit speed to 120 RPM.
    - Deliverables: Calibrated sensors and operational safety features.
    - Storyline: Ensuring precision and safety in the operational setup.
    - Story Points: 10
    - Progress: 30%
    - 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: 0%
    - Comments: Pending completion of prior sprint, sourcing high-resolution camera.

- Sprint 5: Calibration, Testing and Iteration
    - Objective: Achieve final functionality and optimization.
    - Timeline: April 11, 2025 – April 21, 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: 0%
    - Comments: Adjustments will be based on feedback from initial testing phases.

### 7.4 Project Procurement/Equipment/Travel List

Table 8. 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 9. Design A cost analysis.

| ITEM NO. | PART NUMBER | QTY./Length (ft) | STATUS | ORDER PRIORITY | TOTAL PRICE |
|---|---|---|---|---|---|
| 1 | T-Slotted Aluminum Extrusions | 20*1.5ft | Available | Fall | $36 |
| 2 | Outside Corner Brackets for Single Rails | 12 | Not Bought | Fall | $200 |
| 3 | Sprocket (12 teeth) | 2 | Not Bought | Fall | $50 |
| 4 | Surface Brackets for Single Rails | 16 | Available | Fall | $48 |
| 5 | Roller Chain | 1 | Available | Fall | $24 |
| 6 | Bushings | 4 | Not Bought | Fall | $14 |
| 7 | Slip Rings | 2 | Not Bought | Winter | $84 |
| 8 | Screws (M3, M4 and M5) | 1 | Not Bought | Fall | $23 |
| 9 | NEMA 34 | 1 | Not Bought | Fall | $72 |
| 10 | Driver | 1 | Not Bought | Fall | $32 |
| 11 | Motor Power Supply | 1 | Not Bought | Fall | $33 |
| 12 | Printer Power Supply | 1 | Not Bought | Fall | $51 |
| 13 | Coupler | 1 | Not Bought | Fall | $19 |
| 14 | Motor mount | 1 | | | $32 |
| | **Total Cost (not including taxes and shipping)** | | | | **$719** |
| | **Total Cost (including taxes and shipping)** | | | | **$828** |

Table 10. 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 11. Design B 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 for all three designs provides a detailed breakdown of expenses, aligning with budget constraints and Agile principles. Design A, costing $828, is the most balanced option, combining affordability, safety and effectiveness. It uses readily available aluminum extrusions and standardized components, ensuring cost-effectiveness. Design B, at $937, is more expensive due to the use of thicker steel plates, steel shafts and a custom steel housing for the 3D printer, making it robust but costly. This design also emphasizes electrical components, increasing overall complexity. Design C, costing $757, is the most economical, utilizing a hollow steel base and reduced material usage. However, its simplicity impacts effectiveness and longevity. The sourcing plan for all designs include key items like motors, shafts and slip rings. As for specific travel, some aluminum extrusions were acquired from Hamilton, thus slightly increasing cost. The thorough cost analysis shows a clear strategy for balancing performance, safety and budget requirements across all designs.

### *7.5 Risk Register*

The following risk register details potential challenges to the Gravity Gizmo project, highlighting significant hazards that may affect the clinostat system's schedule, operation and safety. The likelihood and impact of each risk have been evaluated, and suitable mitigation techniques and backup strategies have been established to cope with them. This table offers an organized approach to risk management, ensuring that the project stays on course while reducing the risk of delays.

Table 12. Risk Register

| **Risk Register** | | | | | |
|---|---|---|---|---|---|
| **Project Name** | | **Gravity Gizmo** | | | |
| **#** | **Risk** | **Risk Description** | **Probability Factor (1-5)** | **Impact Factor (1-5)** | **Risk Score (PF*IF)** |
| 1 | Delay | Project timeline may be delayed due to vibration related issues. | 3 | 4 | 12 |
| **Risk Response Type** | | **Risk Response Plan** | | **Contingency Plan** | |
| Mitigate | | Accelerate testing for vibration issues and allocate extra time and resources to mitigate such a risk. | | Develop a simplified prototype to test for the overall functionality of the system while mitigating/refining vibration solutions. | |
| **#** | **Risk** | **Risk Description** | **Probability Factor (1-5)** | **Impact Factor (1-5)** | **Risk Score (PF*IF)** |
| 2 | Component Failure | Key components such as the motor or the sensors, may fail during high-speed operation or testing. | 2 | 5 | 10 |
| **Risk Response Type** | | **Risk Response Plan** | | **Contingency Plan** | |
| Avoidance | | Ensure sourced components are high quality with complete warranty and conduct further testing before complete integration into the system. | | Keep spare parts/components for immediate replacements if necessary. | |
| **#** | **Risk** | **Risk Description** | **Probability Factor (1-5)** | **Impact Factor (1-5)** | **Risk Score (PF*IF)** |
| 3 | Calibration Errors | Incorrect calibration of the rotational controls/sensory equipment may lead to discrepancies in the results. | 3 | 4 | 12 |
| **Risk Response Type** | | **Risk Response Plan** | | **Contingency Plan** | |
| Mitigate | | Use components that are precisely calibrated or use calibration tools and perform tests to validate their accuracy. | | Addition of software features to correct minor calibration errors in real time. | |
| **#** | **Risk** | **Risk Description** | **Probability Factor (1-5)** | **Impact Factor (1-5)** | **Risk Score (PF*IF)** |
| 4 | Safety | Miniaturized printer team’s components resistant to 4g’s of force during high speed rotations. | 3 | 5 | 15 |
| **Risk Response Type** | | **Risk Response Plan** | | **Contingency Plan** | |
| Mitigate | | Components will be tested at high-speeds, with rotational forces exceeding 4g’s. Components will be equipped with precise rotational speed control safety mechanisms to prevent failures. | | In case of failure, implement an emergency brake and kill switch, with extra funds allocated for component replacement (maintaining backup components to minimize downtime). | |

With a risk score of 15, safety is the risk that has been identified as having the highest priority. The project places a strong emphasis on strict safety procedures, like the use of protective enclosures and frequent risk assessments. By taking these precautions, the team and the equipment are guaranteed to be protected during operation.

Delays due to vibration issues scored fairly high (12). By focusing on building a much simplified prototype and accelerating vibrations damping testing, the team aims to mitigate said concerns as much as possible. Furthermore, this approach allows for addressing a major issue while maintaining a progressive setup for other key functionalities.

Another risk that scored as highly as the one previously mentioned is calibration errors (12). Though it is systematic, based upon manufacturer specs, components with incorrect calibration can lead to unfavourable results. Thus, such an issue can be well mitigated through initial testing and with the Addition of software features to correct minor calibration errors in real time.

Finally, because of the system's operational needs, component failure presents a moderate risk (10). Maintaining a supply of spare parts and ensuring high-quality parts minimize downtime and ensure seamless replacements when necessary.

## 8.0 Team Reflections

### *8.1 Team Member Statements*

Table 13. Team Reflections

| Team Member | Role | Key Contributions | Areas for Improvement | Strengths |
|---|---|---|---|---|
| **Gaith Al-Adwan** | Mechanical Engineer | - CAD Modelling<br>- Calculations<br>- Assembly<br>- BOM | Presentation skills and electrical modelling. | Leading the team and keeping team members up to date with their tasks.<br>Design and calculations. |
| **Omar Almufleh** | Mechanical Engineer | - Assembly<br>- CAD Modelling<br>- BOM | Being more active during scheduled meetings and electrical circuitry. | Material mechanics, stress analysis, CAD modelling and simulations |
| **Herman Balagan** | Mechanical Engineer | - Vibration Analysis<br>- Led mini-capstone day presentation. | Expressing ideas more often.<br>Dismiss my ideas too quickly when others suggest alternatives. | Skilled in vibration control and stakeholder communication. |
| **Navroz Bir** | Electrical Engineer | - Wiring Schematics<br>- PSU Selection<br>- Motor Selection | Ensure effective communication of electrical aspects to mechanical engineers. | Knowledge of circuit design and programming. |
| **Ibrahim El Zamzamy** | Mechanical Engineer | - Sensor Selection<br>- Power Calculations | Time organization and keeping up with deadlines | Sensors and motors. |
| **Omar Tawil** | Mechanical Engineer | - Power Delivery<br>- Torque Calculations<br>- CAD Modeling<br>- BOM | - Get involved more.<br>- Listen to peer's needs more often. | Design calculations and CAD modeling |

### *8.2 Individual and Team ITPMetrics Review Statements*

#### *8.2.1 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.

#### *8.2.2 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.

### *8.2.3 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.

#### *8.2.4 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.

### *8.2.5 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.

### *8.2.6 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.

### *8.3 Self-Evaluation*

Table 14. Self-Reflection

| Criterion | Self-Evaluation Ranking | Justification |
|---|---|---|
| Apply an iterative process to refine or assign solutions for a given engineering design problem. | Meeting | Iterative refinement was applied to the PSU setup and motor integration, with ongoing sensor adjustments (Sections 3.1, 3.4). |
| Achieve a system design breakdown for management and implementation. | Meeting | Clear task breakdown facilitated progress in assembly and integration tasks (Sections 7.1, 7.3). |
| Justify the strengths and limitations of the solution and make recommendations for possible improvements. | Meeting | Strengths like compact design and motor reliability are documented, with improvements suggested for vibration control (Section 4.2). |
| A concise and coherent document that reflects critical analysis and synthesis. | Exceeding | The report is professional, well-structured, and critically analyzes all project aspects (Section 7.3, Appendix 11.1). |
| Design has been reviewed for sustainability impact and potential for adverse unintended consequences. | Meeting | Sustainability impacts are addressed, with UN-SDG connections outlined in Section 6.2. |
| Adjust project schedule based on project status. | Exceeding | The timeline was adjusted for sensor calibration and vibration control while meeting overall goals (Section 7.3). |
| Monitor risks during the life cycle of the project. | Meeting | Key risks like vibration and motor reliability are monitored and documented (Section 7.5). |
| Apply all appropriate engineering concepts and fundamentals, theories, and practices to solve engineering problems | Exceeding | Engineering principles like torque and vibration analysis are effectively applied (Sections 3.5, 4.1). |
| Contribute to the team in an appropriate and meaningful way | Exceeding | Consistent contributions include task completion, feedback, and collaboration (Section 8.2). |

## 9.0 Conclusions and Future Work

This phase of the project achieved significant milestones in developing the two-axis clinostat, designed to simulate microgravity and hypergravity environments. Key highlights include:

- **Technical Achievements**: Advancements in motor selection for precise torque control, integration of environmental sensors for temperature and humidity monitoring, and compact CAD modeling that ensures structural and operational efficiency. A modular design approach guarantees compatibility with the downsized 3D printer.
- **Electrical System Design**: A dual-PSU setup was planned, with one PSU dedicated to the 3D printer and another for powering the motor and components like temperature and humidity sensors, as well as the integrated camera. This configuration minimizes power distribution issues and ensures efficient operation. The camera power source remains under evaluation, with the team considering direct PSU integration versus battery power to reduce wiring complexity.
- **Management Insights**: The agile methodology facilitated efficient task prioritization, iterative sprint reviews, and timely stakeholder feedback integration. Collaboration with Group 35 on 3D printer modifications highlighted the value of cross-functional teamwork.
- **Team Dynamics**: Peer reviews acknowledged strengths in technical expertise, collaboration, and commitment. Identified areas for growth include improved task distribution and fostering more critical discussions to optimize designs further.

### Future Work

Looking forward to the winter semester, the team aims to prepare for the **test readiness/early testing phase** or **alpha release update** through the following initiatives:

1. **Finalizing Prototype Assembly**:
    - Complete integration of the modified 3D printer with the clinostat framework.
    - Ensure motor and control system optimization for stable and precise rotation at target speeds.
    - Complete electrical system wiring, verifying connections between the PSUs, sensors, and control systems.
2. **Testing and Calibration**:
    - Conduct initial tests to validate sensor accuracy, motor performance, and overall system stability.
    - Address vibration damping and load balancing issues to ensure accurate data collection.
    - Test the dual-PSU setup to confirm effective and interference-free power distribution.
3. **Enhancing Environmental Monitoring**:
    - Refine sensor placement and insulation to improve accuracy during operation.
    - Develop and test software for real-time environmental data visualization and logging.
    - Ensure seamless integration of the camera system for live monitoring and recording capabilities.

4. **Alpha Release Update**:
    - Deliver a fully functional prototype for stakeholder review, integrating all core features.
    - Introduce a user-friendly interface for controlling rotational speeds, environmental parameters, and power monitoring.
5. **Iterative Improvements**:
    - Incorporate feedback from initial testing and the alpha release to refine design elements.
    - Evaluate the practicality of battery-powered options for components like the camera to enhance modularity.
    - Mitigate potential challenges related to timeline management and cost optimization without compromising functionality.

By focusing on these objectives, the team remains committed to delivering a robust and innovative device, enabling research breakthroughs in space manufacturing and bioprinting. These efforts will support the transition to the beta release phase, further aligning with the project's long-term goals.

## 10.0 References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# 11.0 Appendix

## *11.1 List of Meeting Minutes Since the Progress Report*

**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:**<br>Motor & Weight, Vibrations, Driver and Safety.<br>Requirements divided between team members.<br>**Requirements Done:**<br>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 7th , 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:**<br>Have a design and a finalized BOM.<br>Chain transmission calculation and CAD.<br>Inertia and center of mass calculations.<br>Sensor integration.<br>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.<br>Decide whether to use bushings or weld the shaft.<br>Purchase the majority of the parts, make value out of time.<br>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 |

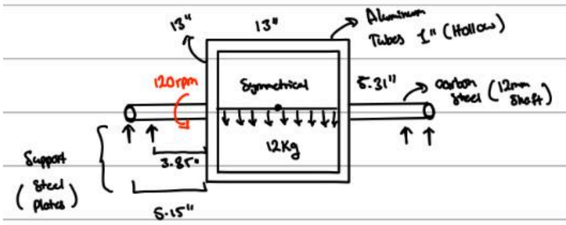
| Progress Report on Last Week's Activities | | | |
|---|---|---|---|
| # | Name | % Completed | Comment (provide the reasoning only if 100% is not completed) |
| 1 | Gaith Al-Adwan | 90% | PV, Completion of the design is pending due to some part and printer team. |
| 2 | Omar Almufleh | 90% | PV, Completion 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. |

### *11.2 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.<br><br>- 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.<br><br>- 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.<br><br>- Better implants for individuals who may need them (i.e. dental implants lasting longer) |
| - Organizations like NASA, ESA, SpaceX. | - Expensive space-based research.<br>- Limited access to simulate hypergravity conditions. | - One rotation enables precise gravity simulations.<br>- Compact, modular design fits into existing lab setups.<br>- 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<br><br>- 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 allowing for stronger models and less material wasted over time caused by faulty prints |

## *11.3 Supporting Files*

### *Capstone*




Weight = 12Kg

Force = 12x10 = 120N

Frame width = 14" = 0.3556 m

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

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

Moment of Inertia => $I = m \times r^2 = 12(0.2515)^2 = 0.759$ Kg.m²

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

Torque => $T = I\alpha$ , $\alpha = \omega / t$ , assume 10 seconds to reach 120rpms => $\alpha = \frac{12.56}{10} = 1.256$ rad/s²

$T = 0.759 \times 1.256 = 0.954$ 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 x 0.0978 = 11.74 Nm   (3.85")

Section Modulus => $Z = \frac{\pi d^3}{32} = \frac{\pi(0.012)^3}{32} = 1.7 \times 10^{-7}$ m³

Bending Stress => $\sigma = \frac{M}{Z} = \frac{11.74}{1.7 \times 10^{-7}} = 69.2$ 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 , $J = \frac{\pi d^4}{32} = \frac{\pi(0.0127)^4}{32} = 2.55 \times 10^{-9}$ m⁴

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