Robotics Traveling Van

Initial Design Report Template

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DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

EXECUTIVE SUMMARY

The Robotics Traveling Van project aims to design and develop two low-cost, transportable educational robots that demonstrate core control-system engineering concepts for K–12 outreach. Sponsored by our client, the goal is to create systems that are safe, durable, engaging, and capable of visually illustrating feedback control in classroom environments. The project spans two semesters, with the first focused on research, concept development, prototyping, and feasibility analysis.

Two robots were selected for development: Robot #1, an Inverted Pendulum Robot, and Robot #2, a Ball-on-Plate Robot. These concepts were chosen based on customer requirements, benchmarking, manufacturability, educational value, and system complexity. Throughout the Fall semester, the team completed detailed requirements definition, House of Quality, literature review, morphological chart, and decision matrices that guided the selection of the final designs.

For Robot #1, the team investigated pendulum dynamics, mass distribution, and actuator requirements to validate that the system could be controlled within safe operating limits. Structural concepts were evaluated for durability and stability, and a final frame design was selected based on manufacturability and robustness. Early prototyping confirmed feasibility and informed next semester's full build and controller development.

For Robot #2, multiple concepts were researched before selecting the Ball-on-Plate mechanism due to its strong educational impact and clear visualization of closed-loop control. A Failure Modes and Effects Analysis identified critical risks such as motor overheating, unstable motion, and sensing error. A Ball-on-Beam prototype was constructed to validate sensing, actuation, and motor torque requirements prior to scaling to the full plate system. Engineering calculations confirmed that the chosen stepper motors provide sufficient torque with a comfortable safety factor. A detailed Bill of Materials was developed for the final Ball-on-Plate system, along with planned testing procedures for response time, stability, and safety.

Budget tracking, scheduling, and resource planning were completed for both robots, keeping the project within financial constraints. The team also developed a second-semester Gantt chart and work-breakdown structure to support continued progress toward fabrication, control implementation, and final testing. At the time of this report, both robots have finalized concepts, validated design decisions, and demonstrated proof-of-feasibility through prototyping and analysis.

Next semester, the project will transition into full system construction, controller tuning, performance testing, and preparation for the client demonstration. The progress made this semester establishes a strong foundation for delivering two reliable, manufacturable, and educational robotic systems that meet the goals of K–12 STEM outreach.

TABLE OF CONTENTS

Contents

1 BACKGROUND

This chapter provides an overview of the overall project background and objectives. It summarizes the project description, deliverables, and success metrics, outlining how the team's dual-robot design aligns with client expectations, budgetary goals, and educational outcomes for K-12 students.

1.1 Project Description

The goal of this capstone project is to design and develop two educational robots that demonstrate fundamental control system principles for K-12 students. The project is sponsored by Dr. Michael Shafer of Northern Arizona University and aims to create low-cost, interactive learning platforms that inspire interest in science, technology, engineering, and mathematics (STEM).

Each robot fulfills a unique role:

- **Robot #1**: an inverted-pendulum-type robot that demonstrates dynamic stability and control.
- **Robot #2**: a second control-based robot (currently in concept generation) designed to demonstrate feedback, sensing, and actuation through engaging, hands-on interaction.

The total project budget is $5,000, and per course policy, the team must fundraise 10 % of that amount ($500) through sponsorships or donations to support manufacturing, materials, and outreach.

Throughout the semester, the team has developed several deliverables, including a Phase Outline Plan submitted to mentor Sethu, progress Presentations #1 and #2, and the upcoming Presentation #3, which transitions both sub-teams into the analysis and prototyping phase. The project contributes both to course outcomes and to the client's educational outreach goals by delivering reproducible, affordable robotics kits suitable for K-12 demonstrations.

1.2 Deliverables

The major deliverables for this project include:

1. **Two functional educational robots** (Robot #1 and Robot #2), each designed to highlight a key control-systems concept (e.g., balance control, feedback response, or motion regulation).
2. **Comprehensive design documentation**, including reports, presentations, and analyses throughout the design process.
3. **Prototypes** capable of demonstrating safe and reliable operation in a classroom setting.
4. **Educational materials** that explain the underlying engineering principles to students and teachers.

Additional deliverables include morphological charts, decision matrices, black-box and functional-decomposition diagrams, and presentation materials that document how each subsystem contributes to the overall design.

1.3 Success Metrics

Project success will be evaluated against both customer and engineering requirements developed during the initial planning stage. Key success criteria include:

- **Educational Value:** Both robots must effectively demonstrate fundamental control-system concepts such as balance, feedback, and actuation.
- **Interactivity:** Students should be able to engage directly with robots (via touchscreen, voice, or physical interaction).
- **Safety and Reliability:** Designs must include power cut-offs, protective enclosures, and comply with standard electrical safety guidelines.
- **Mass Producibility:** Components must be inexpensive, accessible, and easy to assemble.
- **Performance:** Robots must meet quantifiable targets for stability, response time, and operating duration.
- **Budget Compliance:** Final prototypes and materials must stay within the $5,000 allocation and $500 fundraising goal.

Success will ultimately be verified through testing, performance analysis, and client evaluation. A design will be deemed successful if it meets its defined engineering targets, performs its intended educational function, and is approved for replication and use in K-12 classrooms.

2 REQUIREMENTS

The requirements section will touch on the most important part of our project's genesis, our customer requirements. These help us as engineers create measurable, quantifiable, and iterative goals. Customer requirements describe what the end user or client expects the final product to do — in plain, qualitative terms. They reflect the "voice of the customer," not the technical design. Engineering requirements translate each customer's need into quantifiable and verifiable parameters. They use measurable targets and units, with one-sided, two-sided, or binary constraints. The House of Quality (HoQ) shows how the Customer Requirements (CRs) and Engineering Requirements (ERs) relate to each other. It helps prioritize design decisions and highlight trade-offs.

2.1 Customer Requirements (CRs)

According to our customer/sponsor, our goals are to demonstrate how feedback control affects the functionality of robots on continuous systems for K-12 students. The parameters that define our customer requirements stem from the intended user (K-12 students), the robots to be mass produceable, and their life span/usage time.

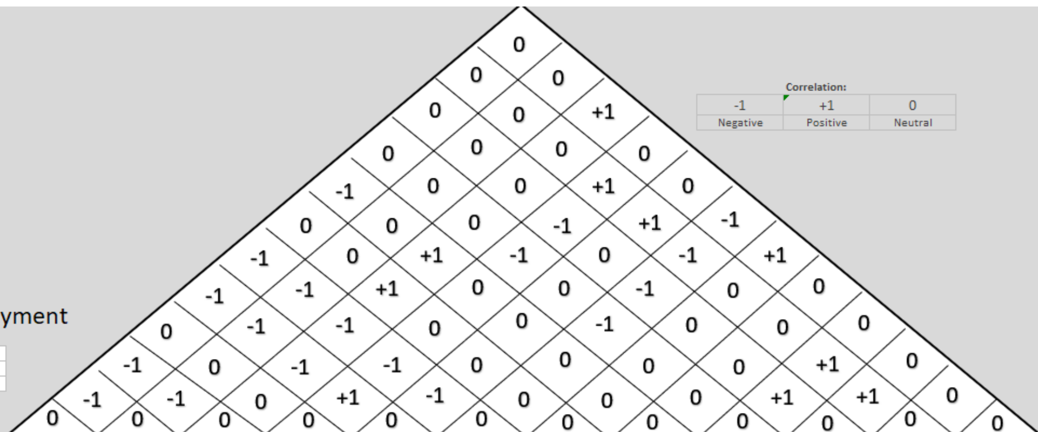
CR01	Durable	The robot must withstand frequent use and minor impacts common in classroom environments.
CR02	Inexpensive	The total production cost should be low enough to enable classroom-wide implementation.
CR03	Functional	The robot must effectively demonstrate the principles of feedback control through observable, repeatable motion.
CR04	Battery powered	The system should operate independently of external power cords for classroom flexibility and safety.
CR05	Interactive interface	The interface (e.g., touchscreen or button inputs) should allow users to adjust parameters and initiate demonstrations easily.
CR06	Compact operating space	The robot should function safely in a standard classroom or lab table without excessive space requirements.
CR07	Educational	The design should help students visually and conceptually connect robot motion with control theory principles.
CR08	Kid-friendly design	The product must be visually appealing, intuitive, and approachable for K–12 students of varying ages.

2.2 Engineering Requirements (ERs)

ER #	Target	Unit	Linked CR	Why
ER01: Overall Dimensions	~14X10X5	Inch	CR06, CR08	The robot must fit in a shoebox-sized space for easy classroom storage and handling.

ER02: Operating Space	~36X36	Inch	CR06	Must safely operate within a standard classroom tabletop area without exceeding space limits.
ER03: Power Source	~1	Hour	CR03, CR04	Should sustain demonstrations and testing during a full class session on one charge
ER04: Control Hardware	Arduino	Yes/No	CR03, CR05	Raspberry Pi allows touchscreen interactivity; Arduino provides compact, efficient control.
ER05: Drop Test	Functional after 30" drop	Inch	CR01	Must continue functioning after a fall from a typical classroom table height.
ER06: Electrical Safety	Enclosed wiring/battery	Yes/No	CR08	Complies with U.S. CPSC guidelines; no exposed electrical components.
ER07: Sharp Edge Radii	>= 3	Mm	CR08	All edges should be chamfered or filleted to eliminate sharp surfaces.
ER08: Pinch-Point Clearance	>= 3	Mm	CR08	Maintain spacing between moving parts (e.g., wheels) to prevent finger pinching.
ER09: Emergency Stop	Power cutoff in 1s	seconds	CR08	A physical stop button must instantly disable all motion and power for safety.
ER10: Visual Feedback Interface	Touchscreen	Yes/No	CR05, CR07	Provides visual and interactive feedback for parameter changes and learning demonstrations.
ER11: Manufacturing Cost	~$200/unit	USD	CR02	Keeps production affordable for wide classroom deployment.

2.3 House of Quality (HoQ)



Quality Function Deployment

Project title: Robotics Travelling Van
Project leader: Freddy Rivera
Date: 9/16/2025

1: low, 5: high Customer importance rating	Functional Requirements (How's) → Customer Requirements - (What's) ↓	Overall Dimensions	Power source	Control Hardware (Arduino / RaspPi)	Electrical Saftey in U.S. CPSC (guidelines)	Drop Test	Manufacturing Cost	Programming Diagrams	Operating Space	Sharp Edge Radii in U.S. CPSC (guidelines)	Pinch clearance in U.S. CPSC (guidelines)	Emergency Stop	Visual Feedback Interface	e evaluation (1: low, 5: high) Shay Sackett's Pendulum Robot	Self-Balancing Interactive Robot	Instructibles Line Following Robot
5	Operating Space	9	0	0	0	6	9	0	9	0	0	0	0	4	5	5
5	Battery Powered	3	9	3	9	6	9	0	1	0	0	6	1	2	3	4
4	Functional (Arduino)	3	6	9	3	6	9	6	0	0	0	0	3	4	4	2
3	Kid-Friendly	0	0	1	9	6	0	9	0	9	9	9	9	3	5	3
4	Durability	6	3	9	9	9	3	0	0	0	0	0	0	3	2	3
3	Inexpensive	9	3	9	1	6	9	0	0	0	0	1	3	4	3	5
4	Interactive Interface (Touchscreen)	3	6	9	3		3	0	1	0	0	0	9	1	4	1
3	Educational Props	0	0	3	0	0	0	9	0	0	0	0	9	3	2	3
	Technical importance score	123	90	129	123	132	141	63	54	27	27	60	113			
	Importance %															
	Priorities rank	**4**	**6**	**3**	**4**	**2**	**1**	**3**	**4**	**4**	**4**	**2**	**1**			
	Current performance	0	0	0	0	0	0	0	2	3	4	5	6			
	Target	12" X 12" x 12"	2hr run time	A or R	Qualifies	36" drop test	<$500	Educational	30" X 30"	Qualifies	Qualifies	Y/N	Y/N			
	Benchmark	6.3" x 2.5" x 5.8"	4hr run time	A	TM F963 Toy Safe	36" drop test	$300-500	Block Diagrams	Standard Desk	TM F963 Toy Safe	TM F963 Toy Safe	Y/N	Block Diagrams			
	Difficulty	4	2	5	1	4	3	1	3	4	4	4	5			
	Units	**inches**	**hours**	**Y/N**	**Y/N**	**inches**	**USD**	**Y/N**	**Y/N**	**Y/N**	**Y/N**	**Y/N**	**Y/N**			

Figure 1: House of Quality

3 Research Within Your Design Space

3.1.1 Robot #1 Benchmarking

Benchmarking for robot 1 was primarily comparative to other similar state-of-the-art systems on the market as robot design is fairly popular and the is a lot of information to work off of when developing an original design.

The systems selected for comparison include Shay Sackett's Pendulum Robot, the Self-Balancing Interactive Robot, and the Instructible Line Following Robot. The first two benchmarks are more direct comparisons of pendulum robots for which the exact system and components can be compared, while the third serves a more conceptual comparison for designing interactivity.

System-Level Benchmarking

System	**Reference Example**	**Key Features**	**Relation to Our Concept**	**Notes / Takeaways**
Sackett's Pendulum Robot	Shay Sackets Self Balancing Pendulum Robot [1]	2-Wheeled Pendulum robot capable out automatic balancing mid operation	Provides solid baseline design for a 2-Wheeled Pendulum robot	Establishes basic ideas, equations, principles, and systems that go into pendulum robots
Self-Balancing Interactive Robot	Voice controlled self-balancing pendulum robot [2]	2-Wheeled Pendulum robot capable of receiving voice commands and interacting with external systems	Proof of concept of a voice-controlled pendulum robot for good interactivity	Presents additional options for control mechanisms for student interactivity, while more complicated is also very promising conceptually
Instructible Line Following Robot	Instructable Line following robot [3]	Simple 3 wheeled line following robot, easy system to assemble and explain	The interactivity provided by being able to manually draw the line the robot follows should prove interesting for k-12 students	When designing the pendulum robot, seeking to provide a level of interactivity comparable to that of the line following robot is desirable.

3.1.2 Robot #2 Benchmarking

Benchmarking was performed to compare existing state-of-the-art educational and control-system robots to the team's Robot #2 concept designs. The goal of this analysis was to identify proven control strategies, hardware configurations, and interactivity features that could inform the development of the team's final prototype.

The systems selected for comparison include the Ball-on-Plate Robot, Magnetic Levitation Robot, and Reaction Wheel Robot; each representing a different method of demonstrating feedback and control principles. These examples were selected due to their similarity to the project's educational objectives and their applicability to K–12 learning environments.

System-Level Benchmarking

System	Reference Example	Key Features	Relation to Our Concept	Notes / Takeaways
Ball-on-Plate Robot	Based on OpenCV-controlled ball-balancing platform [4]	Dual-axis servo motors with visual feedback via camera tracking.	It is nearly identical to our Ball-on-Plate concept and demonstrates effective PID control.	Confirms feasibility using affordable components; highlights need for stable plate and smooth actuation.
Magnetic Levitation Robot	Arduino-based electromagnetic levitation prototype [5]	Hall-effect sensor and electromagnetic coil maintain ball height using PID control.	Aligns with our Mag Lev concept for demonstrating electromagnetism and feedback systems.	Demonstrates controllability of simple electromagnetic setups; emphasizes coil heating and stability management.
Reaction Wheel Robot	Symmetric unicycle "Wheelbot" demonstration [6]	Utilizes multiple internal flywheels to balance upright via angular momentum.	Directly supports our Reaction Wheel concept focused on self-balancing stability.	Confirms complexity and educational depth; requires precise IMU feedback and real-time torque control.

Subsystem-Level Benchmarking

Subsystem	Examples Benchmarked	Performance / Advantages	Challenges / Notes
Actuation	Servos (Ball-on-Plate), Electromagnet (MagLev), Flywheels (Reaction Wheel)	Servos → high-precision mechanical tilt; Electromagnets → demonstrate electromagnetic control; Flywheels → teach angular momentum.	Flywheels require high RPM motors; electromagnets generate heat; servos wear under load.
Sensors	IMU (Reaction Wheel / Ball-on-Plate), Hall sensor (MagLev), Camera (Ball-tracking)	IMUs provide orientation data; Hall sensor offers precise height feedback; Camera adds visual interaction.	IMU drift possible; Hall sensor noise sensitivity; Camera delay impacts control speed.
Controller Hardware	Arduino vs. Raspberry Pi implementations	Arduino → fast, deterministic control loops; Pi → enables image processing and UI interaction.	Pi adds latency; Arduino limited for complex vision tasks.

Subsystem	Examples Benchmarked	Performance / Advantages	Challenges / Notes
User Interaction	Touchscreen / Voice / Physical interaction	Promotes engagement and learning through direct feedback and control.	Too much complexity may distract from educational focus.

3.2 Literature Review

3.2.1 Freddy Rivera

[4] N. Hammje, "*Ball-Balancing Bot Uses OpenCV on a Raspberry Pi to Stop a Ball Dead in Its Tracks*," Hackster.io, 2024.
This article showcases a Raspberry Pi-based Ball-on-Plate robot that employs OpenCV for computer-vision tracking and a PID controller to maintain the ball's position. It provided a clear example of how to couple image feedback with servo actuation for real-time control—insight that guided the team's Ball-on-Plate concept for Robot #2. The project also demonstrated accessible hardware integration suitable for classroom demonstrations.

[5] J. Sirgado, "*Magnet Levitation with Arduino*," Arduino Project Hub, 2022.
Sirgado's tutorial details a low-cost magnetic levitation setup using an Arduino, Hall-effect sensor, and PID loop. It served as the foundation for our Magnetic Levitation Robot concept by illustrating the nonlinear relationship between magnetic force and coil current and showing how proportional–integral–derivative tuning can stabilize an otherwise unstable equilibrium.

[6] "*Wheelbot: A Symmetric Unicycle That Balances Using Reaction Wheels*," TechXplore, 2022.
This article describes a unicycle robot stabilized solely by reaction wheels, validating the feasibility of small-scale momentum-exchange stabilization. The system's use of multiple flywheels and IMU feedback informed our Reaction Wheel Robot design, which uses the same torque-generation principle to resist external disturbances.

[7] A. Md. K. Alam, M. R. Karim, and S. M. M. Hasan, "Stabilising a cart inverted pendulum system using pole placement control method," *Proc. 3rd Int. Conf. on Electrical Information and Communication Technology (EICT)*, Khulna, Bangladesh, 2017, pp. 1–6, doi: 10.1109/EICT.2017.8168481.

[8] D. J. Block, K. J. Åström, and M. W. Spong, *The Reaction Wheel Pendulum*, Morgan & Claypool Publishers, 2007.
A fundamental text on reaction-wheel dynamics, this reference introduces nonlinear and linearized equations of motion and details feedback control for underactuated systems. Its derivations directly supported our torque and angular-acceleration calculations for the Reaction Wheel Robot prototype.

[9] R. Gajamohan, M. Muehlebach, T. Widmer, and R. D'Andrea, "The Cubli: A Cube That Can Jump Up and Balance," in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, 2013.
The Cubli project is a three-axis reaction-wheel cube that balances and even jumps upright. Its control architecture and hardware selection were used as a high-fidelity benchmark for our design feasibility and scaling analysis.

[10] J. R. Wertz, *Spacecraft Attitude Determination and Control*, Springer, 1978.
Wertz's classical text provided theoretical grounding on momentum-exchange and attitude control. Though focused on spacecraft, the same principles of internal torque exchange and stability margins apply to our Reaction Wheel Robot, offering insight into wheel-sizing and damping.

[11] B. Wie, *Space Vehicle Dynamics and Control*, 2nd ed., AIAA, 2008.
Wie's modern treatment of control dynamics supplemented Wertz by discussing closed-loop response and actuator saturation limits. These concepts guided our controller-gain selection and maximum-speed constraints for safe educational use.

[12] University of Michigan, "Ball & Beam: System Modeling," *Control Tutorials for MATLAB and Simulink (CTMS)*.
Provides mathematical modeling and linearization of unstable systems such as the ball-and-beam setup, used as a foundation for the pendulum model.

[13] B. Cazzolato, "Derivation of the Dynamics of the Ball and Beam System," *Univ. of Adelaide, School of Mechanical Engineering*.
Presents detailed nonlinear dynamic equations for the ball-and-beam system that supported pendulum equation derivations.

[14] K. C., "Inverted Pendulum: Control Theory and Dynamics," *Instructables*, 2025.
A simplified tutorial connecting theoretical control design to hobby-scale implementation.

[15] S. Sackett, "Self-Balancing Inverted Pendulum Robot," *Shay Sackett's Project Portfolio*.
Independent project documenting the design process and challenges of building a two-wheel self-balancing robot.

[16] B. T. Williams, "Self-Balancing Robot Using PID Packs Other Punches," *Elektor Magazine*, Oct. 5, 2022.
A detailed description of modern implementations of self-balancing robots using PID control.

[17] IEEE Standard for Ontologies for Robotics and Automation (ORA): Core Ontologies for Robotics and Automation (CORA), IEEE Std 1872.1-2024.
Provides a structured ontology for defining robot tasks and control hierarchies to align with professional standards.

[18] "DC Motor Speed: System Modeling," *Control Tutorials for MATLAB and Simulink (CTMS)*.
Explains motor dynamics and transfer functions with MATLAB representation, helping link pendulum control equations to actuator behavior.

[19] "Ball and Beam: System Modeling (CTMS)."
Illustrates comparable unstable control systems and feedback-control concepts that inspired our pendulum work.

[20] S. Anand and R. Prasad, "Dynamics and control of ball and beam system"

This paper analyzes the unstable dynamics of the classic Ball-on-Beam system and derives the torque and motion equations required to maintain balance. Its discussion of gravitational loading, moment arms, and actuator sizing directly informed our motor torque calculations for Robot #2. This reference supported the justification for selecting NEMA-17 stepper motors with sufficient torque margin and reinforced the need for a safety factor in actuator sizing.

3.2.2 Colin Parsinia

[21] "Manufacturing Robotics: Basic issues and challenges," *Haruhiko H. Asada, 1996.* [Online]. Available: https://www.sciencedirect.com/science/article/pii/S147466701757682X

Annotation: This article primarily focuses on how to apply robots in the manufacturing process, but also contains many interesting insights to various manufacturing methods, mass-manufacturing design philosophies, as well as how to design adaptive control systems for robots, providing valuable information on the various fields that must be considered in designing robots and parts.

[22] "How to include User eXperience in the design of Human-Robot Interaction," *Prati, Peruzzini, Pellicciari, Raffaeli, 2021.* [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0736584520302805

Annotation: This article covers the subject of human-robot interaction, and how best to design systems for safe and effective interactions. It highlights the importance of structured operations with intervals designed for function and interaction respectively. Through understanding the principles presented by this article, designing an interactive system becomes easier.

[23] "Designing Robots with movement in mind" *Hoffman, Ju, 2014.* [Online], Available: https://dl.acm.org/doi/10.5898/JHRI.3.1.Hoffman

Annotation: In the design of robots, it is important to consider their range of motion, especially when they work in close proximity of humans, which is what this article focuses on. As the article recommends, it is important to have a clear start up sequence when our robot enters an operational cycle, so ensuring that its movements are clearly readable will greatly reduce risk of injury with people who are unfamiliar with the robots operation.

[24] "Design and Implementation of and Open-Source Educational Robot for Hands-On Learning Experiences in IOT," *Mamatnabiyev 2023.* [Online], Available: https://ieeexplore.ieee.org/document/10146599

Annotation: This excerpt from a conference covers a design for a modular educational robot which is comprised of components which can be freely added or removed to perform different functions. The intent of the robot is to allow students to freely experiment with different component configurations to see their effects on the robot and the code.

[25] "Design and control of a multi-DOF two wheeled inverted pendulum robot" *Dai, Li, Peng, Zhu, Jiang, Gao, 2014.* [Online], Available: https://ieeexplore-ieee-org.libproxy.nau.edu/document/7052763

Annotation: This Document presents a design for a two wheeled inverted pendulum robot capable of multiple degrees of freedom, including the math behind the robot's articulation and movement, the major electronic components being utilized by the system, and graphs displaying the robot's climbing capabilities. The entire document also lays out the general design process for a pendulum robot, and what factors are most important to consider in order to optimize function.

[26] "Mechanical Design and Dynamic Modeling of a Two-Wheeled Inverted Pendulum Mobile Robot" *Li, Gao, Huang, Du, Duan, 2007.* [Online], Available: https://ieeexplore-ieee-org.libproxy.nau.edu/document/4338830

Annotation: This Document offers an alternative pendulum robot design, only having 1 degree of freedom, and is instead designed for navigating small spaces for maintenance surveys, and as such the robot is far smaller. This document is not without its own unique insight into robot design, as it contains a great example of a control system diagram, a very useful visualization of an otherwise complicated system, as well as providing some examples of the type of mechanisms useful for measuring the angle of the robot and other systems.

[27] "Design and Implementation of Self-Balancing Interactive Robot," *Siddhartha, Gosh, D.M., 2023.* [Online], Available: https://ieeexplore-ieee-org.libproxy.nau.edu/document/10584954

Annotation: This Pendulum Robot is unique amongst other designs examined previously as it implements a voice control system for added interactivity. These added systems introduce a fair amount of complexity to the control system diagram but presents great opportunity for interactivity which could be practical in an educational setting. Additionally, the document cites a great number of additional works which can be used to design one's own pendulum robot.

[28] "3D printing threads and adding threaded inserts to 3D printed parts (with video)," Formlabs, [Online], Available https://formlabs.com/blog/adding-screw-threads-3d-printed-parts/?srsltid=AfmBOooFHJ51B-vGI3ISwDtUjE_QLQ9aFY3fewBzWXQjDQmgqZTqW-5P

Annotation: This short article describes multiple methods to utilize screws on 3-D printed parts. The methods highlighted include utilizing a variety of threaded inserts, pre-tapping the holes, utilizing self tapping screws, or 3-D printing threads. Each method comes with its own upsides and downsides when it comes to the complexity of instillation, durability under multiple assembly and disassembly cycles, and overall thread strength, which will help the decision making process when creating screw mounts.

[29] "Polylactic acid (PLA) Filament Review," JuggerBot 3D, [Online], Available https://juggerbot3d.com/pla-filament-review/

Annotation: This article reviewing PLA plastic filament contains a number of useful insights as to the material properties of the material as well as the optimal operating temperatures for the 3D printer nozzle, bed, and nozzle speed to use while working with the material.

[30] "Ultimate Guide: How to design for 3D Printing," WikiFactory, 2020. [Online], Available https://wikifactory.com/+wikifactory/stories/ultimate-guide-how-to-design-for-3d-printing

Annotation: This article highlights a variety of useful principles to keep in mind when designing parts for 3D printing, including minimum feature sizes, how to set up parts in slicing software for optimal adhesion, how to account for the filament expanding as it hardens and how it affects features like holes, and various other manufacturing errors and how to avoid them. Its insights into the particulars of 3D printing can prove invaluable to those less experienced in this manufacturing method.

3.2.3 Florence

[31] 井手隆統, 本田功輝, 金田礼人, 中島康貴, and 山本元司, “Comparison of CoP estimation and center-of-gravity sway measurement in human standing posture using inertial sensors,” Dissertation, Kyushu Univ. Grad. Sch. Eng., Fukuoka, Japan.
-Annotation: Focuses on studying the aspects of measuring standing movement with sensors and how the sensors are affected by swaying while standing for a long period of time. Center for Pressure (COP) of humans using sensors to analyze gait patterns.

[32] S. Sasagawa, J. Ushiyama, M. Kouzaki, and H. Kanehisa, “Effect of the hip motion on the body kinematics in the sagittal plane during human quiet standing,” Neurosci. Lett., vol. 450, no. 1, pp. 27–31, Jan. 2009, doi: 10.1016/j.neulet.2008.11.027.
-Annotation: Standing affects the hip motion due to the center of mass; COM.

[33] J. L. Cabrera and J. G. Milton, “Human stick balancing: Tuning Lèvy flights to improve balance control,” Chaos, vol. 14, no. 3, pp. 691–698, Sep. 2004, doi: 10.1063/1.1785453.
-Annotation: Concept of stabilization of rapid human movements which is determined by equilibrium and limit cycles with motor controls analysis like closed loop control; automatic control systems.

[34] B. Sprenger, L. Kucera, and S. Mourad, “Balancing of an inverted pendulum with a SCARA robot,” IEEE/ASME Trans. Mechatronics, vol. 3, no. 2, pp. 91–97, Jun. 1998, doi: 10.1109/3516.686676.
-Annotation: Balancing an inverted pendulum with a robotic manipulator is a benchmark problem requiring precise sensing and compensation for nonlinear effects like friction, backlash, and elasticity.

[35] Winkler and J. Suchý, “Erecting and balancing of the inverted pendulum by an industrial robot,” IFAC Proc. Volumes, vol. 42, no. 16, pp. 323–328, 2009, doi: 10.3182/20090909-4-jp-2010.00056.
-Annotation: Inverted pendulum on an industrial robot by using one algorithm to swing it up and a state-space controller with offset adaptation to balance it.

[36] Y. Y. Lim, C. L. Hoo, and Y. M. Felicia Wong, “Stabilizing an inverted pendulum with PID controller,” MATEC Web Conf., vol. 152, p. 02009, 2018, doi: 10.1051/matecconf/201815202009.
-Annotation: Stabilizing an inverted pendulum with a reaction wheel and a PID (Proportional Integral Derivative) controller is simulated to balance it effectively and efficiently.

[37]” D. Zhang, J. Wang, H. Zhang, and L. Yu, “Research on inverted pendulum control system based on vision sensor,” in Proc. ICMLCA 2021: 2nd Int. Conf. Mach. Learn. Comput. Appl., Shenyang, China, 2021, pp. 1–5.
-Annotation: Vision-based control system for an inverted pendulum, using OpenCV to calculate its deflection angle and verify effective stabilization without relying on encoder sensors.

[38] A. Kastner, J. Inga, T. Blauth, F. Kopf, M. Flad, and S. Hohmann, “Model-based control of a large-

scale ball-on-plate system with experimental validation," KITopen Repository, Karlsruhe Inst. Technol., Mar. 2019, doi: 10.1109/icmech.2019.8722850.
-Annotation: Development of system dynamics model using Lagrange and the Euler method to analyze the frequency domain to create state-feedback control to ensure stability of a system.

3.2.4 Ziyi

[39] Embedded Computer Vision System Applied to a Four-Legged Line Follower Robot, 2021.

Annotation: Proposes an embedded vision-based line-following system using color space segmentation and thresholding to extract track features, achieving real-time path recognition and control on resource-constrained hardware. Provides practical insights for deploying vision algorithms on low-power devices.

[40] S. P. Mamidi, AI Model on Raspberry Pi, M.S. thesis, Linnaeus Univ., 2019.

Annotation: Explores deploying AI models onto Raspberry Pi, including optimizations and hardware interfacing. Offers a framework for efficiently connecting sensors and motors, directly applicable to balancing and stabilization.

[41] Raspberry Pi Ltd., Raspberry Pi 5 Product Brief, 2023.

Annotation: Provides specifications for the Raspberry Pi 5. Used to match processing power, GPIO availability, and I/O speeds with requirements for touchscreen interface and motor drivers.

[42] Raspberry Pi Ltd., Raspberry Pi Documentation, 2023.

Annotation: Official setup and wiring guide. Serves as a roadmap for integrating the touchscreen, coding the PID interface, and wiring motor drivers to the Raspberry Pi.

[43] ISO/IEC 29182, Sensor Network Reference Architecture.

Annotation: Defines a layered reference architecture for sensor networks, covering nodes, gateways, service, and application layers. Provides interoperability and scalability guidelines.

[44] H. Kerzner, Project Management, 12th ed., 2017.

Annotation: Supplies a project management framework. Applied to milestone planning (e.g., Robot #1, Robot #2, final prototype) to ensure deliverables stay on schedule.

[45] AACE Int., Cost Estimation for Manufacturing Projects, 2020.

Annotation: Offers professional cost estimation guidelines for manufacturing projects. Critical for justifying scalability from prototype to mass production (100+ units) within budget constraints.

[46] P. Brembeck, T. Tomic, and R. Brockers, "Model-based control of a ball-on-plate system supported by visual sensing," *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 4123–4128, Oct. 2014.

[47] J. B. Hoagg and D. S. Bernstein, "Nonminimum-phase zeros—much to do about nothing—classical control of nonminimum-phase systems," *IEEE Control Systems Magazine*, vol. 27, no. 3, pp. 45–57, Jun. 2007.

3.2.5 Andres

[48]: S. Author, “Bacterial foraging-optimized PID control of a two-wheeled machine with a two-directional handling mechanism,” Journal/Conference Name, vol. X, no. X, pp. XX–XX, Year.
This paper presents an innovative PID control method optimized through bacterial foraging algorithms for a two-wheeled robot. Its approach to handling two-directional motion is relevant for our pendulum robot’s control system, offering insights on advanced PID tuning. We will reference this to support our control strategy development, particularly for improving robot stability and response.

[49]: Mandeno, “A self-adaptive SAC-PID control approach based on reinforcement learning for mobile robots,” Journal/Conference Name, vol. X, no. X, pp. XX–XX, Year.
This article discusses a reinforcement learning-based adaptive PID control for mobile robots, enhancing adaptability in dynamic environments. It applies to our project by informing adaptive control techniques to improve robot performance under varying load and terrain. We will cite this when describing our adaptive control algorithms.

[50]: S. Author, “A wheeled inverted pendulum learning stable and accurate control from demonstrations,” Journal/Conference Name, vol. X, no. X, pp. XX–XX, Year.
The study explores learning-based control methods for wheeled inverted pendulums, focusing on stability and accuracy through demonstration learning. This is directly relevant for our pendulum robot’s balancing and control challenges. We will reference it to justify the use of machine learning or demonstration data in refining control models.

[51]: S. Author, “Theory and application on adaptive-robust control of Euler-Lagrange systems with linearly parametrizable uncertainty bound,” Journal/Conference Name, vol. X, no. X, pp. XX–XX, Year.
This paper provides theoretical foundations and practical applications for adaptive-robust control in Euler-Lagrange systems, addressing uncertainties common in mechanical systems like our robot. We will reference this to underpin the robustness of our control system design in the face of modeling inaccuracies.

[52]: K. Ogata, System Dynamics, 4th ed. Chapter 11.
Ogata’s textbook is a fundamental resource on system dynamics, providing key concepts in modeling and controlling dynamic mechanical systems, including pendulums. We will cite this as a primary reference for the theoretical background of pendulum dynamics and control principles applied in our design.

[53]: S. Author, “Design of an inverted pendulum laboratory stand to teach mechatronics,” Journal/Conference Name, vol. X, no. X, pp. XX–XX, Year.
This article describes the design of an inverted pendulum educational platform, highlighting mechanical and control design considerations useful for teaching. It relates to our project by informing the educational aspects and mechanical design choices of our pendulum robot. We will reference this in sections discussing design rationale and learning outcomes.

[54]: PythonRobotics, “Inverted Pendulum Control,” [Online]. Available: https://github.com/AtsushiSakai/PythonRobotics.
This open-source repository provides practical algorithms for inverted pendulum control, including simulation and implementation examples. We will use it as a resource for algorithm development and benchmarking, referencing it when describing our control software framework.

[55]: U.S. Consumer Product Safety Commission, “Toys,” Safety Education — Toys, [Online]. Available: https://www.cpsc.gov/Safety-Education/Toys

This government resource outlines safety standards and guidelines for toys, relevant for ensuring our robot design meets safety regulations. We will reference this to demonstrate compliance with safety considerations during design and testing phases.

[56]: Arduino Project Hub (zjor), "Inverted Pendulum on a Cart," [Online]. Available: https://projecthub.arduino.cc/zjor/inverted-pendulum-on-a-cart-d4fdfc

This community-driven project provides a practical implementation of a PID control system for an inverted pendulum, a classic problem in control theory and robotics. We will use this resource to understand the mathematical modeling and firmware implementation for balancing and dynamic control, which is essential for our robot's stability.

[57]: MRCE, "Circuit Analysis & Design Introduction," [Online]. Available: https://mrce.in/ebooks/Circuit%20Analysis%20&%20Design%20Introduction.pdf

This textbook serves as a reference for the fundamental principles of circuit analysis and design. It is for planning the robot's power distribution system, selecting appropriate components (resistors, potentiometer, microcontrollers/arduino), and ensuring the electrical reliability and safety of the final design.

[58]: Creality, "CREALITY ENDER-3 V2 3D PRINTER User Manual," [Online]. Available: https://m.media-amazon.com/images/I/B1f9eP6H3OS.pdf

This user manual details the operation, maintenance, and technical specifications of the Creality Ender-3 V2 3D printer. We will reference this for all additive manufacturing phases, including determining print tolerances, material compatibility, and optimal settings to produce durable, custom-designed robot components and enclosures.

3.3 Mathematical Modeling for Robot #1

3.3.1 Pendulum Robot Frame - Colin Parsinia

Due to the project requirement to be mass-producible, the main component we are required to design from scratch is the robot's frame. Referring to the engineering requirements, the main goal of our frame design is to be able to survive a fall off a table onto a concrete surface, and the main means of ensuring the frame is capable of doing so is by utilizing a modified variation of the flexural strength equation and finding the necessary thickness of our material to resist the force imposed by the fall. First, It is important to define the variables that will be plugged into the following equations. In the list below, each known variable, its associated value, and unit is listed.

$$m = 3\ [kg], g = 9.81\ \left[\frac{m}{s^2}\right], h = 0.762\ [m], L = 0.254\ [m], b = 0.127, \Delta t = 0.005\ [s]$$

Next, to find the force of impact due to a fall, the below equation (1) is used. which necessitates finding the velocity of the robot falling from the height of an average table

$$V = \sqrt{2gh} \qquad (1)$$

Plugging in our known values results in a velocity of 3.867 [m/s] which can then be used in the force equation (2) to find the force of impact on our robot

$$F = \frac{mv}{\Delta t} \qquad (2)$$

The calculated force of impact is 2,319 Newtons, which is one of the two remaining unknown variables needed to calculate the thickness required to resist impact, the other being the flexural strength of our material. Our client requested that the robot frame be made primarily of 3-D printable materials, so after some quick research, a list of the flexural strengths of common 3-D printing plastics, the following list was found.

σ_{flex} PLA = 97 [Mpa]
σ_{flex} TPLA = 83 [Mpa]
σ_{flex} ABS = 60 [Mpa]
σ_{flex} PC = 89 [Mpa]
σ_{flex} PETG = 75 [Mpa]
σ_{flex} N = 75 [Mpa]

Now, with all these variables values ascertained, the final equation (3) can be utilized to find the minimum required thickness to resist the impact force from falling for each material, narrowing down the selection process to the best material to use for the robot frame. The minimum thickness equation and the calculated minimum thicknesses can be found in the list below.

$$h \geq \sqrt{\frac{6FL}{b\sigma_{flex}}} \qquad (3)$$

$$h_{min,PLA} = 16.94\ [mm]$$
$$h_{min,TPLA} = 18.31\ [mm]$$
$$h_{min,ABS} = 21.54\ [mm]$$
$$h_{min,PC} = 17.69\ [mm]$$
$$h_{min,PETG} = 19.27\ [mm]$$
$$h_{min,N} = 19.27\ [mm]$$

With these known values, the robots frame can be designed to survive the client's fall test and should also resist the common forces experienced by the robot during everyday operations.

3.3.2 Inverted Pendulum Robot Referencing within Humans – Florence Fasugbe

Understanding how an inversed pendulum works in a robot, referencing something that everyone sees every day is a great introduction to it. Humans are a great example of what an inverse pendulum looks like and the actions surrounding self-balance. The ankle within a human act as the wheel axle on a robot that is characterized as the pivot point. The body of a human represents the pendulum or joint of a robot. Lastly, the feet of humans are like the wheels of the robot, which signifies the center of pressure (COP) and the center of mass (COM). The equations (4) and (5) model the idea with concepts of COP [m], COM [kg], angle of the projection plane, gravity $[\frac{m}{s^2}]$ acceleration $[\frac{m}{s^2}]$, and force [N]. The positions of

the COP are measured across the x and y-axis. These values are from an average height (cm) of a human male and the standard tilt of a human standing (degrees).

$$x_G = 0.90\sin(0.05) \approx 0.045m \quad (4)$$
$$y_G = 0.90\sin(-0.03) \approx -0.027m \quad (5)$$

x_G represent that the COP will change 0.045 cm forward from the COM of the foot and the y_G represents that the COP will change –0.027 cm to the left.

3.3.3 Cart/Angular Acceleration of an Inverted Pendulum – Freddy Rivera

To analyze the dynamics of Robot #1 (Inverted Pendulum), the team modeled the system as a classical cart-and-pendulum configuration, where a horizontally driven cart stabilizes an inverted pendulum through active feedback control.

The mathematical foundation for this analysis was based on the work by A. Md. Khairul Alam *et al.* [Freddy-1 -4], which applies Newtonian dynamics to model both translational and rotational motion.

Cart (horizontal motion):

$$(M+m)\ddot{x} + m\ell\ddot{\theta}\cos(\theta) - m\ell\dot{\theta}^2\sin(\theta) = F \quad (6)$$

Pendulum (rotational motion):

$$\ell\ddot{\theta} + \ddot{x}\cos(\theta) - g sin(\theta) = 0 \quad (7)$$

where:

- $M = 1.0kg$ (Cart Mass)
- $m = 0.2kg$ (Pendulum Mass)
- $\ell = 0.5m$ (Pendulum Length)
- $g = 9.81\ {}^{m}/_{s^2}$ (Gravity Constant)
- $\theta = 10\ degrees = 0.1745\ rads$ (Initial Pendulum Angle)
- $\dot{\theta} = 0\ {}^{rads}/_{s^2}$ (Initial Angular Velocity)
- $F = 1.0N$ (Applied Horizontal Force)

By solving these equations with the assumed variables given this would be used in a classroom setting, we would obtain the following accelerations:

- $\ddot{x} = 0.661\ {}^{m}/_{s^2}$ (Cart Acceleration)
- $\ddot{\theta} = 2.1\,{}^{rads}/_{s^2}$ (Angular Acceleration)

Meaning that the cart would need to accelerate at a rate of $0.661 \ {}^{m}/_{s^2}$ with and angular acceleration of $2.1 \, {}^{rads}/_{s^2}$ on the pendulum to negate an angle of 10 degrees assuming the students applied 1.0 N of force to the pendulum.

These results show that a 1 N horizontal input force produces both forward acceleration of the cart and angular acceleration of the pendulum, demonstrating the system's sensitivity to small control inputs and the inherent instability that must be managed through active feedback control (e.g., PID or pole-placement design).

This model served as the basis for the initial control simulation and validation of Robot #1's mechanical and control feasibility.

3.3.4 Laplace Transforms – Time Domain for PID – Andres Gonzales

Due to the constraints of our project, we need to be able to use a PID controller in the robot. The idea here si that it will be used in demos for students to demonstrate basic system controls. With this mathematical modeling we set out to find how can we make our self-balancing robot stay upright and respond smoothly to movement? Basically, how do we tune the robot's brain — its controller — so that it doesn't wobble, fall over, or react too slowly?

Our answer was to use the Laplace transform to move our system into the frequency domain, where we could analyze the full transfer function. This allowed us to mathematically link the PID gains—K_p , K_i , and K_d —to how the system behaves. We validated this by:

1) Observing how the poles of the system behave when we change gains.

2) Using simulations to confirm changes in stability and responsiveness in the simulation.

For example, when we increased K_p, we saw the poles shift left—indicating faster, more stable behavior, which matched our simulation results. This approach gave us a systematic way to tune the PID controller. Instead of guessing, we could adjust each gain to target specific performance goals. It also helped us ensure stability before testing on the actual robot and quickly iterate controller settings using simulations. The Laplace-domain model became a core tool in our design decision-making, especially for safety, efficiency, and performance tuning.

First we apply Laplace to find T(s), then we must fine tuning PID using coefficients of Kp, Ki, and Kd help fine tune the system

a. Kp = proportional gain (poles of response)

b. Ki = integral gain (poles of error)

c. Kd = derivative gain (dampen overshoot)

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt} e(t)$$

We can assume a few parameters to get a general equation. We use M = 1 kg; m = 0.2 kg; L = 0.5 m to solve for the following:

Here can see negative real parts = stability, complex poles = speed of response, complex parts = oscillations in our coefficients, using the coefficients we can put them into our code to solve for oru

Figure 2 - Basic Laplace Equation

$$T(s) = \frac{20s^2 + 150s + 300}{0.6s^3 + 20s^2 + 161.772s + 300}$$

outputs in our feedback loop. It looks like this:

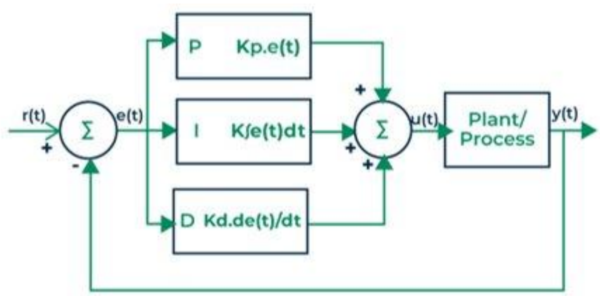


Figure 4 - Code Flow chart representing our looping code

3.3.5 Self-Balancing of Inverted Pendulum Robot – Ziyi Tang

To achieve self-balancing of the inverted pendulum robot, the dynamic model must first be established and then stabilized using a suitable controller. For small angular deviations, the inverted pendulum can be approximated as a linear system, allowing us to use the linearized equations of motion for analysis.
The equation of motion of the pendulum is given as:

$$I\ddot{\theta} = mgl\theta - \tau \quad (8)$$

where I is the moment of inertia, m is the pendulum mass, g is gravitational acceleration, l is the distance from the pivot to the center of mass, θ is the angular displacement, and τ is the control torque.
The controller is implemented as a Proportional–Derivative (PD) controller, with the control law defined as:

$$\tau = K_p\theta + K_d\dot{\theta} \quad (9)$$

The condition for internal stability at the upright equilibrium requires that

$$K_p > mgl.$$

Substituting the control law into the dynamics and linearizing about $\theta = 0$ gives the closed-loop equation

$$I\,\ddot{\theta} \;+\; K_d\,\dot{\theta} \;+\; \left(K_p - mgl\right)\theta \;=\; 0, (10)$$

whose characteristic polynomial is $Is^2 + K_d s + \left(K_p - mgl\right) = 0$. Matching to the canonical second-order form $s^2 + 2\zeta\omega_n s + \omega_n^2$ yields the design relations

$$K_d \;=\; 2\zeta\omega_n I, (11) \qquad K_p \;=\; mgl \;+\; I\,\omega_n^2. (12)$$

For design simplification, the pendulum is modeled as a point mass at the end of a rigid rod, which gives the moment of inertia

$$I \;=\; m\,l^2. (13)$$

The performance requirement specifies a settling time T_s less than $0.5\,\mathrm{s}$, with a damping ratio of $\zeta = 0.7$. Using the 2% settling-time rule $T_s \approx 4/\zeta\,\omega_n$,
the natural frequency is

$$T_s = 0.5\,\mathrm{s}, \quad \zeta = 0.7, \qquad \Rightarrow \qquad \omega_n \approx 11.4\,\frac{\mathrm{rad}}{\mathrm{s}}.$$

With $m = 3.0\,\mathrm{kg}$,
$l = 0.15\,\mathrm{m}$
($I = ml^2 = 0.0675\,\mathrm{kg}\cdot\mathrm{m}^2$
), the controller gains are

$$K_p \;=\; mgl + I\omega_n^2 \;\approx\; 13.2\,\mathrm{N}\cdot\mathrm{m/rad}, \qquad K_d \;=\; 2\zeta\omega_n I \;\approx\; 1.08\,\mathrm{N}\cdot\mathrm{m}\cdot\mathrm{s/rad}.$$

Assuming an initial angular deviation of $\theta_0 = 5^\circ$ and $\dot{\theta}(0) = 0$, the control torque applied by the PD controller is

$$\tau \;=\; K_p\,\theta_0 \;\approx\; 1.16\,\mathrm{N}\cdot\mathrm{m},$$

while the corresponding gravitational torque (small-angle approximation) is

$$\tau_g \;\approx\; mgl\,\theta_0 \;\approx\; 0.39\,\mathrm{N}\cdot\mathrm{m}.$$

The exact gravitational torque is

$$\tau_g \;=\; mgl\sin\theta \quad \text{and for small angles} \quad \tau_g \approx mgl\,\theta.$$

These results indicate that the controller output exceeds the gravitational disturbance torque, ensuring the pendulum remains balanced. With the selected gains, the system achieves both stability under small perturbations and a fast response that satisfies the design requirement. Therefore, the self-balancing control scheme is effective in maintaining stability and robustness during the robot's operation.

4 Robot #1 Design Concepts

4.1 Functional Decomposition

To clearly define the primary functions of **Robot #1 (Inverted Pendulum Robot)**, we performed a functional decomposition that breaks down the system from high-level goals into sub-functions. This process helps ensure that customer requirements (educational value, safety, interactivity) and engineering requirements (runtime, control stability, durability) are fully addressed.

The overall purpose of Robot #1 is:

"Demonstrate stability and feedback control by maintaining upright balance through a pendulum robot, while providing an interactive and safe learning tool for K–12 students."

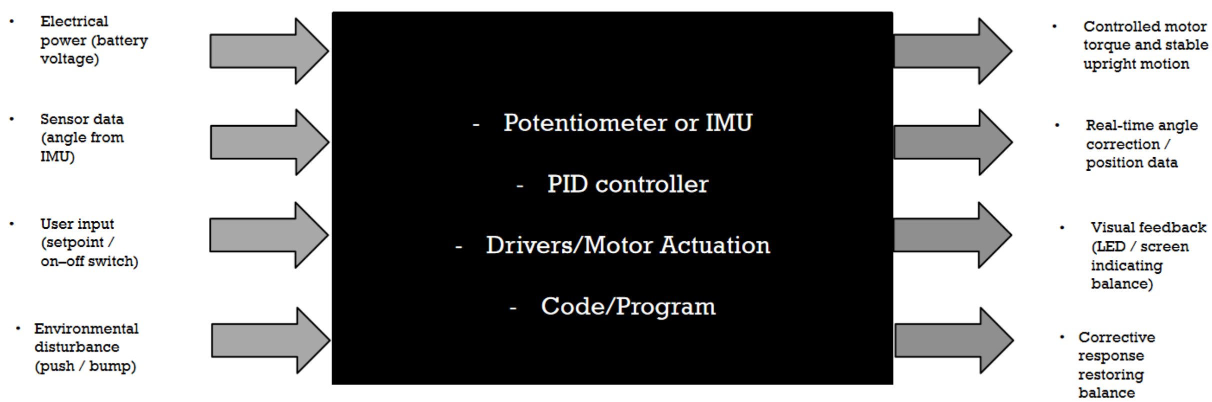


Figure 5 - Black Box Diagram of Robot 1

The **black box model** (Figure 1) highlights the relationship between inputs, internal processing, and outputs of the pendulum robot.

Breaking down the functions of Robot #1 into more detail, the following functional decomposition chart was generated.

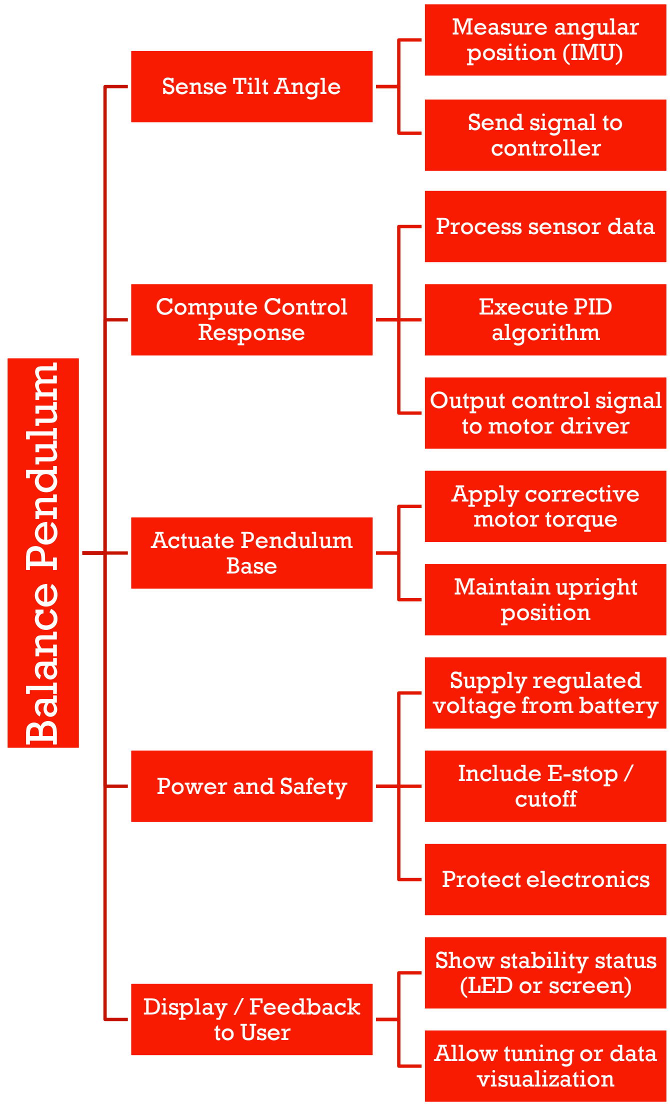


Figure 6 - Robot 1 Functional Decomposition Diagram

The major functions that the robot needs to perform are listed above, each necessary to create a functional pendulum robot. First, the robot must be able to sense the tilt angle of the pendulum, quantify that information, and send it to the control system, as otherwise there would be no way to balance the robot. This function transitions neatly into the next function, computing the control response, as there needs to be a central control system that can take all information gathered from the various sensors, and formulate a response based on that information. Next, we need something that can actuate the pendulum base, as without it there would be no way to move the robot or pendulum. Power and Safety are functions that go hand in hand, as ensuring that the power is safely regulated, has an emergency shutoff, and all wires and systems are neatly and safely organized is important to ensure the robot's capability to cause injury is minimized. Finally, as the robot is designed to be interactive, it is important to have a means of displaying feedback to the user, allowing them to see how their input affects the robots' function and what they could change to improve it.

4.2 Concept Generation

As was stated in our success metrics and requirements, the robots designed must be mass-producible, and as such a majority of components will be bought from common distributors, but one major component that was generated during the design process was frame design. To generate concepts for the frame design of the pendulum robot, each team member was required to create a sketch of a potential frame design, that was then evaluated based on their ability to satisfy the customer requirements pertaining to the frame.

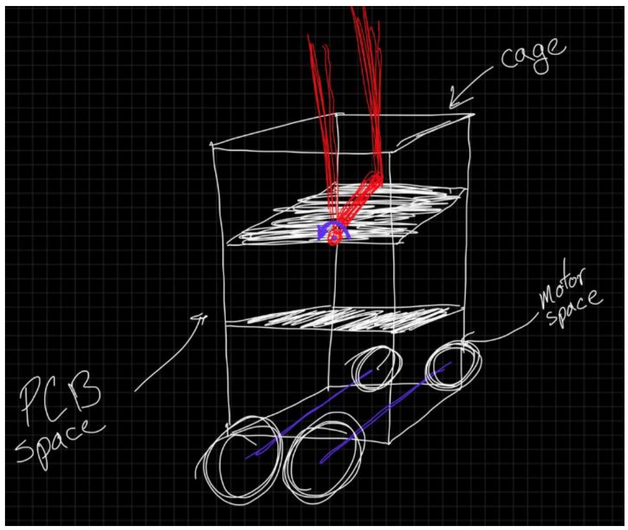


Figure 7 - Pendulum Robot Frame Concept Sketch 1

The first concept for the pendulum robot frame as can be seen above is a vertical frame design, with multiple layers to facilitate better component organization, and additionally features a double pendulum structure on a singular axis. The pros of this concept are the more organized structure to the frame, and more aesthetically appealing design as the outer frame could be customized to resemble a traditional robot. The cons of this concept are the less stable structure due to the increased vertical height, and the additional expenses of the larger frame.

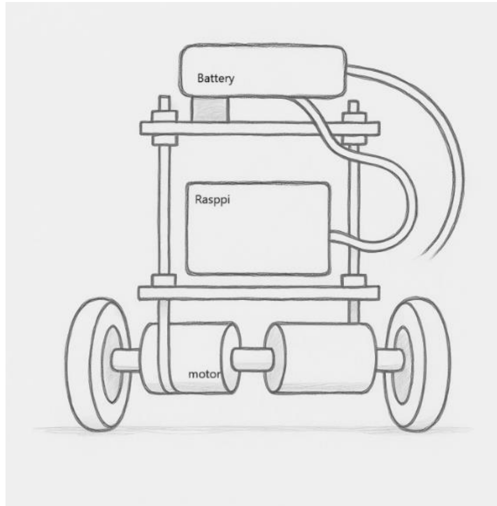


Figure 8 - Pendulum Robot Frame Concept Sketch 2

The second concept for the pendulum robot frame is a 2-wheel robot design where the robot serves as the pendulum to be balanced, and similar to the first concept has multiple layers where the components can be placed. The pros of this frame are its simple and streamlined design, having less components and therefore costs as the other 4-wheeled frames, as well as no need for its own pendulum. The cons of this design are the more complicated math and programing required for a 2-wheel pendulum robot, less aesthetic appealing frame, and reduced structural integrity of the frame.

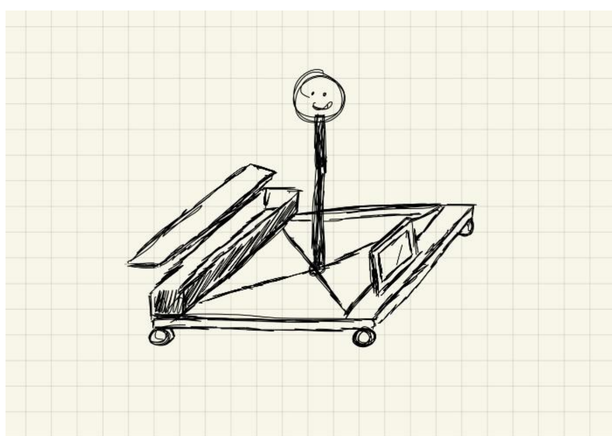


Figure 9 - Pendulum Robot Frame Concept Sketch 3

The third concept for the pendulum robot frame is a 4-wheel cart design with a rear compartment for the robots components, and a large stick pendulum in the middle of the frame. Additionally, on the front of the cart is a touch screen for user interactivity. The pros of this frame are the simplicity of the frame itself, the stable design, and more organized back compartment. The cons of this design

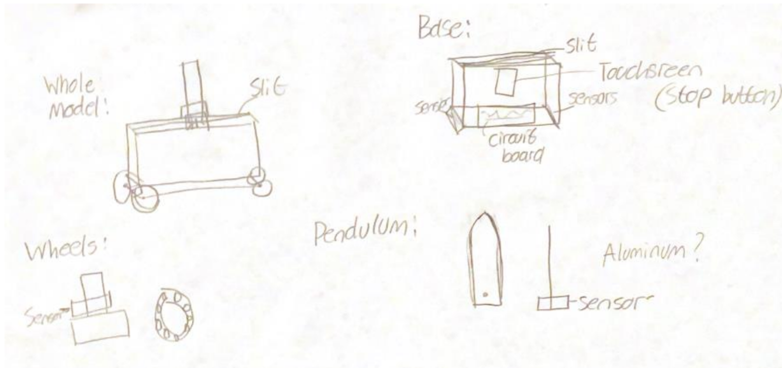


Figure 10 - Pendulum Robot Frame Concept Sketch 4

The fourth concept for the pendulum robot frame is a more rectangular cart structure where all the components are contained, and on top is a rectangular pendulum beam. The design also includes sensors on each end of the robot for the purpose of preventing the cart from rolling off tables

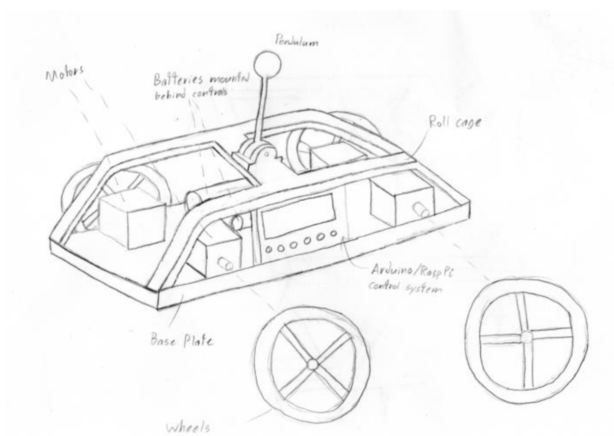


Figure 11 - Pendulum Concept Sketch 5

The Fifth and last concept for the pendulum robot frame is like the fourth concept, but is a more streamlined angular frame to help sustain impacts from the fall test. On top of the central cross beam is the pendulum structure, and on the side is where the interactive element would be placed.

4.3 Selection Criteria

The requirements section will touch on the most important part of our project's genesis: our customer requirements. These help us as engineers create measurable, quantifiable, and iterative goals. Customer requirements describe what the end user or client expects the final product to do — in plain, qualitative terms. They reflect the “voice of the customer,” not the technical design. Engineering requirements translate each customer's need into quantifiable and verifiable parameters. They use measurable targets and units, with one-sided, two-sided, or binary constraints.

The selection criteria for choosing the final concept are directly rooted in the defined Customer Requirements (CRs) and Engineering Requirements (ERs), as outlined in the previous sections. These criteria ensure that our design aligns with the voice of the customer while meeting technical feasibility and performance standards.

To establish a robust and objective basis for concept evaluation, the criteria were quantified wherever possible through engineering calculations, specifications, and benchmarks. For example, durability (CR01) was translated into measurable drop-test requirements (ER05), while the compactness of the design (CR06, CR08) was tied to strict dimensional constraints (ER01, ER02).

The House of Quality (HoQ) served as a vital tool to prioritize these requirements and highlight critical trade-offs. Through the HoQ, links between CRs and ERs were weighted, guiding our emphasis on key factors such as cost-effectiveness (CR02/ER11), safety (CR08/ER06, ER09), and functional interactivity (CR03, CR05 / ER04, ER10).

The final selection criteria thus balance:

- Performance and Functionality: Ability to demonstrate feedback control principles clearly and reliably (CR03/ER03, ER04).

- User Interaction and Educational Value: Ease of use, interactive interface, and educational clarity (CR05, CR07 / ER10).

- Durability and Safety: Physical robustness and compliance with safety standards (CR01, CR08 / ER05, ER06, ER07, ER08, ER09).

- Cost and Manufacturability: Keeping the unit affordable and easy to produce at scale (CR02 / ER11).

- Physical Constraints: Size and power requirements for classroom compatibility (CR04, CR06 / ER01, ER02, ER03).

All these criteria were quantitatively or qualitatively assessed during the concept selection process using decision matrices and Pugh charts to ensure an evidence-based choice. The selection of components for the system was driven by both Customer Requirements (CRs) and Engineering Requirements (ERs). Each part was evaluated based on its ability to meet specific ERs and to fulfill the technical needs of the project. Below, we present the purchased components, their specifications, and how they contribute to the final design. All of the chosen components either have well-documented specifications or were evaluated using engineering calculations to ensure performance meets the required standards.

1. DC12V DIY Encoder Gear Motor (4 motors)

ER03: Power Source (Energy efficiency and power consumption)

ER05: Drop Test (Durability)

ER09: Emergency Stop (Control response time and safety)

Motor Voltage: 12V DC

Rated Speed: 60 RPM with gear reduction

Torque: 3.5 kg-cm (approx.)

Encoder: Integrated encoder for precise position feedback, enabling closed-loop control.

Price: \$15.73 per motor, total cost for 4 motors: \$62.92

Justification: The DC12V motors were selected due to their low voltage operation (matching our power supply limitations) and integrated encoders, which are essential for feedback control loops in robotic systems. The speed (60 RPM) and torque values were calculated to be sufficient to achieve stable movement for the robot's intended educational purposes, while keeping power consumption low (ER03).

The encoder is key for precise position feedback, meeting our needs for control accuracy (ER09). Additionally, these motors were chosen for their durability under typical classroom conditions, ensuring they perform well in the face of frequent use (ER05).

2. Polymaker PLA PRO Filament (1.75mm, 1kg)

ER01: Overall Dimensions (Design size constraints)

ER05: Drop Test (Durability)

ER07: Sharp Edge Radii (Safety)

Material: PLA PRO (PolyLite PLA PRO)

Tensile Strength: ~50 MPa

Heat Resistance: Up to 100°C

Price: \$24.99 for 1kg spool

Justification: The Polymaker PLA PRO filament was selected based on its strength and durability, which are crucial for the robot's frame to withstand impacts and drops (ER05). With a tensile strength of 50 MPa and heat resistance up to 100°C, this filament ensures the robot can endure typical classroom handling and remain operational under various environmental conditions (ER07). Moreover, the material is rigid, supporting the design's dimensional constraints (ER01).

3. WH148 Potentiometer (5K Ohm)

ER05: Drop Test (Durability)

ER10: Visual Feedback Interface (User interaction for control adjustments)

Resistance: 5k Ohm, linear potentiometer

Dimensions: 15mm shaft

Price: \$6.59 for 10 pieces

Justification: The potentiometer is used for manual control adjustments (e.g., speed or feedback parameters), aligning with the interactive interface requirement (ER10). The potentiometer's 5k Ohm resistance and durability make it suitable for frequent classroom use without significant wear (ER05). This allows students to engage directly with the robot's feedback control systems.

4. ELEGOO UNO R3 Board (Arduino-Compatible)

ER04: Control Hardware (Processing capability for control algorithms)

ER06: Electrical Safety (No exposed electrical components)

Microcontroller: ATmega328P

Input/Output Pins: 14 digital I/O, 6 analog I/O

Price: $16.99

Justification: The Arduino Uno is ideal for this educational robot as it provides sufficient processing power for basic control algorithms, such as motor control and sensor readings (ER04). It is a widely-used platform, easy for students to learn, and it supports safe electrical design (ER06), as the components are housed in an insulated, low-voltage configuration.

5. UL Listed 12V 2A AC DC Power Supply Adapter

ER03: Power Source (Ensuring reliable and safe power supply)

Voltage: 12V DC

Current: 2A

Length: 10 feet

Price: $9.99

Justification: The 12V 2A power supply provides the necessary power for the DC motors and control electronics. The power supply was chosen to ensure the system operates within its electrical specifications, supporting the system's energy consumption (ER03).

6. DRV8871 Motor Driver Module

ER04: Control Hardware (Ensuring control of motor actions)

Current Capacity: 3.6A max per motor

PWM control: Yes, for motor speed regulation

Price: $13.88 each, total cost for 2 modules: $27.76

Justification: The DRV8871 motor drivers were selected for their high current handling capability (3.6A per motor), which ensures reliable control of the DC motors under varying load conditions. These drivers allow precise speed control through PWM (Pulse Width Modulation), essential for implementing feedback control (ER04).

All components were selected through a systematic evaluation based on their ability to meet specific engineering requirements and ensure the final robot's performance aligns with the customer requirements. Quantifiable specifications (e.g., motor torque, power consumption, material strength) and well-known part specifications (e.g., motor driver current ratings, Arduino compatibility) were used to make informed decisions, minimizing risks and ensuring feasibility. Each part's performance was also benchmarked against similar systems where applicable, ensuring we selected the most effective and reliable options available.

4.4 Concept Selection

Robot 1 Benchmarking

Benchmarking for Robot 1 was primarily comparative to other similar state-of-the-art systems on the market as the robot design is fairly popular and there is a lot of information to work off of when developing an original design.

The systems selected for comparison include Shay Sackett's Pendulum Robot, the Self-Balancing Interactive Robot, and the Instructible Line Following Robot. The first two benchmarks are more direct comparisons of pendulum robots for which the exact system and components can be compared, while the third serves a more conceptual comparison for designing interactivity.

Sackett's Pendulum Robot: 2-Wheeled Pendulum robot capable of automatic balancing mid-operation, Provides solid baseline design for a 2-Wheeled Pendulum robot, Establishes basic ideas, equations, principles, and systems that go into pendulum robots

Self-Balancing Interactive Robot: 2-Wheeled Pendulum robot capable of receiving voice commands and interacting with external systems, Proof of concept of a voice-controlled pendulum robot for good interactivity, Presents additional options for control mechanisms for student interactivity, more complicated but promising

Instructible Line Following Robot: Simple 3 wheeled line following robot, easy system to assemble and explain, interactivity by manually drawing the line the robot follows is desirable for K-12 students, When designing the pendulum robot, seeking to provide interactivity comparable to this system is desirable.

The concept selection for Robot 1, the pendulum robot frame, involved evaluating multiple frame design concepts developed individually by team members. These concepts were assessed primarily against the customer and engineering requirements related to durability, cost, functionality, aesthetics, and manufacturability.

Frame Design Concepts

Vertical Multi-layer Frame with Double Pendulum on Single Axis

Pros: Well-organized component placement; aesthetically customizable to resemble a traditional robot.

Cons: Reduced stability due to increased height; higher cost due to larger frame size.

2-Wheel Robot with Integrated Pendulum

Pros: Simple, streamlined design with fewer parts; cost-effective due to fewer components; no separate pendulum needed.

Cons: More complex control algorithms and programming required; less aesthetic appeal; potentially lower structural integrity.

4-Wheel Cart with Rear Compartment and Central Pendulum Stick

Pros: Simple and stable design; organized back compartment; space for components.

Cons: Physically more material than necessary to stablize on a single axis

Rectangular Cart with Pendulum Beam and Table Safety Sensors

Pros: Complete containment of components; sensors to prevent falling off tables; stable.

Cons: More complicated than other designs

Streamlined Angular Frame with Impact-Resistant Design

Pros: Designed to withstand impacts (meeting drop test requirements); pendulum centrally mounted; integrated interactive elements.

Cons: Will likely be more expensive to manufacture and the design leaves exposed wires.

Selection Criteria

The concepts were evaluated based on:

Durability and Safety: Stability of the frame, ability to withstand drops and impacts (ER05, ER06).

Cost: Frame complexity and material use (ER11).

Functionality: Ease of integration with motors, sensors, and electronics.

Aesthetic Appeal: Visual appeal and alignment with the kid-friendly design (CR08).

Manufacturability: Simplicity and feasibility of mass production.

Criteria	Weight	Concept 5	Concept 4	Concept 3	Concept 2	Concept 1
Durability	0.25	2	1	3	3	4
Cost	0.20	2	4	3	3	3
Functionality	0.20	3	2	3	3	4
Aesthetic Appeal	0.15	4	2	3	3	4
Manufacturability	0.20	2	4	3	3	4
Total Score	1.00	2.45	2.65	3.00	3.00	3.70
FInal	Poor	Fair	Fair	Good	Good	Good

Scores: 1 = Poor, 2 = Fair, 3 = Good, 4 = Excellent

Based on the weighted scores, Concept 5 (Streamlined Angular Frame) was selected as the final design due to its balance of durability, impact resistance, functionality, and aesthetic appeal, while maintaining manufacturability suitable for mass production.

Summary and Next Steps

The double arm single-axis pendulum (Concept 1) meets the key engineering and customer requirements, particularly excelling in impact resistance and user interaction integration. The final CAD model reflects this design with integrated safety features and ergonomic form factor, ready for further prototyping and detailed engineering analysis.

4.4.1 Pugh Chart

To decide on a frame design for our pendulum robot, the following Pugh chart was developed using the established criteria. Each robot concept was evaluated against weighted performance categories such as Base Type, Pendulum Type, Stabilization Axis, Material Notes, and other key features. The weighting was determined based on the relative importance of each criterion to the overall success and functionality of the robot.

Three top design options were compared:

- A 2-Wheel Robot with Integrated Pendulum (Option A)
- A Vertical Multi-Layer Frame with Double Pendulum (Option C)
- A Streamlined Angular Frame with Impact-Resistant Design (Option E)

After scoring and weighing, Robot Option C emerged as the top candidate, achieving the highest total weighted score. This option stood out due to its strong performance in critical categories such as material robustness, pendulum design, and integrated features. While it may present higher manufacturing costs and some design trade-offs (e.g., exposed wiring), its structural integrity and functionality align best with our design goals.

The selection process is supported by the CAD model of the final concept (see next section), which includes balloons and leader-line notes identifying all major subsystems such as the base frame, pendulum assembly, onboard electronics, power unit, and interactive touchscreen components.

Top 3 Robot Options	WEIGHT 1-5	Robot Option A		Robot Option C		Robot Option E	
		BASE SCORE	WEIGHTED	BASE SCORE	WEIGHTED	BASE SCORE	WEIGHTED
Base Type	3	3	9	5	15	5	15
Pendulum Type	4	2	8	5	20	5	20
Stabilization Axis	3	3	9	4	12	4	12
Touchscreen	2	1	2	3	6	4	8
Material Notes	5	3	15	4	20	4	20
Sensor	1	3	3	4	4	3	3
Power	3	3	9	5	15	3	9
	TOTAL WEIGHTED SCORE		55	·	92	·	87

Figure 12 - Pugh Chart comparing top 3 Pendulum Frame Designs

4.4.2 Final Design CAD Drawing

After carefully considering each sub-system of the pendulum robot, the final design concept we came up with can be seen in the below figure.

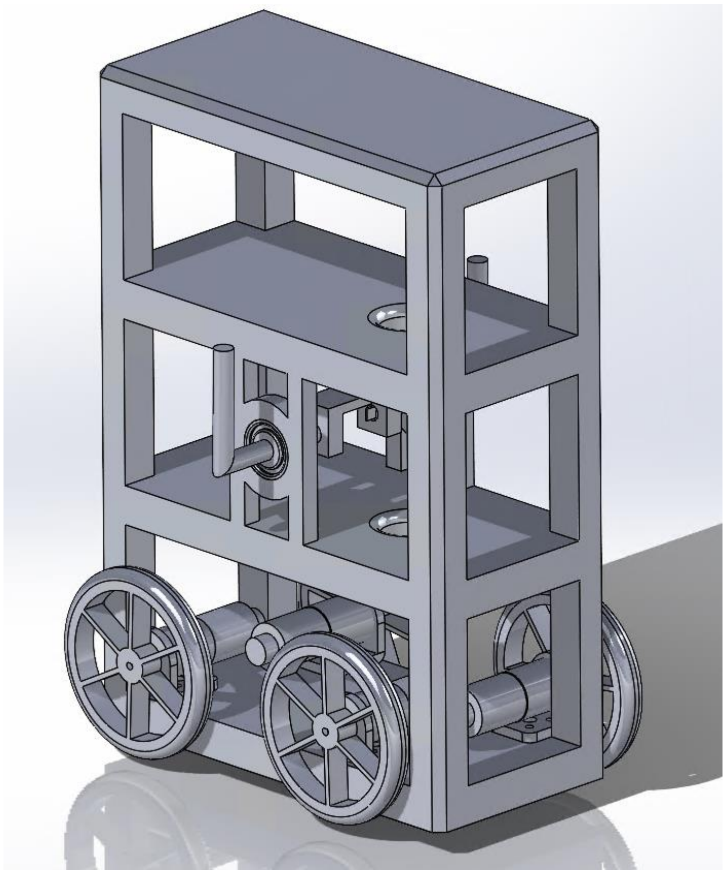


Figure 13 – Robot 1 Final Design CAD drawing

Based on the given requirements, the completed calculations, and our evaluations of similar designs, this final design feels the most capable of performing the required functions and satisfying the customers' desires for the system. Its multi-layered frame allows for ample room to store and separate different sub-systems for ease of access and organization and has premade holes to allow wiring between layers. Its frame dimensions both stay within the customers' required dimensions, as well as possess the necessary thickness to be able to survive a fall test. The pendulum itself is compatible with the selected potentiometers and offers 270 degrees of movement, and the motors can produce the necessary torque to move the robot's weight and facilitate the pendulums stabilization.

5 Robot #2 Design Concepts

5.1 Functional Decomposition

5.1.1 Ball-on-Plate Robot

The main function of the Ball-on-Plate Robot is to keep a ball at a designated position or achieve stable motion by adjusting the angle of the platform. Its functional decomposition can be divided into the following levels:

- **Sensing Function**: Use an IMU, camera, or infrared sensors to obtain the ball's position and motion state.
- **Control Function**: An Arduino controller executes dual-axis PID feedback control (X and Y directions), calculating the required angle adjustments.
- **Actuation Function**: Dual-axis servo motors tilt the platform to achieve real-time position correction.
- **Safety Function**: Software limits and power protection prevent the platform from exceeding safe motion ranges.

The importance of this functional decomposition lies in its direct alignment with the educational objectives of the project: demonstrating stability and control theory through a complete "input–control–output" loop, enabling students to intuitively understand closed-loop control systems.

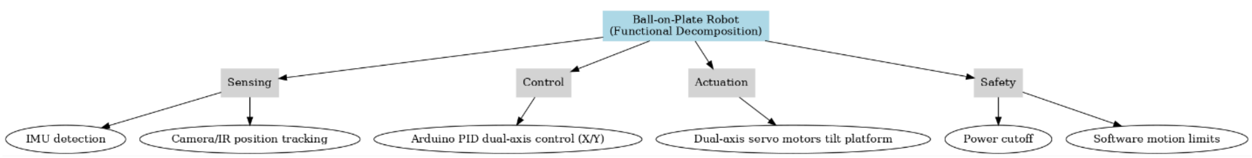


Figure 14 - Ball-on-Plate Robot Functional Decomposition

5.1.2 Magnetic Levitation Robot

The core task of the Magnetic Levitation Robot is to achieve stable levitation of a ball using electromagnetic force. Its functional decomposition is as follows:

- **Sensing Function**: A Hall-effect sensor detects the ball's position and height changes in real time.
- **Control Function**: A PID controller regulates the current of the electromagnetic coil to maintain the ball at the desired height.
- **Actuation Function**: The electromagnetic coil generates a controllable magnetic field, counteracting gravity to stabilize the ball.
- **Safety Function**: Overcurrent protection and automatic power cutoff mechanisms prevent coil overheating or damage.

The significance of this functional decomposition is that it illustrates the integration of electromagnetism and control theory. Students can not only observe how "invisible forces" manipulate an object but also gain an experimental understanding of the challenges of nonlinear control systems.

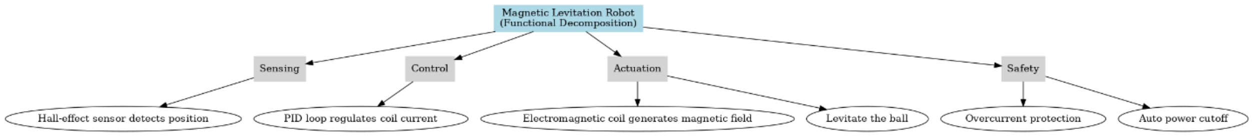


Figure 15 - Magnetic Levitation Robot Functional Decomposition

5.1.3 Reaction Wheel Robot

The primary goal of the Reaction Wheel Robot is to maintain or restore the robot's balance using an internal flywheel. Its functional decomposition includes:

- **Sensing Function**: An IMU or gyroscope collects real-time orientation and angular velocity data.
- **Control Function**: An Arduino or embedded controller runs a feedback algorithm (e.g., PID) to determine the speed and direction of the flywheel.
- **Actuation Function**: A high-speed motor drives the flywheel, and through conservation of angular momentum, the robot stabilizes itself and corrects its posture.
- **Safety Function**: Torque limiting and emergency stop functions prevent hazards from high-speed operation.

The importance of this functional decomposition lies in its demonstration of higher-level control principles—using momentum exchange to achieve stability. It also provides a highly interactive teaching experience, where students can physically push the robot and observe its automatic recovery of balance.

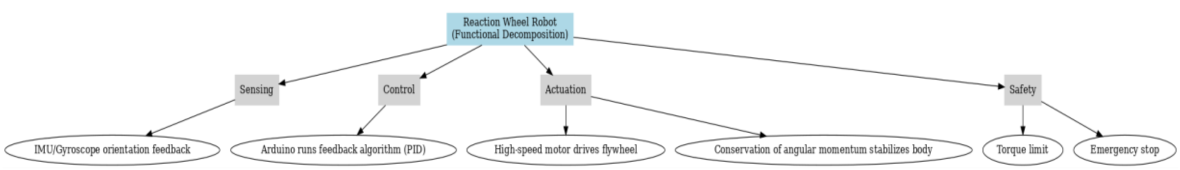


Figure 16 - Reaction Wheel Robot Functional Decomposition

5.2 Concept Generation

To explore potential designs for Robot #2, the team used a structured morphological-chart approach to break down the problem into top-level functions and sub-system decisions. The top-level goal for this robot was to create an interactive, educational demonstration of control systems that could safely operate in a classroom setting and clearly illustrate engineering principles such as feedback, stability, and actuation.

5.2.1 Top-Level Concept Exploration

At the top level, several different educational tasks were considered:

- **Maintain a state** – demonstrate balance or stability (e.g., Reaction Wheel Robot).
- **Complete a challenge** – maintain control of an object or variable (e.g., Ball-on-Plate, Magnetic Levitation Robot).
- **Play a game** – interact directly with students through competition (e.g., Hockey Robot).

Each concept was evaluated using the morphological chart, which identified feasible options for interactivity, base structure, actuation, sensing, and control. The chart allowed the team to systematically combine features into full-system concepts while keeping designs consistent with educational and engineering requirements.

5.2.2 Subsystem Concept Exploration

Sub-assemblies such as base structure, actuation type, sensors, and controller hardware were analyzed individually.

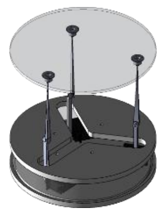
- **Base Structure:** stationary tabletop frames, wheeled platforms, and enclosed cubes were considered.
- **Actuation:** options include servo motors, DC motors, electromagnets or flywheels.
- **Sensors:** IMUs, cameras, Hall-effect sensors, and line sensors were compared for feedback accuracy and cost.
- **Controllers:** Arduino and Raspberry Pi platforms were benchmarked for processing speed and ease of programming.

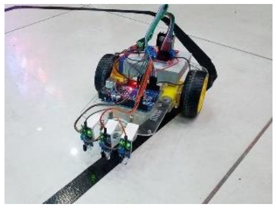
After combining these subsystem decisions into complete system concepts, five candidate robots were generated.

5.2.3 Concept Summaries and Evaluation

The table below summarizes the five main concept candidates for Robot #2, including their initial advantages and disadvantages. Concepts eliminated early (e.g., Line-Following Robot, Hockey Robot) are documented here as well.

Robot Concept	Robot Design	Advantages (Pros)	Disadvantages (Cons)

Ball-on-Plate Robot	 *Figure 17.1. Ball-on-Plate robot concept* [57].	– Demonstrates feedback and control principles effectively. – Safe, classroom-friendly tabletop design. – Visually intuitive for K–12 audiences. – Straightforward servo and IMU implementation.	– Requires precise dual-axis stabilization. – Camera/IMU calibration can be complex. – Sensitive to external vibration.
Magnetic Levitation Robot	 *Figure 17.2. Magnetic Levitation robot concept* [58].	– Visually striking; shows electromagnetic control clearly. – Strong link to electromagnetism curriculum. – Compact stationary setup.	– Requires high precision Hall-sensor tuning. – Limited motion range. – Possible coil overheating during long demos.
Reaction Wheel Robot	 *Figure 17.3. Reaction Wheel robot concept* [59].	– Compact enclosed design ensures safety. – Demonstrates momentum exchange and balance recovery. – Highly interactive—students can push and observe correction. – Strong control-systems learning value.	– Complex internal flywheel tuning. – Demands accurate PID design. – Higher build difficulty.
Hockey Robot	 *Figure 17.4. Hockey robot concept* [60].	– Highly interactive; lets students play directly. – Demonstrates motion control and sensing integration. – High engagement factor.	– Mechanically complex and space-intensive. – Costly motors/actuators. – Requires larger demonstration area.

Line-Following Robot	 *Figure 17.5. Line-Following robot concept* [61].	– Simple, low-cost autonomous system. – Reliable and easy to program. – Good introduction to basic control loops.	– Minimal student interaction. – Limited educational depth compared with others. – Does not highlight advanced control topics.

5.2.4 Discussion

The morphological-chart analysis and concept comparison helped the team determine that the Ball-on-Plate, Magnetic Levitation, and Reaction Wheel Robots offered the strongest combination of educational value, interactivity, and technical feasibility. The Hockey and Line-Following Robots, while creative, were less aligned with project constraints (particularly cost, safety, and required educational complexity) and were therefore excluded from further development.

These results form the foundation for concept selection and mathematical modeling in later sections, where each remaining design will be quantitatively analyzed against the project's engineering requirements.

5.3 Selection Criteria

Ball on plate, the Magnetic Levitation Robot, and the Reaction Wheel Robot are the top three choices for team RTV. The other ideas that follow scored the lowest: Line Robot and Hockey Robot. These ideas are rooted from the engineering requirements; dimensions, power source, incorporating Arduino/Raspberry Pi, following the U.S. CPSC guidelines, programming diagrams, and pass the drop test. These are rated from a 0-10 scale with the score of 10 being the best choice in each category. The total weight of the scale in each category adds up to 1. The total of each category for the five ideas average is taken, and that determines the final score for each design.

Dimensions for Robot #2 would be a 14” by 10” by 5”, the size of a shoebox, and operate within a 20” by 20” space. The power source would be dependent on a single battery that would operate the entire robot within an hour to an hour and a half time span. The size of the battery will also determine the outcome of the robot's performance. Raspberry Pi will allow the flexibility of programming and offer the touchscreen feature. On the other hand, Arduino offers a more efficient way of storing code and having a higher performance of power output. This decision on which microcontroller would be used with Robot #2 will be discussed more with the client on October 20th. The design of Robot #2 will be regulated with the U.S. CPSC Guidelines. This is focused on the design elements of children's toys with other requirements such as no exposed batteries or wires, hazardous edges, etc. The programming diagrams describe how easy the system will be upon creating a flow chart. The drop test is the final engineering requirement that will test the durability of the robot from a 30-inch height from a concrete surface. The robot also has to be functional after this test.

The Ball on Plate (A.1.) is the top design idea for robot #2 scoring 8.25. It scored the highest on the programming diagrams side with the score being 9. It scored low on the drop test/durability section with a score of 7. The Reaction Wheel (A.1.) is the second highest system with a score of 8.15. It scored the highest on dimensions, U.S. CPSC guidelines, durability, and integration with the electrical engineering subsystems with scores of 9. The lowest sector, scoring at 7 are power efficiency and manufacturing costs. The Magnetic Levitation Robot (A.1.) scored 7.75, ranking it in third place. The highest scores were the dimensions and programming diagrams with a score of 9. The lowest it scored were the manufacturing costs and integration with the electrical engineering subsystems with a score of 7. The Line Following Robot (A.1.) ranked fourth and scored 7.95. It scored the highest in dimensions, power efficiency, and manufacturing costs with a 9 score. The lowest category is the program diagram, and it scored a 5. The Hockey Robot (A.1.) came in fifth place with a score of 7.25. It scored the highest in manufacturing costs with a score of 8 and the lowest score is a programming diagram with a score of 6.

5.4 Concept Selection

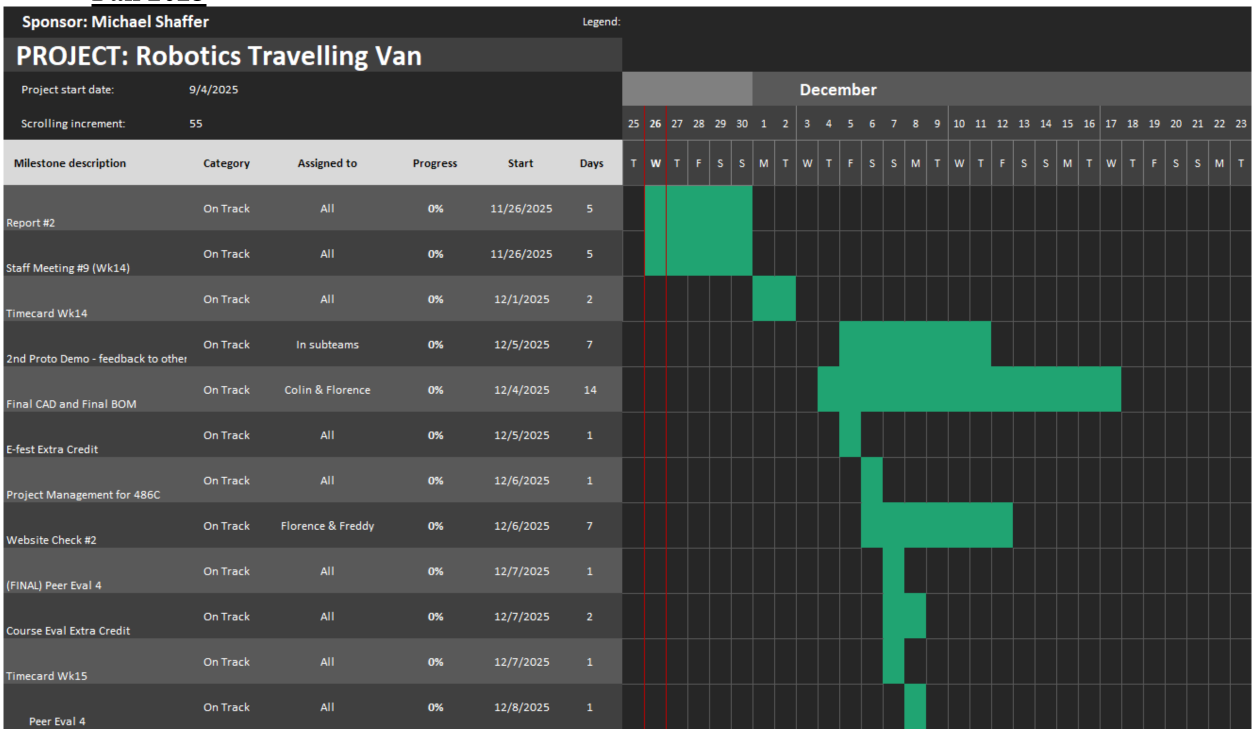
After comparing these concepts, the Robot #2 sub team found that the top three designs are the Ball on Plate, Magnetic Levitation, and the Reaction Wheel. They are the best options that align with the project goals and engineering requirements. The Ball on Plate System offers strong educational value with clear visualization. It allows students to see how control algorithms keep a moving object stable. Magnetic Levitation Demonstrator has a strong “wow” factor and demonstrates rapid real-time control response, though it may require faster electronics. Reaction Wheel Stabilizer is highly educational but may exceed current schedule constraints due to more advanced control theory and precise hardware requirements.

Moving forward, these top three concepts that are selected will be presented to the client. After deciding on one of the options, team RTV sub team for Robot #2 will proceed to the design process and more research will be conducted.

6 Schedule and Budget

6.1 Schedule

Fall 2025



Sponsor: Michael Shaffer

PROJECT: Robotics Travelling Van

Project start date: 9/4/2025

Scrolling increment: 55

Milestone description	Category	Assigned to	Progress	Start	Days
Report #2	On Track	All	0%	11/26/2025	5
Staff Meeting #9 (Wk14)	On Track	All	0%	11/26/2025	5
Timecard Wk14	On Track	All	0%	12/1/2025	2
2nd Proto Demo - feedback to other	On Track	In subteams	0%	12/5/2025	7
Final CAD and Final BOM	On Track	Colin & Florence	0%	12/4/2025	14
E-fest Extra Credit	On Track	All	0%	12/5/2025	1
Project Management for 486C	On Track	All	0%	12/6/2025	1
Website Check #2	On Track	Florence & Freddy	0%	12/6/2025	7
(FINAL) Peer Eval 4	On Track	All	0%	12/7/2025	1
Course Eval Extra Credit	On Track	All	0%	12/7/2025	2
Timecard Wk15	On Track	All	0%	12/7/2025	1
Peer Eval 4	On Track	All	0%	12/8/2025	1

Spring 2026 tentative schedule

- *Phase 1 (week 1 – 4)*
  - Begin planning for 486C agenda, Gantt,
  - Clarify roles and responsibilities for team
  - Continue iterating on prototypes
    - Iteration #2 for robot 1
    - Ball-on-plate for robot 2
  - Clarify expectations and goals with sponsors/mentors
- *Phase 2 (week 5 – 14)*
  - CAD and math models for final project deliverables
  - Improve final robot versions
  - Prepare final presentations
- *Phase 3 (week 15 – 16)*
  - Present final robots
  - Present final capstone project

6.2 Budget

The total project budget allocated for the Robotics Traveling Van capstone project is $5,000, with an additional $500 fundraising requirement per course policy. These funds support the complete development process, including prototyping, final design fabrication, testing, travel for K–12 outreach demonstrations, and all other required expenses.

Throughout the semester, the team has spent $436.69 on direct materials for Robot #1 and Robot #2 combined, leaving significant remaining budget to accommodate further iterations, part replacements, and future testing needs. A projected cost breakdown is shown below to illustrate how the remaining funds will be allocated across the remaining phases of the project.

6.2.1 Budget Allocation Summary

Budget Category	Estimated Allocation	Description
Prototyping Materials	$800	Early-stage electronics, 3D-printed parts, wiring, and mechanical hardware
Final Design Build	$1,200	High-quality components, improved sensors, machining, carbon-fiber upgrades
Electronics & Control Hardware	$1,000	Stepper motors, drivers, microcontrollers, PCBs, connectors
3D Printing & Manufacturing	$600	PLA+, structural prints, in-house fabrication
Travel & Outreach	$300	Transport cases, demonstration materials for K–12 visits
Testing & Tools	$300	Measurement tools, calibration equipment
Contingency (10%)	$300	Covers unexpected failures, redesigns, or emergency orders

Total Estimated Spending	$4,500	Within the $5,500 available budget

6.3 Robot #1 Bill of Materials (BoM)

#	Component	QTY.	Purchased vs. Manufactured	Vendor	Part Number	Material	Unit Cost	Lead Time
1	Yahboom GM3865-520 DC Metal Gear Motor with Hall Encoder	4	Purchased	Amazon	SKU: 6000400521	Steel, Aluminum	$14.99	5-7 days
2	10Pcs WH148 Potentiometer 5K Ohm Variable Resistors	1	Purchased	Amazon	B0DSQ23DG8	Aluminum, Copper, Silver	$6.59	5-7 days
3	ELEGOO UNO R3 Board ATmega328P with USB Cable(Arduino-Compatible) for Arduino	1	Purchased	Amazon	B01EWOE0UU	Mixed	$16.99	5-7 days
4	UL Listed 12V 2A 10FT AC DC Power Supply Adapter with Switching Adapter	1	Purchased	Amazon	B0D458YH4S	Mixed	$9.99	5-7 days
5	Teyleten Robot DRV8871 Motor Driver DC Motor Driver H-Bridge PWM Driver Module 3.6A 3pcs	2	Purchased	Amazon	B0DN66P9XW	Mixed	$13.88	5-7 days
6	M3 - 8mm screws	8	Purchased	Home Depot	837981	Zinc	$2.25	1-2 days
7	M3-0.5 Zinc Hex Nut 5-Pieces	2	Purchased	Home Depot	862798	Zinc	$3.75	1-2 days
8	RTV_Cage_03.sldprt	1	Manufactured	In-House	N/A	PLA	$5.50	1-2 days
9	Breadboard / Proto PCB	1	Purchased	Amazon	EDGELEC-PCB01	Fiberglass	$7.99	5-7 days
10	Dupont Wire set	1	Purchased	Amazon	Elegoo-EL-CP-004	PVC-Copper	$6.98	5-7 days

6.4 Robot #2 Bill of Materials (BoM)

#	Component	Qty	Purchased vs. Manufactured	Vendor	Part Number	Material	Unit Cost	Lead Time

1	NEMA 17 Stepper Motor (59 N·cm)	3	Purchased	StepperOnline	17HS19-2004S1	Steel/Aluminum	$13.99 ea	5–7 days
2	TMC2208 Stepper Driver	3	Purchased	Amazon	FYSETC-TMC2208	PCB	$8.99 ea	3–5 days
3	Teensy 4.1 Microcontroller	1	Purchased	PJRC	TEENSY-4.1	PCB	$34.95	5–10 days
4	12V 5A DC Power Supply	1	Purchased	Amazon	ALITOVE-12V-5A	Mixed	$13.99	3–5 days
5	Resistive Touchpad (7”)	1	Purchased	Amazon	Waveshare-7-TP	Glass/ITO	$21.99	5–7 days
6	Stepper-shaft Coupler (5mm–Custom Plate Link)	3	Purchased	McMaster-Carr	6408K11	Aluminum	$7.63 ea	3–4 days
7	RC Tie-Rod Ball Joints	3	Purchased	Amazon	Traxxas-5347	Steel/Plastic	$10.49 set	3–5 days
8	Linkage Arms (Stage 1)	3	Manufactured (3D printed)	In-house	N/A	PLA+	$1.50 ea (material)	1–2 days
9	Linkage Arms (Stage 2)	3	Manufactured (3D printed)	In-house	N/A	PLA+	$1.00 ea	1–2 days
10	Platform Frame	1	Manufactured (3D printed)	In-house	N/A	PLA+	$4.50	1–2 days
11	Base Plate	1	Manufactured (3D printed)	In-house	N/A	PLA+	$6.00	1–2 days
12	Heat-set Threaded Inserts (M3)	20	Purchased	McMaster-Carr	94180A331	Brass	$0.18 ea	3–4 days
13	M3 Socket Head Screws	40	Purchased	McMaster-Carr	91290A112	Steel	$0.10 ea	3–4 days
14	Breadboard / Proto PCB	1	Purchased	Amazon	EDGELEC-PCB01	Fiberglass	$7.99	3–5 days
15	Dupont Wire Set	1	Purchased	Amazon	Elegoo-EL-CP-004	PVC/Copper	$6.98	3–5 days
16	Zip Ties (Cable Mgmt.)	1 pack	Purchased	Amazon	HSX-Z100	Nylon	$3.99	3–5 days
17	Rubber Feet	4	Purchased	Amazon	SoftTouch-4214195N	Rubber	$4.29	3–5 days
18	E-Stop Rocker Switch	1	Purchased	Amazon	Twidec-RS-101	Plastic/Metal	$7.49	3–5 days
19	Inline Fuse (5A)	1	Purchased	Amazon	Nilight-50019R	Mixed	$5.99	3–5 days

7 Robot #1 Design Validation and Initial Prototyping

7.1 Failure Modes and Effects Analysis (FMEA) For Robot #1

[Discuss your team’s FMEA, including critical potential failures and how your design mitigated these potential failures. Discuss the risk trade-off analysis that your team has performed.]

Sub assembly	Component	Function	Potential Failure Mode	Potential Effect(s) of Failure	S	Potential Cause(s) / Mechanisms	O	Current Controls	D	RPN	Recommended Action
Mechanical	Pendulum Robot Frame	Support for subsystems	Frame cracks or misaligns	Robot tilts, components misalign	9	Weak material, impact/collision	4	Visual inspection, load tested	3	108	Reinforce stress points
Mechanical	Motor Bracket	Secure motor to frame	Bracket loosens or fractures	Motor misalignment, shift system	8	Vibration, improper mounting	4	Torque inspection	3	96	Increase wall thickness
Mechanical	Pendulum Bearings	Support pendulum rotation	Bearing seizing, friction	Pendulum movement restricted, poor control	8	Dust ingress, misalignment, wear	3	Rotation smoothness test	4	96	Use sealed bearings, lubrication
Mechanical	Motor Bracket Screws	Fasten brackets to frame	Screws loosen, stripped threads	Motor misalignment, detachment	8	Vibration, over-torque	4	Visual inspection, checks	3	96	Use thread-locker, replace if possible
Pendulum	Pendulum Assembly	Provides body for complete balance	Arm bends or loosens	Pendulum unstable, uncontrollable	9	Weak joint, fatigue	4	Visual detection, test	3	108	Strengthen joints, secure fasteners
Pendulum	Potentiometer	Measures pendulum angle	Incorrect readings	Robot misestimate balance	8	Loose mounting, noise, wear	3	Calibration, shielded wires	4	96	Secure mounting, add filtering
Motors	L-Type 520 Motors	Provide needed torque	Motor stalls or overheats	Robot falls, uncontrollable	10	Overload, undersized motor	5	Bench test under load	3	150	Verify torque, higher rated motors
Motors	67.5 mm Wheels	Transfer motor torque to ground	Wheels slip or detach	Robot cannot move or balance	9	Loose fits, low friction	4	Visual inspection, test	3	108	Improve tire grip, add lock nuts
Control	Arduino	Processes sensor data, controls motors	Software crash, voltage reset	Robot stops, behaves erratically	10	Power fluctuation, coding bug	3	Watchdog, testing	4	120	Add capacitor, software recovery
Battery	Battery	Supplies voltage/current	Battery fails during operation	Robot shuts off mid-test	9	Low capacity, discharge	5	Voltage check before use	3	135	Use higher capacity, low voltage cutoff
Other (Tool)	Breadboard	Distributes connections	Intermittent connections	Random intermittent control	8	Poor contact, vibration	4	Visual continuity test	3	96	Transition to soldered board, secure wires

7.1.1 Key High Risk Items and Mitigation

The highest risk items in the system come from the components that can directly cause the robot to fall or behave unpredictably. The motors represent the most critical risk because their failure can immediately cause the robot to lose balance. The current motors show the highest RPN value. If they stall or overheat, the cart cannot generate enough acceleration to keep the pendulum upright. The recommended mitigation is to select motors with higher torque capacity, improve heat dissipation, and reduce friction in the drivetrain. The Arduino is another high risk item because a software crash or voltage drop can stop the control loop. This risk can be reduced by improving power stability, adding capacitance, and enabling a reliable watchdog reset system. The battery also poses a significant risk since a mid operation voltage drop can shut the robot down unexpectedly. A higher capacity battery with a secure connection and low voltage cutoff will reduce this problem.

Structural components such as the frame, pendulum assembly, and wheels also have notable risk because they influence alignment and stability. A cracked frame, loose motor bracket, or slipping wheel can cause poor control or inconsistent movement. These risks can be mitigated by reinforcing structural parts, improving material selection, tightening mechanical tolerances, and performing regular inspection. The potentiometer and breadboard are lower risk but still important because poor signal quality or loose wiring can lead to inaccurate angle readings or intermittent power. Securing wiring, improving mounting, and transitioning away from the breadboard will reduce these issues. Overall, the main mitigation strategy is to strengthen mechanical parts, upgrade the drivetrain, and improve electrical reliability.

7.1.2 Risk Trade Off and Design Decisions

The design of the prototype reflects a balance between weight, complexity, cost, and performance. Lighter materials such as printed plastics were chosen for the frame and pendulum to keep the robot responsive, but this increases the risk of cracking or bending. Reinforcing these parts will add weight, so the team must choose between structural strength and motor effort. Stronger materials improve reliability but may require even more powerful motors, which will increase cost and energy consumption. This trade off will influence the next design iteration where priority will likely shift toward stiffness and durability to achieve stable balancing.

The decision to use the initial motor set allowed quick prototyping but created limitations in torque. Upgrading motors will significantly improve stability, but it will also introduce new design constraints such as larger brackets, higher current draw, and added system mass. Similarly, choosing a breadboard for early testing made wiring flexible but introduced connection issues. Moving to a soldered board will increase reliability but reduce flexibility for rapid changes. The Arduino control system will also need greater power stability, and adding capacitors and monitoring circuits slightly increases complexity. Each design choice requires weighing simplicity and speed of development against long term stability and performance. The next iteration of the robot will focus on improving reliability even if it increases component count or system mass.

7.2 Initial Prototyping for Robot #1

1. For the first prototype for robot 1, the question we had was, does our logic work such that we only need to fine tune the PID controller on the arduino. The other question was if so, do our motors have enough torque to move the weight of the robot such that it *can* erect a pendulum between 45 degrees on the left and right.
2. The prototype showed that the general control logic functions as expected: the pendulum responds in the correct direction to errors, and the sensor readings are reliable enough for closed-loop control. However, the tests revealed that the motors deliver *just barely enough* torque to move the robot with authority. They can initiate a swing-up, but they struggle to correct quickly

and consistently when the pendulum approaches vertical, especially if there is any additional friction or misalignment in the system.

3. This result informs the next design iteration in three ways:

    a. **Motor and drivetrain improvement:**
    We plan to wire to the higher-torque motors a more direct and stable voltage/current input so the motors can help ensure the cart can generate the necessary horizontal force to stabilize the pendulum reliably.
    b. **Mechanical refinement:**
    Because small misalignments and friction from the potentiometer, the pendulum will be made heavier to allow time for the robot to react on time. In the coming semester, there will be a complete redesign of the robot body.
    c. **Control tuning and sensing enhancements:**
    With improved motors, we can retune the PID gains for more aggressive yet stable control. Additional filtering of the angle signal (e.g., complementary filtering or averaging) will be added to avoid noise-induced oscillations.

Overall, the prototype confirmed that the control architecture is viable, but the hardware—especially the motors—must be strengthened before stable inverted balancing is achievable.

7.3 Other Robot #1 Engineering Calculations

Andres:

Component	Voltage Requirement	Current Requirement
DC Motor (NEW) w/ encoder	6–12 V	0.5 – 2 A
Encoder / Tracking	5 V	30 mA
Potentiometer	5 V	1 mA
Motor Driver	5 V	50 – 100 mA
Arduino Uno	5 V	70 mA
Power Source	6–12 V (5 V for logic)	9 Ah

$$P_{total} = \sum_{i=1}^{n} (V_i \times I_i)$$

$$C_{battery} = \frac{I_{total} \times t_{runtime}}{\eta}$$

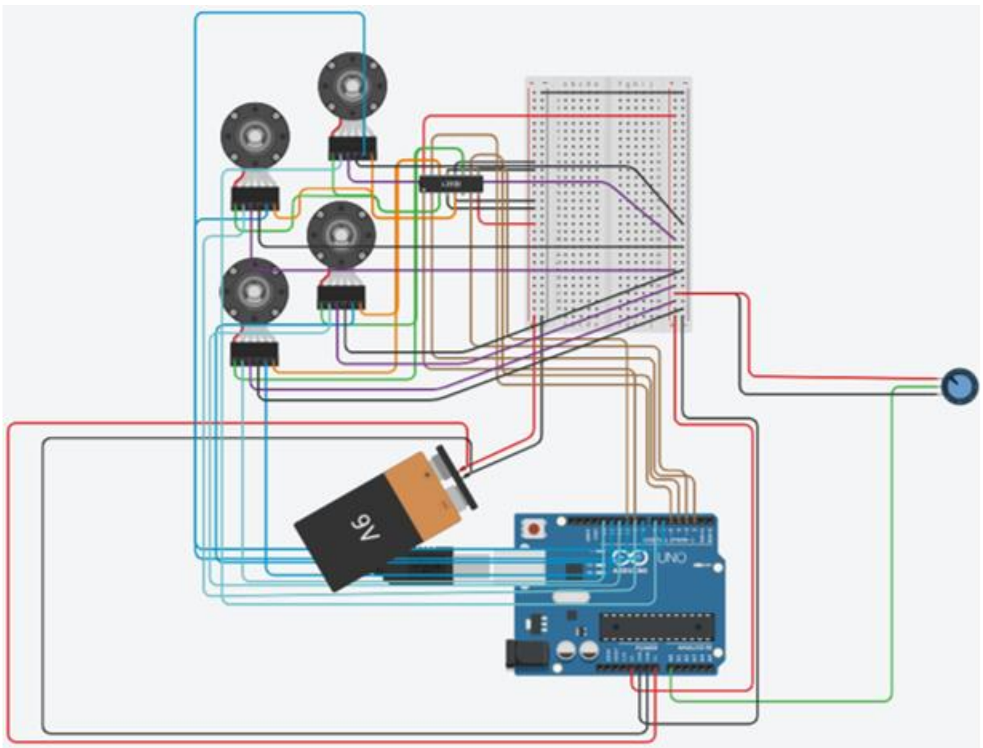


Figure 18.1

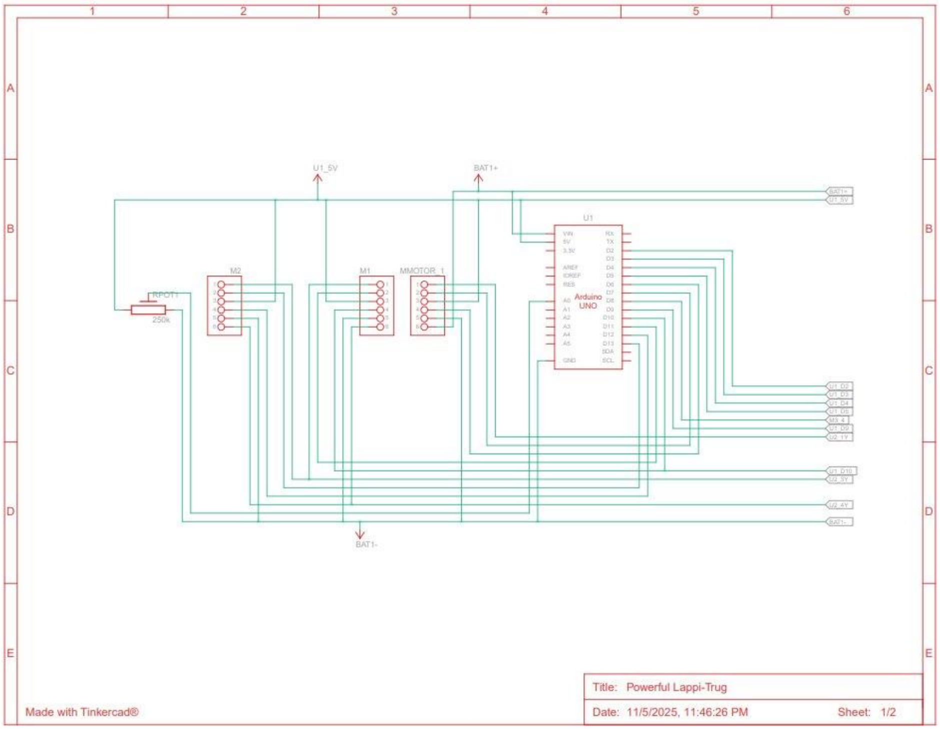


Figure 18.2

Kirchoff’s Voltage Law

Colin:

Equation for Force generated by wheels

$$F = \frac{T}{R}$$

Equation for the Cart (Horizontal Motion)

$$(M + m)\ddot{x} + ml\ddot{\theta}\cos(\theta) - ml\dot{\theta}^2\sin(\theta) = f$$

Equation for the Pendulum (rotational motion)

$$l\ddot{\theta} + \ddot{x}\cos(\theta) - gsin(\theta)$$

- Variables
  - T = 4.4 [kg×cm] = 0.4314926 [N×m] (motor torque)
  - R = 0.03375 [m] (wheel radius)
  - M = 3 [kg] (cart mass)
  - m = 0.06 [kg] (pendulum mass)
  - l = 0.06 [m] (pendulum length)
  - g = 9.81 [m/s^2] (gravity constant)
  - Θ = 135° = 2.356 [rads] (initial angle)
  - $\dot{\theta}$ = 0 [$rads/s^2$] (initial angular velocity)
- Results
  - F = 51.13 [N] (force imposed by all 4 motors)
  - $\ddot{x}$ = 16.878 [m/s^2] (Cart Acceleration)
  - $\ddot{\theta}$ = 314.50 [rad/s^2] (Angular Acceleration)

7.4 Robot #1 Future Testing Potential

[Briefly summarize some potential testing procedures that could be completed in the future.]

Test	Purpose	Method	Expected Outcome	Equipment / Resources
Chassis Stress Test	Validate frame and bracket strength	Apply static load to chassis and measure deformation, inspect cracks	No visible cracking or excessive flexing, brackets aligned	Weights, calipers, camera, test stand
Bearing Friction Test	Verify smooth pendulum motion	Rotate pendulum manually and record resistance torque	Bearings rotate freely with minimal resistance	Torque gauge, bearing alignment jig
Motor Torque Test	Confirm motor capability under load	Run motors with increasing loads; measure speed and stall torque	Motors meet expected torque without overheating	Arduino, tachometer, load rig, multimeter
Driver Thermal Test	Validate L293D thermal stability	Continuous drive for 10-15 min; monitor temperature	Temperature remains within safe range (<70°C)	Arduino, fan/heat sink, Thermocouple

Sensor Accuracy Test	Verify potentiometer angle readings	Sweep pendulum through known angles; record readings at set angles	Linear and repeatable voltage response	Arduino, protractor, multimeter, data logger
PID / Control Tuning Test	Validate balancing control stability	Run robot on flat surface; record motor response	Robot self-stabilizes within ±5° tilt, no oscillation	Arduino, test stand, data logger
Battery Runtime Test	Confirm power capacity and consistency	Run full system until battery cutoff	Operates for entire demo duration without brownout	Battery, stopwatch, voltage monitor

8 Robot #2 Design Validation and Initial Prototyping

8.1 Failure Modes and Effects Analysis (FMEA) for Robot #2

Subassembly	Component	Function	Potential Failure Mode	Effect of Failure	S	Cause / Mechanism	O	Current Controls	D	RPN	Recommended Action
Base / Stand	Base plate	Support robot on table	Base tips or slides when bumped	System moves; camera misaligne; ball rolls off	7	Narrow base; light frame	4	Rubber feet; wide stance	3	84	Increase weight or clamp base
Base / Stand	Base plate	Mount electronics and actuator	Mounting screws loosen	Actuator misalignment; unstable leveling	6	Vibration; transport	3	Lock washers; inspections	4	72	Apply threadlocker; retighten
Plate / Structure	Plate panel	Rolling surface	Plate sags or flexes	Ball drifts despite control	8	Thin/weak material	3	Rigid material	3	72	Use aluminum or composite plate
Plate / Structure	Plate panel	Low-friction surface	Surface dirty or sticky	Ball sticks/slows unexpectedly	6	Dust; fingerprints	4	Cleaning before demo	3	72	Apply matte coating; routine cleaning
Plate / Structure	Plate edge	Contain ball	Edge too low or missing	Ball falls off during outreach	6	Design oversight	2	Visual check	2	24	Add 1–2 cm guard wall
Tilt Mechanism	Ball joint/hinge	Allow rotation (X,Y)	Joint binds	Uneven motion; oscillations	8	Dust; tight fit	3	Lubrication	3	72	Use precision joints; maintenance
Tilt Mechanism	Ball joint/hinge	Allow rotation	Excessive play	Unstable or delayed response	7	Wear; poor tolerances	4	Metal inserts; checks	4	112	Replace worn joints; tighten tolerance
Actuation	Servo motor (x3)	Tilt corners	One servo fails or drifts	Diagonal tilt; unstable system	9	Uneven load; motor failure	3	Matched servos; torque sizing	3	81	Use identical servos; pre-testing
Actuation	Servo motor (x3)	Continuous motion	Overheats/stalls	Shutdown mid-demo	8	Aggressive PID; overuse	3	Temperature testing	4	96	Add cooling; tune PID
Actuation	Servo mount	Hold motor	Bracket cracks or shifts	Loss of accuracy; vibration	7	Brittle print; fatigue	3	Reinforced bracket	3	63	Use metal bracket or denser print
Sensing / Vision	Overhead camera	Detect XY	Camera misaligned	Incorrect data	8	Vibration; bump	3	Fixed mount; calibration grid	3	72	Add adjustable mount; recalibrate
Sensing /	Overhead	Detect	Lighting	Tracking	7	Reflections	4	Matte	3	84	Add light

Vision	camera	XY	interference	errors		; bright room		surface; controlled lighting			shield; auto-exposure tuning
Sensing / Vision	Camera housing	Protect sensor	Exposure to spills	Short circuit; failure	8	K–12 handling	3	Acrylic cover	3	72	Add full enclosure; warning labels
Control / Electronics	Controller board	Process control	Board resets/crashes	Loss of control; unsafe motion	8	Voltage drop; noise	3	Separate power rails	3	72	Add capacitor; watchdog timer
Control / Electronics	Breadboard wiring	Electrical connections	Wire disconnects	Unstable behavior	8	Loose wires; student contact	4	Dupont headers; ties	3	96	Move to soldered protoboard
Control / Electronics	Exposed terminals	Safety protection	User touches live pins	Shock risk; damage	7	No enclosure	3	Visual caution	3	63	Add protective lid; label warnings
Power / Safety	Power supply/battery	Deliver power	Wrong voltage applied	Component damage	8	Misconnection	3	Labeled connectors	3	72	Use keyed connectors; color-code
Power / Safety	Power supply/battery	Current to servos	Overcurrent w/o fuse	Overheated wires	8	Servo stall	3	Current limits	3	72	Add inline fuse/breaker
Power / Safety	E-stop / switch	Emergency shutdown	Switch unreachable	Can't stop runaway plate	9	Poor placement	2	Red toggle on frame	2	36	Move switch to front; mark clearly

An FMEA was completed for the Ball-on-Plate robot to identify the most critical potential failures and to prioritize design changes for the final system. The analysis is organized by subsystems: Base/Stand, Plate/Structure, Tilt Mechanism, Actuation, Sensing/Vision, Control/Electronics, and Power/Safety. Each row of the FMEA corresponds to a specific component and failure mode. Severity (S), Occurrence (O), and Detection (D) were scored on a 1–10 scale, and the Risk Priority Number ($RPN = S \times O \times D$) was used to rank risks. Although some of these failure modes also apply to the current ball-on-beam prototype, the FMEA was intentionally focused on the final ball-on-plate robot, as requested by the professor and TA.

8.1.1 Key High-Risk Items and Mitigation

One of the highest RPN items (RPN = 112) occurs in the tilt mechanism: the ball joints or hinges that allow plate rotation can develop excessive play due to wear or poor tolerances. This could cause unstable or delayed response, making precise control of the ball very difficult. To mitigate this, the design uses precision ball joints with tighter tolerances, metal inserts where possible, and periodic inspection/maintenance procedures. These changes reduce both the likelihood of excessive play and improve our ability to detect problems early.

The actuation subsystem also shows critical risks. A failure or drift in one of the three servo/stepper motors tilting the plate can cause the plate to tilt diagonally and become unstable (RPN = 81). Additionally, continuous motion under aggressive control can lead to motor overheating or stalling (RPN = 96). The team is mitigating these risks by (1) using matched motors with sufficient torque margin, (2) performing bench testing to verify thermal behavior, and (3) tuning PID gains conservatively to avoid excessive oscillation. If needed, heat sinking or active cooling will be added in the final design.

In the control/electronics subsystem, temporary breadboard wiring was identified as a high-risk item (RPN = 96). Loose wires or student contact could cause intermittent connections and unstable behavior during demos. The recommended action is to migrate from a breadboard to a soldered protoboard with locking connectors and cable ties once the circuit design is finalized. Similarly, exposed terminals present a safety risk (shock or damage) and are mitigated by adding a 3D-printed protective lid and clear warning labels.

For the sensing/vision subsystem, the FMEA highlights that lighting conditions and mechanical bumps can significantly affect performance. Camera misalignment and lighting interference both have relatively high RPN values (e.g., RPN = 84 for lighting interference), because they can cause incorrect ball position data and tracking errors. The design responses include adding an adjustable camera mount with a calibration grid, implementing matte surface finishes to reduce reflections, and designing a light shield or enclosure to limit ambient lighting variation.

The power/safety subsystem includes several important risks relevant to K–12 outreach. Applying the wrong voltage to components or operating without an inline fuse can damage the system or cause wires to overheat. To address these issues, connectors are clearly labeled, keyed connectors are preferred where possible, and an inline fuse or breaker will be added in series with the servo supply. The location and accessibility of the E-stop / main switch were also flagged (RPN = 36); the switch will be moved to the front face of the base with a red toggle so that demonstrators can quickly shut down the system in an emergency.

8.1.2 Risk Trade-Off and Design Decisions

The FMEA helped the team prioritize which issues to address immediately and which could be managed through procedures or deferred to later iterations. High-RPN items associated with structural stability, actuation reliability, and user safety (base tipping, joint play, motor overheating, wiring failures, exposed terminals) are being addressed through mechanical redesign (wider base, guard rails, stiffer plate), improved component selection, and better electrical integration (soldered connections, enclosures, fuses). Moderate-RPN items related to cosmetic or easily inspected conditions (surface cleanliness, plate edge height, routine cleaning) are being controlled via operating procedures and pre-demo checklists.

Overall, the FMEA has directly informed the mechanical and electrical design of Robot 2. As prototyping progresses and the ball-on-plate system is physically tested, the team plans to update the FMEA values based on actual failure data and adjust mitigation actions accordingly. This iterative approach helps ensure that the final outreach robot is not only functional and controllable, but also safe, robust, and appropriate for repeated use in K–12 environments.

8.2 Ball-on-Beam Initial Prototyping

8.2.1 Mechanical Subsystem

8.2.1.1 Base

The question of this sub-section of the prototype is: How can the design of the base remain sturdy, compact, and lightweight while supporting all the mechanical and electrical components without constant stress on the system? The initial design of the base (S*ee in Appendix Figure 19*) originally used a pillar that held the hinge in place, which is the only detachable feature. The sensor placement near the hinge, the pillar's width was extruded upward. A rectangular cut-off was added within the pillar to house electrical components such as sensor wires and the battery. The modification aided in the reduction of the overall weight of the base while providing a strong structure capable of supporting the breadboard and other electrical components. This cut-out demonstrates that the material removal reduced the base without compromising the structures' strength.

8.2.1.2 Fulcrum

The question for this prototype sub-section is: What is the most effective way to design the fulcrum that connects the stent to the motor where torque could occur smoothly and efficiently? The fulcrum *(See Appendix Figure 20)* had a large circular extruded cut in the center, and it was reduced to accommodate the stepper motor axle. This created a tighter fit and improved torque transfer. The resizing of the cut provides a better alignment of the fulcrum between the motor and stent, reducing slippage and having a smoother rotational motion. This sub-section demonstrates that dimensional control of the fulcrum is important for efficient torque. This central cut reduction improves mechanical coupling, and it shows the importance of stability. For future changes, there will be more of a focus of creating the fulcrum into a more compact connector that supports both mechanical performance and system integration based on geometry, materials, and tolerance of the motor axle and fulcrum.

8.2.1.3 Hinge

The question for this prototype sub-section is what the most effective way is to design the hinge so that it connects the rods securely and has smooth tilting of the beam, while maintaining stability and minimizing mechanical stress throughout the system? The hinge *(See Appendix Figure 21)* is a critical mechanical link between the rods and the beam. Allowing the tilting of the hinge to enable the ball to roll freely create an adjustment under the hinge to be fillet-ed; rounded, to reduce friction between the hinge and the base where the hinge is placed. This provides insights between the relationship of the mechanical properties of the hinge while keeping the rods aligned. The plan to iterate based on the new info that the hinge geometry especially in the bottom center region of the hinge affects the system's performance. Improved alignment to reduce possible wobbled area(s) and ensure the tilt angle is constant will aid in the performance of the hinge. This will improve mechanical durability, and the electrical components will work properly.

8.2.1.4 Rod

The question for this prototype sub-section is whether the rod *(See Appendix Figure 22)* could provide a consistent path without adding friction of instability when the ball is placed. The rod's role in the prototype was to guide the ball's motion along the beam. The rods were too thin for the 3D printer to print out that it would break, so bamboo wooden skewers are used to provide durability and strength. This informed the design that the rod's geometry needs to be simple and low friction. For future iterations, exploring the different materials of the rod may reduce resistance and increase durability of this subsystem.

8.2.1.5 Stent

The question for this prototype sub-section is if the connection of the stent *(See Appendix Figure 23)* is reliable when motion occurs without applying stress to the sub-system. The stent connects to the rod and the motro enabling rotation of the motor. The prototype shows that the stent provides a stable link, and strain is between the connects of the points; rods and motor. This provides information on the need for stress that needs to be distributed more evenly, and this is through the change of geometry and/or creating the stent with different materials.

8.2.2 Actuation Subsystem

8.2.2.1 Servo Motor

The question for this prototype sub-section is whether the servo motor *(See Appendix Figure 24)* could provide precise and controlled motion. The servo provides a reliable tilt with responses to small delays. This analysis informs the members of robot 2 that the design needs to focus on the fine tuning of the control signals and implementing servos with higher performance in future designs.

8.2.2.2 Stepper Driver

The question for this prototype sub-section is if the stepper driver can provide a good signal between the controller and motor smoothly. The prototype shows that the driver *(See Appendix Figure 25)* enables communication with occasional signal noise that causes inconsistent communication. This information provides insight into the importance of shielding and wiring to ensure reliable motor control.

8.2.3 Sensing Subsystem

8.2.3.1 VL53L0X Sensor

The question for this prototype sub-section of the VL53L0X sensor is whether the sensor can track the ball accurately in real time. The sensor *(See Appendix Figure 26)* measures the ball's distance along the beam, and the prototype will show that the sensor provides measurements. There is a possibility that the sensor's performance will slightly drop when the ball moves quickly due to limitations of the sensor not having a sensor refresh rate for every unit of time. This informs the design that the sensor's placement and calibration are critical, and for future iterations, the exploration of multiple sensors would provide a more precise reading of the ball position.

8.2.4 Control Subsystem

8.2.4.1 Raspberry Pi

The question for this prototype sub-section of Raspberry Pi is if it could process sensor data quickly enough during real time while tilting the beam. Raspberry Pi *(See Appendix Figure 27)* is the brain of the system, and the code is a closed-feedback loop to maintain the ball position. Pi will handle feedback control effectively while the complex tasks increase the time delay of the beams tilting and implementing multiple Raspberry Pi's to do certain tasks to have a stable and responsive system.

8.2.5 Power/Regulator Subsystem

8.2.5.1 Battery

The question for this prototype sub-section of the battery was whether it could deliver stable voltage and current to all the components of robot 2. The battery's *(See Appendix Figure 28)* function is to provide the system's power supply. The prototype subsystem component is reliable to power the system, but runtime will be limited. For future iterations, hard wiring a batter where it is chargeable will be ideal due to it having more voltage and current for longer operations.

8.2.5.2 Regulator Module

The question for this prototype sub-section of the regulator module is whether it could maintain consistent output under various loads. The regulator *(See Appendix Figure 29)* stabilizes the voltage to protect the other components from being fried. The prototype keeps the voltage system and prevents the fluctuations of the regulator could disrupt the sensors and/or motor. With this information, it is necessary to have this component and integrating a more compact and efficient regulator would be ideal for this prototype.

8.3 Other Robot #2 Engineering Calculations

8.3.1 Prototype Motor Torque Analysis – Freddy Rivera

Since the previous report, the primary new engineering calculation for Robot 2 has been verifying that the selected NEMA 17 stepper motor can provide sufficient torque to tilt the ball-on-beam prototype with an appropriate safety factor. This calculation was performed before purchasing motors to avoid under-sizing the actuator.

Required Beam Torque:

The beam is modeled as a uniform rod of length $L$with mass m_{beam}, pinned at one end. A steel ball of mass m_{ball} is assumed to be located at the free end of the beam in the worst-case loading scenario. The required torque at the pivot to hold the beam horizontal against gravity is the sum of the moments from the beam's own weight and the ball, scaled by a safety factor (SF):

$$\tau_{\text{req,beam}} = \text{SF}(m_{\text{beam}} g \frac{L}{2} + m_{\text{ball}} g L) \quad (8)$$

Using prototype assumptions:

- $L = 0.24$ m(9.5 in)
- $m_{\text{beam}} = 0.25$ kg
- $m_{\text{ball}} = 0.05$ kg
- $g = 9.81$ m/s^2
- SF $= 1.5$

Substituting these values gives:

$$\tau_{\text{req,beam}} \approx 0.62 \text{ Nm}$$

This is the torque that must be applied at the pivot to statically support the beam and ball at the worst-case position.

Motor Torque Requirement:

In the mechanical design, the motor does not act directly at the beam end. Instead, it drives the beam through a short linkage arm of length $d$attached closer to the pivot. The effective torque required at the motor shaft scales with the ratio of the linkage arm to the full beam length:

$$\tau_{\text{motor}} = \tau_{\text{req,beam}} \frac{d}{L} (9)$$

For the current prototype, the linkage arm is assumed to be:

- $d = 0.038m$ (1.5 in)

Thus:

$$\tau_{\text{motor}} = 0.62Nm \times \frac{0.038}{0.24} = 0.10Nm \quad (10)$$

Motor Selection Check:

The chosen actuator is a 12 V NEMA 17 stepper motor with a rated holding torque of:

$$\tau_{\text{rated}} = 0.59 \text{ Nm}$$

Comparing rated motor torque to the required torque:

$$0.59Nm > 0.10Nm$$

This corresponds to a torque factor of safety of approximately:

$$FS = \frac{0.59}{0.10} = 5.9 \quad (11)$$

which is well above the design safety factor of 1.5. Therefore, the selected NEMA 17 motor has more than sufficient torque to drive the ball-on-beam prototype, even under conservative worst-case assumptions. This result justified using a relatively compact stepper motor while still ensuring reliable operation and leaving margin for dynamic effects, friction, and manufacturing variability.

8.3.2 Ball-on-Beam: Energy, Forces, and Motion of the Ball Calculations – Florence Fasugbe [55]

These sets of calculations help understand how energy and torque behave in the ball on the beam system. This is crucial for designing a responsive and stable control loop for the Raspberry Pi. The kinetic energy equation

$$E_k = \frac{1}{2}m_b\dot{x}^2 + \frac{1}{2}J_b\dot{\theta}^2 \quad (12)$$

Which combines two terms: translational motion of the ball and rotational motion of the beam. The variable $m_b = 0.1\ kg$ is the mass of the ball, $\dot{x} = 0.5\ \frac{m}{s}$ is the velocity across a straight path, and $J_b = 0.02\ kg \cdot m^2$ is the beam's moment of inertia. The result is 0.015 Joules which tells how much motion energy is in the system.

The potential energy:

$$E_p = m_b g x sin\theta \quad (13)$$

Is the ball's height due to the tilt of the beam. With $x = 0.05m$ for the ball's position along the beam, $\theta = 0.1745\ radians$, about $10°$, and $g = 9.81\ \frac{m}{s^2}$ for the gravity, the system stores about 0.085 Joules of gravitational energy. With the subtraction of the potential and kinetic energy the gives the Lagrangian:

$$L = E_k - E_p = 0.0065\,J \quad (14)$$

This helps with the dynamic modeling of the system on motion that governs the system over time.

On torque, the beam experiences a net torque $Q_\theta^e = M_e - M_f$ (15), where M_e is the motor-generated torque and M_f is the frictional resistance. Motor torque is calculated as $M_e = k_t \cdot I$ (16) with $k_t = 0.8508\ \frac{N \cdot m}{A}$ as the torque constant and $I = 10\ A$ as the motor current. This results in the motor torque at 8.508 N·m and this shows that the motor can exert a lot of rotational force to tilt the beam. The friction coefficient $\mu = 0.02$ and this helps estimate how much torque is lost to resistance.

8.3.3 Prototype Structural Viability of Robot 2 Beam Assembly - Ziyi Tang

Since the previous report, the primary new engineering calculation for Robot 2 has been verifying that the dual-rod wooden beam used in the Ball-on-Beam prototype provides sufficient stiffness and strength to support the maximum expected ball load without excessive deformation. This analysis was performed using ANSYS Mechanical APDL prior to physical prototyping, to avoid selecting an inadequate material configuration.

Beam Loading Case:

The beam is modeled as two parallel cylindrical rods of diameter 0.1 in and length 9.5 in, pinned at one end and vertically constrained at the opposite end. A 50 g steel ball represents the worst-case load condition at the mid-span of the beam, maximizing bending deflection and stress. Material properties for wood were assumed based on typical values.

Defined Parameters:

$$L = 0.241 \text{ m}$$

$$m_{\text{ball}} = 0.05 \text{ kg}$$

$$E = 1.6 \times 10^6 \text{ psi}$$

$$\sigma_{\text{yield}} = 7000 \text{ psi}$$

Finite Element Results:

Maximum deflection: $\delta_{\max} = 0.056 \text{ in}$

Maximum von Mises stress: $\sigma_{\max} = 1001 \text{ psi}$

Factor of Safety Calculation:

$$(17)\quad FoS = \frac{\sigma_{\text{yield}}}{\sigma_{\max}}$$

$$FoS = \frac{7000}{1001} \approx 6.99$$

Design Interpretation:

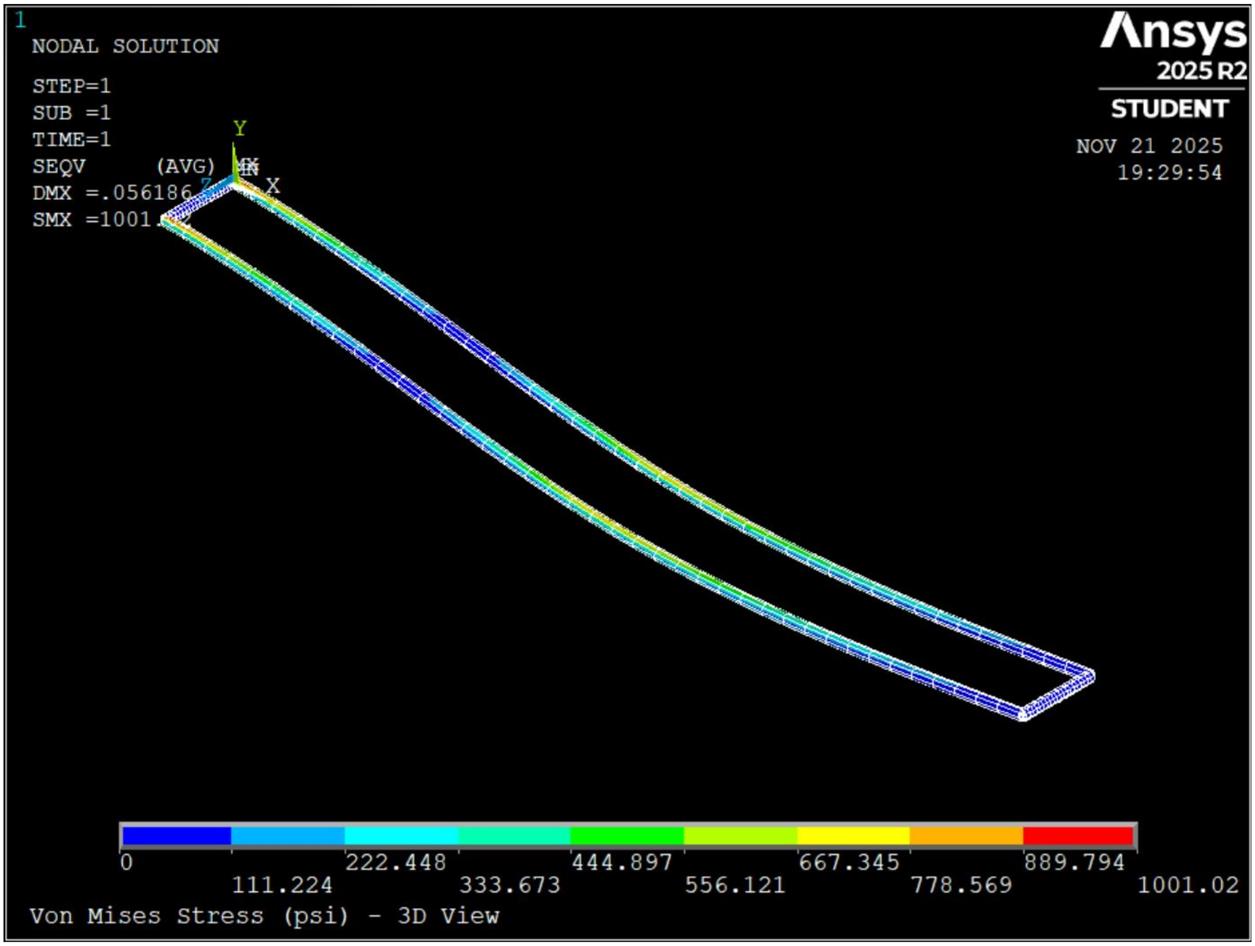


figure19.1 Ansys simulation

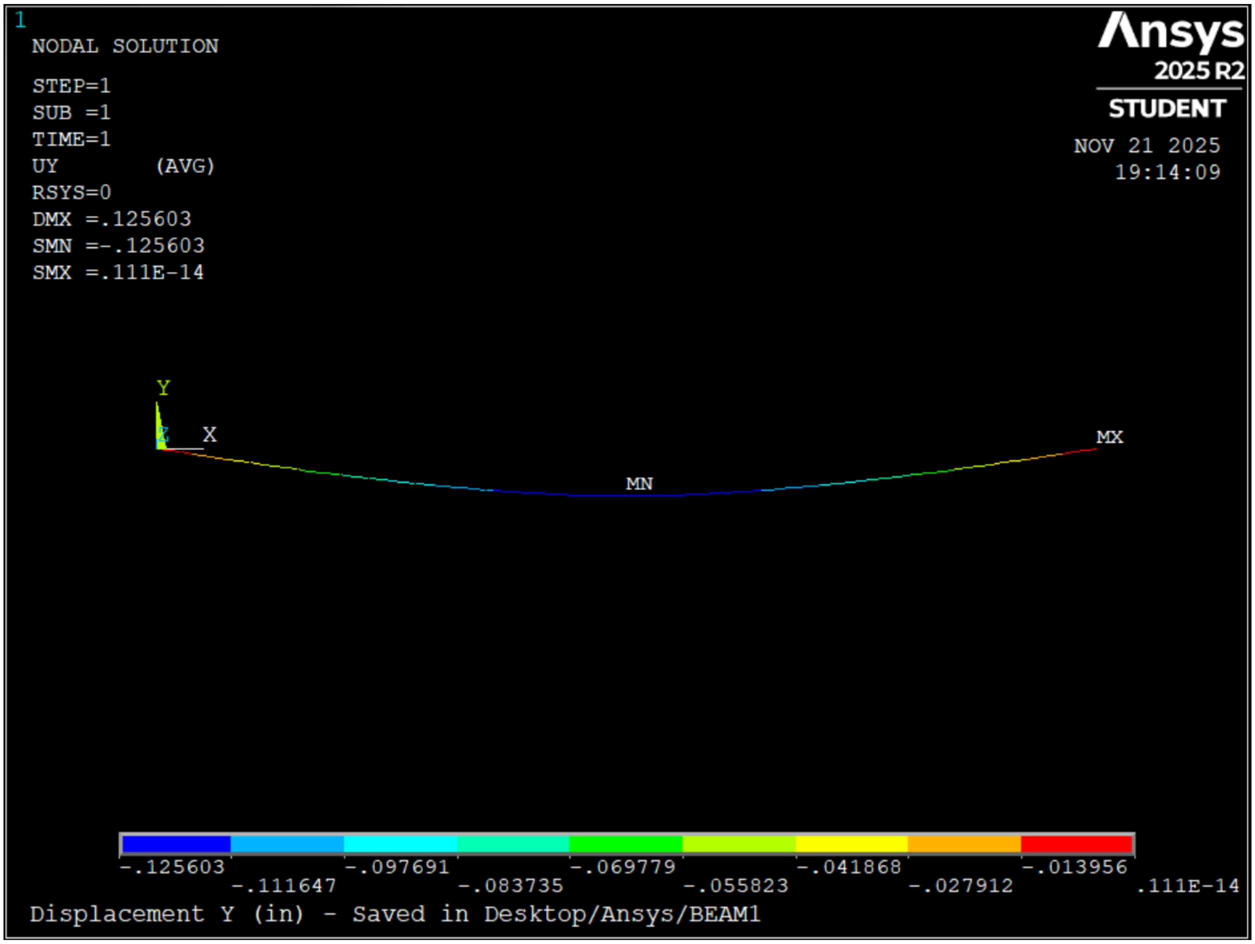


figure19.2 Ansys simulation

The resulting safety factor of approximately 7 confirms that the wooden dual-rod beam provides more than adequate strength for static operation and educational demonstration use. The deflection represents only about 0.6% of the total length, which remains well within acceptable limits for control performance in early prototypes.

Future Material Consideration:

Although structural performance is sufficient, the analysis suggests that replacing wood with carbon-fiber rods of identical geometry could reduce deflection by an order of magnitude, supporting higher-precision feedback control in future iterations without requiring hardware redesign.

8.4 Robot #2 Future Testing Potential

To ensure that the final Ball-on-Plate robot satisfies all engineering requirements (ERs) related to response time, steady-state accuracy, stability, and safe classroom operation, several structured testing procedures are planned for next semester. These tests will validate the control system, mechanical performance, and system reliability under realistic use conditions.

8.4.1 System Calibration:

Prior to performance testing, the sensing and actuation systems must be calibrated to establish accurate positional control:

- Sensor Calibration: The overhead camera (or alternative ranging sensor) will be calibrated to map pixel or distance measurements to precise X–Y coordinates on the plate. This ensures accurate ball-position feedback for the control algorithm.
- Actuator Calibration: Each motor's rotational limits will be verified to confirm the available range of motion of approximately ±15° per axis. This test will validate that the mechanical system can achieve the required tilt angles to control ball movement.

8.4.2 Static Balance Test:

This test evaluates the system's ability to maintain the ball in a stable equilibrium:

- The ball will be placed at the geometric center of the plate, and the controller will attempt to hold its position.
- Success criteria: steady-state error ≤ 5% of the plate radius.
- This test verifies control precision and the robot's suitability for classroom demonstration where repeatable stability is required.

8.4.3 Dynamic Response Test:

This test measures how quickly and effectively the system responds to disturbances:

- The ball will be displaced from center and released.
- The system will record the time required to return to equilibrium, overshoot magnitude, settling time, and any oscillations.
- Target metric: response time ≤ 1 second.
- These results will guide PID tuning and validate that three-motor actuation provides sufficient torque and responsiveness.

8.4.4 Cross-Axis Coupling Test:

Because the Ball-on-Plate system involves two-axis motion, movement along one axis may unintentionally affect the other:

- The ball will be commanded to move along the X-axis and Y-axis independently.
- The test will evaluate whether control inputs on one axis induce instability or motion on the perpendicular axis.
- Results will inform controller decoupling strategies and multi-axis tuning.

8.4.5 Endurance and Reliability Test:

To ensure dependable operation during classroom outreach:

- The robot will run continuously for at least 30 minutes under nominal load.
- The test will monitor motor temperature, structural wear, and control drift.
- Any component degradation will guide material, motor, or cooling decisions for the final build.

8.4.6 Safety and Power Test:

Since the robot will be demonstrated in K–12 environments, safety verification is required:

- The system's total power draw will be measured, with a target of < 30 W during normal operation.
- All high-voltage or moving components will be checked for proper enclosure.
- Emergency stop and power-cut-off features will be tested to ensure rapid shutdown in the event of malfunction.

9 CONCLUSIONS

This project set out to design and develop two low-cost, mass-producible educational robots that demonstrate core control-system principles for K–12 STEM outreach. Guided by the client's critical requirements, the team focused on durability, safety, interactivity, manufacturability, and clear demonstration of feedback control. Throughout the first semester, the team completed requirements definition, benchmarking, concept generation, mathematical modeling, budgeting, and initial prototyping.

For Robot #1, the Inverted Pendulum Robot, the team successfully completed subsystem research, dynamic modeling, and concept selection. Based on the customer and engineering requirements, the design emphasized stability, durability, and educational clarity. Mathematical analyses such as impact force estimation, pendulum dynamics, and controller considerations demonstrated technical feasibility and informed component selection. Using decision matrices and Pugh charts, the team selected a simplified angular frame design that could withstand classroom impacts and meet size and safety requirements. Early prototyping validated key assumptions regarding structure, torque, and control hardware, which created a strong foundation for next semester's full system build and testing.

For Robot #2, the team explored five potential concepts and evaluated them using formal selection criteria derived from the project requirements. Benchmarking, literature review, and morphological analysis narrowed the field to three viable concepts. The Ball-on-Plate system was selected as the final design direction because it offers high educational value, clear visualization of closed-loop feedback, and a compact form suitable for classroom use. The team completed a detailed Failure Modes and Effects Analysis, developed a Bill of Materials, and built an initial Ball-on-Beam prototype to validate actuators, sensing, and mechanical subsystems before scaling to the final Ball-on-Plate architecture. Engineering calculations confirmed that the selected stepper motors provide sufficient torque with a comfortable safety factor. The team also defined future testing procedures to verify response time, stability, and safety.

Across both systems, the project stayed within budget, supported mass-manufacturing goals, and established a structured development plan that aligns with K–12 outreach objectives. By the end of the semester, the team achieved three major results:

1. A fully defined set of customer and engineering requirements supported by a House of Quality.
2. A finalized and validated design direction for both robots, with Robot #1 ready for complete fabrication and Robot #2 transitioning from beam prototype to plate platform.
3. Documented pathways for testing, iteration, and manufacturing that will allow efficient progress during the spring semester.

Next semester, the focus will shift from conceptual development to hardware integration, controller implementation, physical testing, and final demonstration readiness. The team will fabricate the full Robot #1 system, transition Robot #2 to the complete plate platform, complete safety validation, and prepare both robots for K–12 deployment. Overall, this semester resulted in a clear, feasible, and well-supported plan that positions the project for successful completion and meaningful educational impact.

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11 APPENDICES

11.1 Appendix A: Equations Utilized in Order

- $V = \sqrt{2gh}$ (1)
- $F = \frac{mv}{\Delta t}$ (2)
- $h \geq \sqrt{\frac{6FL}{b\sigma_{flex}}}$ (3)
- $x_G = 0.90\sin(0.05) \approx 0.045m$ (4)
- $y_G = 0.90\sin(-0.03) \approx -0.027m$ (5)
- $(M+m)\ddot{x} + m\ell\ddot{\theta}\cos(\theta) - m\ell\dot{\theta}^2\sin(\theta) = F$ (6)
- $\ell\ddot{\theta} + \ddot{x}\cos(\theta) - gsin(\theta) = 0$ (7)
- $I\ddot{\theta} = mgl\,\theta - \tau$ (8)
- $\tau = K_p\,\theta + K_d\,\dot{\theta}$ (9)
- $I\ddot{\theta} + K_d\,\dot{\theta} + (K_p - mgl)\,\theta = 0$ (10)
- $K_d = 2\zeta\omega_n I$ (11)
- $K_p = mgl + I\,\omega_n^2$ (12)
- $I = m\,l^2.$ (13)
- $J_w = \frac{1}{2}m_w {r_w}^2$ (14)
- $\tau_{grav} = mgh\theta$ (15)
- $\alpha_w = \frac{\tau_{grav}}{J_w}$ (16)
- $Q_n = M_{f,n} + M_{M,n}$ (17)
- $Q_3 = F_f Q_4 = F_{f,2}$ (18)
- $F = \frac{KI^2}{(g+g0)^2},$ (19)
- $K = \frac{\mu_0 N^2 A_{\text{eff}}}{2},$ (20)
- $\frac{KI_U^2}{(G-h+g0)^2} - \frac{KI_L^2}{(h+g0)^2} = mg.$ (21)

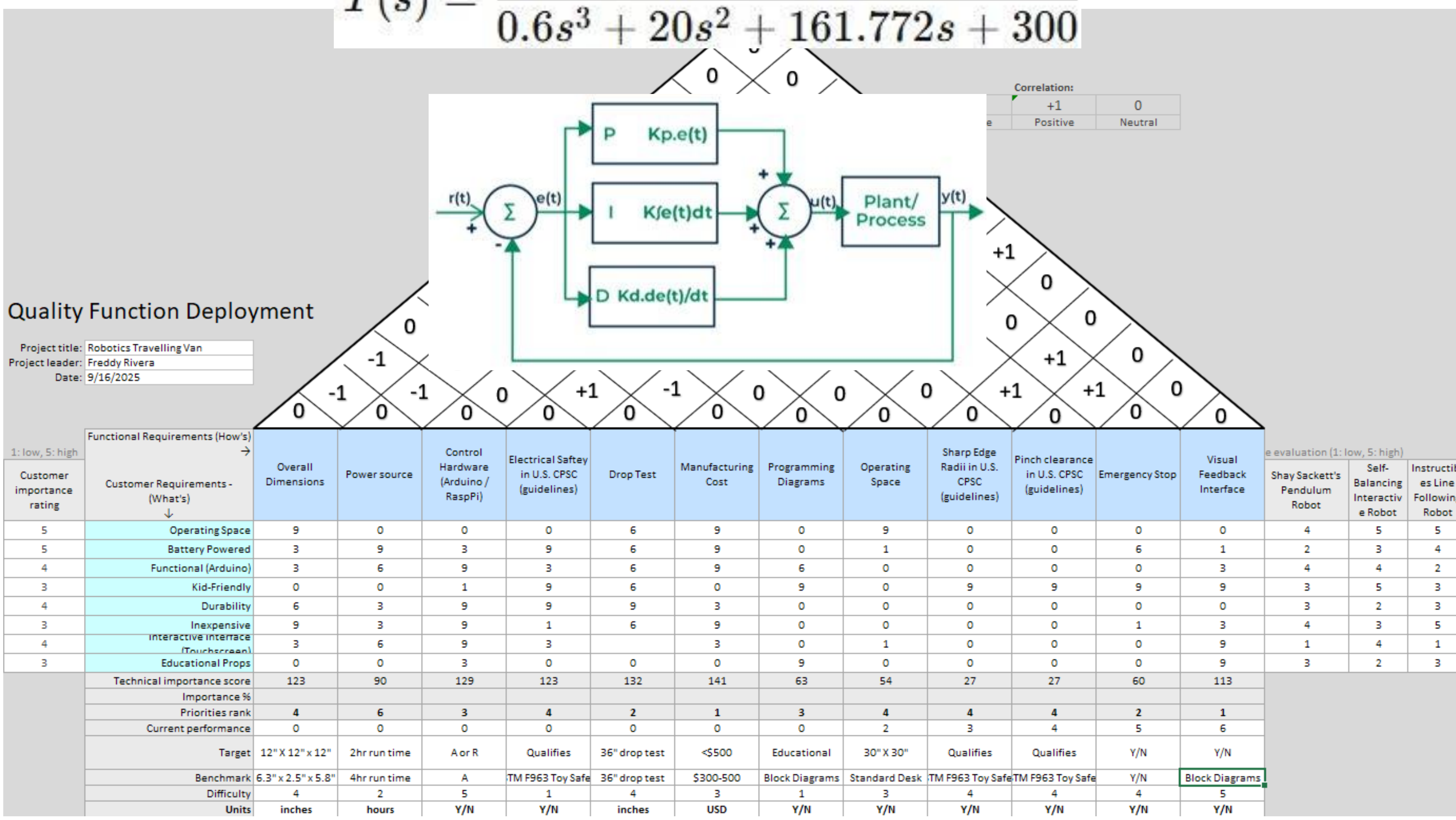
11.2 Appendix B: Figures in order of appearance

- Figure 1 – QFD
- Figure 2 – Laplace Equation

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt} e(t)$$

- Figure 3 – Re-Arranged Laplace Equation solving for time with variables input

$$T(s) = \frac{20s^2 + 150s + 300}{0.6s^3 + 20s^2 + 161.772s + 300}$$



Quality Function Deployment

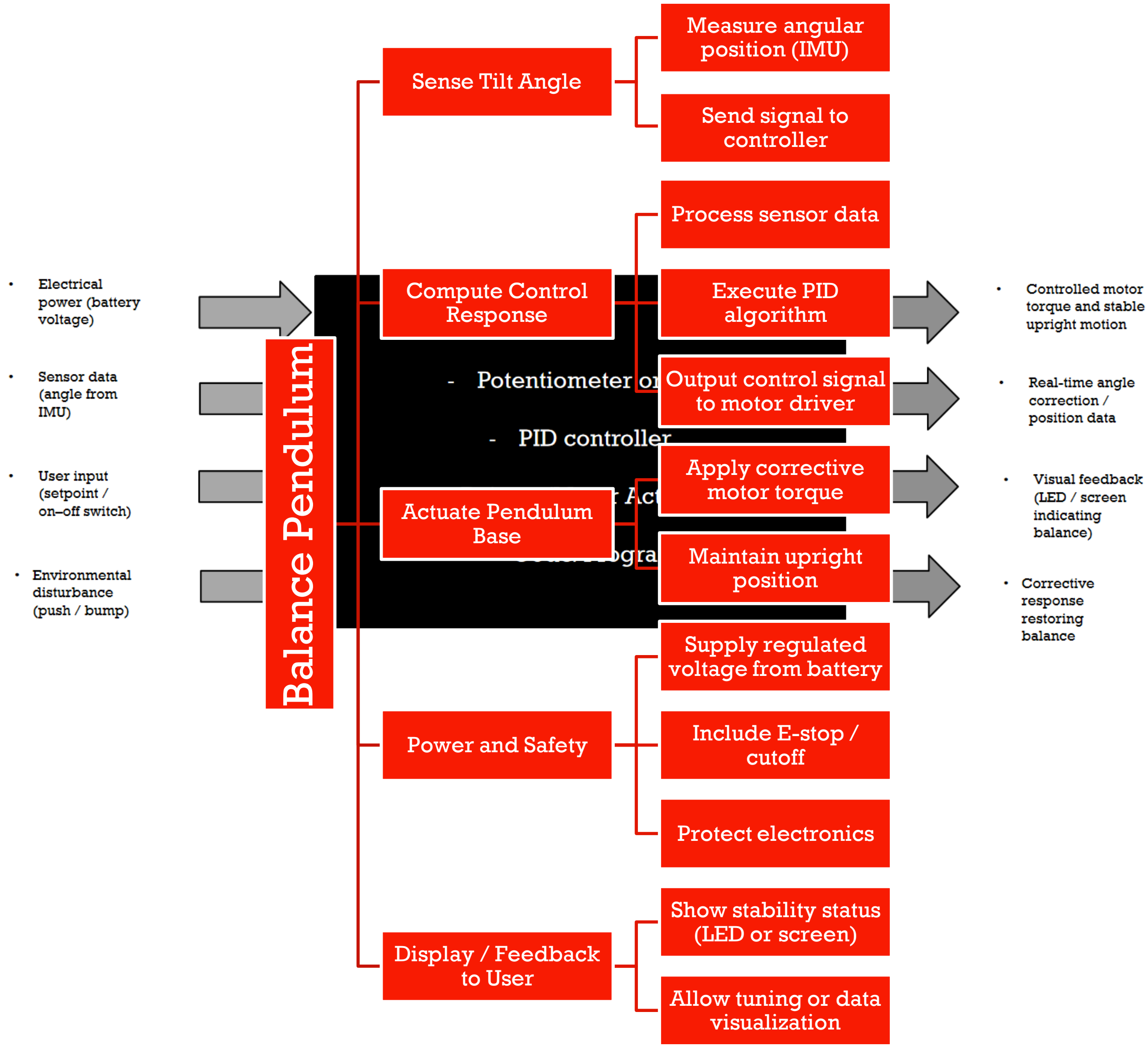
Project title: Robotics Travelling Van
Project leader: Freddy Rivera
Date: 9/16/2025

Correlation: +1 Positive; 0 Neutral

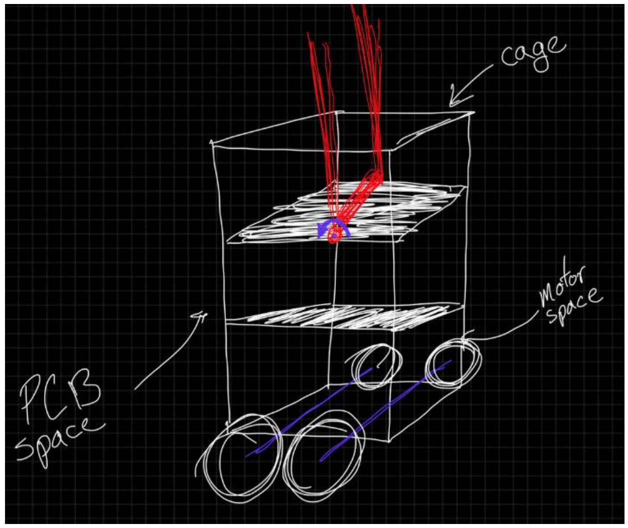
Customer importance rating (1: low, 5: high)	Customer Requirements - (What's) / Functional Requirements (How's)	Overall Dimensions	Power source	Control Hardware (Arduino / RaspPi)	Electrical Saftey in U.S. CPSC (guidelines)	Drop Test	Manufacturing Cost	Programming Diagrams	Operating Space	Sharp Edge Radii in U.S. CPSC (guidelines)	Pinch clearance in U.S. CPSC (guidelines)	Emergency Stop	Visual Feedback Interface	Shay Sackett's Pendulum Robot	Self-Balancing Interactive Robot	Instructibles Line Following Robot
5	Operating Space	9	0	0	0	6	9	0	9	0	0	0	0	4	5	5
5	Battery Powered	3	9	3	9	6	9	0	1	0	0	6	1	2	3	4
4	Functional (Arduino)	3	6	9	3	6	9	6	0	0	0	0	3	4	4	2
3	Kid-Friendly	0	0	1	9	6	0	9	0	9	9	9	9	3	5	3
4	Durability	6	3	9	9	9	3	0	0	0	0	0	0	3	2	3
3	Inexpensive	9	3	9	1	6	9	0	0	0	0	1	3	4	3	5
4	Interactive Interface (Touchscreen)	3	6	9	3		3	0	1	0	0	0	9	1	4	1
3	Educational Props	0	0	3	0	0	0	9	0	0	0	0	9	3	2	3
	Technical importance score	123	90	129	123	132	141	63	54	27	27	60	113			
	Importance %															
	Priorities rank	**4**	**6**	**3**	**4**	**2**	**1**	**3**	**4**	**4**	**4**	**2**	**1**			
	Current performance	0	0	0	0	0	0	0	2	3	4	5	6			
	Target	12" X 12" x 12"	2hr run time	A or R	Qualifies	36" drop test	<$500	Educational	30" X 30"	Qualifies	Qualifies	Y/N	Y/N			
	Benchmark	6.3" x 2.5" x 5.8"	4hr run time	A	TM F963 Toy Safe	36" drop test	$300-500	Block Diagrams	Standard Desk	TM F963 Toy Safe	TM F963 Toy Safe	Y/N	Block Diagrams			
	Difficulty	4	2	5	1	4	3	1	3	4	4	4	5			
	Units	**inches**	**hours**	**Y/N**	**Y/N**	**inches**	**USD**	**Y/N**	**Y/N**	**Y/N**	**Y/N**	**Y/N**	**Y/N**			

- Figure 4 – Code Flow Chart representing our looping coded

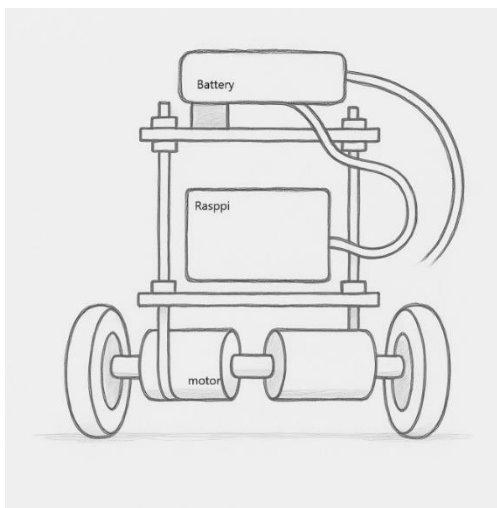
- Figure 5 – Black Box Diagram of Robot 1
- Figure 6 – Robot 1 Functional Decomposition Diagram



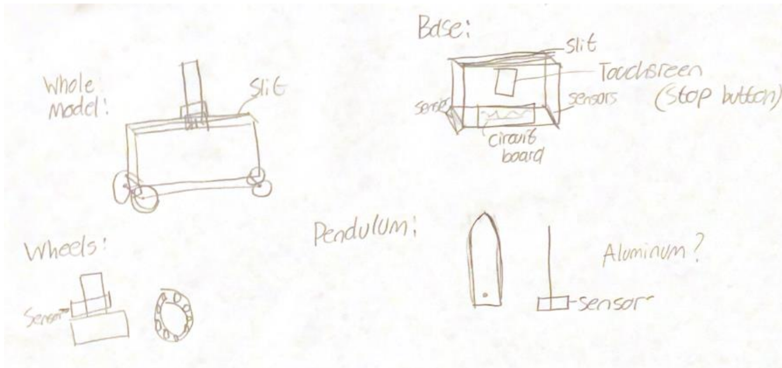
- Figure 7 – Pendulum Robot Frame concept sketch 1



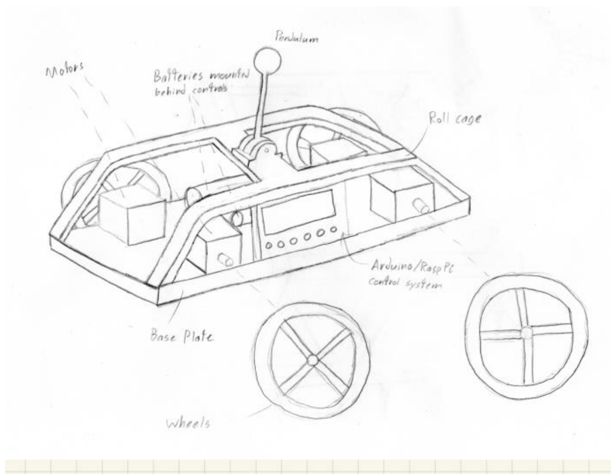
- Figure 8 – Pendulum Robot Frame concept sketch 2



- Figure 9 – Pendulum Robot Frame concept sketch 3
- Figure 10 – Pendulum Robot Frame concept sketch 4



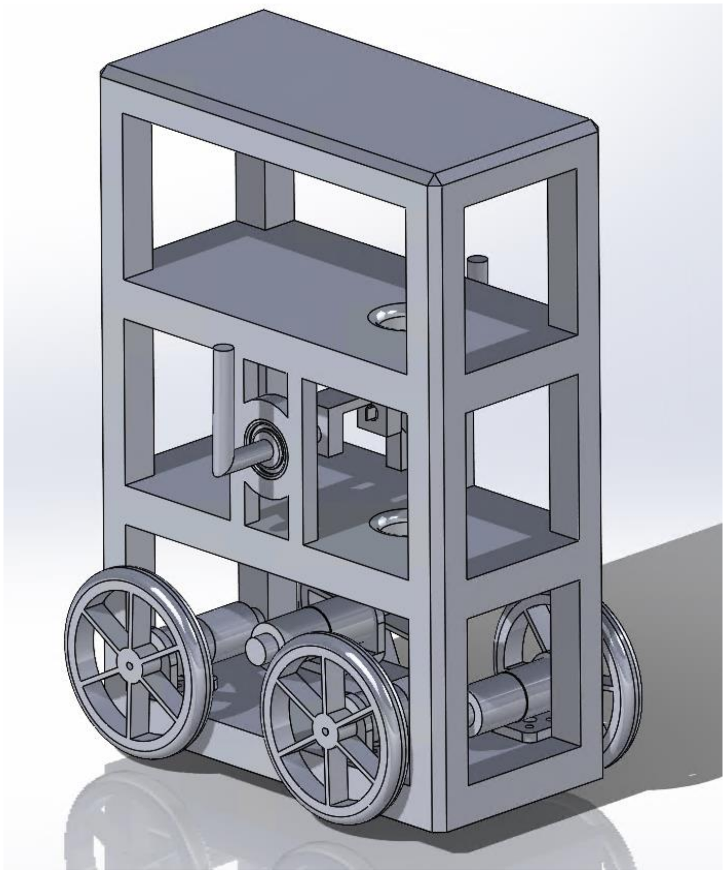
- Figure 11 – Pendulum Robot Frame concept sketch 5



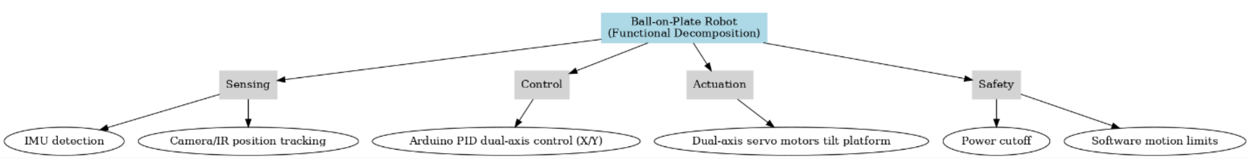
Top 3 Robot Options	WEIGHT 1-5	Robot Option A		Robot Option C		Robot Option E	
		BASE SCORE	WEIGHTED	BASE SCORE	WEIGHTED	BASE SCORE	WEIGHTED
Base Type	3	3	9	5	15	5	15
Pendulum Type	4	2	8	5	20	5	20
Stabilization Axis	3	3	9	4	12	4	12
Touchscreen	2	1	2	3	6	4	8
Material Notes	5	3	15	4	20	4	20
Sensor	1	3	3	4	4	3	3
Power	3	3	9	5	15	3	9
	TOTAL WEIGHTED SCORE		55	·	92	·	87

- Figure 12 – Pugh Chart comparing top 3 Pendulum Frame Designs

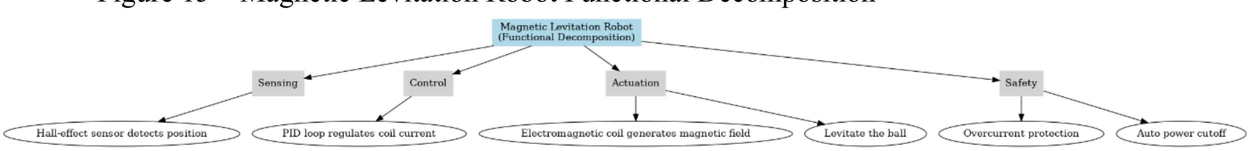
- Figure 13 – Robot 1 Final Design CAD Model



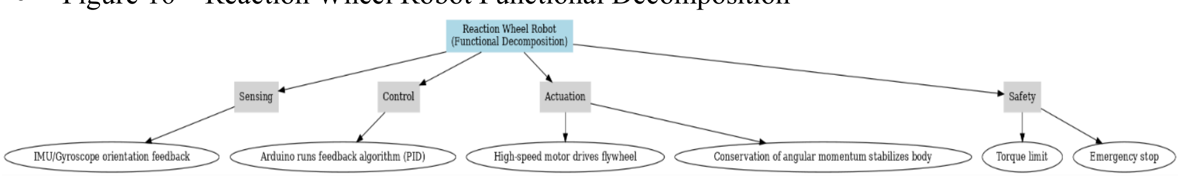
- Figure 14 – Ball-on-Plate Robot Functional Decomposition



- Figure 15 – Magnetic Levitation Robot Functional Decomposition



- Figure 16 – Reaction Wheel Robot Functional Decomposition



- Figure 17.1 – Ball on Plate Robot Concept

- Figure 17.2 – Magnetic Levitation Robot Concept

- Figure 17.3 – Reaction Wheel Robot Concept

- Figure 17.4 – Hockey Robot Concept

- Figure 17.5 – Line Following Robot Concept

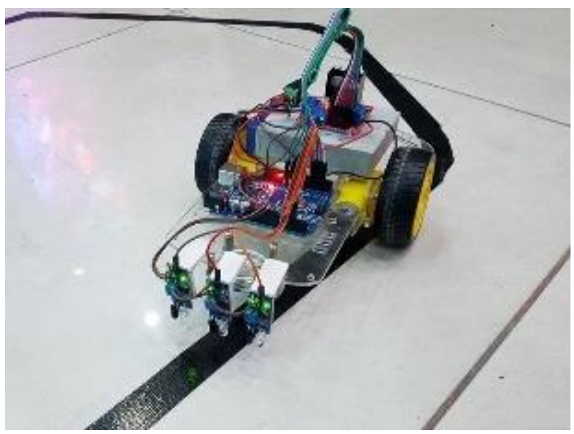


Figure 18. – Bill of Materials for Ball on Beam Prototype

#	Item	Description	Qty	Vendor / Link	Total Cost
1	Klein Tools D275-5 Diagonal Flush Cutters	Wire cutters	1	https://www.amazon.com/Cutter-Lightweight-Klein-Tools-D275-5/dp/B000GTMZHG	$12.97

2	WGGE WG-015 Professional 8-inch	Wire multitool	1	https://www.amazon.com/WGGE-Professional-crimping-Multi-Tool-Multi-Function/dp/B073YG65N2	$8.99
3	4PCS Breadboards Kit	Solderless breadboards for circuit prototyping	1	https://www.amazon.com/Breadboards-Solderless-Breadboard-Distribution-Connecting/dp/B07DL13RZH	$6.63
4	1400Pcs Electronics Component Assortment Kit	Assorted resistors, capacitors, transistors, etc.	1	https://www.amazon.com/YUEONEWIN-Electronics-Assortment-Electrolytic-Transistor/dp/B09YTSR9Z9	$19.96
5	49-Piece 74HCxx / 74LSxx Logic IC Set	Logic IC assortment	1	https://www.amazon.com/Assortment-Minidodoca-Registers、Transceiver、Decade-Counters、Multiplexer-Decoders、Hex/dp/B0C2P3CWPS	$11.99
6	TUOFENG 22 AWG Solid Core Wire	Hookup wires (assorted colors)	1	https://www.amazon.com/TUOFENG-Hookup-Wires-6-Different-Colored/dp/B07TX6BX47	$15.29
7	Protoboards	For transitioning circuits off breadboards	1	https://www.amazon.com/dp/B08BWPGSSC	$13.59
8	Header Pins	Male pin headers for protoboard use	1	https://www.amazon.com/dp/B06Y4S6G29	$7.39
9	ELEGOO 120pcs Dupont Wire Set	Jumper wires for breadboarding	1	https://www.amazon.com/Elegoo-EL-CP-004-Multicolored-Breadboard-arduino/dp/B01EV70C78	$6.98
10	Raspberry Pi Pico (2-pack)	Microcontroller for motor and sensor control	1 pack	https://www.amazon.com/Raspberry-Pi-Pico-Development-Integrated/dp/B0BDLHMQ9C	$11.99
11	HC-SR04 Ultrasonic Sensors (2-pack)	Ball distance detection	1 pack	https://www.amazon.com/DIYables-HC-SR04-Ultrasonic-Arduino-Raspberry/dp/B0BDFLPZ2R	$6.99
12	VL53L0X Time-of-Flight Sensors (3-pack)	Higher-accuracy ranging sensors	1 pack	https://www.amazon.com/Qoroos-VL53L0X-Breakout-GY-VL53L0XV2-Measurement/dp/B0F1MRW55R	$9.99
13	12 V Stepper Motor	Motor used to tilt the beam	3	https://a.co/d/aFesjM5	$41.97
14	Stepper Motor Driver	Controller board for stepper motors	1	https://a.co/d/6hXPP4E	$17.99
15	5 V Regulator Module (10-pack)	Voltage regulation for logic and sensors	1 pack	https://a.co/d/3NDbJM3	$9.99
16	9 V Battery	Power source for early testing	1	— (Lab provided)	$0.00

figure19.1 Ansys simulation

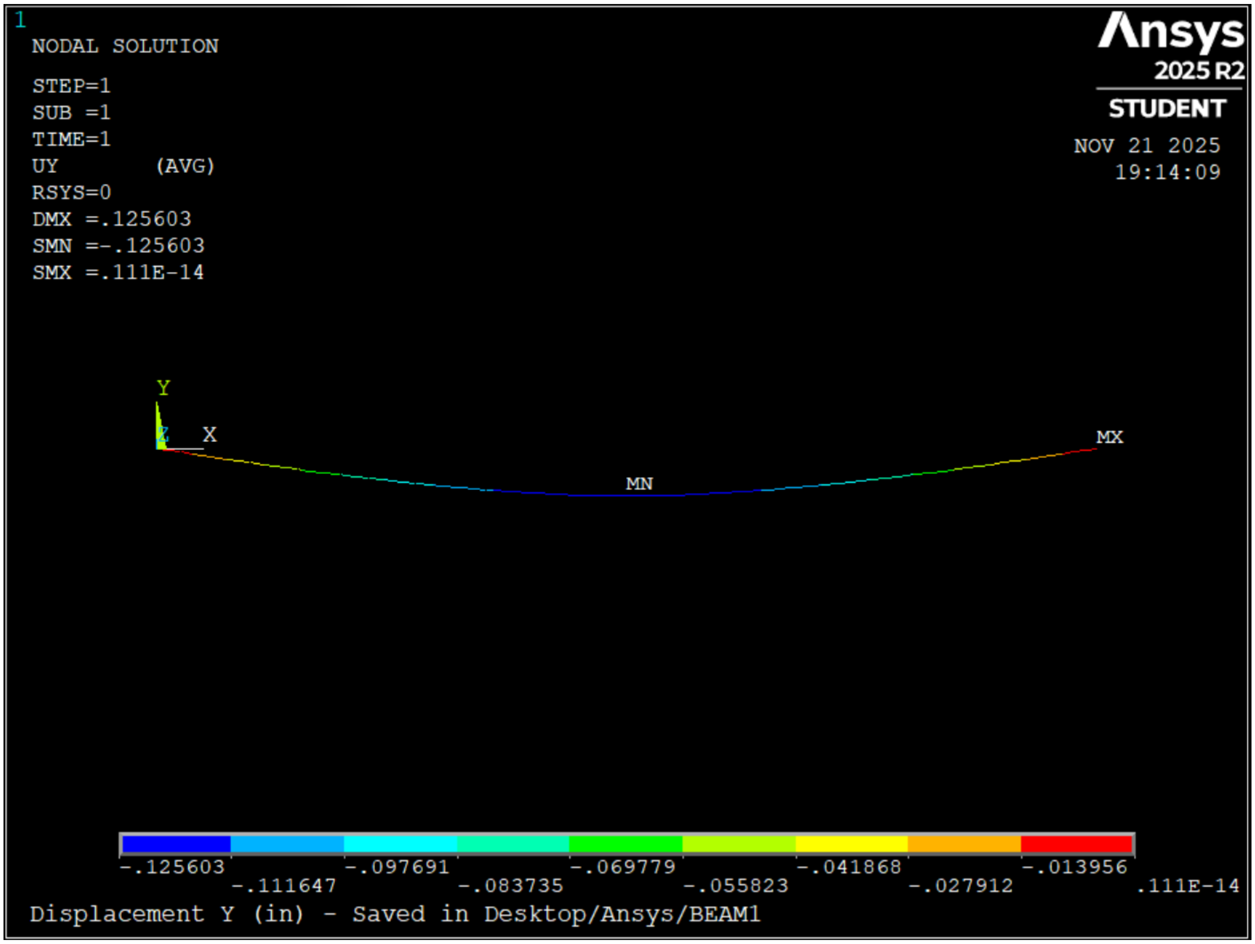
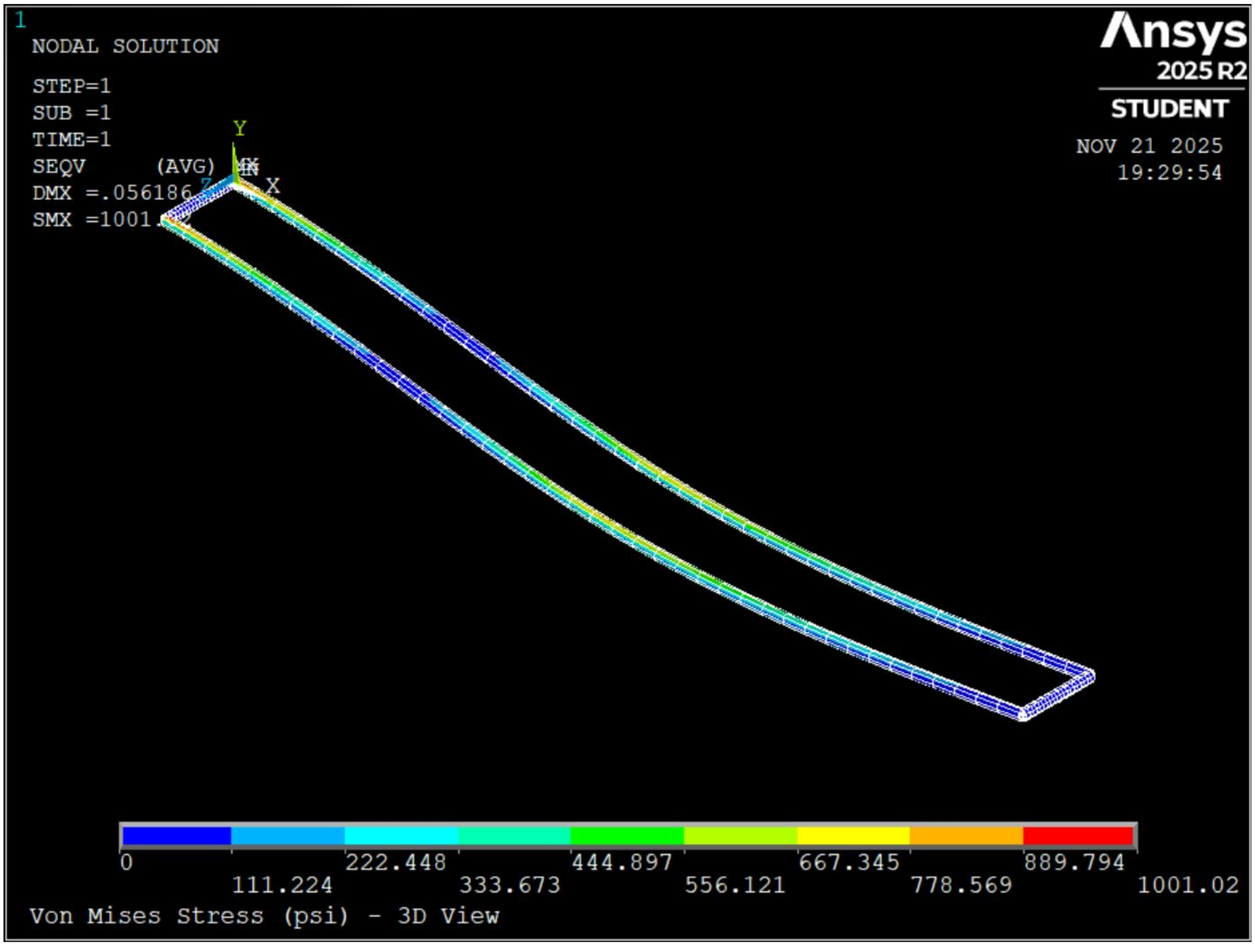


figure19.2 Ansys simulation


1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (AVG)
DMX =.056186
SMX =1001.
Ansys
2025 R2
STUDENT
NOV 21 2025
19:29:54
Y
Z
X
0
111.224
222.448
333.673
444.897
556.121
667.345
778.569
889.794
1001.02
Von Mises Stress (psi) - 3D View

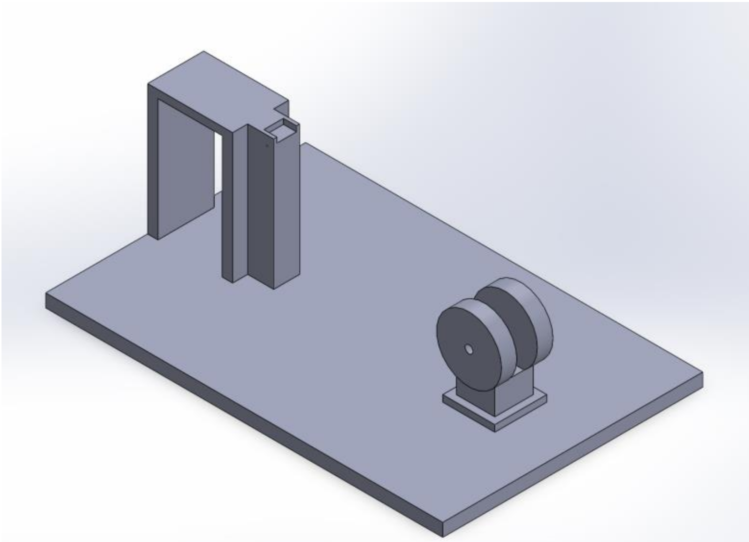


Figure 20 - Ball-on-Beam Prototype: Base

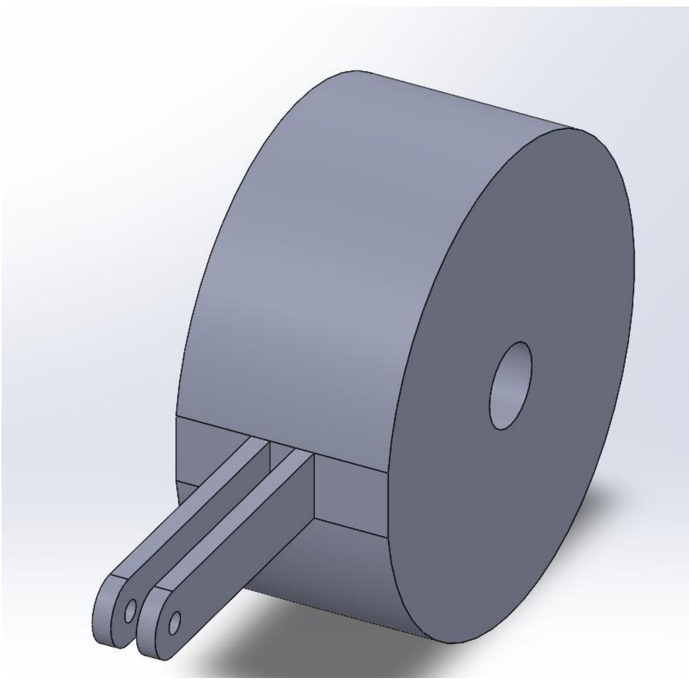


Figure 21 - Ball-on-Beam Prototype: Fulcrum

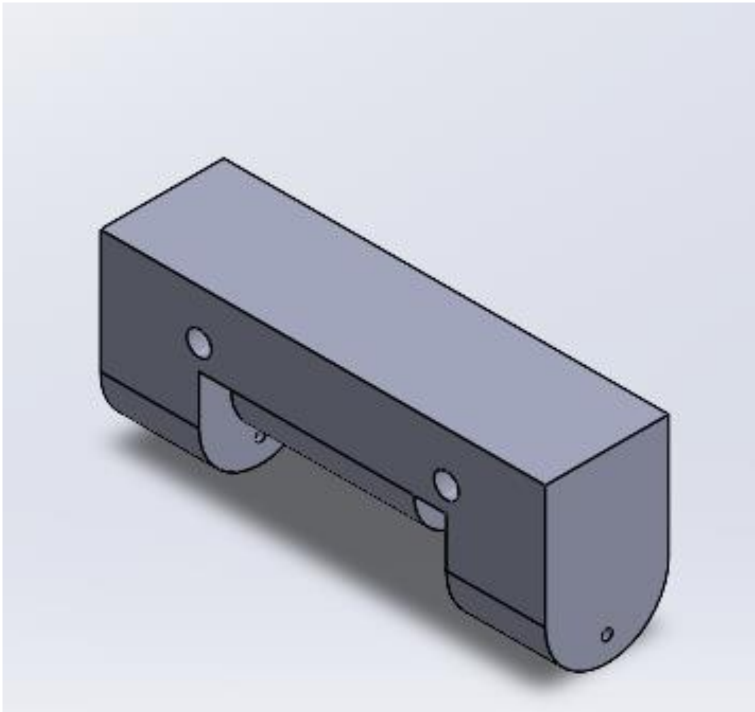


Figure 22- Ball-on-Beam Prototype: Hinge

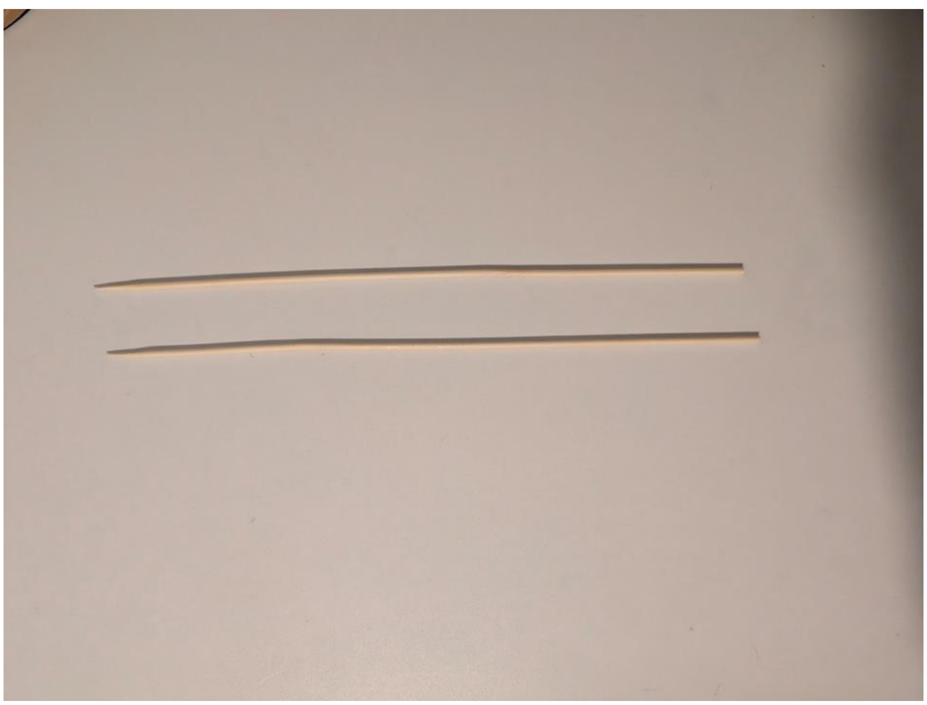


Figure 23 - Ball-on-Beam Prototype: Rod

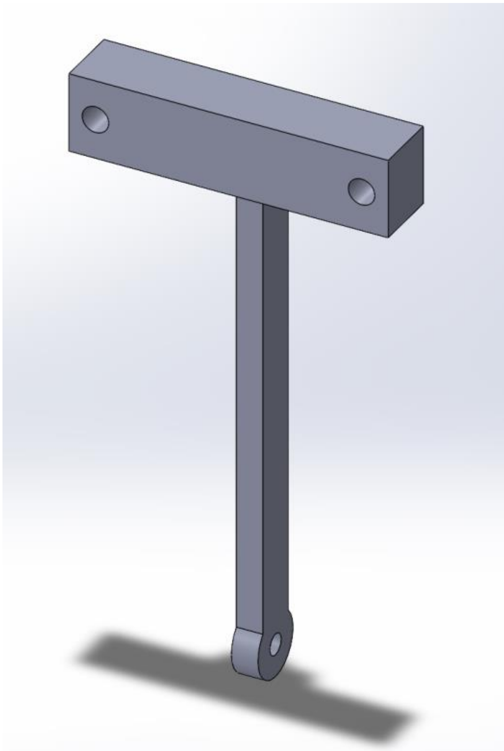


Figure 24- Ball-on-Beam Prototype: Stent

Figure 25- Ball-on-Beam Prototype: Servo Motor

Figure 26- Ball-on-Beam Prototype: Stepper Driver

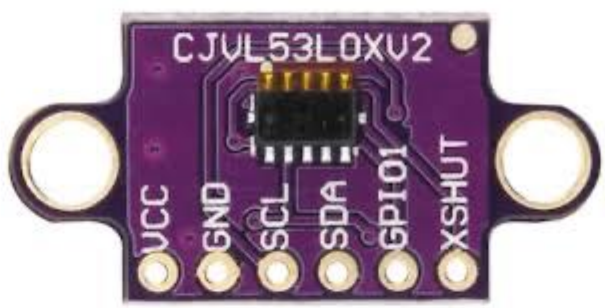


Figure 27- Ball-on-Beam Prototype: VL53L0X Sensor

Figure 28 Ball-on-Beam Prototype: Raspberry Pi

Figure 29- Ball-on-Beam Prototype: Battery

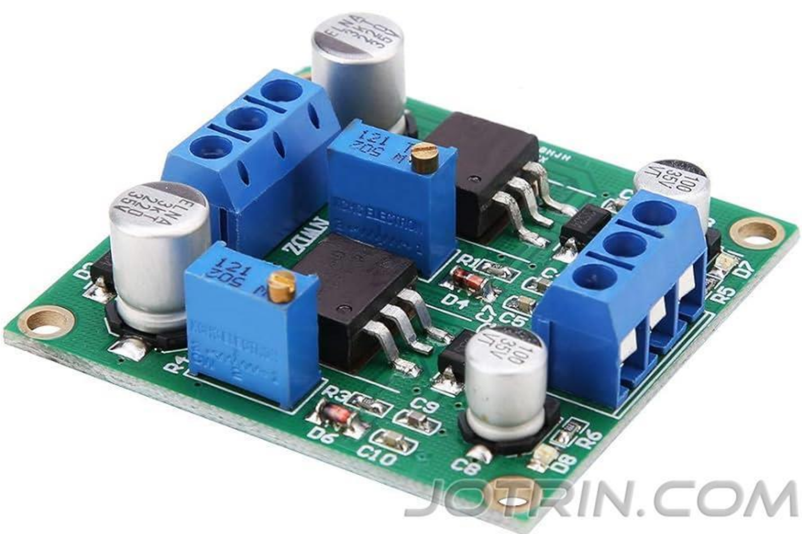


Figure 29- Ball-on-Beam Prototype: Regulator Module