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

This project, conducted under the guidance of Dr. Michael Shafer, focuses on the design, development, and testing of two educational robotics systems intended for K–12 STEM engagement. The primary objective is to create mass-producible, low-cost robots that demonstrate core mechanical and control-system principles while being safe, durable, and interactive for classroom demonstrations. The project is divided into two major systems: Robot #1 – an Inverted Pendulum Robot, and Robot #2 – an Educational Control Demonstrator, for which several design concepts are currently under evaluation.

For Robot #1, significant progress has been achieved toward both mechanical and control-system integration. The sub team has completed CAD models for the inverted pendulum assembly and initiated prototype fabrication. Control algorithms are being implemented using Arduino-based PID feedback, and testing will focus on validating system stability and response. The robot will serve as a hands-on demonstration of dynamic balancing, illustrating principles of feedback control and real-time actuation.

Robot #2 is in the concept generation and selection phase. Through systematic design tools such as morphological charts and decision matrices, the team evaluated several candidate systems based on customer and engineering requirements. These included the Ball-on-Plate Robot, Magnetic Levitation Robot, Reaction Wheel Robot, Line-Following Robot, and Hockey Robot. Using quantifiable metrics such as control complexity, manufacturability, educational value, and interactivity, the team identified three leading designs: the Reaction Wheel Robot, Ball-on-Plate System, and Magnetic Levitation Robot. Each was analyzed using representative mathematical models to ensure feasibility and to determine alignment with project goals. The team will meet with the client to finalize the design selection for Robot #2 before proceeding to modeling and prototype development.

The project operates with a budget of $5,000, with an additional fundraising goal of $500 (10%) to cover unforeseen material or fabrication costs. Major deliverables include two fully functional educational robots, comprehensive documentation of their design and control systems, and outreach-ready demonstration materials.

Overall, the team has established strong progress on Robot #1's physical design and control validation while completing the conceptual groundwork for Robot #2. In the coming development cycle, the focus will shift toward finalizing Robot #2's design, conducting mathematical modeling and subsystem integration, and beginning prototype construction to ensure both systems are ready for testing and educational deployment by the end of the academic year.

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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.

• *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.

• *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.
5. **Mass-production documentation** ensuring that the final designs can be easily replicated and assembled for continued K-12 use.

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.

• *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 our projects 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.

• *Customer Requirements (CRs)*

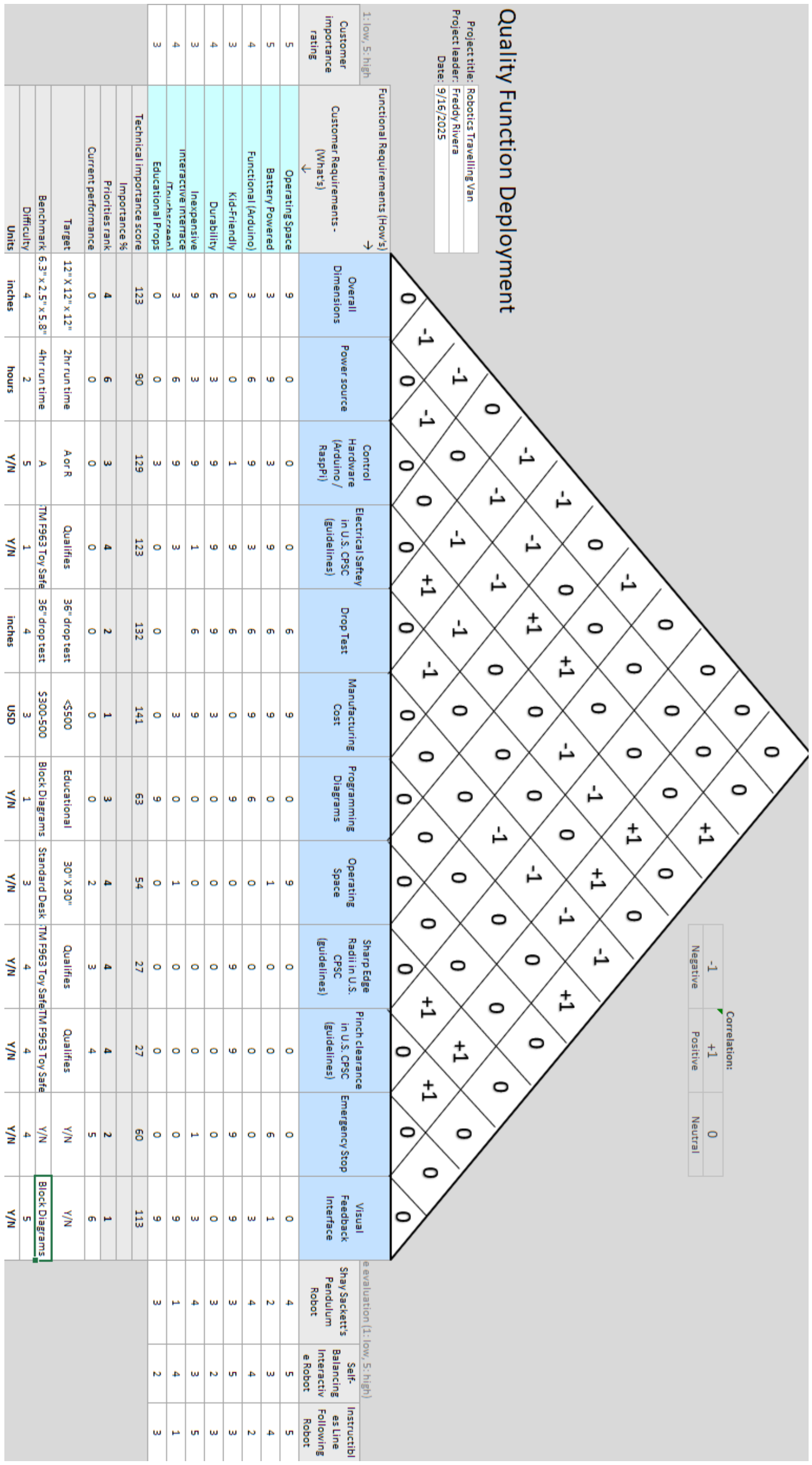
According to our customer/sponsor, our goals are to demonstrate how feedback controls affects the functionality of robots on continuous systems for K-12 students. The parameters that define our customer requirements stem from the intended user (K-12 students), the robots to be mass produceable, and their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

- ***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.

- ***House of Quality (HoQ)***



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 1 - QFD Diagram for Robot 1

3 Research Within Your Design Space

- ***Benchmarking***

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 the 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.	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 MagLev 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-	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.

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

- ***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.

3.2.2 Colin Parsinia

[20] “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.

[21] “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.

[22] “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.

[23] “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.

[24] “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.

[25] “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.

[2] "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.

3.2.3 Florence

[26] 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.

[27] 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.

[28] 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.

[29] 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.

[30] 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.

[31] 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.

[32]” 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.

[33] 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

[34] 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.

[35] 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.

[36] 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.

[37] 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.

[38] 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.

[39] 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.

[40] 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.

3.2.5 Andres

[41]: 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.

[42]: 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.

[43]: 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.

[44]: 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.

[45]: 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.

[46]: 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.

[47]: 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.

[48]: 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.

- ***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.

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

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

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) models 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).

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

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):

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

Pendulum (rotational motion):

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

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.

So 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)

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:

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

Figure 2 - Basic Laplace Equation

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

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

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 outputs in our feedback loop. It looks like this:

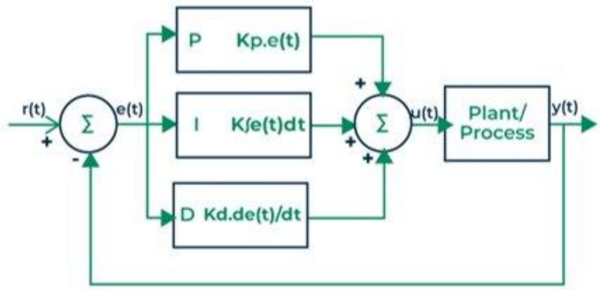


Figure 4 - Code Flow chart representing our looping code

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:

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

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:

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

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 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 $\theta_0 = 5°$ and $\dot{\theta}(0) = 0$, the control torque applied by the PD controller is

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

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

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

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.

- ***Mathematical Modeling for Robot #2***

Following the development and validation of the mathematical model for Robot #1 (Inverted Pendulum), the team began expanding its research and analysis toward Robot #2, which remained in the concept generation and selection phase during this design cycle. To ensure that the second robot concept would be both technically feasible and educationally valuable, the team conducted background research and derived representative equations for each proposed concept. Those being, the Ball-on-Plate, Magnetic Levitation, and Reaction Wheel robots.

These equations served two purposes: (1) to confirm that each design could be modeled and analyzed using fundamental dynamics and control principles suitable for an undergraduate capstone project, and (2) to determine which concepts offered quantifiable, testable parameters aligning with the team's engineering and customer requirements. Through this analytical process, the Reaction Wheel Robot, Ball-on-Plate System, and Magnetic Levitation Robot emerged as the top three concepts for Robot #2.

The following subsections summarize the mathematical foundations used to evaluate these Robot #2 concepts.

3.4.1 Reaction Wheel Sub-assembly – Freddy Rivera

To evaluate the torque and acceleration requirements for the Reaction Wheel Robot, the sub-team modeled the system as a single axis balancing body. The primary governing equation relates the torque produced by the reaction wheel to the body's angular acceleration about its unstable equilibrium. This model is linearized near the upright position for small angular displacements.

Key Equations:

$$J_w = \frac{1}{2} m_w {r_w}^2 \quad (14)$$

$$\tau_{grav} = mgh\theta \quad (15)$$

$$\alpha_w = \frac{\tau_{grav}}{J_w} \quad (16)$$

Where (for a demo-sized cube):

- Body mass $m = 0.50kg$
- Center of mass height about the balance edge $h = 0.05m$
- Body inertia about balance axis $J_b = 6.7 \times 10^2 kgm^2$
- Reaction-wheel (solid disk): $m_w = 0.10kg$,$r_w = 0.05m$
- Gravity: $g = 9.81 \, {}^{m}/_{s^3}$
- Angle: $\theta = 5° = 0.0873$ rads

By solving these equations with the assumed variables for an idealized classroom setting, would obtain the following results:

$$J_w = 1.25 \ \times 10^{-4} \ kg * m^2$$

$$\tau_{grav} = 0.0214 \ Nm$$

$$\alpha_w = 171 \ \frac{rad}{s^2}$$

This result indicates that a single reaction wheel with the specified inertia must accelerate at approximately 171 rad/s² to counteract the gravitational torque produced by a 5° tip. This analysis demonstrates that even a compact wheel–motor assembly can stabilize a small tabletop cube when properly tuned with PD control.

These equations originate from linearized rotational dynamics for reaction-wheel pendulum systems, as outlined by Block et al. in *The Reaction Wheel Pendulum* [Freddy 5 -8].

3.4.2 Ball on Plate – Florence Fasugbe

The equilibrium of the plate has an acceleration of zero and this occurs throughout each joint. The external force on each joint:

$$Q_n = M_{f,n} + M_{M,n} \ (17)$$

There are no external forces except friction being applied directly to the ball.

$$Q_3 = F_f Q_4 = F_{f,2} \ (18)$$

These equations derive from the Laplace equation, and the kinetic and potential energy are subtracted from each other. The potential energy is calculated by multiplying the torque constant ($\frac{N \cdot m}{A}$) of a standardized motor and the current (A) of that motor.

$$0.8508 \ \frac{Nm}{A} \cdot 10 \ A \ = \ 8.51 \ N \cdot m$$

This shows that when the current increases, then the torque increases, and it helps determine how much energy is needed for the motor to rotate.

3.4.3 Magnetic Floating Ball – Ziyi Tang

To achieve stable magnetic levitation of a steel sphere between two coaxial electromagnets, we model the magnetic pull of each gapped core and select coil currents that balance gravity while satisfying thermal limits. Under the unsaturated-core, moderate-gap assumption, the axial attraction of a single electromagnet follows an inverse-square dependence on the effective air gap. With two opposed poles separated by a fixed spacing (G), the upper coil pulls upward while the lower coil pulls downward; a feasible… Assumptions used in the calculation are: two coaxial electromagnets with gap G = 20 mm; each coil has N = 800 turns and effective pole area A = 3.14×10^-4 m^2; a correction gap g0 = 0.5 mm accounts for fringing and assembly tolerance; the levitated object is a steel sphere of mass m = 0.033 kg (weight mg ≈ 0.323 N); and the continuous coil current is limited to I ≤ 0.8 A.

The magnetic force of a single coil is modeled as

$$F = \frac{KI^2}{(g+g0)^2}, (19) \qquad K = \frac{\mu_0 N^2 A_{\text{eff}}}{2}, (20)$$

where g is the instantaneous air gap and _0 is the permeability of free space.

For the two-coil configuration, let h be the ball height measured upward from the lower pole face. The effective gaps are g_U = (G - h) + g0 to the upper pole and g_L = h + g0 to the lower pole. The vertical force equilibrium that determines feasible operating points is

$$\frac{KI_U^2}{(G-h+g0)^2} - \frac{KI_L^2}{(h+g0)^2} = mg. (21)$$

Solving the above relation under the current limit yields a practical levitation band of approximately h ≈ 7–15 mm.
Example operating points consistent with the design are: h = 7 mm: Iu ≈ 0.79 A, Il ≈ 0.22 A
h = 9 mm: Iu ≈ 0.69 A, Il ≈ 0.31 A
h = 15 mm: Iu ≈ 0.36 A, Il ≈ 0.64 A
A rough flux estimate from the same gap model gives B_max ≈ 0.06 T ≪ B_sat. The corresponding electrical power is about P ≈ 4–5 W, which satisfies the steady-state thermal constraint for the specified coils.

These calculations provide the necessary quantitative basis for the maglev ball prototype: they tie the required coil currents to the desired levitation height, confirm a safe operating window under current limits, and verify that the magnetic loading remains well below core saturation.

4 Robot #1 Design Concepts

• *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."

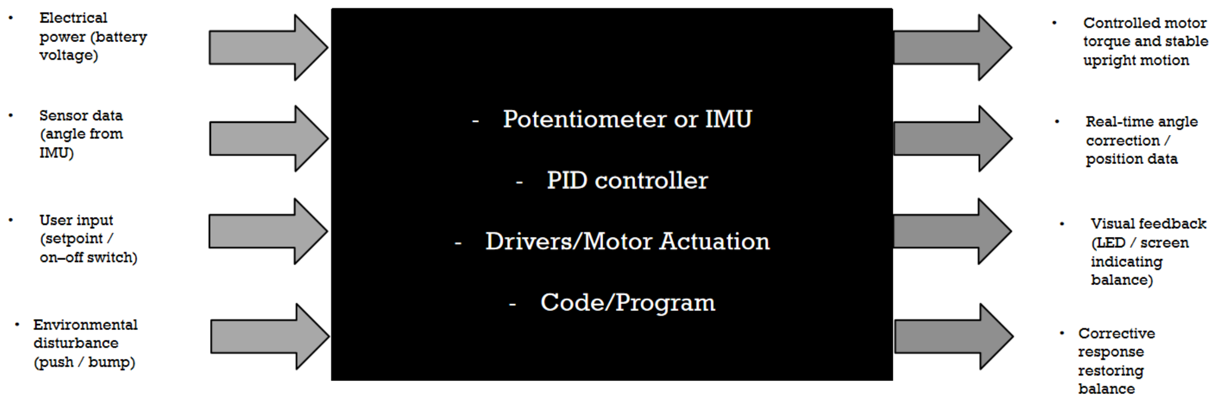


Figure 5 - Black Box Diagram of Robot 1

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.

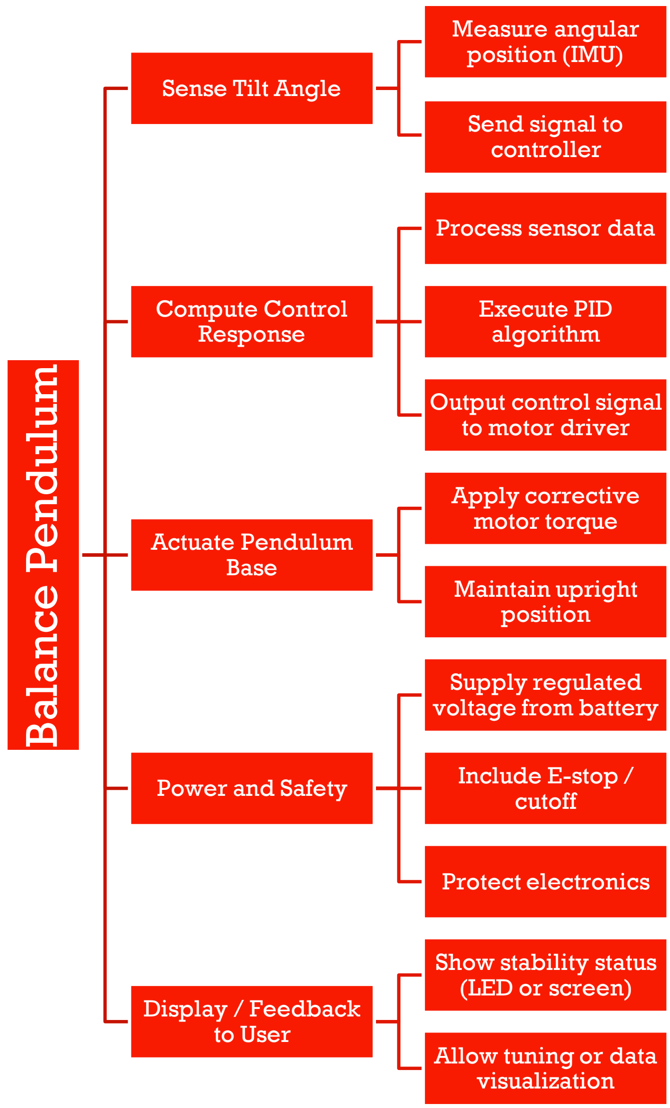


Figure 6 - Robot 1 Functional Decomposition Diagram

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.

• ***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 the 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.

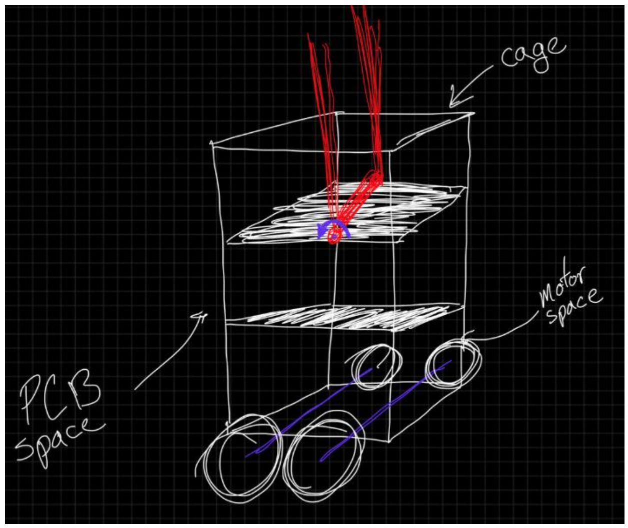


Figure 7 - Pendulum Robot Frame Concept Sketch 1

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

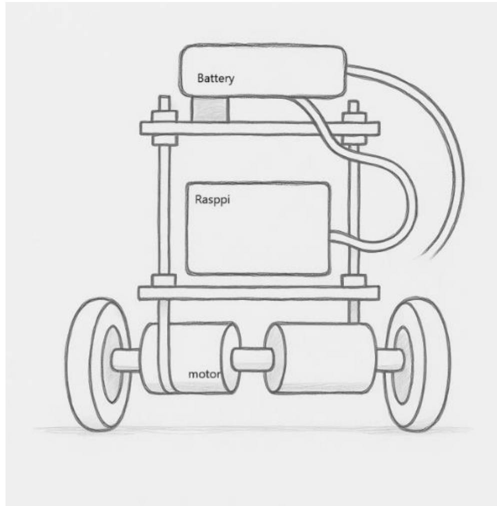


Figure 8 - Pendulum Robot Frame Concept Sketch 2

The second concept for the pendulum robot frame is a 2-wheel robot design where the robot as a whole 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 asthetic appealing frame, and reduced structural integrity of the frame.

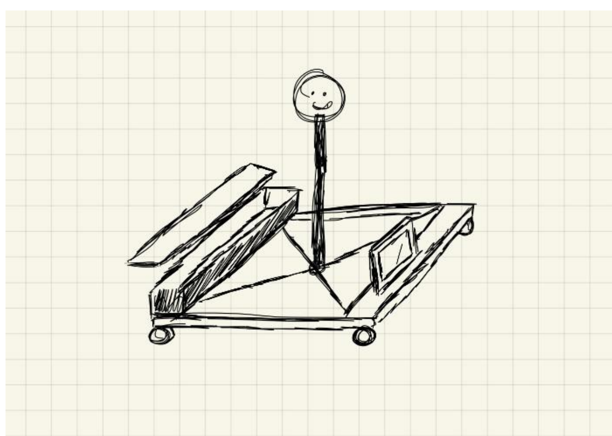


Figure 9 - Pendulum Robot Frame Concept Sketch 3

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

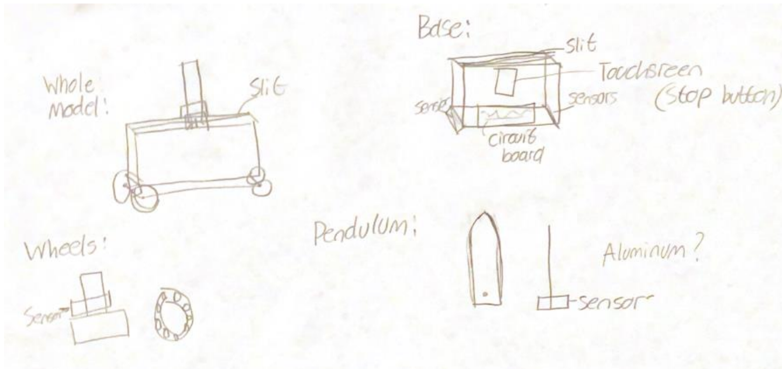


Figure 10 - Pendulum Robot Frame Concept Sketch 4

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

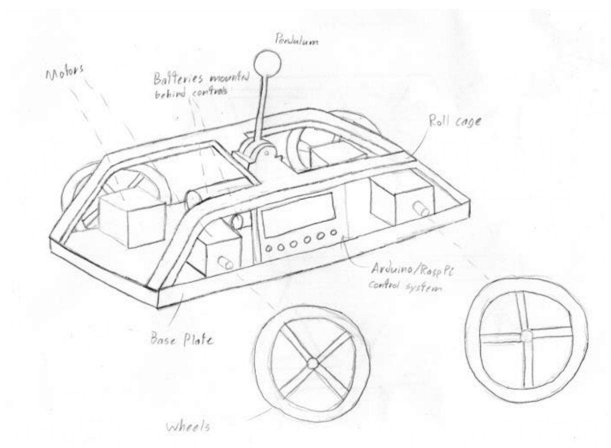


Figure 11 - Pendulum Concept Sketch 5

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.

- ## *4.3.1 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.

- ### *4.3.2 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
Manufacturabi lity	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

In order 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 weighting, 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.

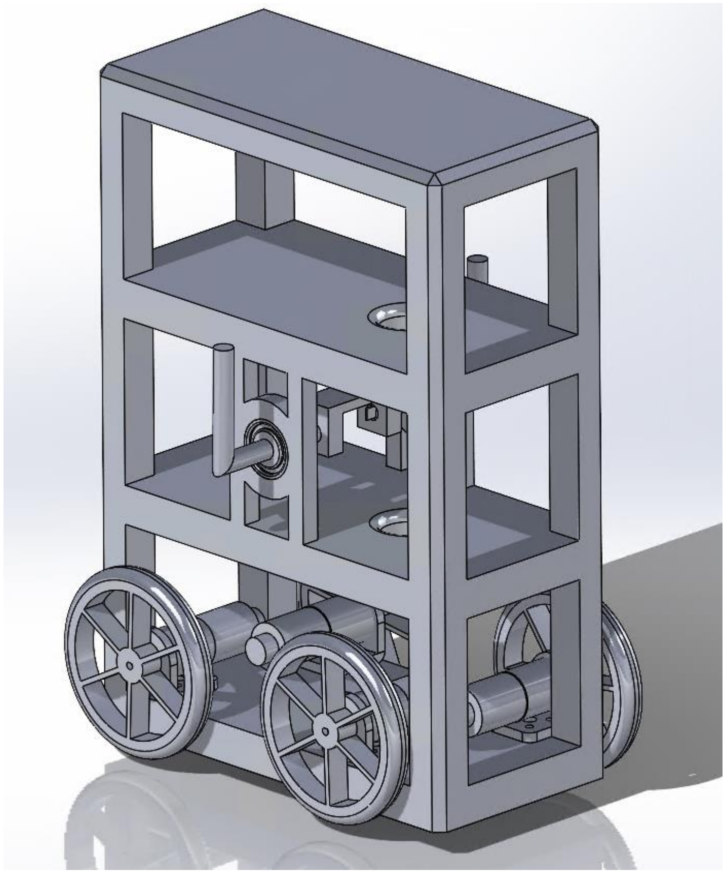


Figure 13 – Robot 1 Final Design CAD drawing

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 are capable of producing the necessary torque to move the robots weight, and facilitate the pendulums stabilization.

5 Robot #2 Design Concepts

• *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.

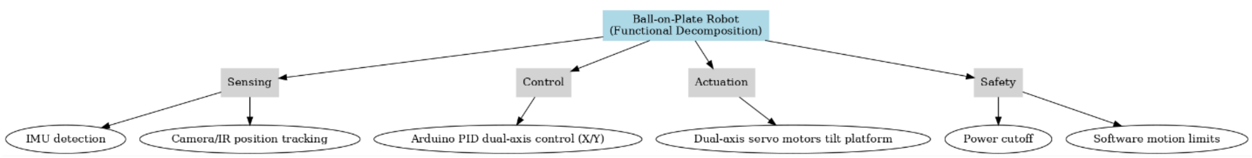


Figure 14 - Ball-on-Plate Robot Functional Decomposition

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.

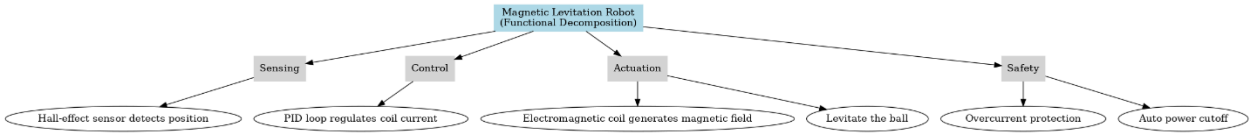


Figure 15 - Magnetic Levitation Robot Functional Decomposition

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.

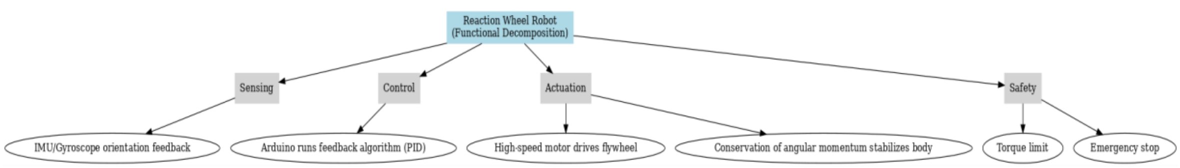


Figure 16 - Reaction Wheel Robot Functional Decomposition

- ## *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.

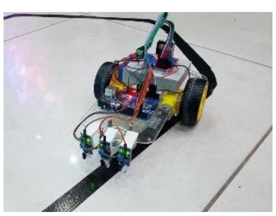
- **Base Structure:** stationary tabletop frames, wheeled platforms, and enclosed cubes were considered.
- **Actuation:** options include servo motors, DC motors, electromagnets or flywheels.
- **Sensors:** IMUs, cameras, Hall-effect sensors, and line sensors were compared for feedback accuracy and cost.
- **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* [49].	– 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* [50].	– 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* [51].	– 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* [52].	– 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* [53].	– 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.

- ***Selection Criteria***

[Outline the selection criteria that was used for concept selection. These must be rooted in the engineering requirements and be quantifiable through calculations (for designed parts) and/or well-known specifications (for purchased parts). These calculation results and specifications MUST be summarized and discussed.]

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 the 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.

- ***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 feedback 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 designing process and more research will be conducted.

CONCLUSIONS

This report outlined the progress and outcomes of our capstone project, which aims to design and develop two educational robots for K–12 STEM outreach. The overarching goal is to create affordable, durable, and interactive robots that demonstrate core control system principles in an engaging and accessible way. A critical requirement of this project is that both robots must be mass-producible, educationally relevant, and capable of demonstrating real-time feedback control for instructional use.

Throughout the semester, the team divided efforts into two subgroups. Robot #1, the inverted pendulum system, represents a classical control challenge centered on balance and stabilization. Its mathematical modeling, control design, and prototype development have shown promising progress toward demonstrating proportional-derivative control in a tangible format. Robot #2 underwent an extensive concept-generation and evaluation process in which several ideas such as a reaction-wheel cube and magnetic levitation device were explored and compared. After consulting with our client, the team finalized the concept selection for Robot #2 as a Ball-on-Plate System, a platform that uses servo actuation and visual feedback to keep a ball centered on a tilting plate. This design was chosen for its high educational value, clear demonstration of multi-variable control, and safe, interactive nature.

By the end of the semester, both sub teams have established strong analytical foundations and preliminary models for their respective designs. The next phase will focus on refining CAD models, implementing control algorithms, and beginning prototype fabrication and testing. Once completed, these robots will serve as powerful instructional tools, enabling students to directly observe and interact with core engineering concepts such as feedback, stability, and system dynamics.

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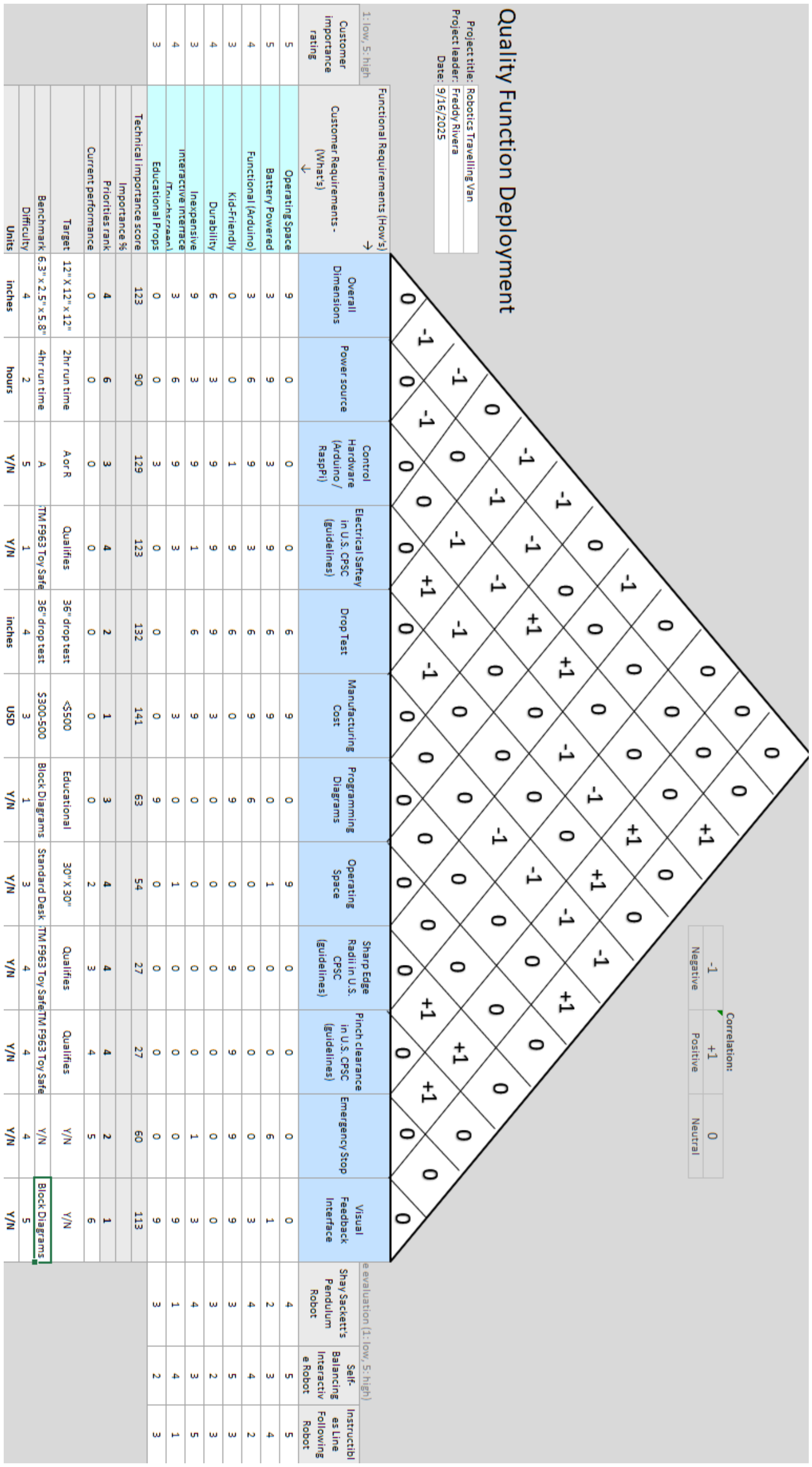
7 APPENDICES

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

- ***Appendix B: Figures in order of appearance***



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			

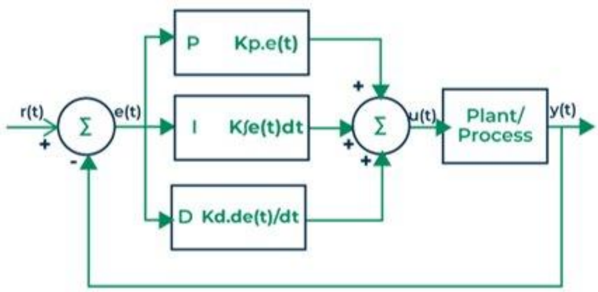
- Figure 1 – QFD
- Figure 2 – Laplace Equation

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

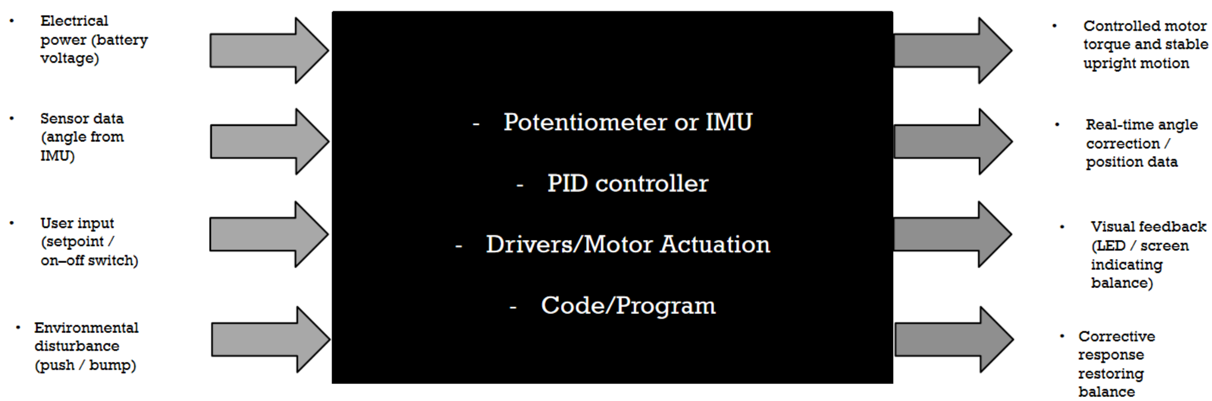
- Figure 3 – Re-Arranged Laplace Equation solving for time with variables input

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

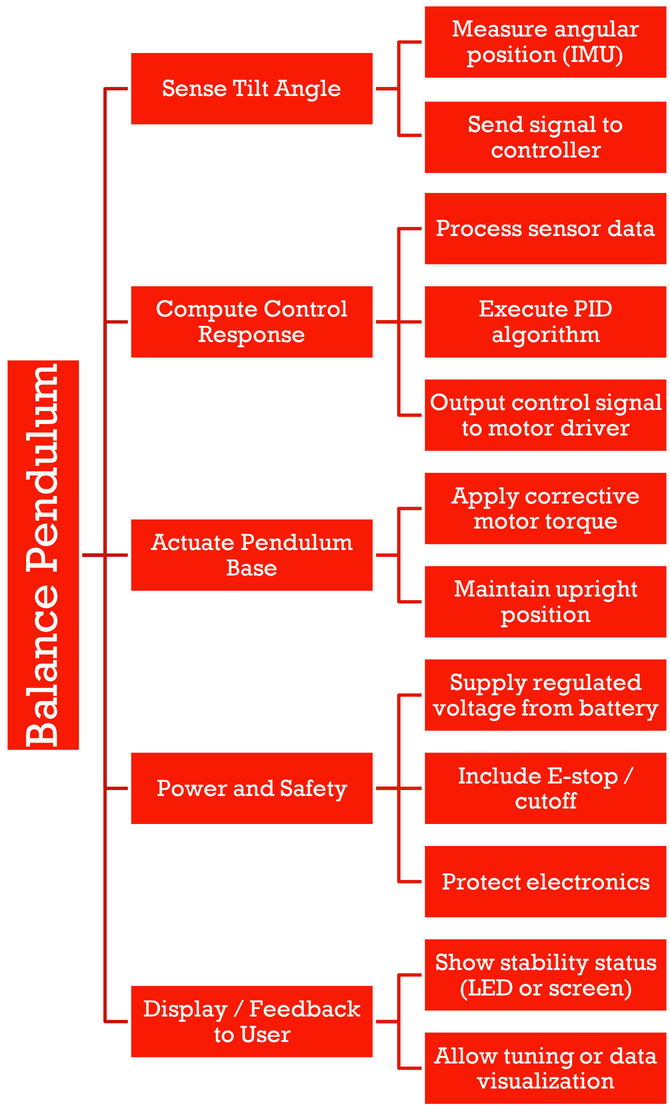
- Figure 4 – Code Flow Chart representing our looping coded



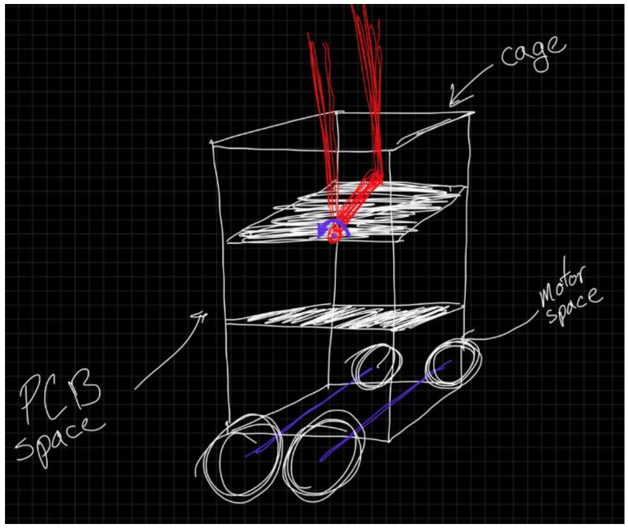
- Figure 5 – Black Box Diagram of Robot 1



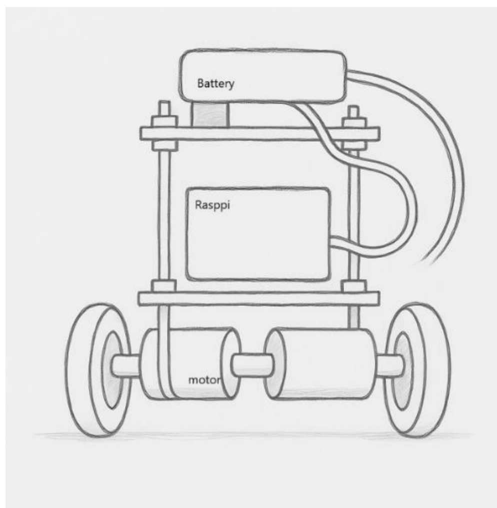
• Figure 6 – Robot 1 Functional Decomposition Diagram



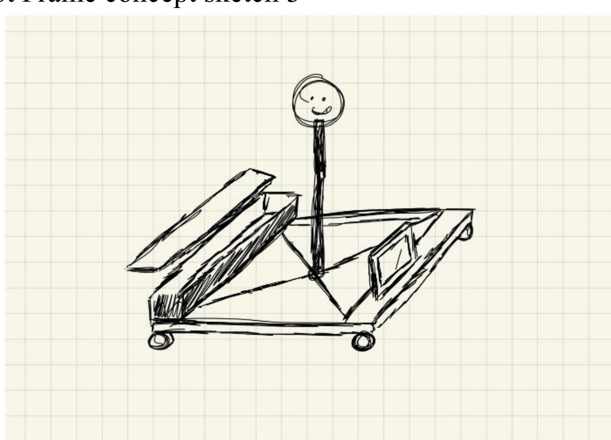
- Figure 7 – Pendulum Robot Frame concept sketch 1



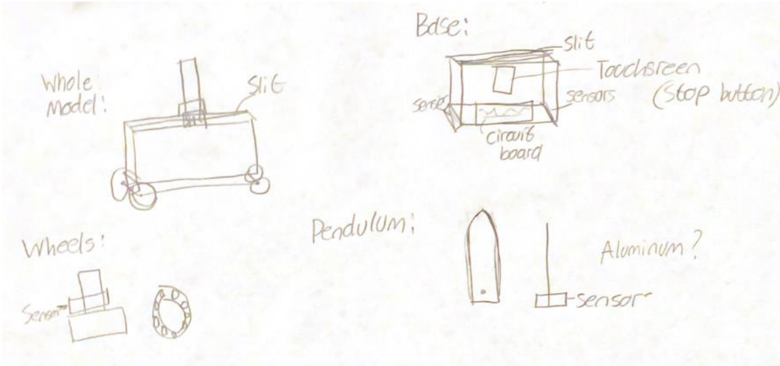
- Figure 8 – Pendulum Robot Frame concept sketch 2



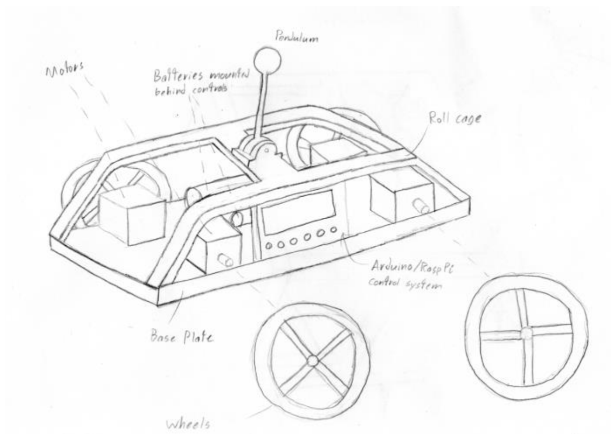
- Figure 9 – Pendulum Robot Frame concept sketch 3



- Figure 10 – Pendulum Robot Frame concept sketch 4



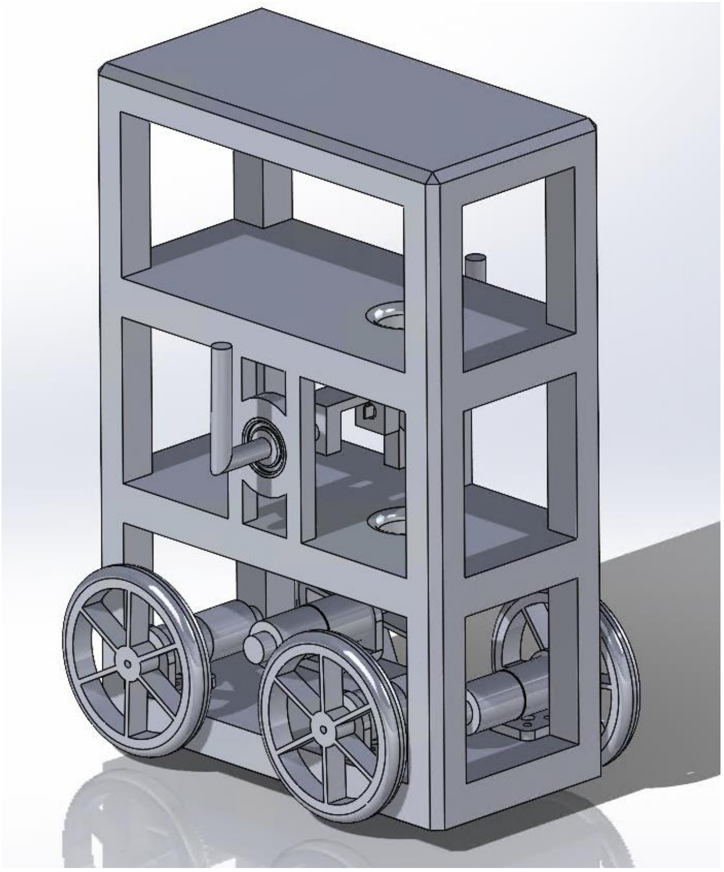
- Figure 11 – Pendulum Robot Frame concept sketch 5



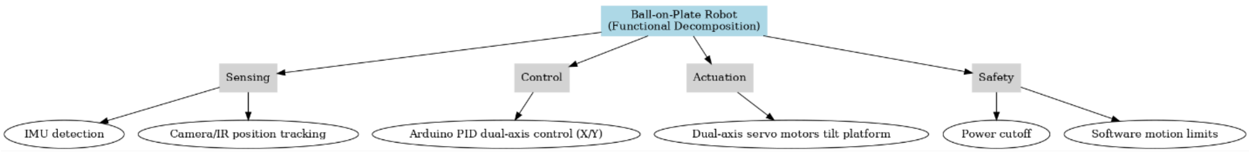
- Figure 12 – Pugh Chart comparing top 3 Pendulum Frame Designs

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

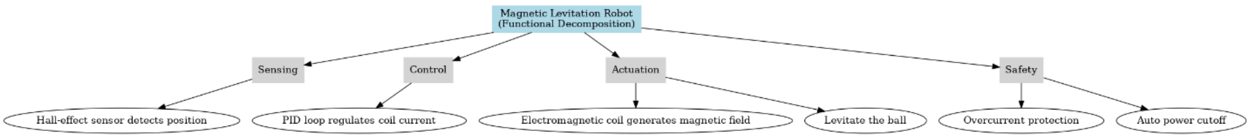
- Figure 13 – Robot 1 Final Design CAD Model



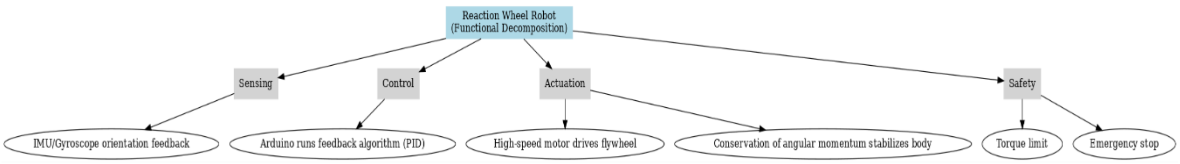
- Figure 14 – Ball-on-Plate Robot Functional Decomposition



- 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