BUILDING TWO PHYSICS ROBOTS FOR EDUCATIONAL USE IN K-12 SCHOOLS

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1. ABSTRACT

One of the most important aspects of building and growing an engineering community is to encourage more people to get excited about the field. By reaching out to K-12 students, the Robotics Traveling Van can help establish this interest in STEM within younger groups. The goal of the project is to design two robots combining the disciplines of mechanical and electrical engineering, which would be inexpensive for schools to buy. The robots would then be used as a tool that teachers can use to demonstrate the principles of engineering, physics, and robotics. With how little time and resources educators have, the goal is to make the design intuitive and give a clear understanding of what is happening. The design requirements entail that the two robots should be accessible for younger students and standard classrooms. They should be able to fit on a cart so that they can be transported from classroom to classroom, be able to survive accidents like falling off a table and make them simple enough to understand. The team picked out two designs to demonstrate. The first being a self-balancing, inverted pendulum robot, and second being a robot that can balance a ball on a plate. A self-balancing robot will balance a rod on its body to demonstrate physics, along with sensor control and input. The ball on a plate robot will use motors to move a circular plate around to center a ball without it rolling off the plate. The design will incorporate a touch screen such that the robot is interactive, while also showing visual output for students to see the thought behind why the robot is moving the way it does. The team's method of building the robot and prototype includes using small computers and

microcontroller interfaces such as the Arduino and raspberry pi. The team will have two complete prototypes by the end of the fall 2025 semester and expand on the prototypes and production beginning spring 2026.

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3. BACKGROUND

The Robotics Travelling Van capstone group aims to build two physics robots which will increase student interest in robotics and physics. The first robot is an inverted pendulum robot, while the second robot incorporates a ball on a plate system. The former robot can give children an example of physics in action and show them what the robot is 'thinking', all while balancing the inverted pendulum. The latter robot is going to be a more interactive, more complex robot. The goal of this robot is to expose school kids to a more complicated and visually interesting robot. To make the robot more interactive, different methods for the kids to interface with the robot are being discussed. Some notable examples are voice activation or a controller, in addition to a touch screen, which both robots will have.

In addition to physics and robotics demonstrations, these robots are educational. The touchscreens on the robots will display the values measured by the robots in real time and show a simple overview of what the robot is thinking. These touchscreens will also allow children to experiment with changing different aspects of how the robot works, either through editing variables or through pre-coded functions.

4. REQUIREMENTS

The two education physics robots will be built with requirements and constraints given to the team by Dr. Willy. The general requirements insist that these robots are durable, inexpensive (under $150 per unit), functional (battery powered, interactive, and works within a confined space), educational, and child friendly. These general requirements were refined into a specific list of engineering requirements, which the team will then use to build the decision matrix from.

From Dr. Willy's requirements, both robots must be under 14" × 10" × 5", or the approximate size of a shoebox. The durability requirements are that the robots must continue to function after a 30" drop onto concrete. To keep within the cost constraints, cheaper boards such as the Arduino Uno and Raspberry Pi Pico were selected over competitors like Raspberry Pi 5 or Raspberry Pi Compute modules. The robots must have the capacity to run for up to 90 minutes between charges, have an interactive touchscreen displaying information about each robot, and stay within a 20" square area. To make these robots educational, the information displayed will explain, at a high level, what the robot is 'thinking' while running. These touchscreens will also allow schoolkids to select from multiple operating modes and change some of the code variables, affecting the function of the robots. Lastly, programming diagrams will be included, which can aid in the explanation of how these robots work for children.

The last requirement is that the robots be kid-friendly, which will be fulfilled as a bi-product of making the robots US CPSC compliant. This consumer product safety standard covers a large variety of toys, with some of their sections applying to the two physics robots. Section 4.7 covers hazardous edges accessible to children, both before and after “use-and-abuse testing” [1]. From Section 4.13, any folding mechanisms and hinges must be designed to eliminate the chances of children hurting themselves [1]. Notably, the inverted pendulum on the first robot will need to be specifically designed to comply with 4.13. Section 4.17 covers wheels, which both robots will have. The wheels on the robots must not “pose a laceration, puncture, or ingestion hazard” before or after use [1]. Lastly, Section 4.25 specifies that battery-operated toys must ensure that the batteries are inaccessible during use [1]

5. OBJECTIVES

The objective of this capstone project is to create two mass-producible robots for the purpose of demonstrating engineering principles. This will allow K-12 students to learn more about the STEM field early in their education and see the thought process that goes into creating devices such as these. As this will be presented to a young audience, the robots will be displayed as an interactive toy to help spark an interest.

With the clear goal of creating two robots, the project's client expressed interest in creating and demonstrating a prototype for each robot by the end of the semester. The Robotics Traveling Van created a timeline that will allow us to satisfy this request and keep the team on schedule.

Fall 2025 Semester

1. Robot Development	Week 6 - Week 12
1.1 Mechanical Design Phase	Week 6 - Week 8
1.1.1 CAD Modeling	Deliverable: 3D CAD model of key components
1.1.2 Material Procurement	Deliverable: Purchase orders, BOM for Robots
1.2 Electrical Design Phase	Week 7 - Week 12
1.2.1 Circuit Design	Deliverable: Schematic & PCB layout
1.2.2 Programming	Deliverable: Control software with basic functionalities
1.2.3 Testing & Debugging	Verify hardware & software integration with debugging reports

Table 1: A timeline that will keep the robotics traveling van capstone project on course to being able to create two prototypes ready for demonstration by the end of the 2025 fall term.

Spring 2026 Semester

2. Robot 2 Development Pt 1	Week 1 – Week 3
2.1 Prototype Testing/Finalization	Week 1 - Week 2
2.1.1 CAD Modeling	Deliverable: 3D CAD model of improved prior prints
2.1.2 Material Procurement	Deliverable: Purchase orders, BOM for Robot
2.2 Electrical Design & Assembly	Week 3
2.2.1 Product Debugging and Finalization	Verify hardware & software integration with debugging reports
3. Robot 2 Development Pt 2	Week 3 – Week 8
4. Robot 1 Development	Week 1 – Week 7
4.1 Prototype Testing/Finalization	Week 1 – Week 3
4.1.1 Equation Formation	Deliverable: Procure equations based on fall prototype
4.1.2 CAD Modeling	Deliverable: 3D CAD model of improved prior prints
4.1.3 Material Procurement	Deliverable: Purchase orders, BOM for Robot
4.2 Electrical Design & Assembly	Week 3-7
4.2.1 Product Debugging and Finalization	Verify hardware & software integration with debugging reports

Table 2: A timeline that will keep the robotics traveling van capstone project on course to being able to final products ready to present to schools by the end of the 2026 spring term.

As seen from table 2, robot 2 will have two development stages. Due to time constraints, a ball-on-beam robot was built in place of the ball-on-plate robot. This is a much simpler design which allows us to have a complete prototype by the end of the fall 2025 term and will be expanded into the ball-on-plate system once robot 1 is completed.

The team will stick to the timeline to stay on track for finishing two working prototypes that are ready to display to the client as well as local high schools at the end of the 2026 spring term.

6. STANDARDS

A requirement for the project is that the design must follow appropriate standards for safety, the law, and be compatible with standards set by the IEEE association for the two robots. The subsequent paragraphs go into more specific detail about the appropriate safety standards and the engineering standards the robots will be using.

As per the United States Consumer Product Safety Commission, a ‘toy’ is any object designed, manufactured, or marketed as a plaything for children under the age of 14 [1] Our objective is to design an educational toy for K-12 students, our robots must comply with the rules set in place by the CSPC regarding toys. These requirements are outlined in ASTM F963 Section 4 [1]. A summary of the relevant subsections detailed:

- The product should be free from infestation (4.1)
- The product should not be flammable (4.2)
- The product should not contain excessive hazardous (toxic, corrosive, irritant, pressure generating, radioactive, etc.) substances (4.3.1)
- The product should not contain excessive heavy elements (lead, chromium, etc.) (4.3.5.2)
- The product should not contain more than 0.1% phthalates (4.3.8)

The product should not contain choking hazards (4.6.1)

The product should not have sharp edges (4.7)

If the sharp edges are required for the function of the product, there should be a warning label (4.7.2)

Metal edges that can be accessed should not have hazardous burrs (4.7.3)

Wires in the interior of the product should not break off and create points (4.10)

The list of standards for toy safety is extensive. More standards that are relevant to this project will be added as needed during this project.

There are also IEEE standards that correlate to the project. Specifically, the IEEE Standard for User Interface Elements in Power Control of Electronic Devices Employed in Office/Consumer Environments. The main goal of these standards is to create a uniform user experience when it comes to power controls. This applies to all consumer electronics, which, if the product is not only being sold to schools, is the category in which our robots lie. The standards are summarized as follows:

- Devices should have three basic power states: on, sleep, and off. There may be additional states, but they must be sub-states of the three main states [2].
- If the device has a sleep state, it must have one or more 'wake events' to bring it back to the on state [2].
- The power consumption for these three states is required to be:
    - Pon > = Psleep
    - Psleep >= Poff
- Holding the power button down for four seconds will cause the product to shut down regardless of what is happening (an emergency override) [2].

As with the previous set of standards, this list of relevant IEEE standards will also continue to grow as the project continues.

7. INVERTED PENDULUM ROBOT DESIGN

The pendulum balancing robot is the first robot the team worked on. The purpose of this robot is to balance a rod on top of itself and be able to move on wheels to correct the rod position when it begins to tilt or fall. For this, the robot will consist of the following parts:

- Arduino Uno
- Wheels x4
- Potentiometer
- 9V DC Motor x4
- Ultrasonic Sensor x2
- Touchscreen Interface

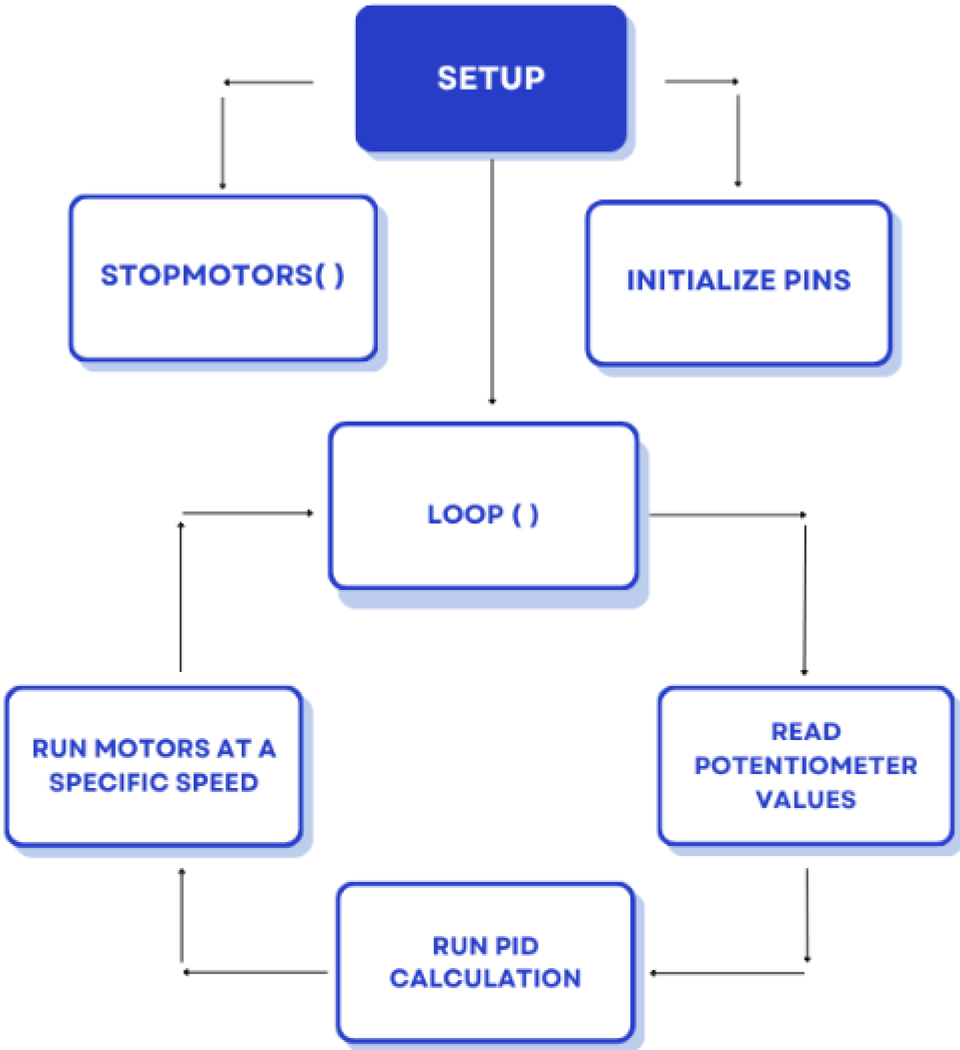

Figure 1: Robot 1 code flowchart showing PID control

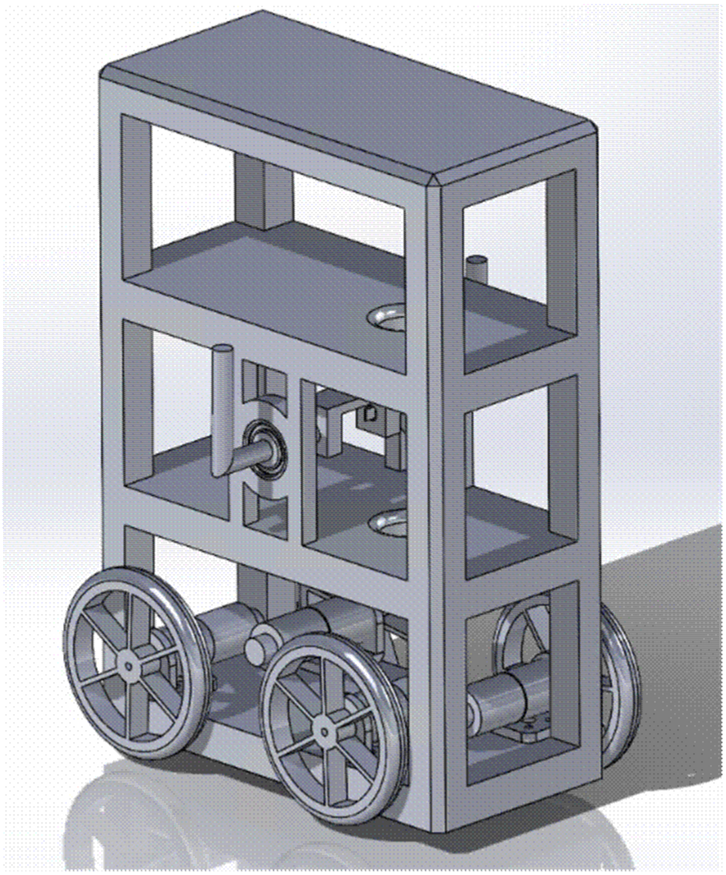

Figure 2: Robot 1 final design CAD model

The team programmed the Arduino Uno to balance the rod on top of the robot. This was done by using potentiometers attached to the rod fixture, which measures the angle of the rod to provide real-time readings of the rod position. The ultrasonic sensors are then used to track the robot's position on the school table so that if the robot gets too close to the edge, it will go in the other direction to avoid falling off. The motor will drive the wheels.

PID Equations:

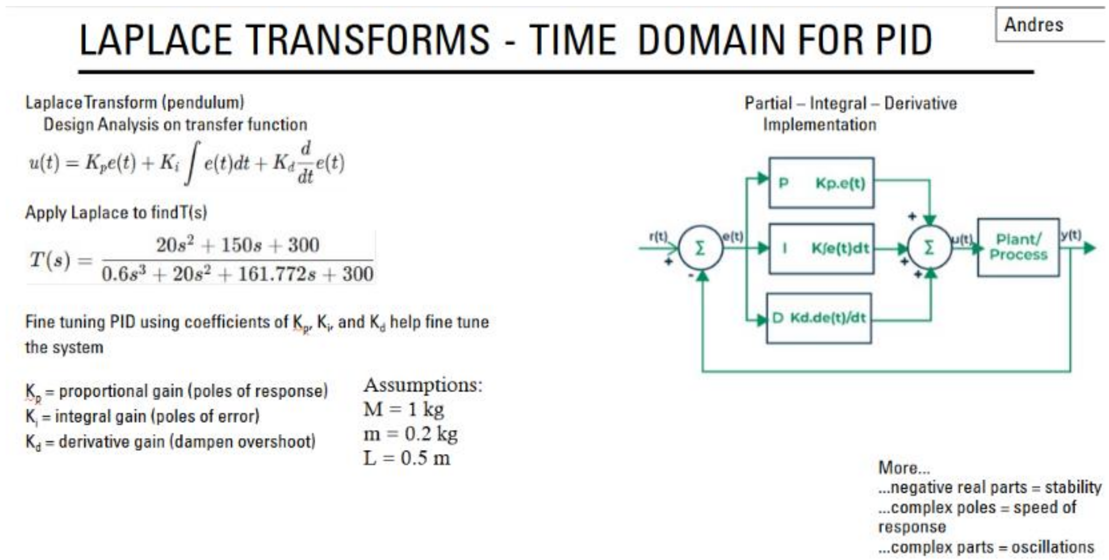

Figure 3: Laplace transforms used in motion equations

- The team will use angular changes in position from potentiometer to detect rod movement and how motors will need to move to correct this change.

The task for the spring term is to implement a touch screen for the robot. Because this is meant to be an interactive experience for students, the touch screen will allow them to control certain variables and be able to experiment with the code themselves. For example, the students may be able to change how quickly the rod will fall, so the robot will have to adjust its speed to stand the rod upright.

8. BALL-ON-PLATE ROBOT DESIGN

The ball-on-plate robot is the second robot the team worked on. This project wasn't proposed until week 12, so due to time constraints, the design was pivoted to a ball-on-beam design to be prototyped in the fall 2025 term. The idea behind this transition is that it would be more feasible to work in two dimensions rather than three, and the concepts and design could then be expanded into the ball-on-beam robot originally proposed in the future.

The purpose of the ball-on-beam robot is to have a ball roll on a beam, but the beam will be moving in a way to try to center the ball, so it doesn't roll off the beam. For this, the robot will consist of the following parts:

- Raspberry Pi Pico
- 12V Stepper Motor
- Ultrasonic Sensor

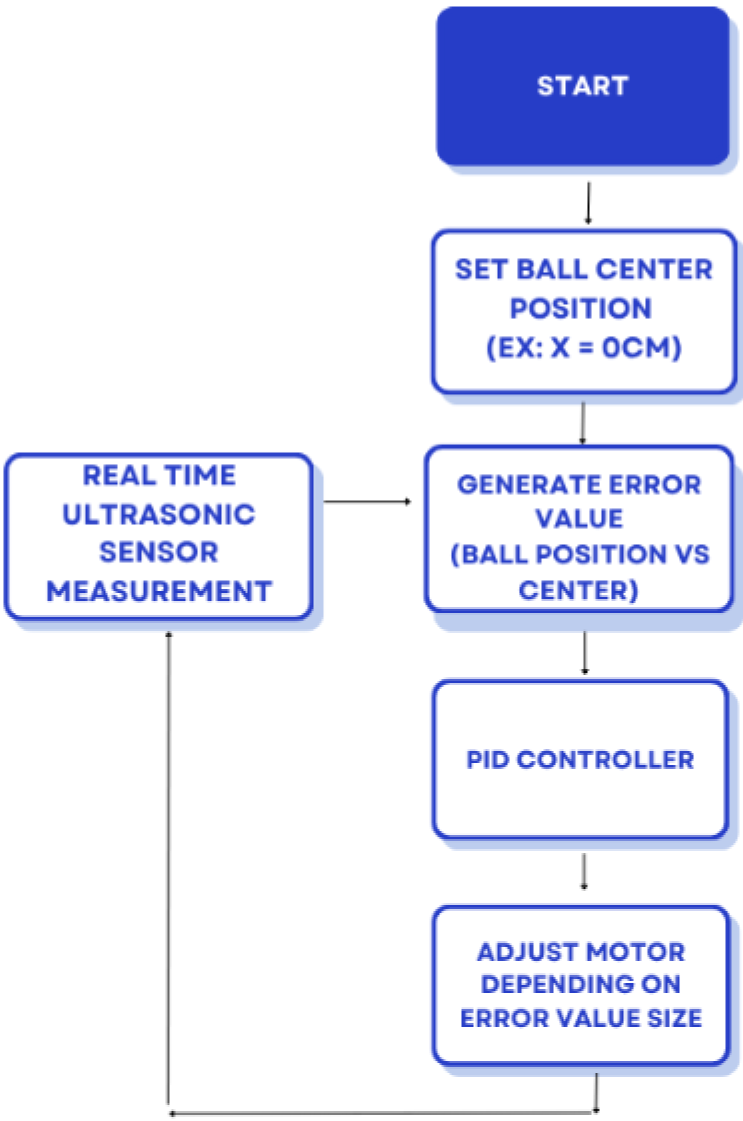

Figure 4: Robot 2 code flowchart showing PID control

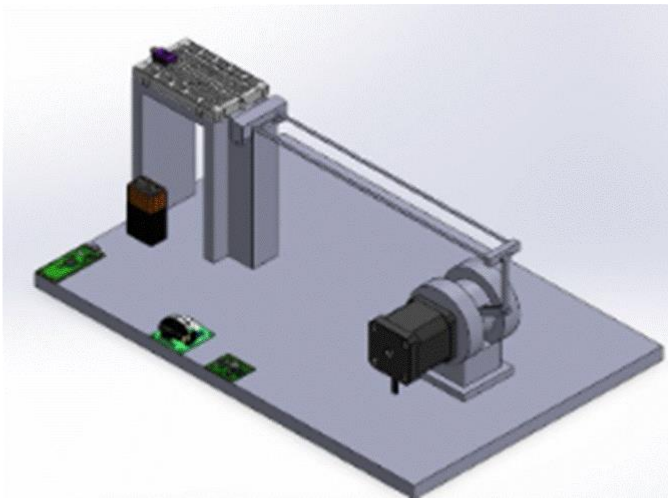

Figure 5: Robot 2 final design CAD model for stage 1

The team used the Raspberry Pi Pico to center the ball when it rolls toward either edge of the beam. This was done by attaching one end of the beam to the 12V motor. The motor adjusts its speed depending on the position of the ball on the beam, which is recorded using the ultrasonic sensor.

As mentioned, the ball-on-beam robot will be expanded to build the ball on a plate robot. This robot will have a ball roll on a plate and will be much more complex to center the ball without it rolling off. An idea for tracking the ball position is to use a resistive touch panel to provide real-time input of ball position. The next step is to make it interactive for students. A thought from the team was to make a controller that students can use to control the plate itself. This way the robot will be like a toy or a game.

9. CONCLUSION

The task assigned to the team was to create robots that would get students interested in STEM early on. Once developed, the devices will be mass produced with an affordable unit at a cost of about $150. The robots will also need to be simple enough for students to understand while showing the fundamental principles of engineering and physics.

The team will develop two robot designs for the purpose of demonstration and to be used as teaching tools for K-12 students, for the client, Dr. Michael Schafer. A prototype has been built and tested for both robots and will be redesigned in the upcoming spring semester based on the client's feedback. As for the design, using Arduino and control modules allows the team to connect and control components within the robots.

The team is looking to present the robots to local schools within Flagstaff for demonstrations and feedback during the spring 2026 term. To accomplish this, future steps include improving current prototypes, and building the ball-on-plate system intended for robot 2.

References

[1] “Toy Safety Business Guidance,” U.S. Consumer Product Safety Commission. https://www.cpsc.gov/Business--Manufacturing/Business-Education/Toy-Safety

[2] “IEEE Standard for User Interface Elements in Power Control of Electronic Devices Employed in Office/Consumer Environments,” *IEEE Std 1621-2004*, pp. 1–18, June 2005, doi: 10.1109/IEEESTD.2005.96205.

[3] S. Sackett, “Self-Balancing Inverted Pendulum Robot - Shay Sackett’s Project Portfolio,” *Shay Sackett’s Project Portfolio*, Aug. 02, 2020. https://www.shaysackett.com/inverted-pendulum-robot/