

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

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# 1. ABSTRACT

It is known that subjects in STEM are some of the most difficult to comprehend and continuously learn. Due to the rigorous nature of learning in this field, it is extremely important to grow this community and get people excited about it from a young age. The Robotics Traveling Van aims to establish interest in this younger audience, specifically K-12 students. The goal of this project is to combine the electrical and mechanical engineering disciplines to create two robots which will be used for presentation purposes. The robots will be inexpensive, transportable, and ultimately be used as a tool that teachers can easily demonstrate the principles of engineering, physics, and robotics. The team collectively chose two robot designs to demonstrate. The first robot is an inverted-pendulum robot. This robot is essentially a self-balancing robot that will balance a rod on its body to demonstrate physics, along with sensor control and input. The second robot will balance a ball on a beam. The beam will move vertically in correspondence to the ball position to center the ball and demonstrate Proportional-Integral-Derivative (PID) control. Additionally, both designs 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 is by using the raspberry pi microcontroller and interface.

## 2. BACKGROUND

The Robotics Travelling Van capstone group was tasked 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 beam system. The former robot will 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 robot. The goal of this robot is to allow kids to change parameters and see how the robot changes as a result. To make the robot more interactive, both robots will have a touch screen that will show a specific function of the robot that makes it operate as intended.

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. The team aims to present these robots to local schools in the Flagstaff, AZ area.

### 3. REQUIREMENTS & STANDARDS

The two educational physics robots will be built with requirements and constraints given to the team by Dr. Willy. The main requirements the team will follow are to make these robots durable, inexpensive (under \$150 per unit), functional (battery powered, interactive, and work within a confined space), educational, and child friendly. These general requirements were refined into a specific list of engineering requirements:

- Robots must be under 14" × 10" × 5", or the approximate size of a shoebox
- Robots must continue to function after a 30" drop onto concrete
- Robots must have the capacity to run for up to 90 minutes between charges
- Must have an interactive touchscreen for educational purposes
- Robots be kid-friendly/safe

To keep within the cost constraints, the team selected the Raspberry Pi Pico as the micro-computer of choice over competitors like Raspberry Pi 5, Raspberry Pi Compute, and Arduino Uno modules. Additionally, to make these robots educational, the information displayed will explain 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. Programming diagrams will then be included, which can aid in the explanation of how these robots work at an understandable level for children.

To meet the requirement of making the robots kid-friendly, the team will ensure both robots are 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 and ensuring they are safe to use. 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]

Additional requirements for the project are 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:
  - o  $P_{on} \geq P_{sleep}$
  - o  $P_{sleep} \geq P_{off}$

- 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.

## 4. 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

<b>1. Robot Development</b>	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.

The team used this timeline to have prototypes ready for demonstration to the client. Following this timeline, the prototypes were finished on time and within expectations. With the success of sticking to this timeline, a second timeline was created for the spring 2026 term.

**Spring 2026 Semester**

<b>2. Robot 2 Development Pt 1</b>	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
<b>3. Robot 2 Development Pt 2</b>	Week 3 – Week 8
<b>4. Robot 1 Development</b>	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.

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



## 5. 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. The first iteration of this robot consisted of the following parts:

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

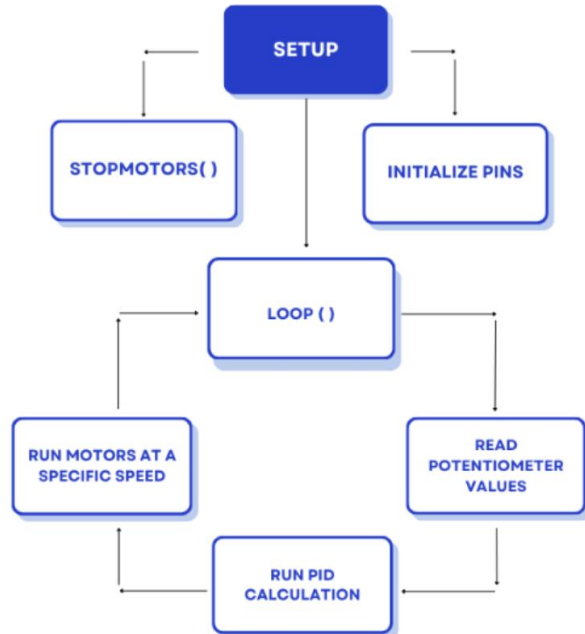


Figure 1: Robot 1 code flowchart showing PID control

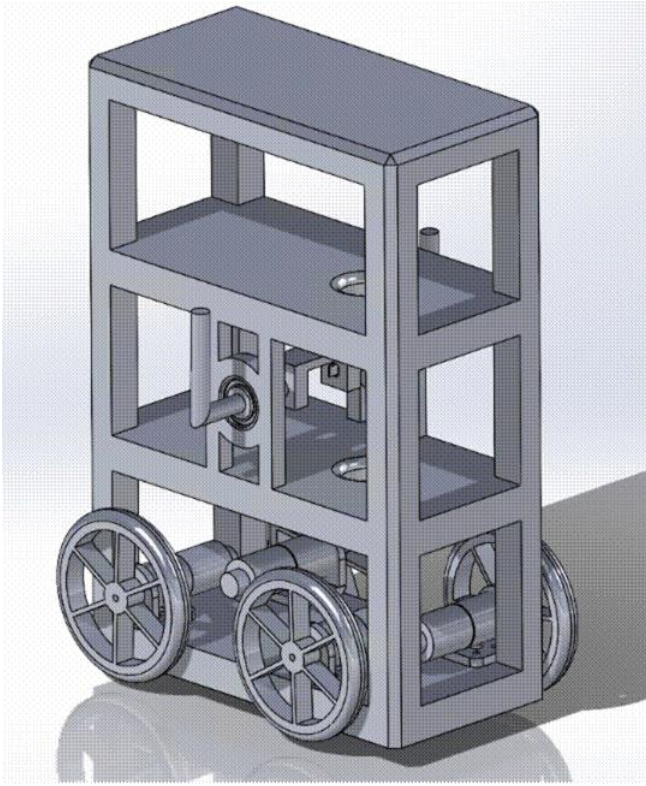


Figure 2: Robot 1 final design CAD model

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.

To lower costs, a Raspberry Pi Pico was used to replace the Arduino Uno in the second (Current) iteration of the inverted pendulum robot. The team then tested components and ran troubleshooting, which several issues were found. One of the main concerns was that the

potentiometer was not accurate enough to relay the rod position, which is essential for knowing how quickly the motor should be rotating to move the robot. Another issue is that the robot would lose power when operating under heavy loads. To fix these issues, a new component list was created:

- Raspberry Pi Pico (Replaced Arduino Uno)
- Wheels x4
- Magnetic Encoder (Replaced Potentiometer)
- 9V DC Motor x4
- Motor Driver
- Ultrasonic Sensor x2
- Touchscreen Interface

**PID Motion Equations:**

**PID Equations:**

# LAPLACE TRANSFORMS - TIME DOMAIN FOR PID

Andres

Laplace Transform (pendulum)

Design Analysis on transfer function

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

Apply Laplace to find T(s)

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

Fine tuning PID using coefficients of  $K_p$ ,  $K_i$  and  $K_d$  help fine tune the system

$K_p$  = proportional gain (poles of response)

$K_i$  = integral gain (poles of error)

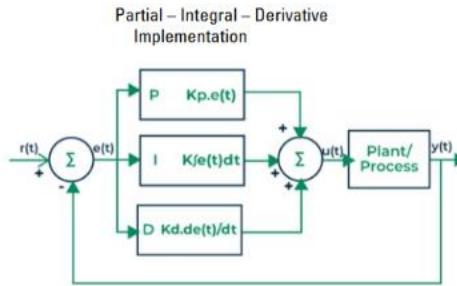
$K_d$  = derivative gain (dampen overshoot)

Assumptions:

$M = 1$  kg

$m = 0.2$  kg

$L = 0.5$  m



More...

...negative real parts = stability

...complex poles = speed of response

...complex parts = oscillations

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 the new components and to finish troubleshooting so the robot will work as intended. Then, the touch screen will be programmed 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.

## 6. BALL-ON-BEAM ROBOT DESIGN

The ball-on-beam robot is the second robot the team worked on. This project wasn't proposed until week 12 of fall 2025, so due to time constraints, the prototype needed to be completed in the spring semester. The robot was intended to be a ball-on-plate system but was changed as that wasn't feasible given the time frame. The idea behind this transition is that it would be more realistic to work in two dimensions rather than three, and the concepts and design could then be expanded into the ball-on-plate 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 the first iteration of the robot, the parts list is as follows:

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

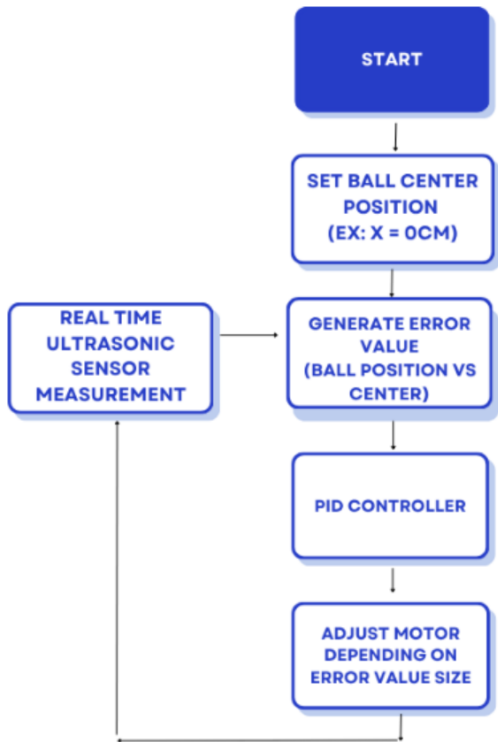


Figure 4: Robot 2 code flowchart showing PID control

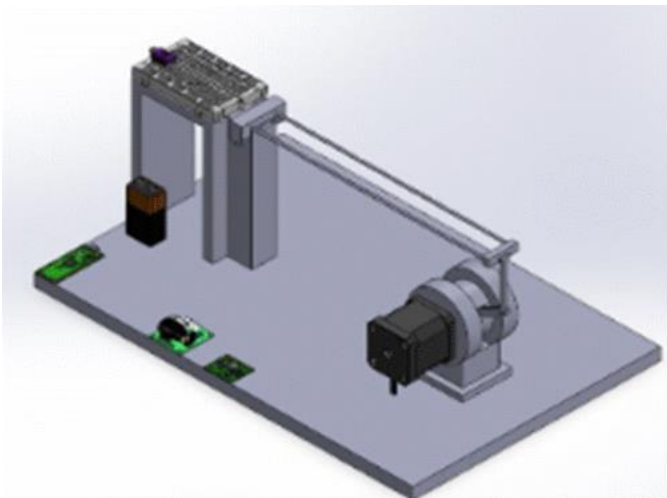


Figure 5: Robot 2 initial design CAD model

The team used the Raspberry Pi Pico to center the ball when it rolled 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 prototyping continued, a second iteration of the build was made. Several issues were found with the design and components previously mentioned. To start, the ultrasonic sensor did not record enough hits per second to accurately tell where the ball was. Additionally, the hits themselves had much more error than anticipated. This issue was resolved by switching to a Time of Flight (ToF) sensor which uses light to measure distance. This sensor was more accurate and recorded more hits per second which was best for its intended use. The new parts list is as follows:

- Raspberry Pi Pico
- DC/DC Buck Converter
- 12V Stepper Motor
- Motor Driver
- Time of Flight Sensor (Replacing Ultrasonic Sensor)
- Touchscreen Interface

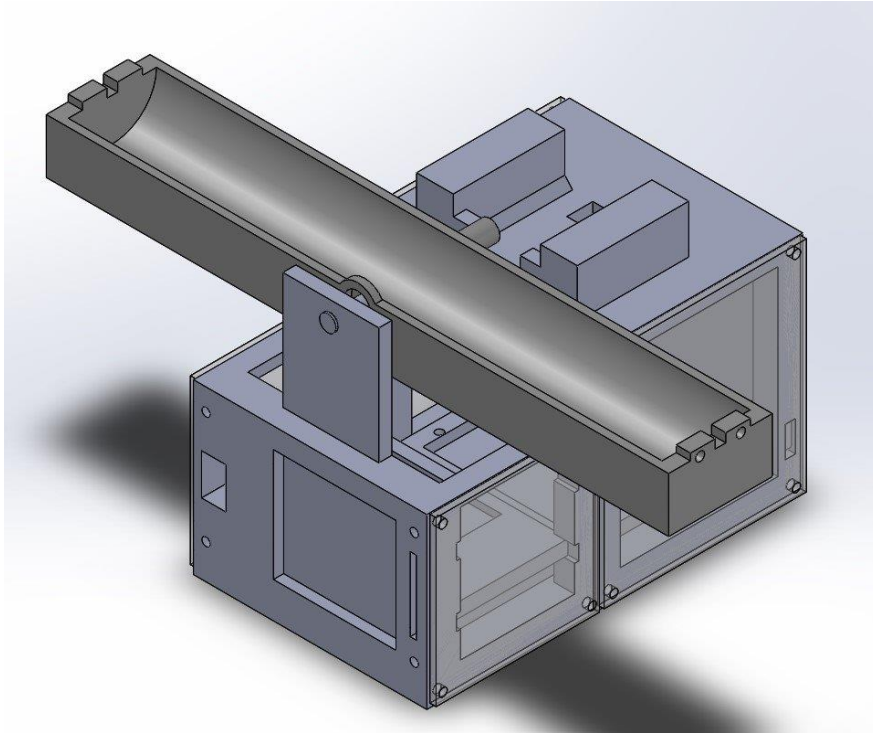


Figure 6: Robot 2 final design CAD model

The final design for the ball-on-beam robot is much more accommodating to the electrical components. There is a designated housing unit for the circuit and battery, which makes it appear more visually appealing while also being safer for children to use it.

The remaining task for the spring semester is to troubleshoot issues found during the test process and to implement the touchscreen interface. It is essentially the same process as the inverted pendulum robot, however there is more work to be done as this robot had a late start during the fall 2025 term. The robot will be shown to the client on March 27th for approval to move onto mass production.

## 7. CONCLUSION

The task assigned to the Robotics Traveling Van capstone group 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. To achieve this, 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 fully completed during the spring 2026 semester for approval.

The robots have undergone intensive testing/debugging and are close to completion. After implementing the new components and designs, the robot will meet all requirements and be ready for display.

The team is looking to present the robots to local schools within Flagstaff for demonstrations and feedback at the end of the term, along with presenting this project at the Undergraduate Symposium.

## 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/>