



Acro-Bots

Microcontroller-Driven Educational Robots
for K-12 Engineering Outreach

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Client: Dr. Michael Shafer | Advisor: Prof. David Willy

ME Capstone — Spring 2026



1

Background

Project Description · Deliverables · Success Metrics

1.1 Project Description

The Mission

K–12 students are naturally captivated by the wonders of the world, and engineering offers them a lens to understand how that world is built. To meet that curiosity, Northern Arizona University required transportable, interactive robotic systems that transform abstract mathematics into something physical, observable, and instantly meaningful.

Client

Dr. Michael Shafer, Northern Arizona University

Two Robots

Robot 1: Inverted Pendulum · Robot 2: Ball-on-Beam

Core Goal

Make invisible control-system math physically observable to K-12 students

Total Budget

\$5,000 allocated | Target: < \$300/unit for fleet replication

Timeline

Fall 2025 – Spring 2026 | Client handoff: May 1, 2026



1.2 Project Deliverables

What we committed to building — and what we delivered

01

Physical Hardware

Two Fully Manufactured Robots

The Inverted Pendulum Robot and Ball-on-Beam System, each with an integrated 4-inch LCD capacitive touchscreen, untethered LiFePO4 battery array, and emergency stop. Demonstration-ready hardware at \$246.46 and \$242.62 per unit respectively.

02

Replication Package

Open-Source Digital Repository

All SolidWorks CAD models, Raspberry Pi Pico code bases, Bills of Materials, and mass-manufacturing blueprints, hosted and documented so NAU or any future engineering team can reproduce the fleet without calling us. Every file version-controlled.

03

Final Design Report

Comprehensive Engineering Documentation

Complete design cycle: requirements, HoQ, benchmarking, literature review, mathematical modeling, FMEA, prototyping iterations, factor-of-safety analyses, design standards compliance, and final testing results, delivered as the Final Design Report.

1.3 Success Metrics

How we define done — verified through 7 physical experiments

Observable Motion

Robots demonstrate feedback control through visible, repeatable physical motion. The math becomes something you can watch in real time.

✓ EXP6 — PID settling time verified

Untethered Runtime

Fully battery-powered operation. Must sustain continuous demonstration through a full outreach event. Calculated at 288 min theoretical, measured ~84–85 min.

✓ EXP4 — Battery endurance verified

Classroom Safety

Organized wiring and electrical components. CPSC-compliant edge radii ($\geq 3\text{mm}$). Pinch clearance $\geq 16.5\text{mm}$. Emergency stop instantaneous. LiFePO4 chemistry, chemically stable around children.

✓ EXP1 — Safety & dimensions verified

Mass Producibility

Per-unit cost must stay under \$500 so NAU can reproduce the fleet at scale. This drove every component selection decision we made.

✓ EXP2 — BOM audit: \$246.46 / \$242.62

2

Requirements

Customer Requirements · Engineering Requirements · House of Quality

2.1 Customer Requirements

What the client needed — in their words

Customer Requirements (CR)

CR01

Durable

Withstands frequent use, rough handling, and physical impacts common in K-12 outreach

CR02

Inexpensive

Cost low enough to enable fleet-wide mass production for NAU outreach programs

CR03

Functional

Effectively demonstrates feedback control through observable, repeatable mechanical motion

CR04

Battery Powered

Operates completely untethered — maximum flexibility during demonstrations

Customer Requirements (CR)

CR05

Interactive Interface

Users can directly adjust control parameters and initiate demonstrations intuitively

CR06

Compact

Functions safely on a standard classroom table without excessive operational clearance

CR07

Educational

Visually connects physical robot motion with control theory concepts for students

CR08

Kid-Friendly

Visually appealing, approachable, and physically safe for students of all ages

2.2 Engineering Requirements

Translating customer needs into verifiable, measurable targets

ER #	Requirement	Target	Unit	Type	CR Link
ER01	Overall Dimensions	< 12×12×12	in	One-sided max	CR06, CR08
ER02	Runtime / Power	> 30	min	One-sided min	CR03, CR04
ER03	Control Hardware	RPi Pico	—	Binary	CR03, CR05
ER04	Electrical Safety	Enclosed	—	Binary	CR08
ER05	Drop Test Survivability	36	in	One-sided min	CR01
ER06	Manufacturing Cost	< \$300	USD/unit	One-sided max	CR02
ER07	PID Settling Time	< 15.0	sec	One-sided max	CR03, CR07
ER08	Sharp Edge Radii	≥ 3	mm	One-sided min	CR08
ER09	Pinch-Point Clearance	≥ 16.5	mm	One-sided min	CR08
ER10	Emergency Stop Response	< 1.0	sec	One-sided max	CR08
ER11	Visual Feedback Interface	LCD Screen	—	Binary	CR05, CR07

2.3 House of Quality

QFD — Prioritizing the right engineering requirements

1: low, 5: high	Functional Requirements (How's)	Overall Dimensions	Power source	Control Hardware (Raspberry Pi)	Electrical Safety in U.S. CPSC (guidelines)	Drop Test	Manufacturing Cost	PID Settling Time	Total System Weight	Sharp Edge Radii in U.S. CPSC (guidelines)	Pinch clearance in U.S. CPSC (guidelines)	Emergency Stop	Visual Feedback Interface
Customer importance rating	Customer Requirements - (What's) ↓												
5	Operating Space	9							3				
5	Battery Powered		9	3					3				
4	Active Dynamic Balancing			9				9					
3	Kid-Friendly	1			9	3			3	9	9	9	1
4	Durability			1	3	9			1	1	1	3	
3	Inexpensive	1	1	3	1	1	9	1	3	1	1	1	3
4	Interactive Interface (Touchscreen)			9								3	9
3	Educational Props			3			3	9					9
	Technical importance score	51	48	76	42	48	39	39	52	34	34	54	84
	Importance %												
	Priorities rank	2	3	1	4	3	4	3	3	4	4	2	1
	Current performance	5	5	5	5	5	5	5	5	5	5	5	5
	Target	< 12"x12"x12"	> 30 mins	Rasp Pi	Qualifies	36" drop test	<\$500	< 15 sec	< 15 lbs	Qualifies	Qualifies	Yes	Touchscreen
	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	minutes	N/A	Y/N	inches	USD	seconds	lbs	Y/N	Y/N	Y/N	Y/N

ER11 — Visual Feedback UI

Students need to see live data — highest priority requirement

ER03 — Control Hardware

RP2040 selected; drives dual-core architecture choice

ER02 — Runtime

Battery life = event viability — drove LiFePO4 selection

ER10 — Emergency Stop

Non-negotiable for K-12 safety — binary requirement

ER01 — Overall Dimensions

Portable = deployable — constrained all chassis design

Benchmarked against: Sackett's Pendulum · Acrome Ball & Beam · High-End STEM Kits

3

Design Space Research

Benchmarking · Literature Review · Mathematical Modeling

3.1 Benchmarking — Robot 1 (Inverted Pendulum)

3 system-level benchmarks + 3 sub-system benchmarks evaluated

System-Level: Three State-of-the-Art Systems



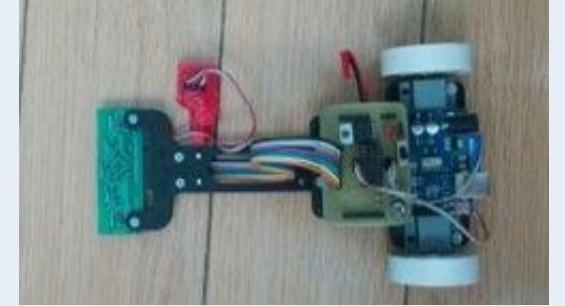
Sackett's Pendulum [1]

Alt: IMU (MPU6050): drifts, needs Kalman |
Optical: dust-sensitive



Voice-Controlled Robot [6]

Alt: Arduino Uno (16MHz, 8-bit) | ESP32 (high power draw)



Instructables Line Follower [7]

Alt: NEMA 17 Stepper: bulky | BLDC: requires expensive ESC

Sub-System Benchmarks — Sensor · Microcontroller · Drive Motor

Sensing ✓ AS5600 Magnetic Encoder — Zero drift · Contactless · 12-bit / 0.087°

MCU ✓ Raspberry Pi Pico (RP2040) — Dual-core · 133MHz · affordable \$4/unit

Motor ✓ 520 L-Type DC Gear Motors — Integrated reduction gearbox · L-shape keeps total size small

3.1 Benchmarking — Robot 2 (Ball-on-Beam)

The commercial benchmark we had to beat on price AND add battery power

System-Level: Three State-of-the-Art Systems



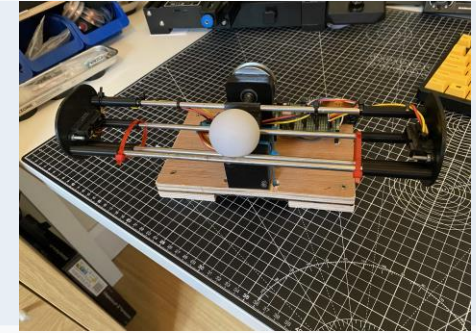
Acrome Ball & Beam [39]

Alt: HC-SR04 Ultrasonic: scatter off beam walls |
Resistive strip: worn out resistive **potentiometer sensor**
(sensing tape/rod)



Microsoft MOAB [40]

Alt: Arduino Uno: 8-bit, can't multitask |
Arduino Mega 2560: same 8-bit limit



Arduino Instructables [41]

Alt: SG90 Servo: plastic gear backlash $\sim 1^\circ$ | Brushed DC:
requires gearing

Sub-System Benchmarks — Sensor · Microcontroller · Actuator

Sensor

✓ VL53L0X Time-of-Flight — 940nm IR · 1.0mm resolution · immune to classroom lighting

MCU

✓ Raspberry Pi Pico (RP2040) — Core 0 = ToF polling | Core 1 = PID · \$4/unit

Actuator

✓ NEMA 17 Stepper + 1/8 micro-step — Direct-drive · $0.225^\circ/\text{step}$ · zero backlash

3.2 Literature Review — Robot 1 Sub-Team

Andres Gonzales

Programming Lead

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Advanced PID tuning strategy. Informed gain optimization beyond baseline pole-placement values.
- [5]
] K. Ogata — System Dynamics, 4th ed. Prentice Hall, 2003, ch. 11.
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Open-source inverted pendulum algorithms. Benchmarking reference and code architecture foundation.
- [10]
] Z. C. M. Davidson, S. Dang, X. Vasilakos — Blended lab design using Raspberry Pi Pico — IEEE Trans. Learning Technologies, vol. 17, 2024.
Confirmed RP2040 dual-core capability for digital circuits — justified full switch from Arduino Uno.
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] S. R. Doty — Python Basics — Computer Science, pp. 1–20, 2008.
Foundational Python syntax reference. Supports Python scripting framework driving Robot 1's hardware logic.
- [2]
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Learning-based control for wheeled pendulums. Justified demonstration-based tuning approaches.
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Practical PID implementation reference. Used for firmware architecture and dynamic control applicable to Robot 1.

Colin Parsinia

Manufacturing Lead

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Methods for heat-set inserts, self-tapping screws, and printed threads. Drove M3 brass heat-set insert strategy.
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PLA material properties and optimal print temperatures. Informed wall thickness decisions and print settings.
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] H. H. Asada — Manufacturing Robotics: Basic Issues and Challenges — IFAC Proc. Volumes, vol. 29, 1996.
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Safe human-robot interaction design with structured operational intervals. Informed K-12 engagement zone safety.
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] G. Hoffman, W. Ju — Designing robots with movement in mind — J. Hum.-Robot Interact., vol. 3, 2014.
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Modular educational robot with configurable components. Validated the team's modular sub-assembly strategy.
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3.2 Literature Review — Robot 2 Sub-Team

Freddy Rivera

Project Manager / Systems Modeling

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Derives torque and motion equations for ball-on-beam. Directly informed Robot 2 motor torque calculations and NEMA-17 selection.
- [31] **University of Michigan — Ball & Beam: System Modeling — Control Tutorials for MATLAB and Simulink (CTMS), 2025.**
Linearized ball-and-beam mathematical modeling. Foundation for Lagrangian plant derivation and pole-placement PID design.
- [39] **Acrome — Ball and Beam — Acrome Control Systems, 2024. [Online]. Available: <https://acrome.net>.**
Primary commercial benchmark (\$300–\$500). Established per-unit cost-parity target and validated 1-axis K-12 control format.
- [40] **Microsoft — Project Moab — Microsoft Autonomous Systems, 2024. [Online].**
High-end 3-axis benchmark. Reviewing MOAB revealed fragile linkage arms — justified pivot away from Ball-on-Plate.
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Confirms 940nm VCSEL laser, 1.0mm resolution, immune to ambient light. Justified sensor selection for K-12 classrooms.
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Confirmed RP2040 32-bit, 133MHz dual-core. Proved Core 0 can isolate ToF and Core 1 run PID, eliminating 8-bit bottlenecks.
- [41] **Arduino Ball and Beam PID Controller — Instructables, 2020. [Online].**
Open-source Arduino baseline. Revealed ultrasonic scatter and servo backlash — drove upgrade to ToF and direct-drive stepper.
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Detailed nonlinear ball-and-beam dynamic equations. Supported Robot 2's Lagrangian plant model derivation.
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- [23] **N. Hammje — Ball-Balancing Bot Uses OpenCV on a Raspberry Pi — Hackster.io, 2024.**
Raspberry Pi Ball-on-Plate with PID. Guided Robot 2 concept phase toward real-time sensor-coupled actuation.

Florence Fasugbe

Design Lead

- [44] **T. Ide et al. — Comparison of CoP estimation in human standing posture using inertial sensors — Dissertation, Kyushu Univ., Japan.**
CoP measurement using inertial sensors during standing. Informed human-balance analogy for K-12 pendulum framing.
- [45] **S. Sasagawa et al. — Effect of hip motion on body kinematics during quiet standing — Neurosci. Lett., vol. 450, 2009.**
Hip motion and COM/COP during standing. Reinforced biological framing of Robot 1 as human-balance demonstration.
- [51] **A. Kastner et al. — Model-based control of a large-scale ball-on-plate system — KITOpen Repository, KIT, Mar. 2019.**
Lagrange/Euler frequency domain analysis for state-feedback control. Directly supported Robot 2 beam FoS derivation.
- [46] **J. L. Cabrera, J. G. Milton — Human stick balancing: Tuning Lévy flights to improve balance control — Chaos, vol. 14, 2004.**
Stabilization via limit cycles and closed-loop control. Connects Robot 2's PID to natural human balance mechanisms.
- [47] **B. Sprenger, L. Kucera, S. Mourad — Balancing of an inverted pendulum with a SCARA robot — IEEE/ASME Trans. Mechatronics, vol. 3, 1998.**
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PID stabilization simulation. Provided comparison results against Robot 2's 8.93-second measured settling time.
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Vision-based pendulum control without encoder. Explored as alternative; validated magnetic encoder superiority for Robot 1.
- [52] **S. E. Mathe et al. — A comprehensive review on applications of Raspberry Pi — Computer Science Review, vol. 52, 2024.**
Reviews Raspberry Pi in ML and experimentation. Confirmed RP2040 hardware capability for real-time control and touchscreen UI.
- [53] **A. S. Silva, R. M. Cotta, L. A. Ismail — Uncertainty analysis of infrared thermography — ResearchGate, 2014.**
Sensor uncertainty analysis. Provided context for VL53L0X ToF uncertainty and informed the 5% error margin target.

3.3.1 Control System & Pendulum Dynamics

Mathematical Modeling — Andres Gonzales — Programming Lead

⚠ Problem

How does the ball balance and how quickly must the RP2040 calculate and apply corrections before the pendulum falls past the recoverable angle?

📐 Equation

$$u_k = K_p e_k + K_i T_s \sum_{j=0}^k e_j + K_d \frac{e_k - e_{k-1}}{T_s}$$

$$l\ddot{\theta} = mgl\sin\theta + \tau$$

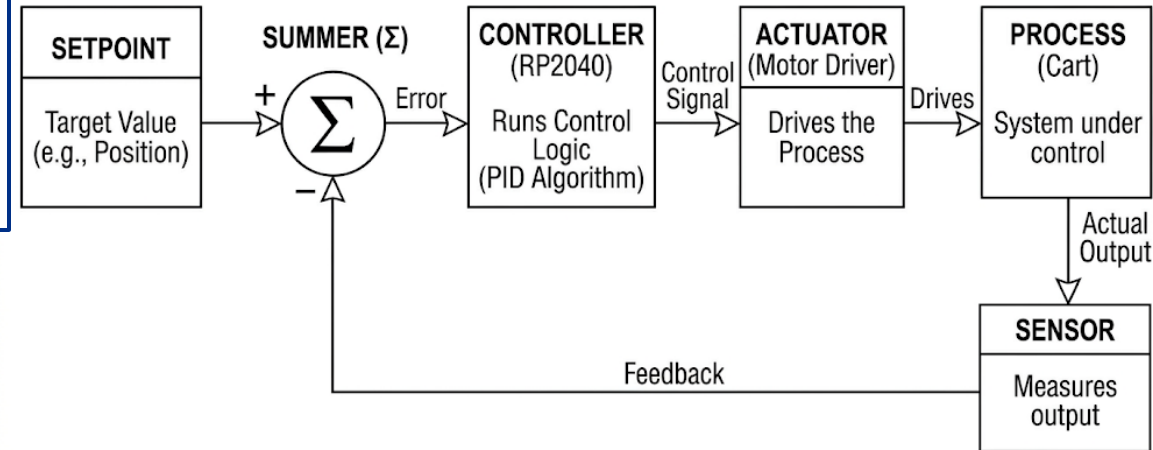
Key Results

- PID loop frequency: 4× pendulum natural fall rate
- Computational FoS = 4.0
- Moving average filter: eliminates noise < 5%
- Sampling: RP2040 @ 133MHz — never lags

✓ Decision

RP2040 dual-core: Core 0 polls encoder at 4× the natural fall rate, Core 1 runs PID and outputs PWM. Computational FoS = 4.0 — the processor never falls behind the pendulum. [12]

SIMPLIFIED 6-BLOCK PID CONTROL LOOP DIAGRAM



3.3.2 Pendulum Robot Frame Structural Integrity

Mathematical Modeling — Colin Parsinia — Manufacturing Lead

⚠ Problem

Can a 3D-printed PLA chassis survive rolling off a classroom table at 36 inches with full electronics and battery load?

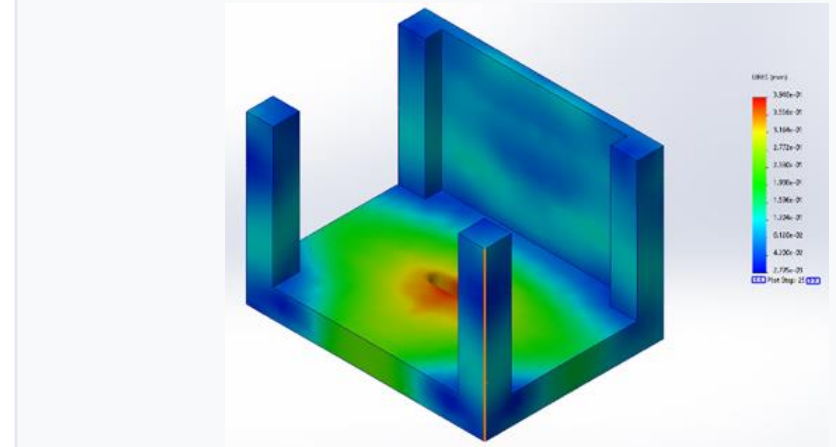
📐 Equation

$$v = \sqrt{2gh}, \quad F = \frac{mv}{\Delta t}, \quad h_{\min} \geq \sqrt{\frac{6FL}{b\sigma_{\text{flex}}}}$$

✓ Decision

PLA Filament for main frame due to having highest flexural strength: $\sigma_{\text{flex}_{PLA}} = 97 [MPa]$

TPU later used for Pendulum Shell due to elastic properties



Key Results

- Impact velocity: $v = 3.867 \text{ m/s}$
- Impact force: $F = 2,319 \text{ N}$
- Min wall: $h_{\min} = 16.94 \text{ mm}$
- FoS = 2.2 — 3 physical drops, 0% failure

3.3.3 Ball-on-Beam Plant Dynamics

Mathematical Modeling — Freddy Rivera — Project Manager / Systems Modeling

⚠ Problem

What are the governing physics that describe how the ping-pong ball moves in response to beam angle and how do we simplify them into a form a PID controller can actually use?

📐 Governing Equation → Simplified Plant

Full Lagrangian — Cazzolato [32]:

$$\left(\frac{J_b}{R^2} + m\right)\ddot{x} + mg\sin(\theta) = 0$$

Apply: 1) small-angle approx $\sin(\theta) \approx \theta$ 2) negligible centrifugal term $\dot{x}v^2 \approx 0$ at low speeds

Simplified Plant + Plant Gain:

$$\ddot{x} = \frac{-3}{5}g\theta \implies K_{plant} = \frac{-3}{5}(9.81) = -5.886 \text{ m/s}^2/\text{rad}$$

✓ Decision

The 3/5 coefficient comes from modeling the ball specifically as a thin hollow sphere, not a point mass. This justifies the Lagrangian approach. $K_{plant} = -5.886$

Key Factors

Source	Full Lagrangian — Cazzolato [32] (Univ. of Adelaide)
Simplification 1	$\sin(\theta) \approx \theta$ (small-angle, valid for $\pm 20^\circ$ range)
Simplification 2	$\dot{x}\theta^2 \approx 0$ (negligible centrifugal at low speeds)
3/5 Coefficient	Rolling inertia of thin hollow sphere ($J_b = 2/3 mR^2$) Solid ball would give 5/7 — different object, different physics
Plant Gain	$K = -5.886 \text{ m/s}^2/\text{rad}$ 1 rad of beam tilt $\rightarrow 5.886 \text{ m/s}^2$ ball acceleration
Valid Range	$\pm 20^\circ$ — enforced by physical hard-stops on chassis

3.3.4 Beam Structural Dynamics & Battery Runtime

Mathematical Modeling — Florence Fasugbe — Design Lead

⚠ Problem

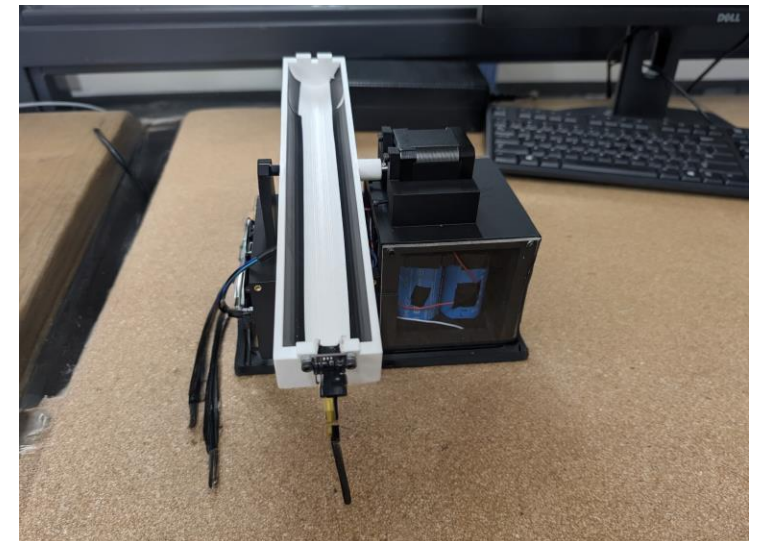
At what beam angle does the ball stop rolling and start slipping — and how long can the system run on one charge?

📐 Equation

$$\theta_{max} = \arctan\left(\frac{5}{2}\mu_s\right)$$

$$t_{run} = \frac{C_{battery}}{I_{op}} = \frac{\text{Battery Capacity}}{\text{Operating Current}} = \frac{\text{mAh}}{\text{mA}}$$

[51][38]



4

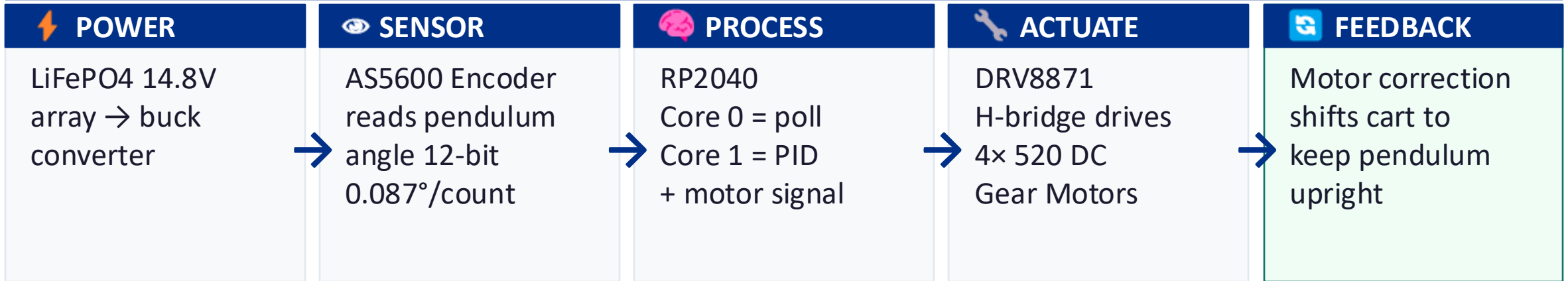
Concept Generation & Selection

Functional Decomposition · Concepts · Weighted Pugh Charts

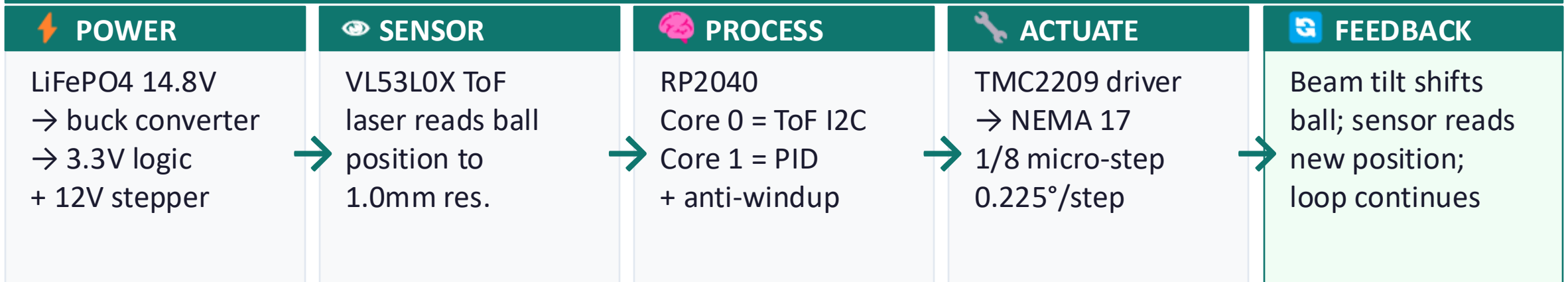
4.1 Functional Decomposition

Both robots operate as closed-loop control systems — latency between SENSE and ACTUATE must be zero

Robot 1 — Inverted Pendulum



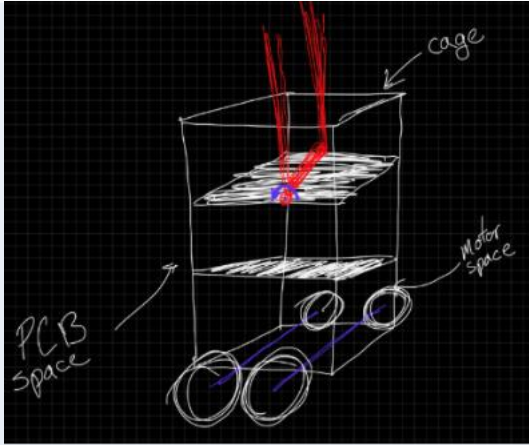
Robot 2 — Ball-on-Beam



4.2 Concept Generation — Robot 1

Three top-level architectures evaluated

C1 — Vertical Multi-Layer Frame



✓ Pros

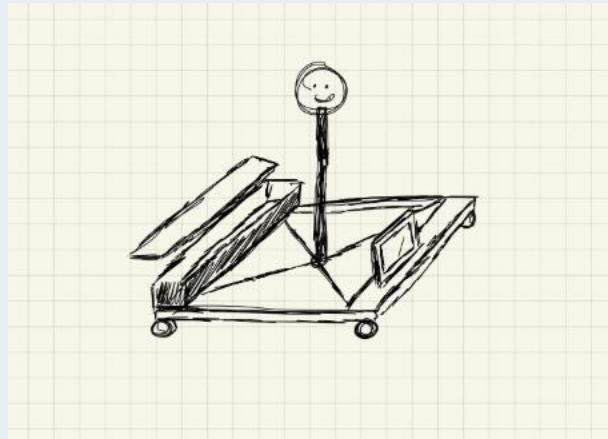
- Organized layout
- Aesthetic appeal
- Double pendulum possible

✗ Cons

- Tall = unstable around kids
- Falls when unpowered
- Higher material cost

Rejected — safety risk

C2 — 4-Wheel Cart Design



✓ Pros

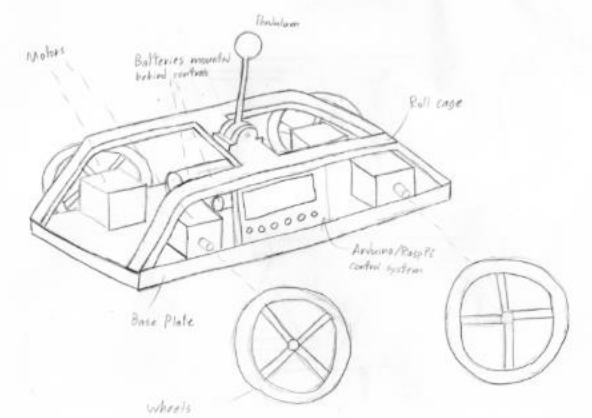
- Stable when unpowered ✓
- Organized rear compartment
- Touchscreen integration space
- Pendulum centered = balanced

✗ Cons

- Larger footprint

✓ SELECTED — stable, safe, adaptable

C3 — Angular Compact Frame



✓ Pros

- Compact and aesthetic
- Impact-resistant angles
- Better CoG height

✗ Cons

- Low CoG = longer arm needed
- Complicates pendulum math
- Harder component routing

Rejected — pendulum math too complex

4.3 / 4.4 Concept Selection — Robot 1

Weighted Pugh Chart + Factor of Safety validation

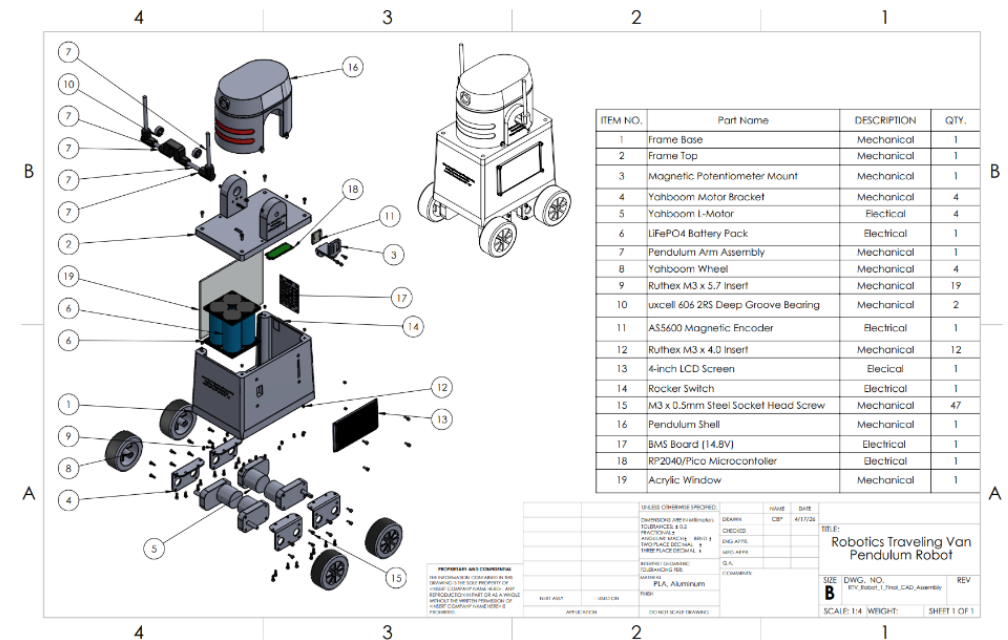
Weighted Pugh Chart

Criteria	Weight	2-Wheel	Angular	4-Wheel ✓
Stability (Static)	25%	1	4	5
Sensing Precision	20%	3	4	5
Impact Resilience	20%	2	5	4
K-12 Interactivity	15%	2	3	5
Complexity / Cost	20%	5	3	2
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Weighted Total	100%	2.65	3.95	4.35

✓ 4-Wheel Cart wins at 4.35 — superior on safety, sensing, and interactivity. Cost tradeoff accepted consciously.

Factor of Safety Summary

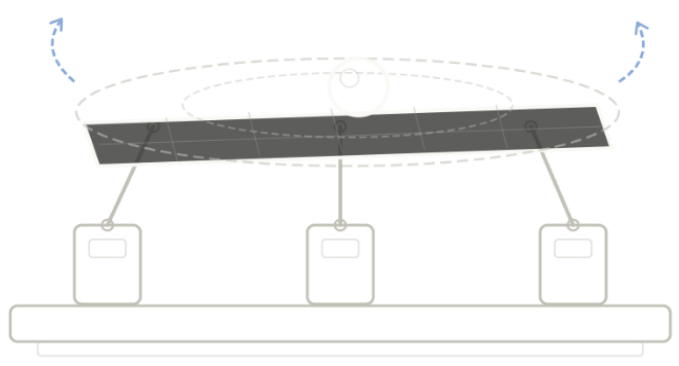
Sub-System	FoS
Main Chassis (PLA)	2.2
Pendulum Axis Pin	3.5
LiFePO4 Battery BMS	1.8
Motor Drivers (DRV8871)	1.4
RP2040 Control Loop	4.0
M3 Screws / Inserts	8.2



4.2 Concept Generation — Robot 2

Three architectures evaluated — the decision was clear

C1 — 2-Axis Ball-on-Plate



✓ Pros

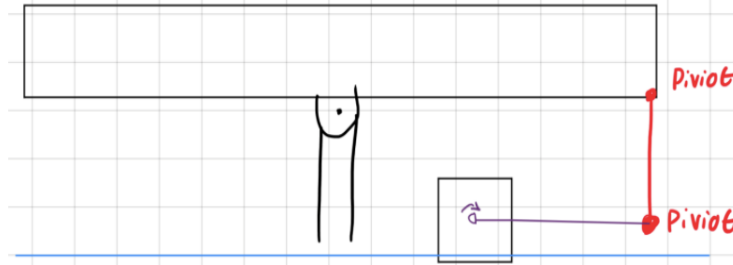
- Visually spectacular
- High engagement factor
- Most impressive K-12 spectacle

✗ Cons

- Over \$300 budget — fails ER06
- Fragile linkage arms = van damage
- 3 synchronized actuators — complex
- Non-linear spatial math

Rejected — over budget AND fragile

C2 — Servo-Linkage Beam



✓ Pros

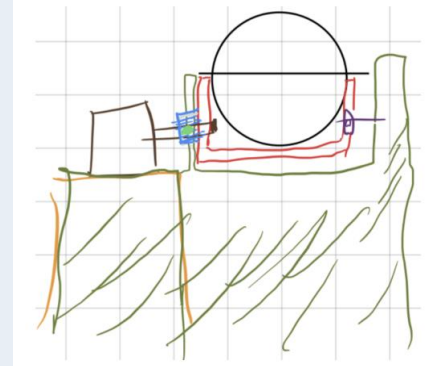
- Cheap and well-documented
- Open-source examples available

✗ Cons

- Servo plastic gear backlash $\sim 1^\circ$
- Non-linear crank-slider math
- Jitter degrades PID performance
- Tested: could not hold equilibrium

Rejected — backlash makes PID unusable

C3 — Direct-Drive Center Mount



✓ Pros

- Zero backlash — D-shaft direct
- $0.225^\circ/\text{step}$ resolution ✓
- Symmetric control math
- Most durable and transportable

✗ Cons

- NEMA 17 costs more than servo

✓ SELECTED — engineering drives the call

4.3 / 4.4 Concept Selection — Robot 2

Weighted Pugh Chart + Factor of Safety (Table 15, Final Design Report)

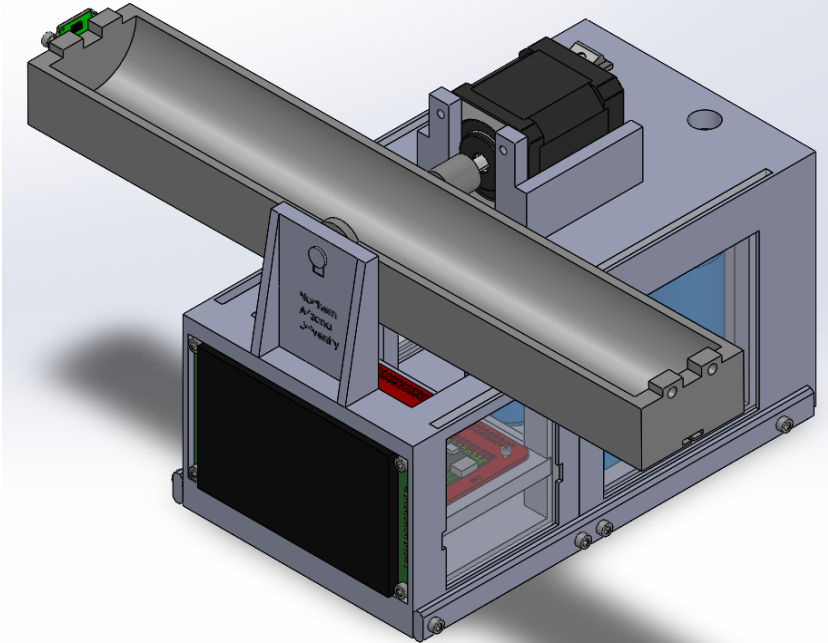
Weighted Pugh Chart — Robot 2 Architecture Selection

Criteria	Weight	Concept 1 2-Axis Gimbal	Concept 2 Servo-Linkage	✓ Selected Direct-Drive
Stability (Dynamic)	25%	2 (Complex)	2 (Slop/Jitter)	5 (Highly Stable)
Sensing Precision	20%	4	2	5 (ToF Laser)
Structural Rigidity	20%	1 (Fragile arms)	3	5 (Solid Direct Mount)
Complexity / Cost	15%	1 (Over \$300)	5 (Very Cheap)	4 (Within Budget)
K-12 Interactivity	20%	5 (Omni-dir.)	3	4 (Highly Accessible)
Weighted Total	100%	2.35	2.80	4.65

Factor of Safety Summary — Robot 2 (Table 15, Final Design Report)

Component / Sub-System	Failure Mode	Calculation Basis	FoS
Main Chassis (PLA)	Hard-Stop Fracture	Motor stall torque vs. 20% infill PLA yield strength	2.5
Dynamic Geometry	Ball Liftoff (Loss of Contact)	Software limit 33.7 rad/s ² vs. liftoff threshold 67.47 rad/s ²	2.0
Battery Array	Power Depletion	Theoretical runtime 288 min vs. 90-min internal requirement	3.2
Stepper Motor (NEMA 17)	Skipped Steps / Stall	Available holding torque 0.44 N·m vs. required dynamic 0.0134 N·m	33

Robot 2 — Selected Design CAD



5

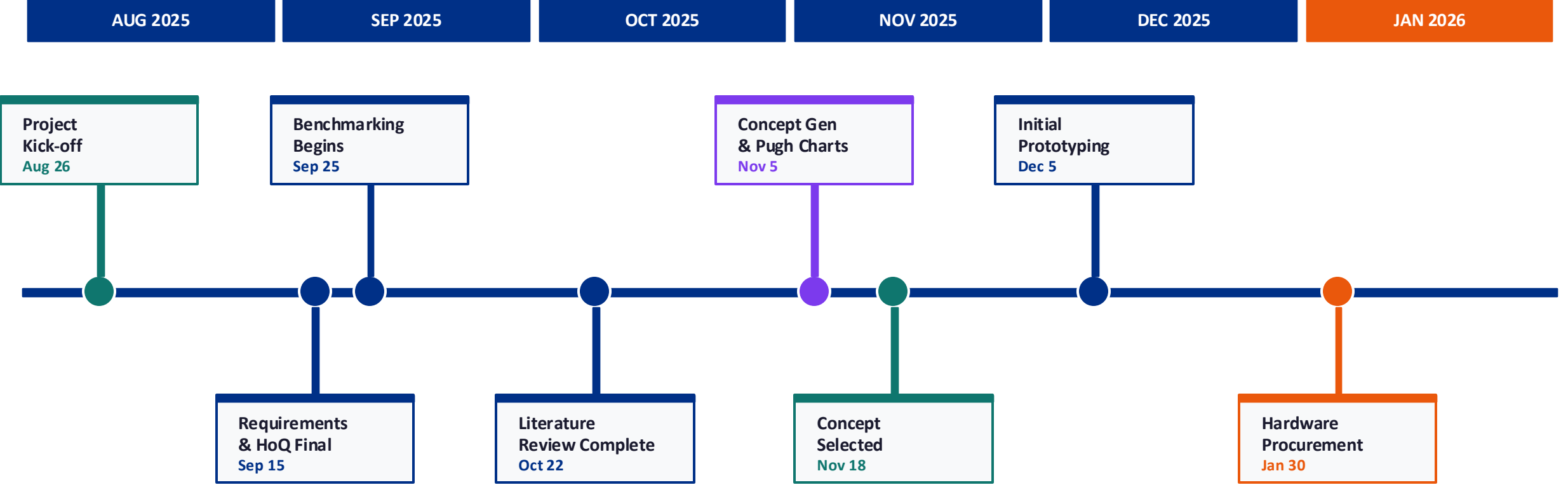
Project Management

Schedule · Budget · Bill of Materials

5.1 Schedule — Semester 1: Fall 2025

Phase 1: Foundation & Research · Aug 2025 – Jan 2026

PHASE 1 — FOUNDATION & RESEARCH



- Phase 1 Deliverables:**
- ✓ Engineering Requirements & HoQ
 - ✓ Benchmarking R1 + R2
 - ✓ Literature Review (40+ refs)
 - ✓ Concept Selection (both robots)
 - ✓ Prototyping + 4 major design pivots
 - ✓ Critical hardware procurement

5.1 Schedule — Semester 2: Spring 2026

Phase 2: Build · Test · Deliver · Jan 2026 – May 2026



PCB Order Placed
Jan 30

67% Hardware Complete
Feb 23

100% Hardware Complete
Mar 25

Symposium Presentation
Apr 24

PCB Delay Managed
Feb 10

Client Demo & Approval
Mar 2

All 7 Experiments Verified
Apr 17

Client Handoff
May 1

- Phase 2 Deliverables:**
- ✓ Both robots fully built
 - ✓ CR + ER spec sheets with tolerances
 - ✓ Open-source repository complete
 - ✓ 7 experiments — 19 ERs verified
 - ✓ Client demo + Dr. Shafer approval
 - ✓ Documentation + operation manual

5.3 Budget — \$5,000 Allocated · \$2,500 Spent

Phase 01 — Prototyping

Fall 2025

- First sensors, motors, microcontrollers
- Early chassis prints — figuring out geometry
- Arduino, potentiometer, ultrasonic sensor
- (all three later replaced in Phase 2)
- Goal: can this work at all?

\$800

Phase 02 — Iteration, Fundraising (\$500), & Testing

Fall 2025 → Spring 2026

- Parallel builds on both robots simultaneously
- 4 major design pivots —
Arduino → RP2040,
ultrasonic → ToF, linkage → direct-drive,
potentiometer → AS5600 encoder
- Goal: which components actually work together?

\$1,200

Phase 03 — Finalization

Spring 2026

- Touchscreen integration + final UI
- Final polished chassis prints
- All 7 experiments — 19 ERs verified
- Documentation (minimal cost)
- Goal: does it meet all requirements?

\$500

Total Budget

\$5,000

Total Spent

\$2,000

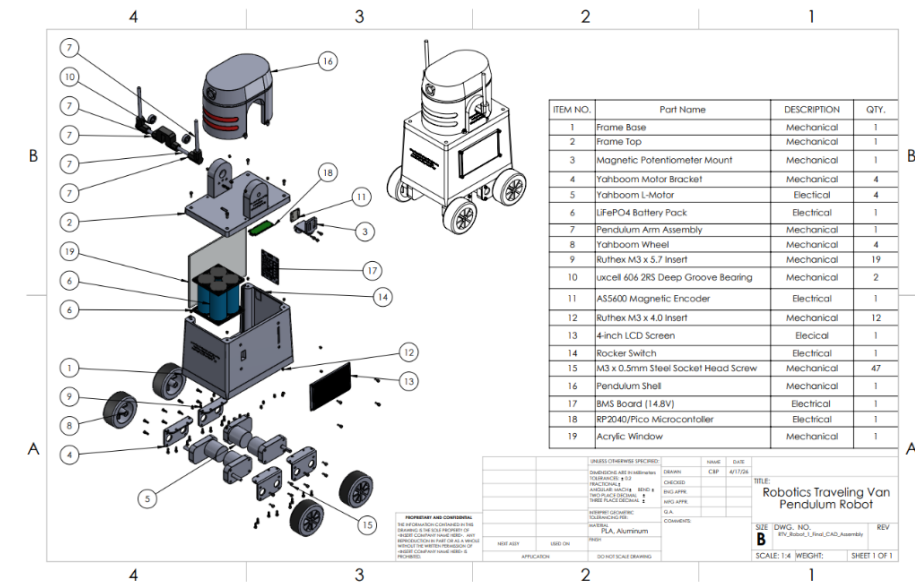
Remaining

\$2,500

5.4 Bill of Materials — Robot 1

Component	Category	Qty	Unit Cost	Total
520 L-Type DC Gear Motors	Mechanical	4	\$7.98	\$31.56
Aluminum Rod (∅6mm)	Mechanical	3	\$1.20	\$3.60
6010 Ball Bearings (6mm)	Mechanical	2	\$0.75	\$1.70
PLA+ Filament (~600g)	Manufacturing	1 roll	\$17.99	\$10.79
TPU Filament (~100g, pendulum)	Manufacturing	1 roll	\$22.99	\$2.30
Raspberry Pi Pico (RP2040)	Electrical	1	\$8.99	\$8.99
LiFePO4 Battery Cells (4×)	Electrical	4	\$12.99	\$38.97
DRV8871 H-Bridge Drivers	Electrical	2	\$4.33	\$8.66
30A BMS Board (14.8V)	Electrical	1	\$8.69	\$8.69
3.3V Buck Converter	Electrical	1	\$1.30	\$1.30
AS5600 Magnetic Encoder	Electrical	1	\$2.60	\$2.60
LiFePO4 Battery Charger	Electrical	1	\$14.99	\$14.99
Rocker On/Off Switch	Electrical	1	\$17.99	\$17.99
4" LCD Touchscreen (320×480)	UI	1	\$20.99	\$20.99
M3/M2 Heat-Set Inserts + Screws	Hardware	assorted	—	\$47.32
TOTAL PER UNIT				\$246.46

Market Comparison	
	Price
Commercial Equivalent (Acrome-class platform)	~\$3,000
Acro-Bot Robot 1 (our build)	\$246.46
Savings	92%



5.4 Bill of Materials — Robot 2

Component	Category	Qty	Unit Cost	Total
NEMA 17 Stepper Motor	Mechanical	1	\$14.99	\$14.99
LiFePO4 Battery Cells (4x)	Electrical	4	\$12.99	\$38.97
PLA+ Filament (~550g)	Manufacturing	1 roll	\$17.99	\$9.00
686 Ball Bearings (10-pack)	Mechanical	1	\$8.59	\$0.86
Ping-Pong Ball (ITTF standard)	Mechanical	1	\$2.39	\$0.27
Raspberry Pi Pico (RP2040)	Electrical	1	\$12.99	\$12.99
VL53L0X ToF Sensor	Electrical	1	\$12.99	\$12.99
TMC2209 Stepper Driver	Electrical	1	incl.	incl.
14.8V BMS Board	Electrical	1	\$8.99	\$8.99
5V / 3.3V Buck Converter	Electrical	1	\$8.69	\$8.69
LiFePO4 Battery Charger	Electrical	1	\$14.99	\$14.99
Rocker On/Off Switch	Electrical	1	\$7.99	\$7.99
22AWG Hookup Wire	Electrical	1 roll	\$15.29	\$15.29
4" LCD Touchscreen (320x480)	UI	1	\$20.99	\$20.99
M3/M2 Heat-Set Inserts + Screws	Hardware	assorted	—	\$37.61
TOTAL PER UNIT				\$242.62

Market Comparison		Price
Acrome Ball & Beam (tethered, wall-powered)		~\$3,000
Acro-Bot Robot 2 (untethered + battery)		\$242.62
Savings		92%

ITEM NO.	Part Name	DESCRIPTION	QTY.
1	Center Hub	Mechanical	1
2	Motor Holder	Mechanical	1
3	Beam	Mechanical	1
4	Stepper Motor	Electrical	1
5	686 Bearing	Mechanical	1
6	Batteries	Electrical	4
7	Shell	Mechanical	1
8	Shaft Plug	Mechanical	1
9	Rocker Switch	Electrical	1
10	M3 8mm Screws	Mechanical	6
11	Time of Flight Sensor	Sensing	1
12	M3 Zinc Nut	Mechanical	2
13	Battery Management System	Electrical	1
14	Protoboard	Electrical	1
15	Raspberry Pi Pico	Electrical	1
16	Motor Driver	Electrical	1
17	Touchscreen	Electrical	1
18	M2 8mm Screw	Mechanical	4
19	Railroad	Mechanical	2
20	M3 12mm Screw	Mechanical	8
21	Center Hub Acrylic	Mechanical	2
22	Motor Hub Acrylic	Mechanical	2

Robot 2 (Ball-on-Beam)
 TITLE: Robot 2 (Ball-on-Beam)
 SIZE: A DWG. NO.: Assembly_Robot2_V6
 SCALE: 1:8 WEIGHT: SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:
 DIMENSIONS ARE IN MILLIMETERS
 TOLERANCES: ±0.2 mm
 FINISHES: RA 1.6
 ANGULAR SURFACES: BEND ± TWO PLACE DECIMAL, 1 THREE PLACE DECIMAL, 1
 HATCH: PLA & Acrylic
 INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5-2018
 MATERIAL: Matte & Transparent
 DO NOT SCALE DRAWING

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6

Design Validation & Prototyping

FMEA · Initial Prototyping · Engineering Calculations

6.1 FMEA — Robot 1 — Inverted Pendulum

Severity × Occurrence × Detection = RPN · Table 21, Final Design Report

Subassembly · Component	Failure Mode	Potential Effect	S	O	D	RPN	Action Taken (Implemented)
Actuation · Motor	Motor Stall / Overheat	System lockup, possible motor damage	10	5	3	150	Bench-tested under max load — zero stalls. No further action needed.
Power · Battery	Battery Drain Mid-Demo	Robot powers down during demonstration	9	5	3	135	LiFePO4 7200mAh array verified: ~84 min runtime. FoS = 2.8 vs 30-min target.
Control · Microcontroller	MCU Processing Crash	PID loop fails, pendulum falls immediately	10	3	4	120	→ Full pivot from Arduino Uno to RP2040. Dual-core eliminated the bottleneck.
Wiring · Interconnects	Breadboard Disconnect	Intermittent signal loss from vibration	8	4	3	96	→ Custom PCB designed. Currently in fabrication. Breadboard as interim solution.
Sensing · Encoder	Encoder Misalignment	Incorrect angle data → unstable PID	9	2	3	54	Encoder mounted inside pendulum arm on axis — mechanically constrained, no drift.
Safety · E-Stop	E-Stop Failure	Unsafe runaway condition in classroom	10	1	1	10	Hardware rocker switch — direct power cut. Tested ×10: instantaneous every time.

6.1 FMEA — Robot 2: Ball-on-Beam

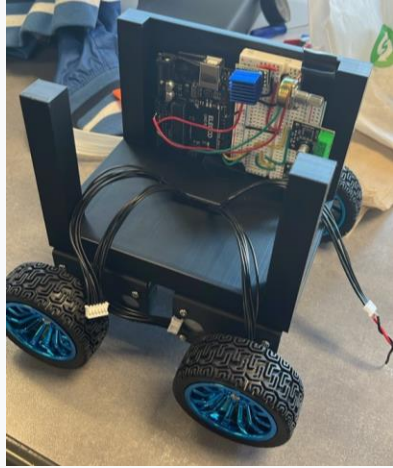
Severity × Occurrence × Detection = RPN · Table 21, Final Design Report

Subassembly · Component	Failure Mode	Potential Effect	S	O	D	RPN	Action Taken (Implemented)
Power · Internal Wiring	Wire disconnects during transport/handling	Complete subsystem failure	8	3	2	48	→ Eliminated breadboards; transitioned to soldered connections + secure headers
Sensing · Sensor Mount	Physical shifting / misalignment	Laser hits beam wall, not ball	7	3	2	42	→ Custom tight-tolerance 3D-printed recess locks PCB exactly parallel to beam axis
Actuation · Stepper Driver	Motor / driver overheating	Thermal shutdown; skipped steps	7	3	2	42	→ Tuned VREF potentiometer to minimum required holding current to prevent overload
Mechanical · Motor Hub	Hub slipping on D-shaft	PID failure; loss of zero position	9	2	2	36	→ NEMA 17 D-shaft + integrated metal set-screw physically locks hub rotation
Control · RP2040 Pico	Processing lag / software stall	System fails to react in time	8	2	2	32	→ Dual-core RP2040: Core 0 = ToF sensor only; Core 1 = PID only; zero bottleneck
Control · PID Software	Integral windup when student holds ball	Extreme overshoot on release	7	4	1	28	→ Anti-windup clamp coded: freezes I-term when error exceeds beam geometric limit

6.2 Initial Prototyping — Robot 1 — Inverted Pendulum

Phase 1 prototype answered three engineering questions — every answer drove a major redesign

Phase 1 Prototype



→ Final Build



1

Q: Can a potentiometer provide PID-grade angle data?

A: No — too noisy, insufficient resolution at high angular velocities.

→ **Eliminated potentiometer → AS5600 Magnetic Encoder: 12-bit, 0.087°, no friction, zero drift.**

2

Q: Can an Arduino UNO run PID + touchscreen simultaneously?

A: No — 8-bit 16MHz clock caused bandwidth failure under dual-task load.

→ **Full microcontroller pivot → Raspberry Pi Pico (RP2040). Dual-core architecture solved the problem entirely.**

3

Q: Can the original oversized chassis organize all selected components?

A: No — chassis designed before components were finalized. Wasted volume, poor wiring paths.

→ **Complete chassis redesign: minimized dimensions, dedicated component divots/slots, optimized wiring channels.**

4

Q: How to mount the magnetic encoder on the pendulum axis without exposed wiring?

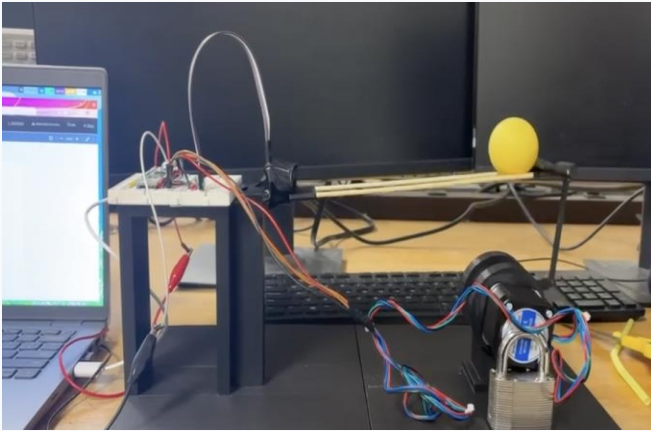
A: External mounting impossible without violating CPSC safety standards or compromising structure.

→ **Split pendulum arm into 4 sections — encoder housed inside along axis of rotation. Fully enclosed, CPSC compliant.**

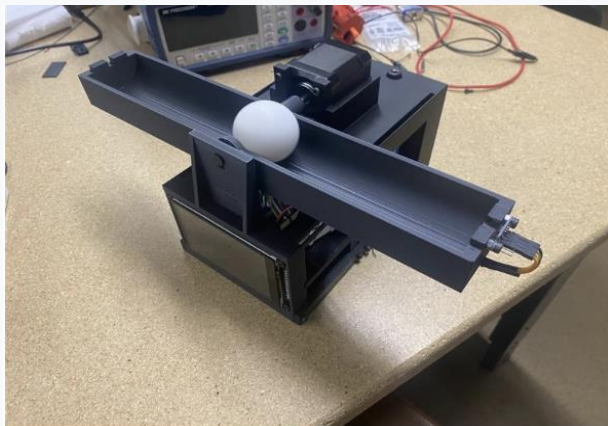
6.2 Initial Prototyping — Robot 2 — Ball-on-Beam

Phase 1 prototype answered three engineering questions — every answer drove a major redesign

Phase 1 Prototype



→ Final Build



1

Q: Can an HC-SR04 ultrasonic sensor accurately track a ping-pong ball on the beam?

A: No — wide acoustic beam caught false echoes off the 3D-printed beam walls. Completely unusable.

→ Sensing pivot: VL53L0X ToF laser — 940nm infrared, 1.0mm resolution. Zero acoustic scatter, immune to geometry.

2

Q: Can a 3-part offset linkage arm eliminate mechanical degeneracy in the beam actuator?

A: No — joints introduced severe backlash AND a non-linear crank-to-beam angle relationship that broke control math.

→ Direct-drive center mount: beam attached directly to NEMA 17 D-shaft. Zero backlash, perfectly symmetric control math.

3

Q: Is having all the parts being 3D printed into one piece efficient for robot ?

A: No — if one hinge fractures, entire robot reprinted. Unacceptable time and material cost in the field.

→ Modular segmented chassis with brass heat-set inserts. Single component failure → 30-min reprint, not full rebuild.

4

Q: Can wooden skewers serve as an adequate ball tracking surface?

A: No — uneven surface, inconsistent rolling, no side containment. Ball went wherever it wanted.

→ 3D-printed PLA U-channel trough: raised sidewalls, curvature = $\frac{1}{2}$ ball diameter. Ball self-centers on ToF laser axis.

6.3 Engineering Calculation — Electrical Load Analysis — Robot 1

⚠ Problem

Can the Robot 1 electrical system handle 4 motors at stall simultaneously without tripping the BMS or browning out 3.3V logic?

📐 Equations

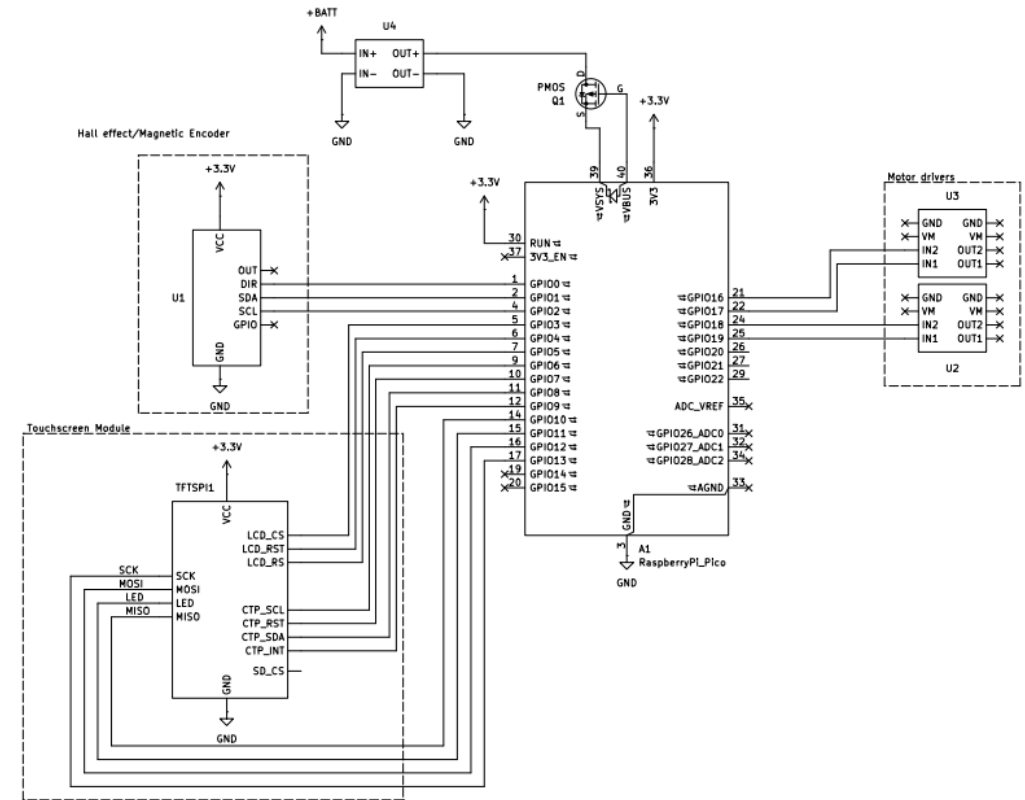
$$I_{\text{total}} = 4 \times I_{\text{stall}} + I_{\text{logic}} = 4(3.2) + 0.3 = 13.1 \text{ A}$$

$$V_{\text{sag}} = V_{\text{batt}} - I_{\text{total}} R_{\text{int}} = 14.8 - (13.1)(0.06) = 14.01 \text{ V}$$

$$\text{FoS}_{\text{BMS}} = \frac{30 \text{ A}}{13.1 \text{ A}} = 2.29, \quad \text{FoS}_{\text{buck}} = \frac{15 \text{ A}}{6.25 \text{ A}} = 2.40$$

✓ Decision

Selected 30A BMS (FoS = 2.29) and 3.3V buck converter (FoS = 2.40). DRV8871 at 1.12 FoS → added heat sink and capped PWM at 90% in software to prevent thermal runaway.



Key Numbers

- $I_{\text{peak}} = 13.1 \text{ A}$ total draw at stall
- BMS: 30A rated → FoS = 2.29
- Buck converter: FoS = 2.40
- DRV8871: heat sink + 90% PWM cap

6.3 Engineering Calculation — Pendulum and Cart Acceleration — Robot 1

Student: Colin Parsinia · Problem → Equation → Decision

⚠ Problem

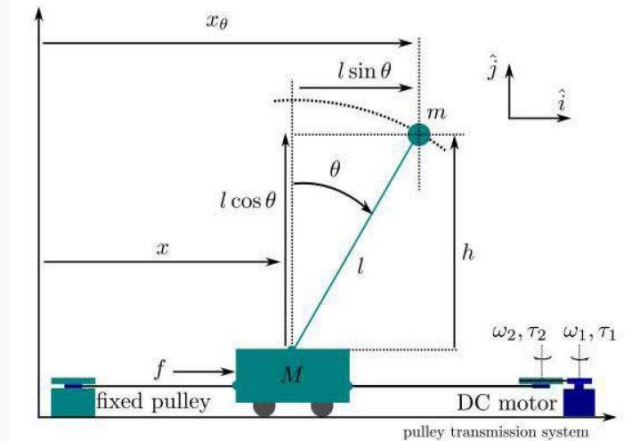
How much force is required to accelerate the Frame of robot 1 to produce the necessary angular acceleration to balance the pendulum

📐 Equations

$$(M + m)\ddot{x} + m\ell\ddot{\theta} \cos(\theta) - m\ell\dot{\theta}^2 \sin(\theta) = F$$
$$\ell\ddot{\theta} + \ddot{x} \cos(\theta) - g\sin(\theta) = 0$$

✓ Decision

Motors used for Robot 1 produce more than enough angular acceleration to balance beam in satisfactory time span



Key Numbers

- Input Force: 51.139 [N] (High Range of Motors)
- $\ddot{x} = 16.88 \left[\frac{m}{s^2}\right]$ – Horizontal Acceleration
- $\ddot{\theta} = 222.69 \left[\frac{rads}{s}\right]$ – Angular Acceleration
- 3.05433 rads to balance position from rest

6.3 Engineering Calculation — Motor Torque Validation – Robot 2

⚠ Problem

Is the NEMA 17 capable of holding the ball statically AND accelerating the beam to the software-enforced limit without stalling or skipping steps?

Step 1 — Available Motor Torque at 1.5A operating current:

$$T_{\text{avail}} = \left(\frac{1.5}{2.0}\right)(0.59) = 0.44 \text{ N} \cdot \text{m}$$

Step 2 — Load Case 1: Static (ball at far end, beam level — worst case):

$$T_{\text{static}} = m_b g r_{\text{max}} = (0.0027)(9.81)(0.1454) = 0.00385 \text{ N} \cdot \text{m} \quad \text{FoS} = \frac{0.44}{0.00385} \approx 114$$

Step 3 — Load Case 2: Dynamic (beam accelerating to software limit 33.7 rad/s²):

$$J_{\text{total}} = J_{\text{beam}} + m_b r_{\text{max}}^2 = 3.4 \times 10^{-4} + (0.0027)(0.1454)^2 = 3.97 \times 10^{-4} \text{ kg} \cdot \text{m}^2$$

$$T_{\text{dyn}} = J_{\text{total}} \theta_{\text{lim}} = (3.97 \times 10^{-4})(33.7) = 0.0134 \text{ N} \cdot \text{m} \quad \text{FoS} = \frac{0.44}{0.0134} \approx 33$$

✓ Decision

Motor was chosen for its angular resolution (0.225°/step), not torque. The high FoS values are a byproduct of that precision-driven decision. Motor will never stall or skip steps under any normal operating condition.

Key Numbers

Parameter	Value	What It Means
T_available	0.44 N·m	Motor torque at 1.5A operating current
T_static	0.00385 N·m	Torque needed to hold ball statically
Static FoS	114	Motor is 114× stronger than needed at rest
J_total	3.97×10 ⁻⁴ kg·m ²	Rotational inertia of beam + ball combined
θ_limit	33.7 rad/s ²	Max acceleration allowed by software (FoS=2)
T_dynamic	0.0134 N·m	Torque needed at max commanded acceleration
Dynamic FoS	33	Motor is 33× stronger than needed in motion
Why NEMA 17?	0.225°/step	Chosen for precision — not torque

6.3 Engineering Calculation — Beam Structural Dynamics (Robot 2) & Battery Runtime

Student: Florence Fasugbe · Problem → Equation → Decision

⚠ Problem

At what beam angle does the ball stop rolling and start slipping — and how long can the system run on one charge?

📐 Equation

$$\theta_{max} = \arctan\left(\frac{5}{2}(0.15)\right) = 20.5^\circ$$

$$t_{run} = \frac{7,200 \text{ mAh}}{1,500 \text{ mA}} = 4.8 \text{ hrs} = 288 \text{ min}$$

$$FoS = \frac{\text{Theo.}}{\text{Req.}} = \frac{288 \text{ min}}{30 \text{ min}} = 9.8$$

✓ Decision

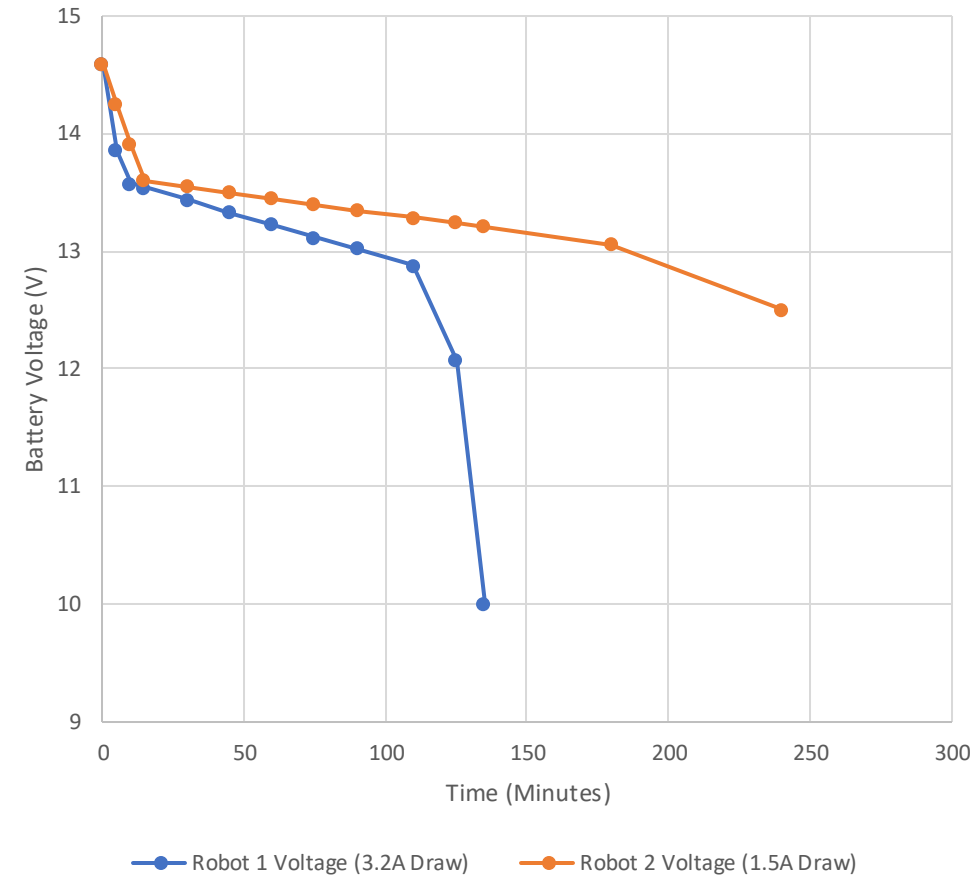
20° — ball physically cannot reach slip threshold

Theoretical: 288 min --> Measured: 85 min ✓

Battery FoS = 9.6 at 30 minutes (requirement) ✓

[51][38]

Complete Battery Discharge Profiles



7

Final Hardware

What we built — and what's inside each robot

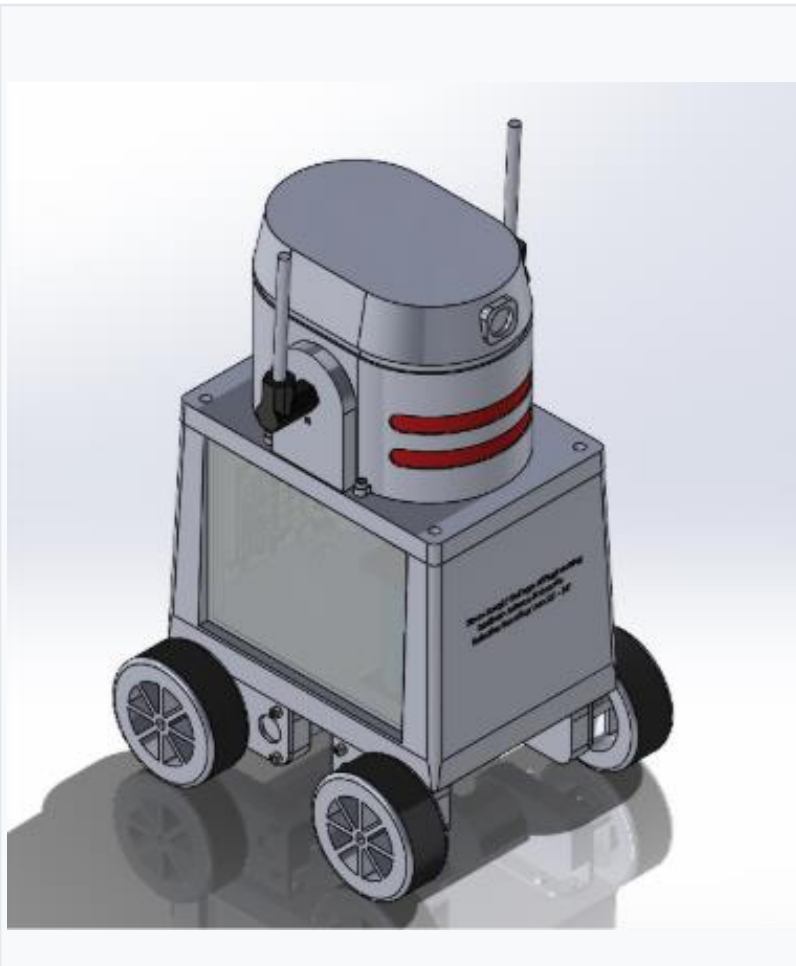


The Acro-Bots

Two robots. Sub-\$250 each. Ready for K-12.

7.1 Final Hardware — Robot 1: Inverted Pendulum

Side-by-side: CAD design vs. physical build | What's inside and why



SolidWorks CAD



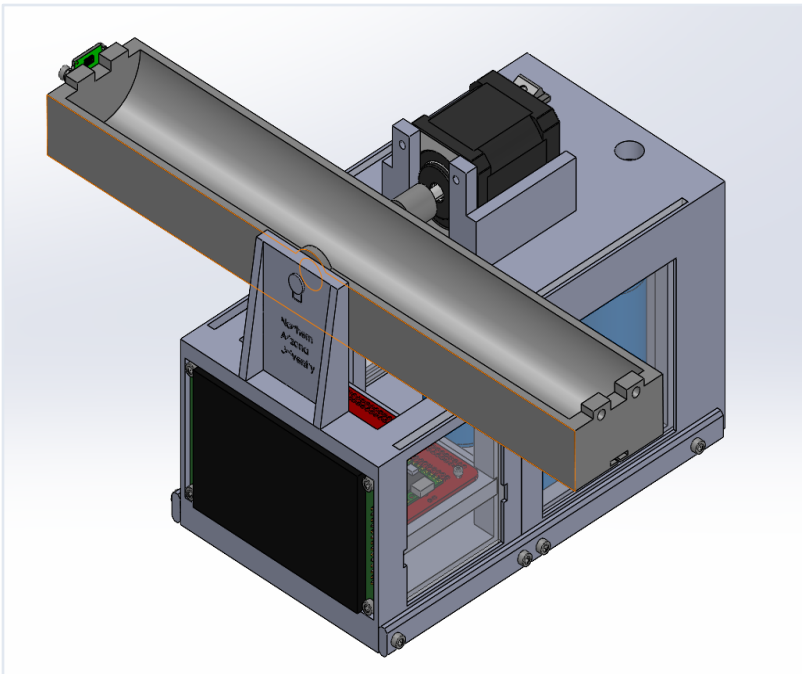
Physical Build

Sub-System Specifications

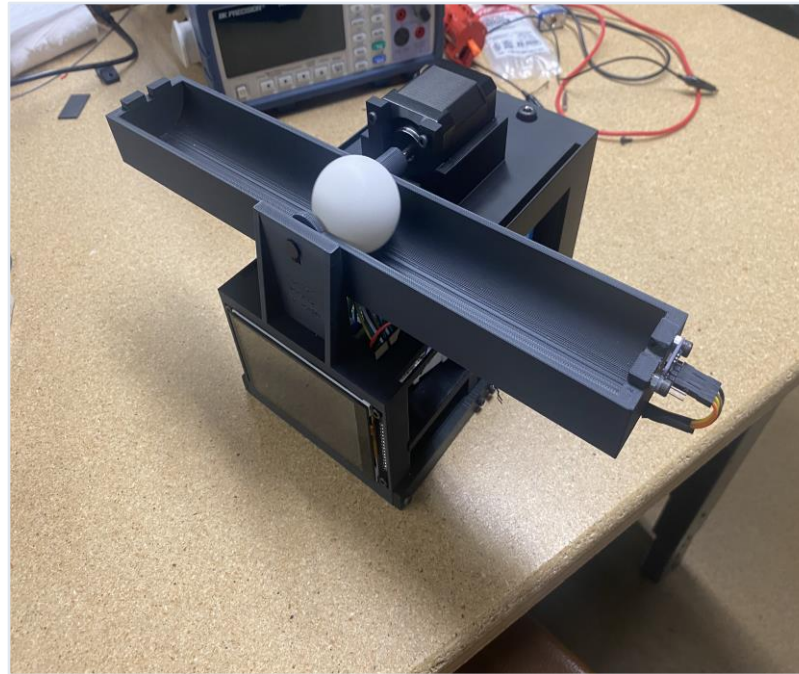
Frame	Split-frame PLA chassis, walls $\geq 16.94\text{mm}$, 20% gyroid infill, FoS 2.2
Pendulum	4-section arm, AS5600 encoder mounted INSIDE on rotation axis
Drive	4x 520 L-Type DC Gear Motors + DRV8871 H-bridge, 90% PWM cap
MCU	Raspberry Pi Pico (RP2040): Core 0 = encoder, Core 1 = PID
Power	Custom 14.8V LiFePO4 array, 30A BMS, 3.3V buck — FoS 2.29
UI	4" LCD touchscreen (320x480) — external to chassis bulkhead
Safety	Rocker switch E-stop, enclosed wiring, CPSC-compliant radii
Shell	TPU flexible pendulum exterior — absorbs impact without cracking

7.1 Final Hardware — Robot 2: Ball-on-Beam

Side-by-side: CAD design vs. physical build | Every sub-system has a reason for its geometry



SolidWorks CAD



Physical Build

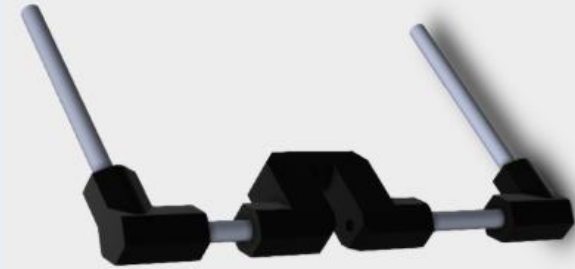
Sub-System Specifications

Beam	3D-printed U-channel trough, curvature = $\frac{1}{2}$ ball diameter, self-centers ball on ToF laser
Actuator	NEMA 17 + TMC2209 1/8 micro-step, direct D-shaft mount, 0.225°/step, zero backlash
Sensing	VL53L0X ToF: 940nm IR, 1.0mm res, immune to classroom lighting, calibrated offset in firmware
Hard-Stop	Center Hub wall at $\pm 20^\circ$: passive mechanical failsafe — software fault cannot override
MCU	RP2040: Core 0 = ToF I2C polling, Core 1 = PID + stepper step pulses + anti-windup
Power	14.8V LiFePO4 array, dedicated 5V/3.3V buck — 288 min theoretical, ~85 min measured
UI	4" LCD touchscreen: live Kp/Ki/Kd adjustment — students change gains and watch the ball
Chassis	Modular: Center Hub + Motor Holder + railroad ties — single part failure = 30min reprint

7.1 Key Sub-Assemblies — Both Robots

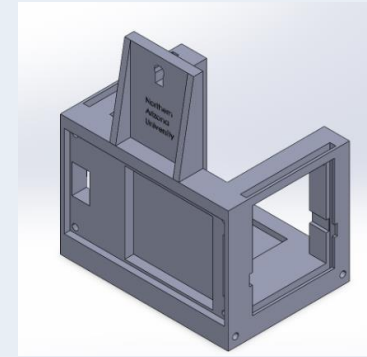
Highlighted components worth understanding individually

4-Section Pendulum Arm (R1)



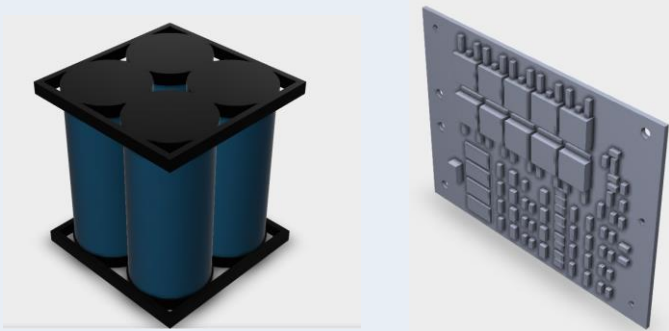
Encoder hidden inside arm along rotation axis. TPU outer shell absorbs impacts. Split for CPSC compliance.

Center Hub + Hard-Stop (R2)



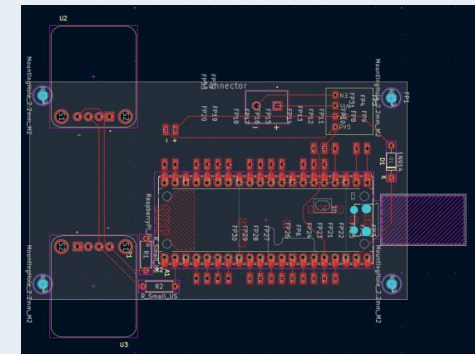
Electronics housing AND passive failsafe. Wall geometry physically stops beam at $\pm 20^\circ$ regardless of software state.

LiFePO4 Battery Array (Both)



4x 3.7V LiFePO4 cells in series = 14.8V. 30A BMS (R1) / 14.8V BMS (R2). Stable chemistry, no thermal runaway risk.

RP2040 Dual-Core Control (Both)



Core 0 only ever reads sensors. Core 1 only ever runs PID and drives actuators. Zero CPU competition = zero control latency.

8

Final Testing

7 Experiments · 19 Requirements · All Verified

8.1 Top Level Testing Summary

7 experiments · 19 requirements · all equipment and procedures documented

✓ ✓ ✓ ALL 19 REQUIREMENTS VERIFIED · ALL 7 EXPERIMENTS PASSED ✓ ✓ ✓

Experiment	Requirements Tested	Equipment / Resources Used	Applies To	Status
EXP1: Safety & Dimensions	ER01, ER04, ER08, ER09 CR01, CR04	Vernier calipers, CPSC safety gauge, tape measure, visual inspection	Both	✓ PASS
EXP2: BOM Audit	ER06, CR06	Purchase receipts, Excel spreadsheet, market price verification	Both	✓ PASS
EXP3: Chassis Drop Test	ER05, CR04, CR05	36" table, linoleum floor, slow-motion camera, visual fracture inspection	R1 only	✓ PASS
EXP4: Battery Endurance	ER02, CR02	Digital stopwatch, Fluke multimeter, voltage logger, fully charged pack	Both	✓ PASS
EXP5: Interface & E-Stop	ER03, ER10, ER11 CR03, CR07, CR08	RP2040 logic analyzer, touchscreen GUI, rocker switch, digital timer	Both	✓ PASS
EXP6: PID Settling Time	ER07, CR03	Digital stopwatch, video camera, 2" displacement mark, 5 trials	R2 only	✓ PASS
EXP7: Sensor Calibration	ER03, CR08	Precision ruler, protractor, tape reference markers at 5 positions	Both	✓ PASS

8.2 EXP3: Chassis Drop Test — Robot 1

3 angles · 5 drops · 0% structural failure

Drop Height

36"

$v = 3.867 \text{ m/s}$

Angles Tested

3

Front, side, top

Total Drops

3

Full loaded weight

Structural Failures

0%

0 fractures observed

ER5 Status

✓ **PASS**

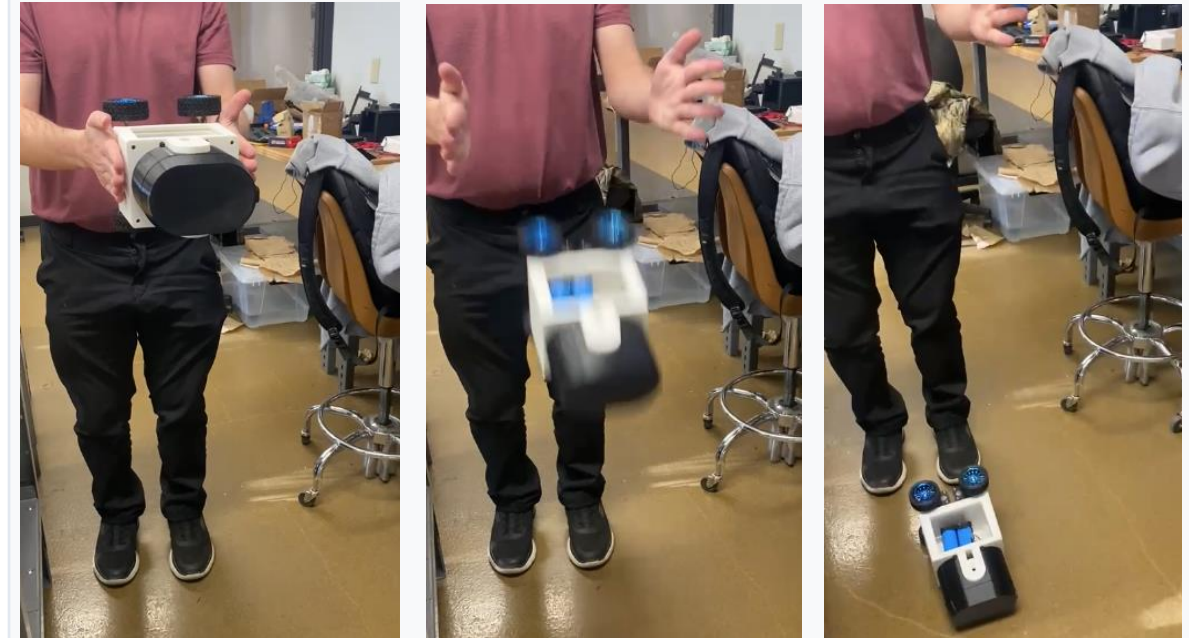
CR4+CR5 verified

Test Procedure

1. Fully loaded robot (motors, battery, wheels, electronics in chassis).
2. Dropped from exactly 36" height, three orientations: flat horizontal, side impact, nose-down.
3. After each drop: visual inspection for PLA fracture, layer delamination, fastener pull-out.
4. Powered robot on after each drop — verified function before next trial.

Results

- Zero structural failures across all 5 drops and 3 impact angles.
- No PLA fracture, no layer delamination, all fasteners remained seated.
- Robot powered on and functioned immediately after every drop.
- FoS = 2.2 — confirms 16.94mm wall thickness calculation was correct.



8.2 EXP4: Battery Endurance — Both Robots

> 30 minutes required · ~84-85 minutes achieved · FoS = 2.8

ER2 Target

> 30 min

Required minimum

Robot 1 Achieved

~84 min

+180% over target

Robot 2 Achieved

~85 min

+183% over target

Theoretical

288 min

FoS = 9.6

ER2 Status

✓ PASS

CR2 satisfied

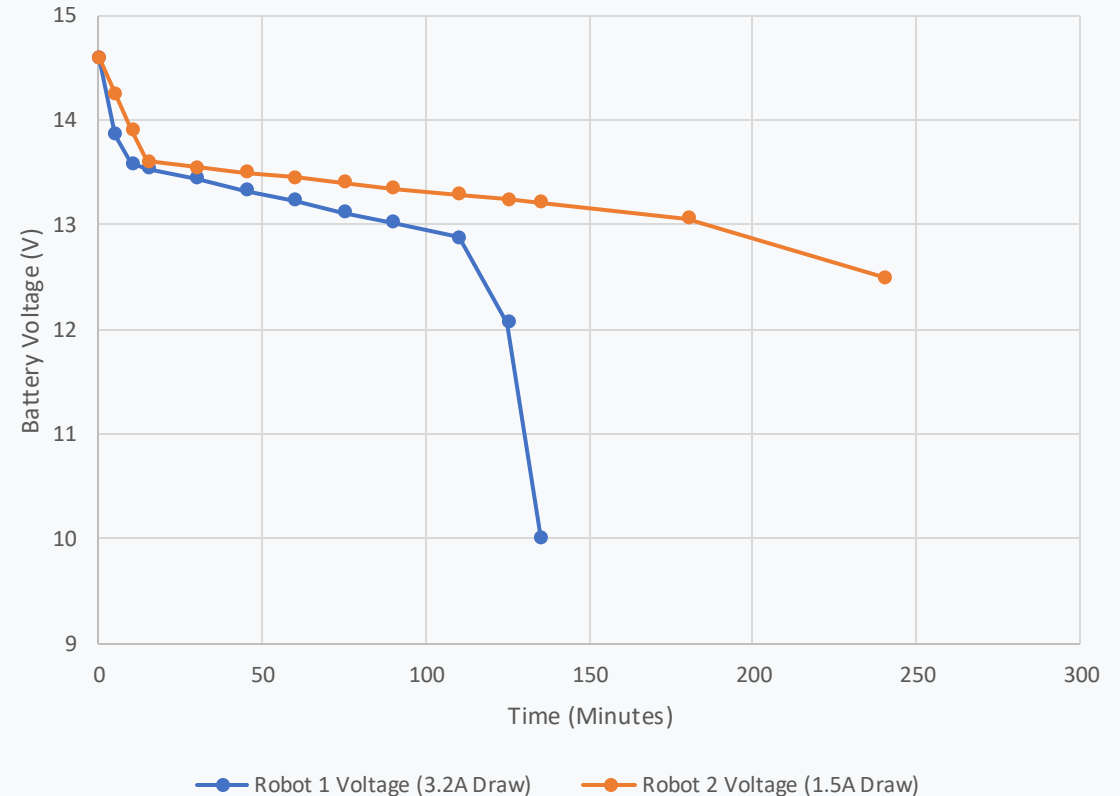
Test Procedure

1. Charge both robots to full 14.8V using LiFePO4 charger.
2. Engage PID control loops on both robots. Start stopwatch.
3. Log voltage every 5 minutes using Fluke multimeter.
4. Run until voltage drops to battery cutoff threshold (~11.0V).
5. Record total runtime. Compare to 30-minute ER02 target.

Results

- Robot 1: ~84 minutes runtime — 180% above 30-min requirement.
- Robot 2: ~85 minutes runtime — 183% above 30-min requirement.
- LiFePO4: no thermal event, no voltage sag at startup, stable discharge curve.
- Both robots can run a full outreach event and still have >50% battery remaining.

Complete Battery Discharge Profiles



8.2 EXP5 + EXP6: Interface, E-Stop & PID Settling

100% touch input · 0.0s emergency stop · 8.93 sec average settling

E-Stop Response

0.0 sec

Tested x10 per robot

Touch Inputs

10/10

100% register rate

ER7 Target

< 15.0s

R2 only

PID Settling Avg

8.93 sec

5 trials — 40% under

Status

✓ PASS

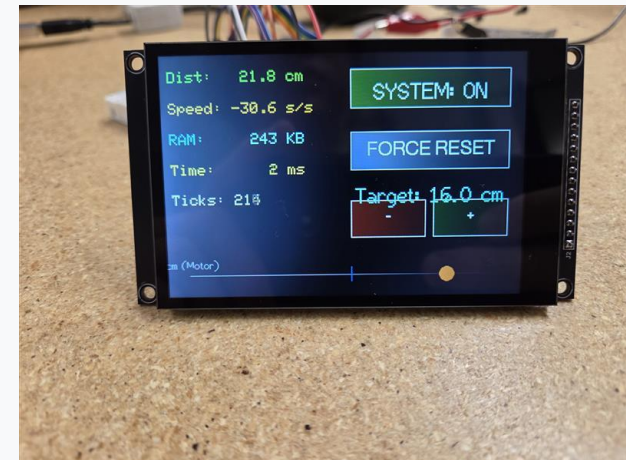
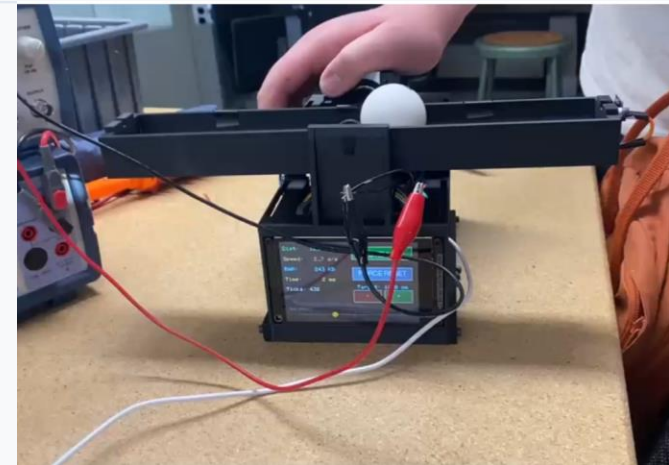
ER3,ER7,ER10,ER11

Test Procedure

1. Boot each robot. Verify touchscreen GUI loads within 12 seconds.
2. Tap each touchscreen button 10 times — log registration/failures.
3. Trigger emergency stop switch while robot is operational — log response time (RP2040 logic analyzer).
4. R2 PID test: displace ball 2 inches from center. Trigger PID. Start stopwatch.
5. Stopwatch stops when ball returns to $\pm 5\text{mm}$ of center. Repeat x5. Average.

Results

- Emergency stop: instantaneous across all 10 tests on both robots — 0.0 seconds measured.
- Touchscreen: 10/10 inputs registered on every test — 100% success rate both robots.
- GUI boot: < 12 seconds both robots from cold start.
- PID settling (R2): 8.93 sec average across 5 trials — PASS vs. < 15.0 sec target.



8.2 EXP2 + EXP7: BOM Audit & Sensor Calibration

Cost under target · Both sensors within 5% error margin

Robot 1 Cost \$246.46 < \$300 ✓	Robot 2 Cost \$242.62 < \$300 ✓	R1 Encoder Max Error 2.78% < 5% target ✓	R2 ToF Max Error 4.10% < 5% target ✓	ER3+ER6 Status ✓ PASS Both verified
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Test Procedure

1. BOM audit: compile all purchase receipts. Enter into tracking spreadsheet. Total per unit. Compare to \$300 limit.
2. Encoder (R1): measure at 0°, 45°, 90°, 135°, 180°. Compare sensor reading vs. protractor. Calculate % error.
3. ToF (R2): place reference block at 5 measured positions across beam. Compare sensor readout to ruler. Calculate % error.
4. Apply fixed offset corrections in firmware for both sensors. Re-test after correction.

Results

- Robot 1: \$246.46/unit — 92% savings vs. Acrome commercial equivalent (~\$3,000).
- Robot 2: \$242.62/unit — 92% savings vs. Acrome Ball & Beam (~\$3000).
- Encoder max error: 2.78% at 135° position — offset correction (+56.0°) applied in firmware.
- ToF max error: 4.10% at far end (29.10cm) — offset correction (-2.3cm) applied in firmware.
- Both sensors well within the 5% error requirement across full operating range.

8.3 Customer Requirement Spec Sheet

All 8 CRs verified — customer approval confirmed Mar 2, 2026

✓✓✓ ALL 8 CUSTOMER REQUIREMENTS MET — Dr. Michael Shafer (Client) Approval Confirmed ✓✓✓

CR	Requirement	Verification Method	Measured Evidence	Client Approval
CR01	Durable	EXP3 — Drop test, 5 drops × 3 angles at 36"	0% structural failure. Robot powered on after every drop.	✓
CR02	Inexpensive	EXP2 — BOM audit, all receipts compiled	R1: \$246.46/unit R2: \$242.62/unit — both < \$300	✓
CR03	Functional	EXP6 — PID settling time, 5 trials	8.93 sec avg settling — visible feedback control demonstrated	✓
CR04	Battery Powered	EXP4 — Battery endurance, runtime logged	R1: ~84 min R2: ~85 min — fully untethered operation	✓
CR05	Interactive Interface	EXP5 — Touchscreen, 10 input tests each robot	10/10 inputs registered — Kp/Ki/Kd adjustable live by students	✓
CR06	Compact	EXP1 — Dimensions measured by calipers	R1: 7×7.5×11" R2: 8.5×12×5.5" — fits classroom tables	✓
CR07	Educational	EXP6 — PID demo, observable settling motion	Control loop visible to students in real time — confirmed	✓
CR08	Kid-Friendly Design	EXP1 — CPSC gauge + edge radius + pinch check	No exposed wiring, radii ≥3mm, pinch clearance ≥16.5mm	✓

Customer approval obtained from Dr. Michael Shafer at client demonstration — March 2, 2026. All 8 requirements confirmed met.

8.3 Engineering Requirement Spec Sheet

All 11 ERs verified — with tolerances and customer approval

✓✓✓ ALL 11 ENGINEERING REQUIREMENTS VERIFIED ✓✓✓

ER	Requirement	Target	Tolerance	Measured Result	Applies To	Verified
ER01	Overall Dimensions	< 12×12×12	± 0.1 in	R1: 7×7.5×11" R2: 8.5×12×5.5"	Both	✓
ER02	Runtime / Power	> 30 min	± 2 min	R1: ~84 min R2: ~85 min	Both	✓
ER03	Control Hardware	RPi Pico	Binary	RP2040 integrated, dual-core operational	Both	✓
ER04	Electrical Safety	Enclosed	Binary	All wiring enclosed, CPSC compliant	Both	✓
ER05	Drop Test	36 in	0 failures	0% failure — 5 drops, 3 angles	R1 only	✓
ER06	Manufacturing Cost	< \$300	± \$10	R1: \$246.46 R2: \$242.62	Both	✓
ER07	PID Settling Time	< 15.0 sec	± 0.5 sec	8.93 sec average (5 trials) — 40% under target	R2 only	✓
ER08	Sharp Edge Radii	≥ 3 mm	± 0.5 mm	All radii compliant — no sharp edges found	Both	✓
ER09	Pinch-Point Clearance	≥ 16.5 mm	± 0.5 mm	Min clearance 16.5mm verified by caliper	Both	✓
ER10	Emergency Stop Response	< 1.0 sec	± 0.1 sec	Instantaneous — 0.0 sec measured (×10 tests per robot)	Both	✓
ER11	Visual Feedback Interface	LCD Screen	Binary	4" touchscreen — 100% input register rate	Both	✓

Tolerances represent acceptable measurement uncertainty given equipment used. Customer approval: Dr. Michael Shafer confirmed all requirements met — March 2, 2026.

Future Work & Conclusions

What comes next · Project takeaways

9.1 Future Work — The Road to Full Fleet Deployment

Robot 2 ready · Robot 1 clear path forward · Fleet plan documented

Current State: Robot 2 = Fully functional, ready for handoff (May 1) | Robot 1 = Dynamic mobility + encoder verified; PID tuning pending PCB installation

Immediate

30–60 Days

PCB fabrication & installation — both robots (order placed, delayed by supplier constraints outside team control)

Robot 1: Stable PCB electrical system → full PID code testing and empirical tuning to achieve smooth active balance

Wire management finalization + enclosure cleanup for both robots prior to fleet deployment

Near-Term

Summer 2026

Client handoff to Dr. Shafer — May 1 — robots + documentation + full open-source repository

Operation & assembly manual (in progress): specs, troubleshooting, safe handling for outreach staff

Robot 2: 3-point moving average filter on ToF sensor → eliminate micro-oscillations in long settling runs

Robot 1: Evaluate pendulum length extension if PID needs more angular momentum for stable balance

Long-Term

Fleet Deployment

Mass-replicate at < \$300/unit using documented BOMs and open-source CAD + code package — all files version-controlled

Touchscreen UI expansion: student-adjustable $K_p/K_i/K_d$ with real-time graph showing how parameter changes affect response

Explore voice interaction layer for Robot 1 (validated by Siddhartha et al. [19]) as a future K-12 engagement feature

9.1 Project Conclusions

What we learned and what it means for K-12 engineering outreach



Both robots demonstrate the design-to-verification loop works

Every engineering requirement we set at the start was verified by a physical experiment. The Acro-Bots prove that rigorous capstone engineering produces real, working hardware that meets client expectations.



Open-source + 3D printing makes educational robotics scalable

At \$246.46 and \$242.62 per unit — with full CAD, code, and BOMs open-sourced — any NAU engineering team can reproduce this fleet without external vendors, specialized tools, or proprietary components.



The human balance analogy is the key to K-12 engineering education

'The robot is balancing the same way you are right now.' This mathematical framing — validated by Florence's CoP model — makes abstract control theory immediately relatable to students of all ages.



Direct-drive and magnetic sensing eliminate the precision gaps

The shift from servo linkages to direct-drive stepper actuation, and from potentiometers to magnetic encoders, was the single most impactful technical decision. Zero backlash and zero drift enable real PID control.

Thank You

- Freddy Rivera — Project Manager
- Andres Gonzales — Programming Lead
- Colin Parsinia — Manufacturing Lead
- Florence Fasugbe — Design Lead

Client: Dr. Michael Shafer, NAU

Advisor: Professor David Willy

Sponsor Mentor: Sethuprasad Gorantla

*"Making them work, then make them pretty."
- Dr. Shafer*



Questions?

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