Final Capstone Presentation: Inverted Pendulum & Ball-on-Beam Systems

Robotics Traveling Van: Microcontroller-Driven Interactive Balancing Robots for K-12 Engineering Outreach

Client & Sponsor: Dr. Michael Shafer, Northern Arizona University

Team: Freddy Rivera, Andres Gonzales, Colin Parsinia, Florence Fasugbe

Agenda

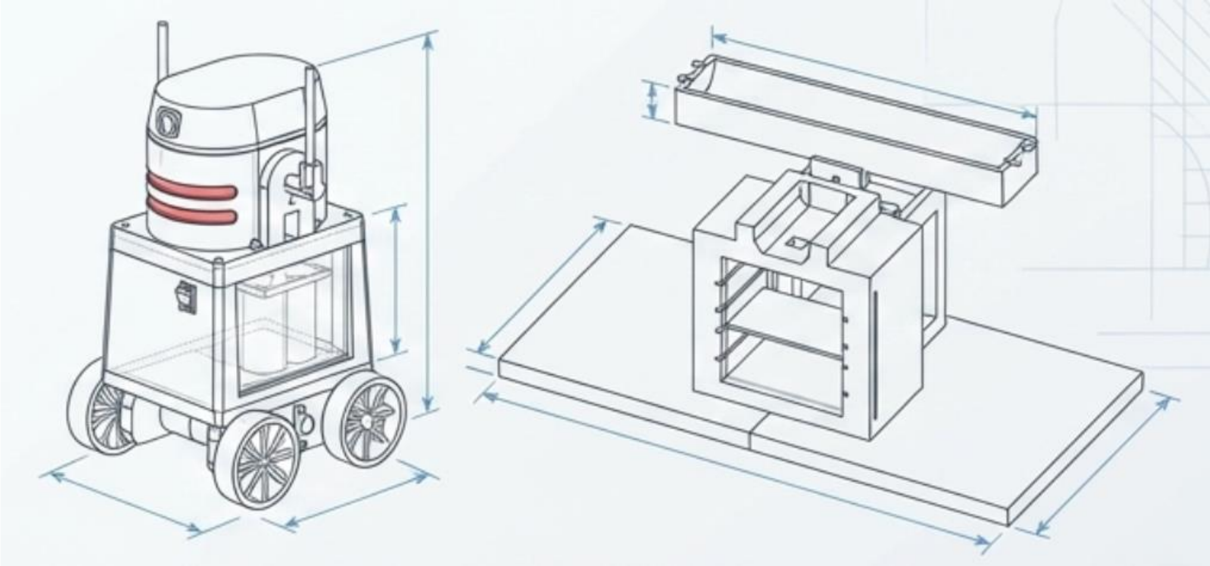
What are we talking about today?

- **Project Requirements:** Translating the "Voice of the Customer" into technical targets.
- **Design Research:** Benchmarking state-of-the-art systems and establishing mathematical models (Newtonian & Lagrangian).
- **Concept Selection:** Functional decomposition and the "Big Pivot" in Robot #2's architecture.
- **Project Management:** A $5,000 budget audit and Bill of Materials (BOM) breakdown.
- **Prototyping & FMEA:** Iterative testing and quantitative risk mitigation.
- **Final Results & Future Work:** Physical verification against 36-inch drop tests and next steps for fleet deployment

The Mission

Why are we doing this?

Project Description

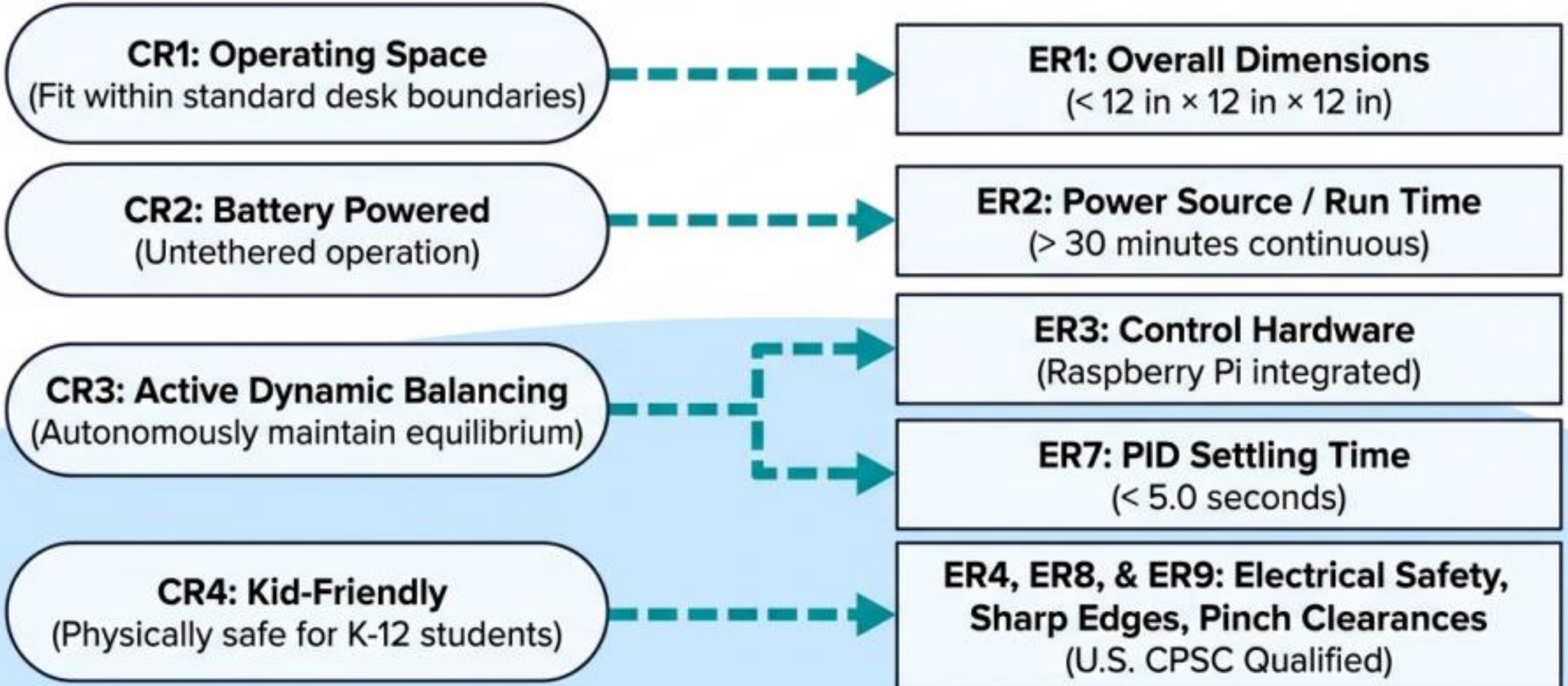


Design, validate, and manufacture two low-cost, transportable educational robots demonstrating core control-system engineering concepts for K-12 outreach.

Success Metrics for the Acro-Bots

1) Educational Value
   - Tangible demonstration of continuous feedback control
2) Classroom Safety
   - U.S. CPSC qualification (no sharp edges, fully enclosed wiring, etc.)
3) Reliability
   - Survive standard classroom handling and repetitive active demonstrations
4) Mass Producibility
   - Maximize cost-effectiveness against current market alternatives.

Core Functionality & Safety: Defining the Physical Operating Parameters



CR1: Operating Space
(Fit within standard desk boundaries)

ER1: Overall Dimensions
(< 12 in × 12 in × 12 in)

CR2: Battery Powered
(Untethered operation)

ER2: Power Source / Run Time
(> 30 minutes continuous)

CR3: Active Dynamic Balancing
(Autonomously maintain equilibrium)

ER3: Control Hardware
(Raspberry Pi integrated)

ER7: PID Settling Time
(< 5.0 seconds)

CR4: Kid-Friendly
(Physically safe for K-12 students)

ER4, ER8, & ER9: Electrical Safety, Sharp Edges, Pinch Clearances
(U.S. CPSC Qualified)

Practicality & User Experience: Engineering for Classroom Deployment

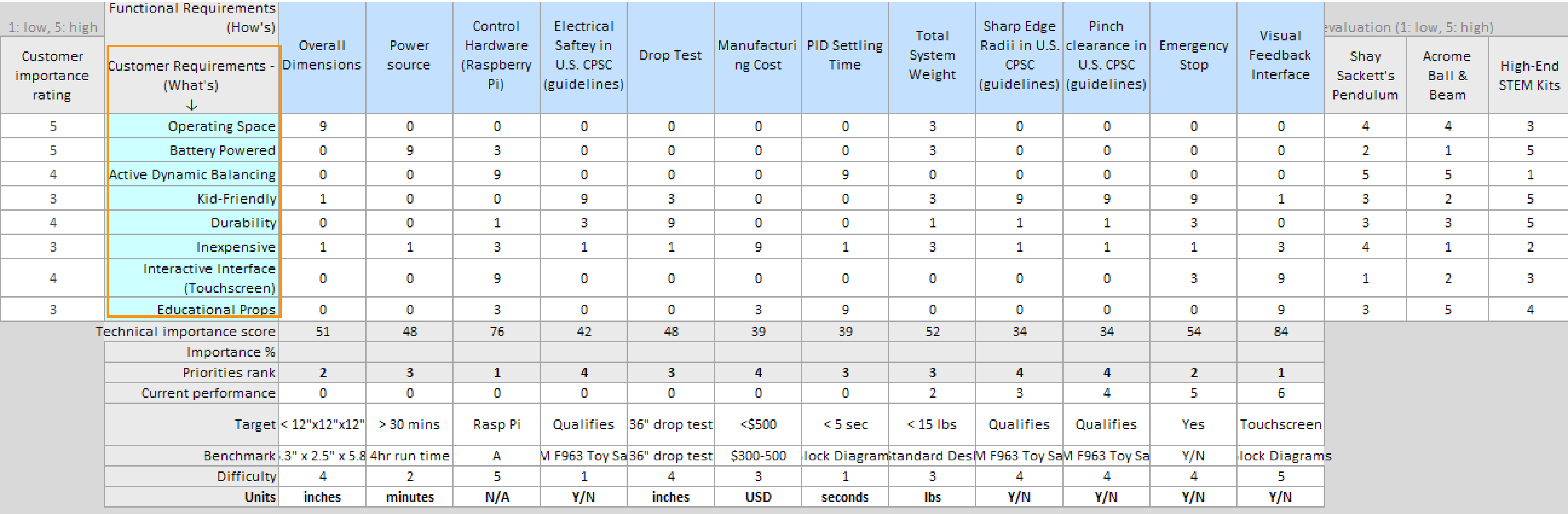
CR5: Durability (Withstand typical classroom handling) → **ER5:** Drop Test (36-inch survivability)

CR6: Inexpensive (Cost-effective for mass production) → **ER6:** Manufacturing Cost (< $500 per unit)

CR7: Interactive Interface (User-accessible touchscreen) → **ER11:** Visual Feedback Interface (Functioning touchscreen)

CR8: Educational Props (Serve as a tangible teaching tool) → **ER10:** Emergency Stop (Integrated mechanism)

QFD



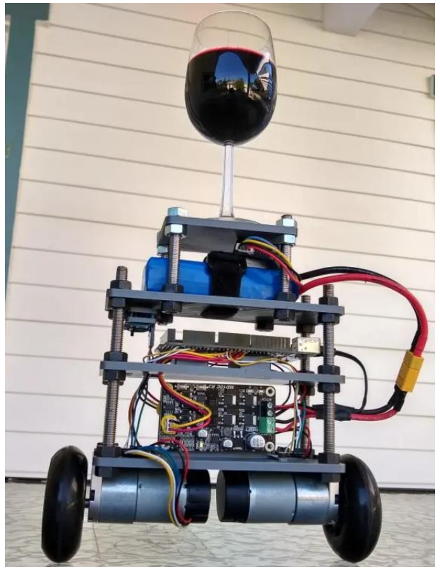
1: low, 5: high	Functional Requirements (How's)	Overall Dimensions	Power source	Control Hardware (Raspberry Pi)	Electrical Saftey in U.S. CPSC (guidelines)	Drop Test	Manufacturing Cost	PID Settling Time	Total System Weight	Sharp Edge Radii in U.S. CPSC (guidelines)	Pinch clearance in U.S. CPSC (guidelines)	Emergency Stop	Visual Feedback Interface	evaluation (1: low, 5: high)		
Customer importance rating	Customer Requirements - (What's) ↓													Shay Sackett's Pendulum	Acrome Ball & Beam	High-End STEM Kits
5	Operating Space	9	0	0	0	0	0	0	3	0	0	0	0	4	4	3
5	Battery Powered	0	9	3	0	0	0	0	3	0	0	0	0	2	1	5
4	Active Dynamic Balancing	0	0	9	0	0	0	9	0	0	0	0	0	5	5	1
3	Kid-Friendly	1	0	0	9	3	0	0	3	9	9	9	1	3	2	5
4	Durability	0	0	1	3	9	0	0	1	1	1	3	0	3	3	5
3	Inexpensive	1	1	3	1	1	9	1	3	1	1	1	3	4	1	2
4	Interactive Interface (Touchscreen)	0	0	9	0	0	0	0	0	0	0	3	9	1	2	3
3	Educational Props	0	0	3	0	0	3	9	0	0	0	0	9	3	5	4
	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	0	0	0	0	0	0	0	2	3	4	5	6			
	Target	< 12"x12"x12"	> 30 mins	Rasp Pi	Qualifies	36" drop test	<$500	< 5 sec	< 15 lbs	Qualifies	Qualifies	Yes	Touchscreen			
	Benchmark	.3" x 2.5" x 5.8	4hr run time	A	M F963 Toy Sa	36" drop test	$300-500	lock Diagram	tandard Des	M F963 Toy Sa	M F963 Toy Sa	Y/N	lock 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**			

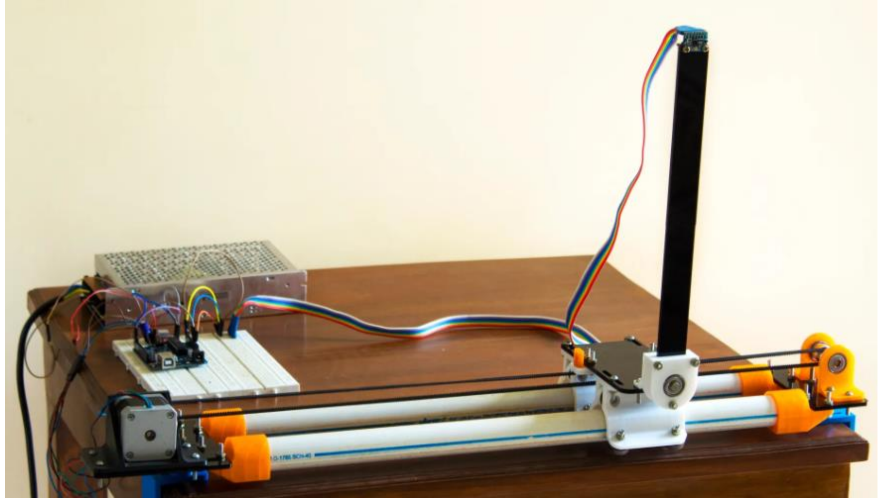
Concept Generation and Selection

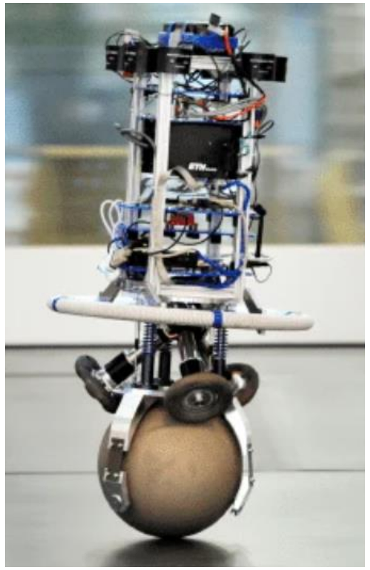
Why our designs?

Concept Generation Robot One:

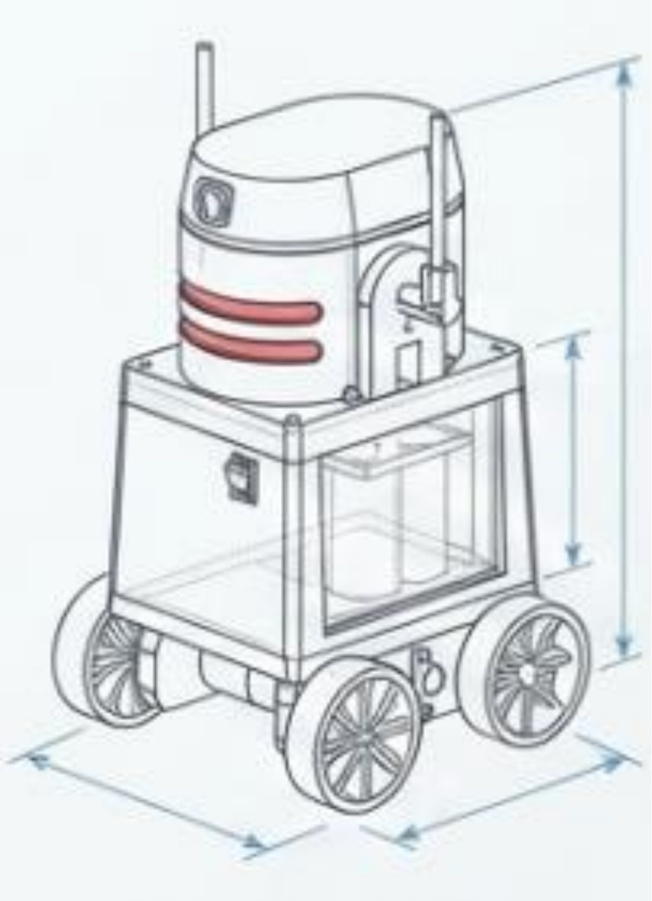
- The team evaluated three primary architectures:
- **2-Wheeled Pendulum (based on Sackett’s design) [1]**
- **Cart-Inverted Pendulum (standard rail system) [2]**
- **Reaction Wheel Pendulum (based on the "Wheelbot" momentum-exchange principle) [3]**







Pugh Chart: Robot 1 Architecture Selection

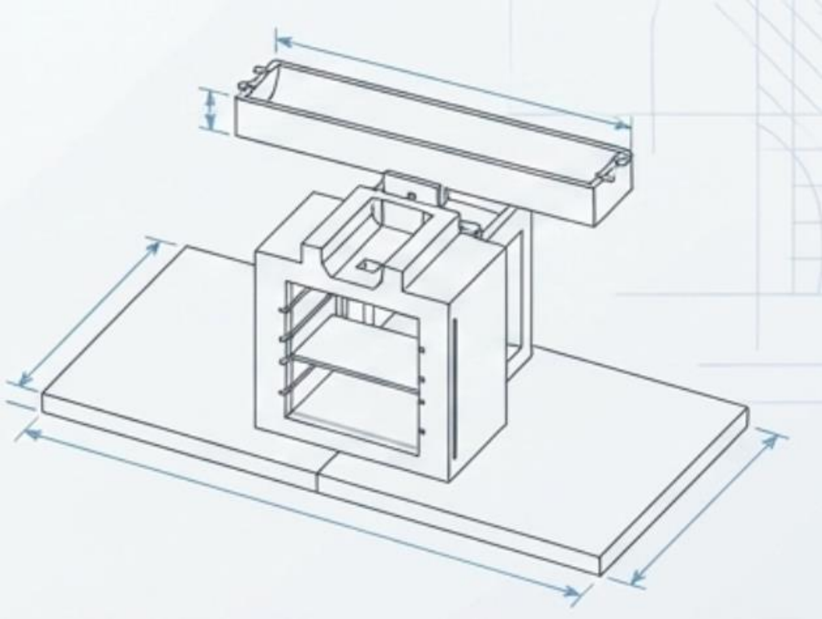


Selection Criteria	2-Wheeled Pendulum (Baseline)	Inverted Pendulum on Cart (Winner)	Reaction Wheel Pendulum
Static Stability (Safety)	0	**+** (Stays upright when unpowered)	**–** (Unstable when off)
Classroom Durability	0	**+** (4-point contact reduces tip-over)	**–** (Sensitive flywheels)
Educational Clarity	0	**+** (Classic textbook Euler-Lagrange)	**0** (Abstract momentum)
Control Feasibility	0	**+** (Standard pole-placement)	**–** (Non-linear complexity)
Manufacturing Cost	0	**0** (Uses COTS motors/wheels)	**–** (High-precision IMUs)
Drop Test Survivability	0	**+** (Reinforced split-frame)	**–** (High impact risk)
Total (+)	0	5	0
Total (–)	0	0	5
Net Score	**0**	**+5**	**–5**

Concept Generation Robot Two:

- The team evaluated three primary architectures:
- 2-Axis Ball-on-Plate (inspired by Hammje's OpenCV bot) [4]
- 1-Axis Ball-on-Beam [5]

Pugh Chart: Robot 2 Architecture Selection



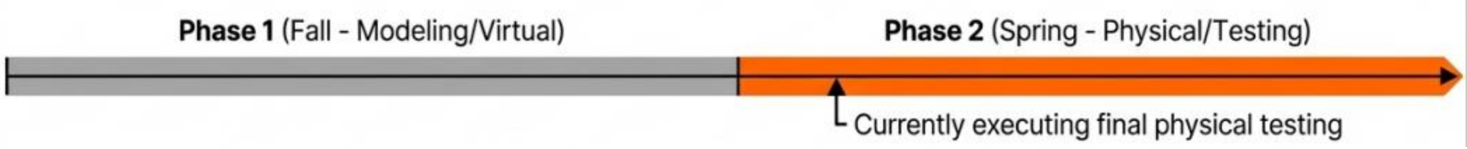
Selection Criteria	2-Axis Ball-on-Plate (Baseline)	1-Axis Ball-on-Beam (Final Design)	Magnetic Levitation (Filtered Early)
Safety (CPSC Compliance)	0	0 (Standard electrical)	– (High voltage/heat)
Educational Clarity	0	+ (1-DoF isolation)	– (Abstract physics)
Mass Producibility	0	+ (Single motor/Simplified)	– (Complex coil winding)
Manufacturing Cost	0	+ (Lowest per-unit cost)	– (Specialized sensors)
Control Complexity	0	+ (Linearizable dynamics)	– (Highly non-linear)
Total (+)	0	4	0
Total (–)	0	0	5
Net Score	0	+4	–5

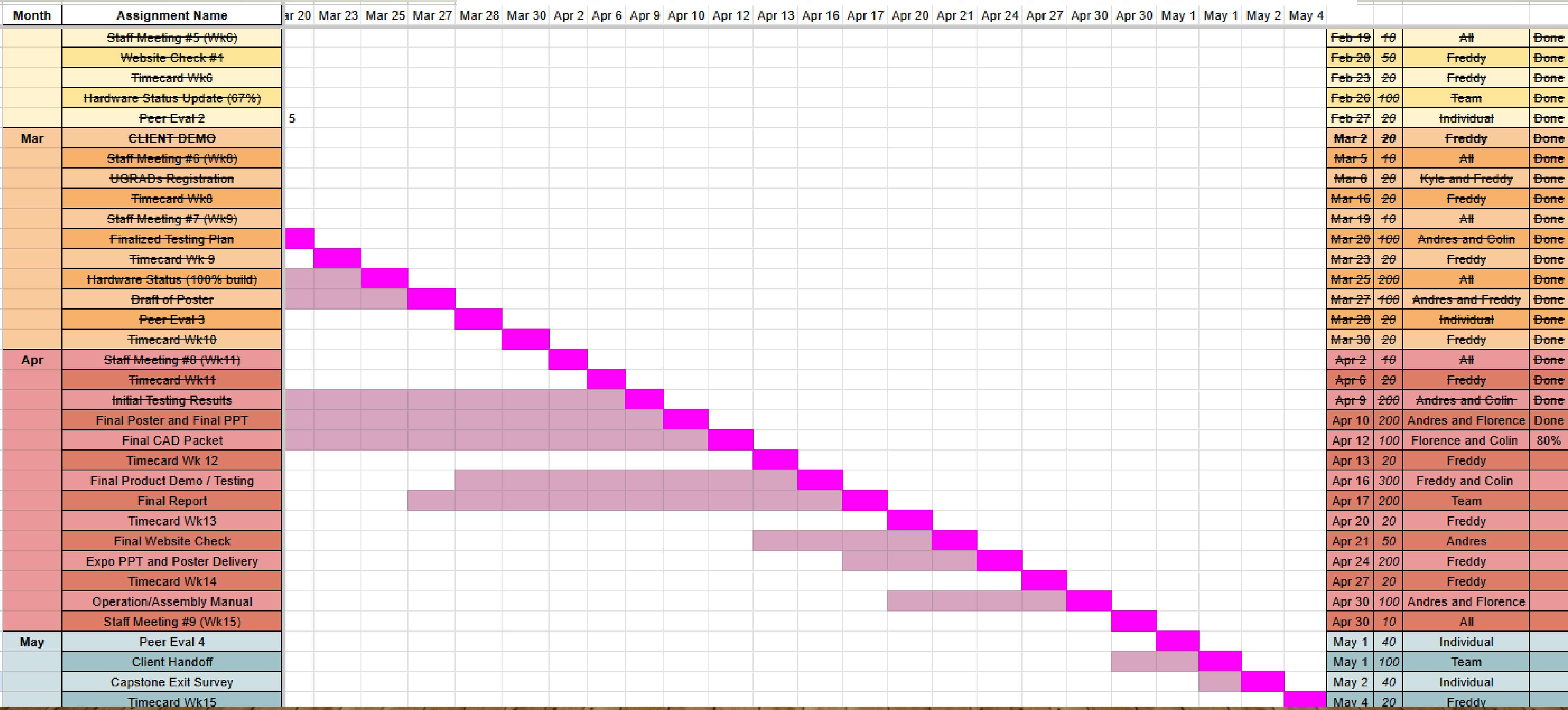
PROJECT MANAGEMENT

When did this happen and

how much did it cost?

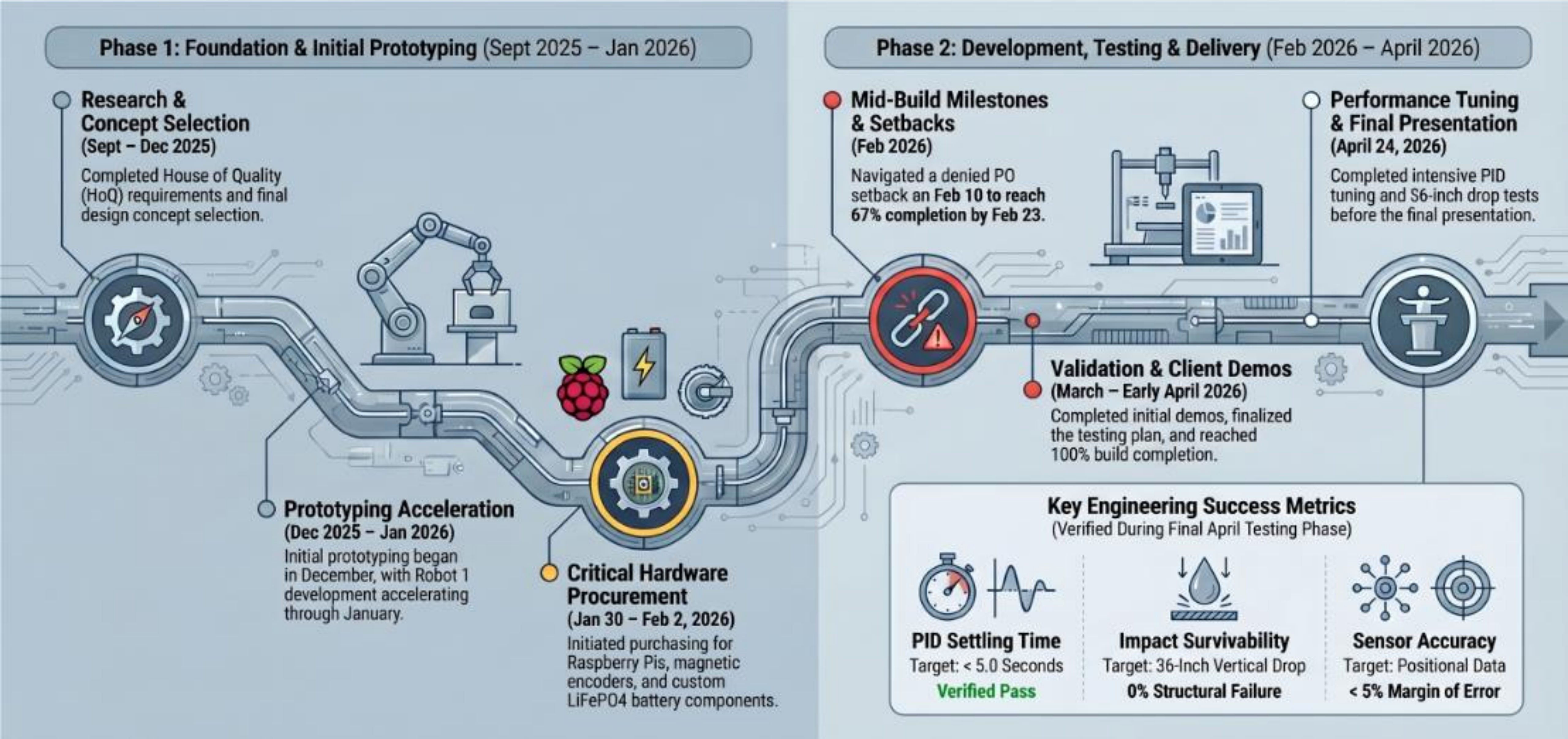
Gantt Chart





Month	Assignment Name	ar 20	Mar 23	Mar 25	Mar 27	Mar 28	Mar 30	Apr 2	Apr 6	Apr 9	Apr 10	Apr 12	Apr 13	Apr 16	Apr 17	Apr 20	Apr 21	Apr 24	Apr 27	Apr 30	Apr 30	May 1	May 1	May 2	May 4				
	~~Staff Meeting #5 (Wk6)~~																									~~Feb 19~~	~~10~~	~~All~~	~~Done~~
	~~Website Check #1~~																									~~Feb 20~~	~~50~~	~~Freddy~~	~~Done~~
	~~Timecard Wk6~~																									~~Feb 23~~	~~20~~	~~Freddy~~	~~Done~~
	~~Hardware Status Update (67%)~~																									~~Feb 26~~	~~100~~	~~Team~~	~~Done~~
	~~Peer Eval 2~~	5																								~~Feb 27~~	~~20~~	~~Individual~~	~~Done~~
Mar	~~CLIENT DEMO~~																									~~Mar 2~~	~~20~~	~~Freddy~~	~~Done~~
	~~Staff Meeting #6 (Wk8)~~																									~~Mar 5~~	~~10~~	~~All~~	~~Done~~
	~~UGRADs Registration~~																									~~Mar 6~~	~~20~~	~~Kyle and Freddy~~	~~Done~~
	~~Timecard Wk8~~																									~~Mar 16~~	~~20~~	~~Freddy~~	~~Done~~
	~~Staff Meeting #7 (Wk9)~~																									~~Mar 19~~	~~10~~	~~All~~	~~Done~~
	~~Finalized Testing Plan~~	■																								~~Mar 20~~	~~100~~	~~Andres and Colin~~	~~Done~~
	~~Timecard Wk 9~~		■																							~~Mar 23~~	~~20~~	~~Freddy~~	~~Done~~
	~~Hardware Status (100% build)~~	▨	▨	■																						~~Mar 25~~	~~200~~	~~All~~	~~Done~~
	~~Draft of Poster~~	▨	▨	▨	■																					~~Mar 27~~	~~100~~	~~Andres and Freddy~~	~~Done~~
	~~Peer Eval 3~~					■																				~~Mar 28~~	~~20~~	~~Individual~~	~~Done~~
	~~Timecard Wk10~~						■																			~~Mar 30~~	~~20~~	~~Freddy~~	~~Done~~
Apr	~~Staff Meeting #8 (Wk11)~~							■																		~~Apr 2~~	~~10~~	~~All~~	~~Done~~
	~~Timecard Wk11~~								■																	~~Apr 6~~	~~20~~	~~Freddy~~	~~Done~~
	~~Initial Testing Results~~	▨	▨	▨	▨	▨	▨	▨	▨	■																~~Apr 9~~	~~200~~	~~Andres and Colin~~	~~Done~~
	Final Poster and Final PPT	▨	▨	▨	▨	▨	▨	▨	▨	▨	■															Apr 10	200	Andres and Florence	Done
	Final CAD Packet	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■														Apr 12	100	Florence and Colin	80%
	Timecard Wk 12												■													Apr 13	20	Freddy	
	Final Product Demo / Testing					▨	▨	▨	▨	▨	▨	▨	▨	■												Apr 16	300	Freddy and Colin	
	Final Report				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■											Apr 17	200	Team	
	Timecard Wk13															■										Apr 20	20	Freddy	
	Final Website Check												▨	▨	▨	▨	■									Apr 21	50	Andres	
	Expo PPT and Poster Delivery														▨	▨	▨	■								Apr 24	200	Freddy	
	Timecard Wk14																		■							Apr 27	20	Freddy	
	Operation/Assembly Manual															▨	▨	▨	▨	■						Apr 30	100	Andres and Florence	
	Staff Meeting #9 (Wk15)																				■					Apr 30	10	All	
May	Peer Eval 4																					■				May 1	40	Individual	
	Client Handoff																				▨	▨	■			May 1	100	Team	
	Capstone Exit Survey																						▨	■		May 2	40	Individual	
	Timecard Wk15																								■	May 4	20	Freddy	

The Acro-Bots Project Timeline 2025-2026



Phase 1: Foundation & Initial Prototyping (Sept 2025 – Jan 2026)

Research & Concept Selection
(Sept – Dec 2025)

Completed House of Quality (HoQ) requirements and final design concept selection.

Prototyping Acceleration
(Dec 2025 – Jan 2026)

Initial prototyping began in December, with Robot 1 development accelerating through January.

Critical Hardware Procurement
(Jan 30 – Feb 2, 2026)

Initiated purchasing for Raspberry Pis, magnetic encoders, and custom LiFePO4 battery components.

Phase 2: Development, Testing & Delivery (Feb 2026 – April 2026)

Mid-Build Milestones & Setbacks
(Feb 2026)

Navigated a denied PO setback an **Feb 10 to reach 67% completion by Feb 23.**

Validation & Client Demos
(March – Early April 2026)

Completed initial demos, finalized the testing plan, and reached 100% build completion.

Performance Tuning & Final Presentation
(April 24, 2026)

Completed intensive PID tuning and S6-inch drop tests before the final presentation.

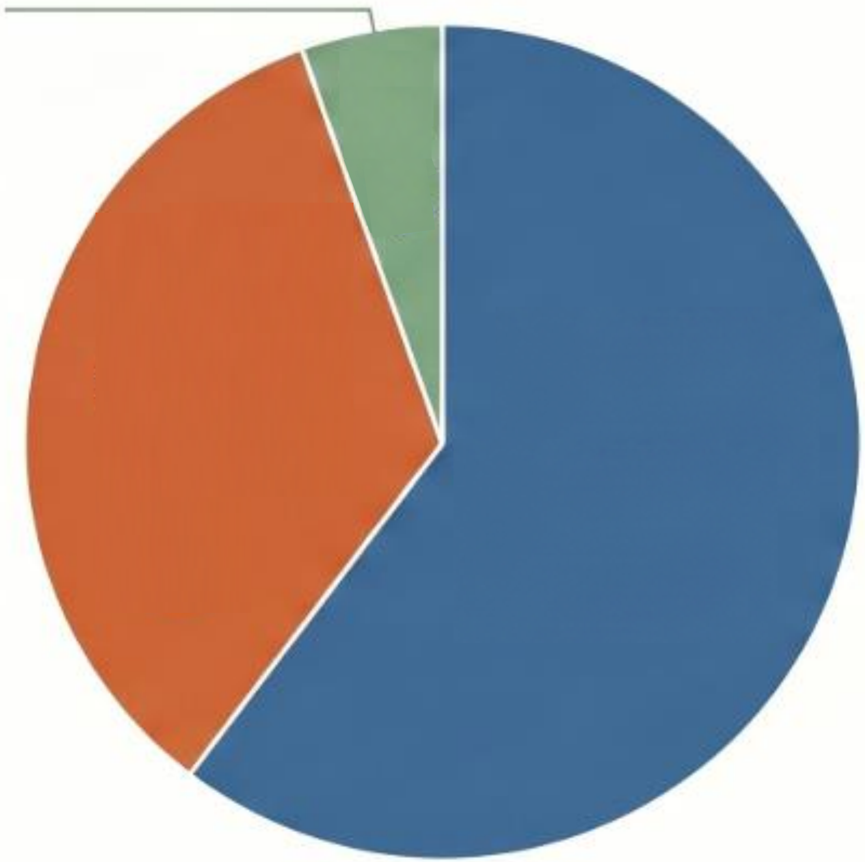
Key Engineering Success Metrics

(Verified During Final April Testing Phase)

PID Settling Time	**Impact Survivability**	**Sensor Accuracy**
Target: < 5.0 Seconds	Target: 36-Inch Vertical Drop	Target: Positional Data
Verified Pass	**0% Structural Failure**	**< 5% Margin of Error**

Financials

Expenditure Breakdown



5%
Filament & Outsourcing
Allocated for 5 PLA Pro rolls and specialized outsourced TPU prints.

35%
Mechanical Components
Includes NEMA 17 stepper motors, DC encoder motors, Al rods, and bearings.

60%
Electrical Systems
Covers LiFePO4 batteries, Raspberry Pi Picos, motor drivers, and LCD touchscreens.

Current Financial Standing

$2,000
Remaining Funds

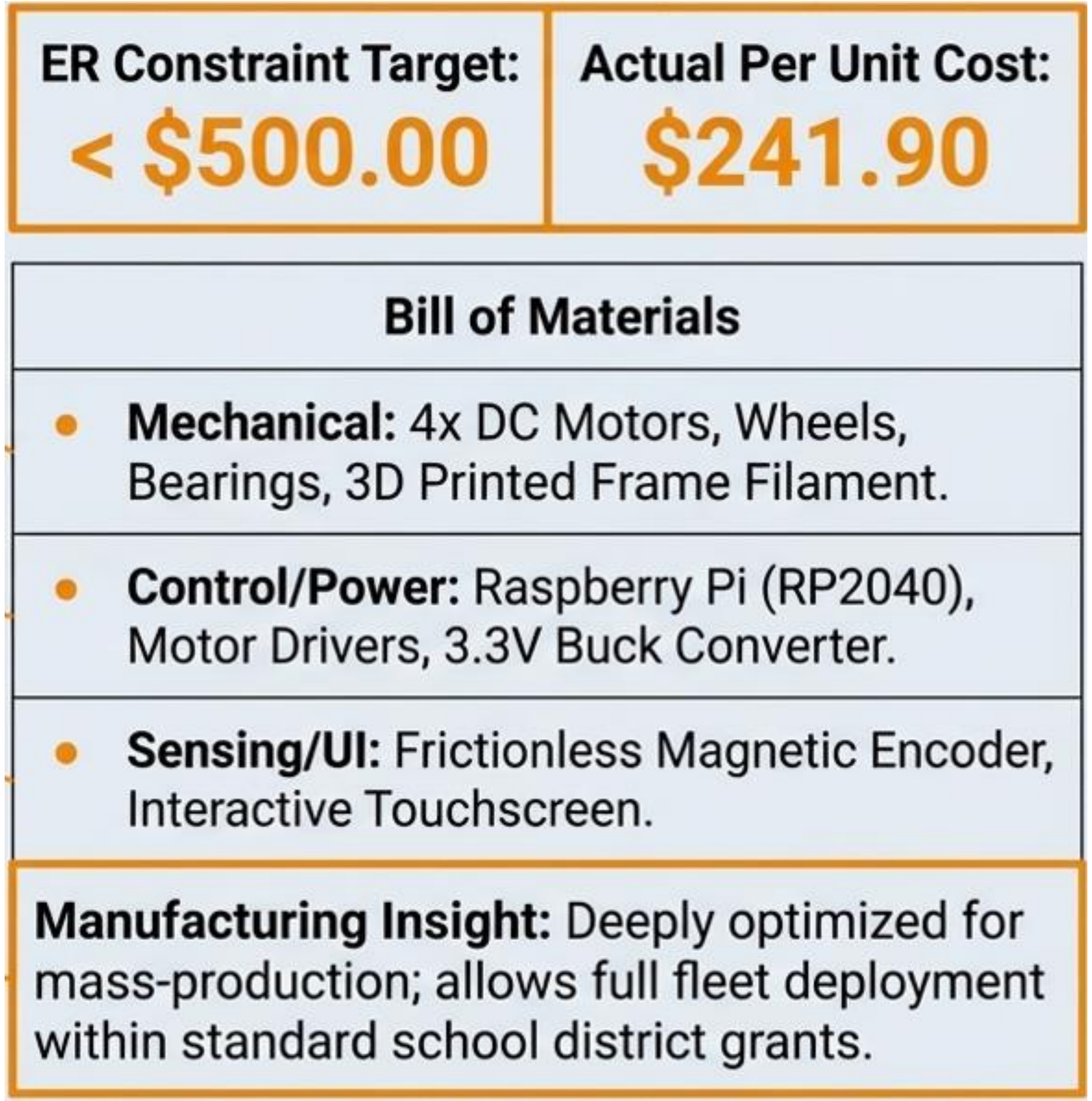
Project has successfully utilized **~$3,000** of the total $5,000 budget.

$900
Supplemental Funding

$550 raised via fundraising with an additional **$350** expected from next event.

Bill of Materials – Robot One

Component	Quantity	Designation	Cost	Total Cost
520 Motors 12V	4	Mechanical	$7.98	$31.56
Wheels	included^	Mechanical	-	-
6010 bearings (6mm)	2	Mechanical	$0.75	$1.70
Aluminum Rods	3	Mechanical	$1.20	$3.60
Acrylic 4"X6"	1 pack	Mechanical	$1.60	$1.60
PLA (grams)	1 roll	Mechanical	$17.99	$17.99
Dupont Jumper Wire Set	1 Pack	Electrical	$6.98	$6.98
Header Pins	1 Pack	Electrical	$7.39	$7.39
Voltage Step-Down	1	Electrical	$1.30	$1.30
BMS Board (14.8V)	1	Electrical	$8.69	$8.69
Microcontroller (RP2040/Pico)	1	Electrical	$8.99	$8.99
LiFePO4 Battery Charger	4	Electrical	$12.99	$38.97
Protoboard Set	1	Electrical	$14.59	$14.59
Rocker Switch (On/Off)	1	Electrical	$17.99	$17.99
Motor Driver (DRV8871)	2	Electrical	$4.33	$8.66
Battery Charger	1	Electrical	$14.99	$14.99
Mag Encoder	1	Electrical	$2.60	$2.60
Longer M3 Threaded Inserts	1 pack	Mech/Shared	$9.99	$5.00
Shorter M3 Threaded Inserts	1 pack	Mech/Shared	$9.99	$5.00
M2 Threaded Inserts	1 pack	Mech/Shared	$9.99	$5.00
M3 x 12mm Socket Screws	1 pack	Mech/Shared	$8.95	$4.48
M3 x 8mm Socket Screws	1 pack	Mech/Shared	$8.95	$4.48
M2 Screw Assortment Box	1 pack	Mech/Shared	$14.99	$7.50
M3 Zinc Hex Nuts (5-piece)	1 pack	Mech/Shared	$3.75	$1.88
LCD Screen (4-inch)	1	UI	$20.99	20.99



ER Constraint Target:	Actual Per Unit Cost:
< $500.00	$241.90

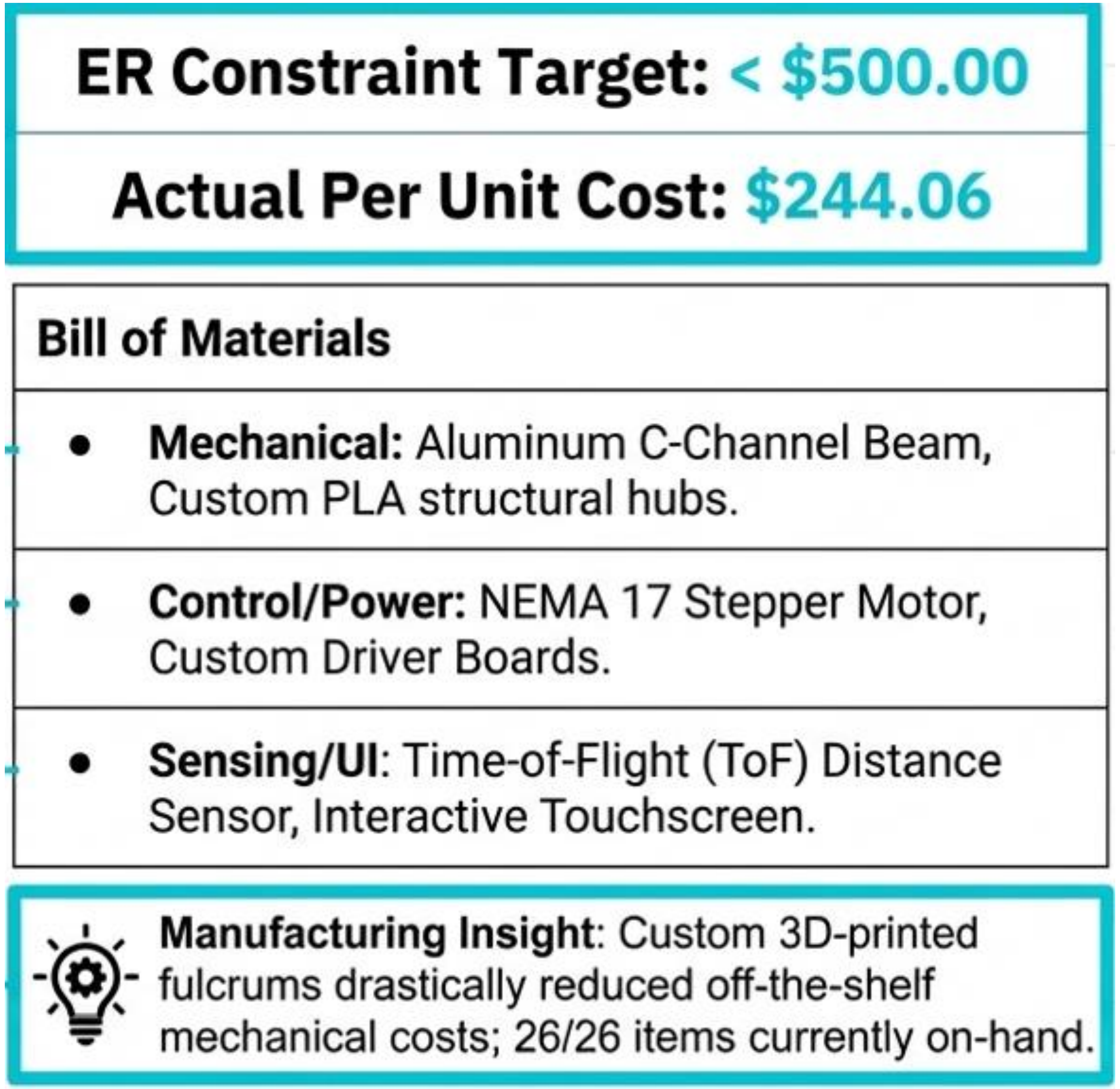
Bill of Materials

- **Mechanical:** 4x DC Motors, Wheels, Bearings, 3D Printed Frame Filament.
- **Control/Power:** Raspberry Pi (RP2040), Motor Drivers, 3.3V Buck Converter.
- **Sensing/UI:** Frictionless Magnetic Encoder, Interactive Touchscreen.

Manufacturing Insight: Deeply optimized for mass-production; allows full fleet deployment within standard school district grants.

Bill of Materials – Robot Two

Component	Quantity	Designation	Cost	Total Cost
Nema 17 Stepper Motor	1	Mechanical	$14.99	$14.99
LiFePO4 Batteries	4	Mechanical	$12.99	$38.97
PLA (grams)	1 roll	Mechanical	$17.99	$17.99
Acrylic 4"x6"	1 pack	Mechanical	$16.99	$6.80
686 Ball Bearings (10-pack)	1	Mechanical	$8.59	$0.86
Longer M3 Threaded Inserts	1 pack	Mechanical	$9.99	$5.00
Shorter M3 Threaded Inserts	1 pack	Mechanical	$9.99	$5.00
M2 Threaded Inserts	1 pack	Mechanical	$9.99	$5.00
M3 x 12mm Socket Screws	1 pack	Mechanical	$8.95	$4.48
M3 x 8mm Socket Screws	1 pack	Mechanical	$8.95	$4.48
M2 Screw Assortment Box	1 pack	Mechanical	$14.99	$7.50
M3 Zinc Hex Nuts (5-piece)	1 pack	Mechanical	$3.75	$1.88
Ping Pong Ball	1	Mechanical	$2.39	$0.27
22 AWG Hookup Wire	1 roll	Electrical	$15.29	$15.29
Dupont Jumper Wire Set	1 pack	Electrical	$6.98	$6.98
Header Pins	1 pack	Electrical	$7.39	$7.39
ToF Sensor (VL53L0X)	1	Electrical	$12.99	$12.99
Voltage Step-Down	1	Electrical	$8.69	$8.69
BMS Board (14.8V)	1	Electrical	$8.99	$8.99
Microcontroller (RP2040/Pico)	1	Electrical	$12.99	$12.99
Battery Charger	1	Electrical	$14.99	$14.99
Protoboard Set	1	Electrical	$13.59	$13.59
Rocker Switch (On/Off)	1	Electrical	$7.99	$7.99
LCD Screen (4-inch)	1	UI	$20.99	$20.99



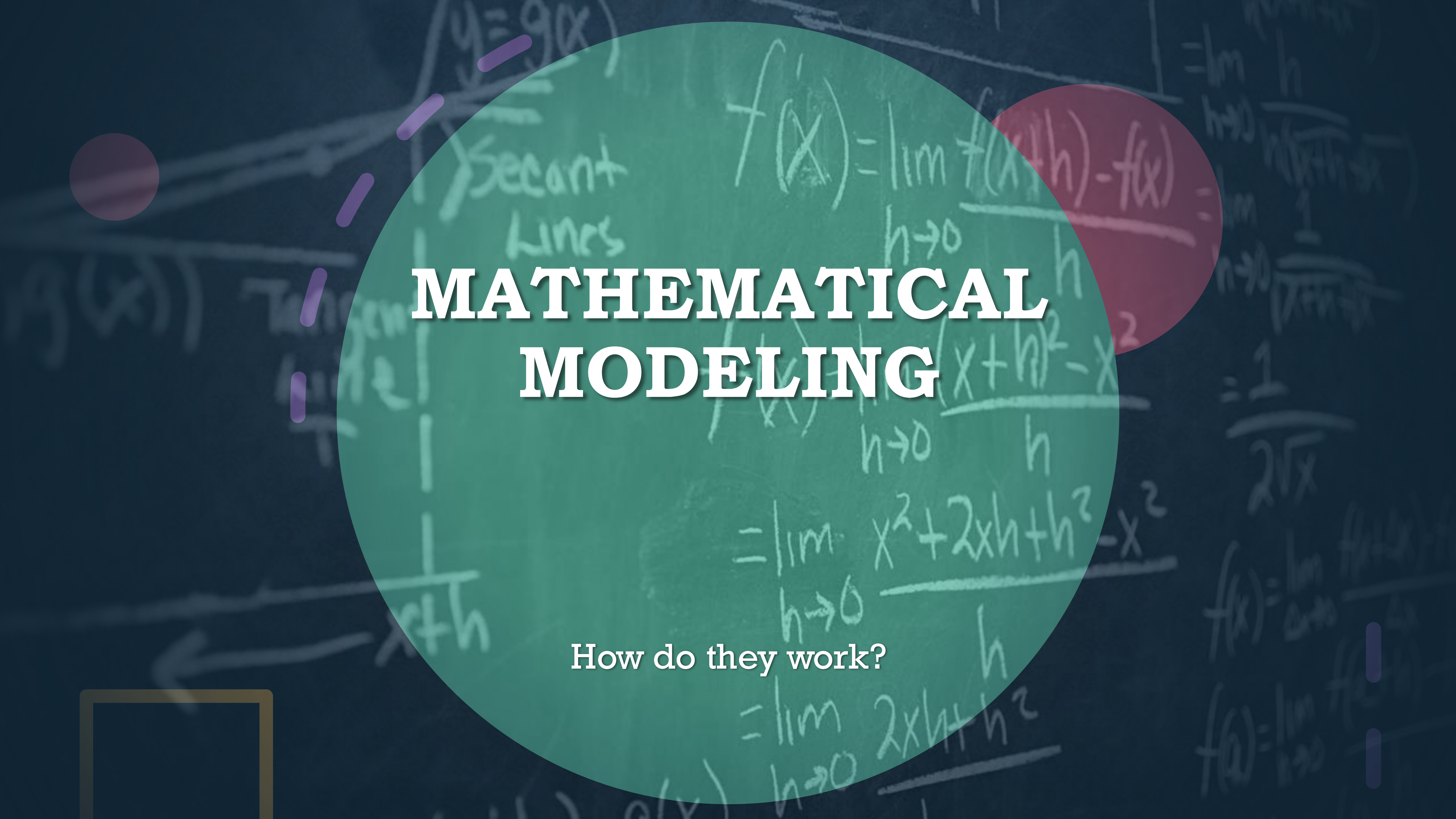
ER Constraint Target: < $500.00

Actual Per Unit Cost: $244.06

Bill of Materials

- **Mechanical:** Aluminum C-Channel Beam, Custom PLA structural hubs.
- **Control/Power:** NEMA 17 Stepper Motor, Custom Driver Boards.
- **Sensing/UI**: Time-of-Flight (ToF) Distance Sensor, Interactive Touchscreen.

Manufacturing Insight: Custom 3D-printed fulcrums drastically reduced off-the-shelf mechanical costs; 26/26 items currently on-hand.

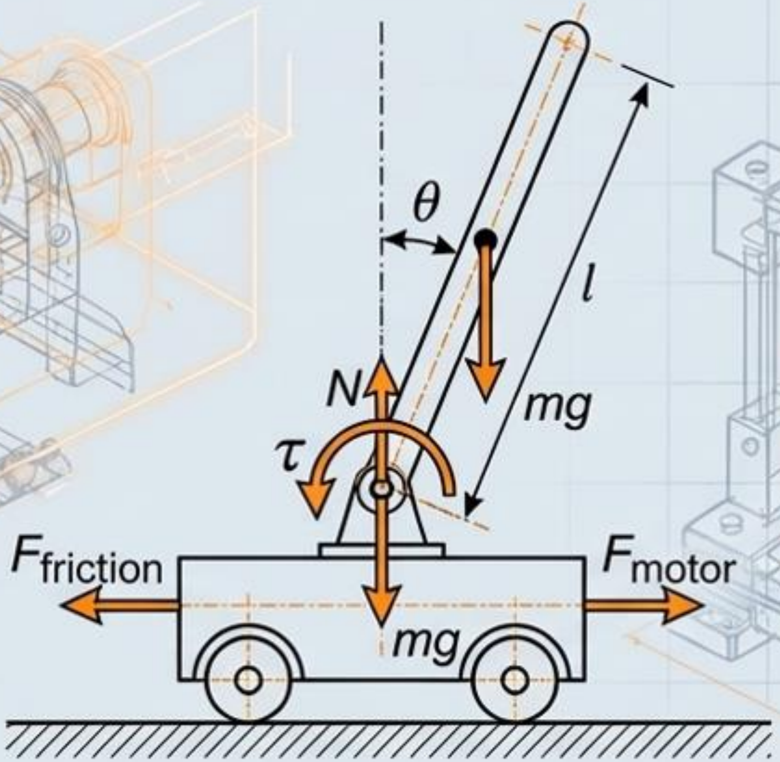


MATHEMATICAL MODELING

How do they work?

Robot 1 Modeling: Newtonian Dynamics & Frequency Response

Cart & Pendulum Dynamics

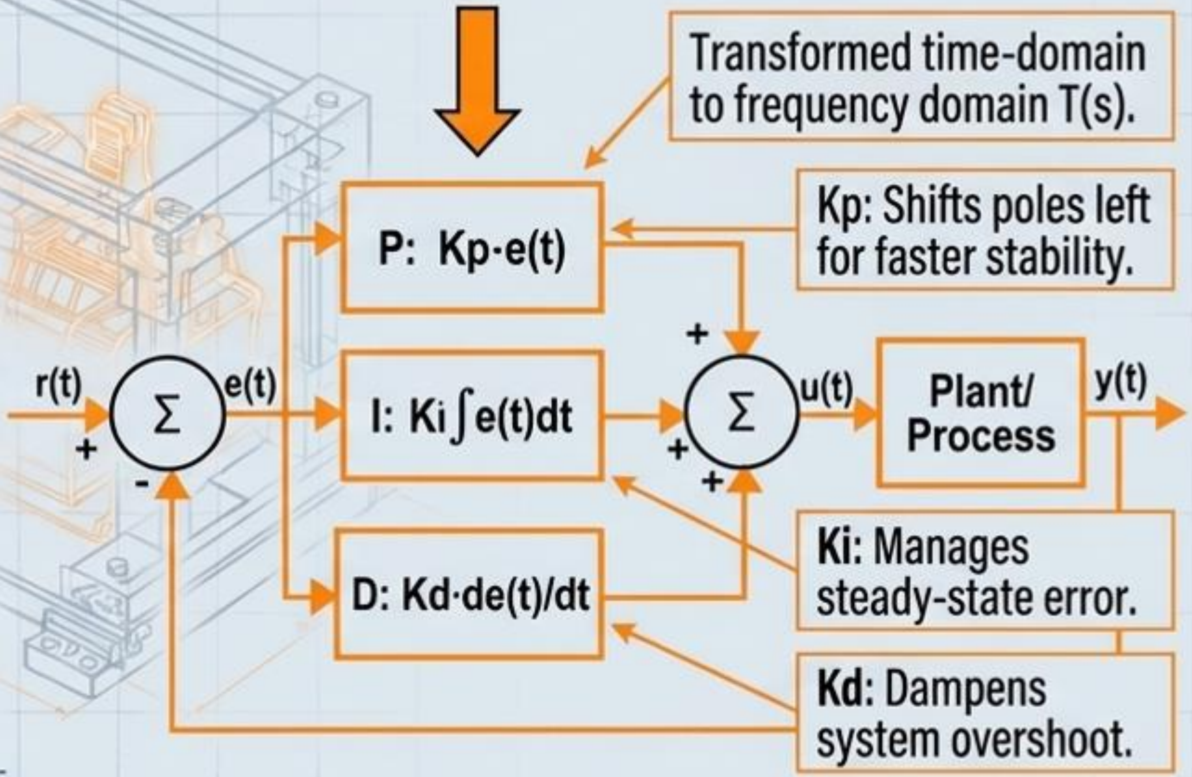


Modeled using Newtonian translational and rotational motion.

$$I\ddot{\theta} = mgl\theta - \tau$$

Laplace Transforms & PID Tuning

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



Transformed time-domain to frequency domain T(s).

Kp: Shifts poles left for faster stability.

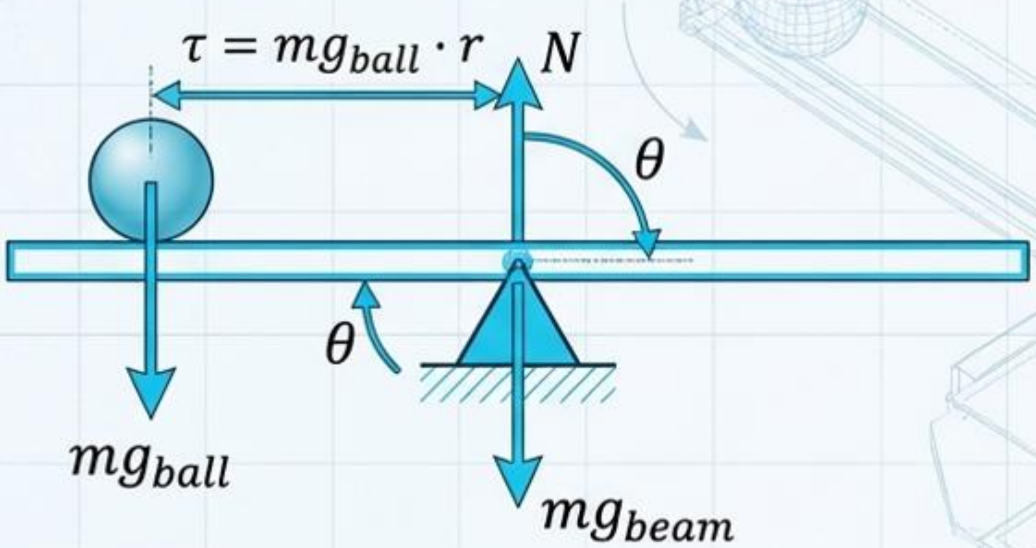
Ki: Manages steady-state error.

Kd: Dampens system overshoot.

Conclusion: Mathematical model eliminated empirical guesswork, guaranteeing internal stability at upright equilibrium prior to fabrication.

Robot 2 Modeling: Lagrangian Energy & Motor Sizing

Unstable Dynamics & State Equations



Derived Lagrangian energy equations to evaluate gravitational loading and moment arms based on center-fulcrum geometry.

Actuator Sizing & Selection

Calculated total beam mass and moment of inertia.

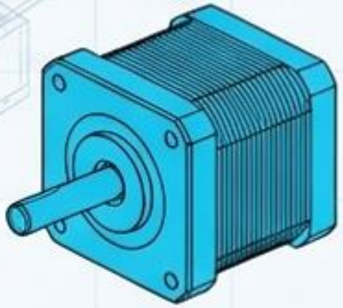
↓

Determined required static torque.

↓

Determined max allowable angular acceleration to catch a 0.1 kg moving ball.

↓



NEMA 17
Stepper Motor

Conclusion: Physics explicitly mandated the selection of the NEMA 17 Stepper motor, mathematically ensuring it overcomes beam inertia without stalling or skipping microsteps.

FMEA

What could go wrong?

Robot 1: Failure Modes and Effects Analysis (FMEA)

Potential Risk	Engineering Mitigation	Trade-off / Result
Chassis Fracture (36" Drop)	Increased wall thickness to **16.94 mm** (PETG/PLA+).	**FoS of 23-44**; 90+ hour print time,.
Mechanical Drag (Potentiometers)	Upgraded to **Contactless Hall-Effect Encoder.**	Eliminated friction; improved PID resolution.
Sensor Noise (Shared Bottleneck)	Integrated **Moving Average Filters** in software.	Achieved **<5.0s settling time** target (ER7).
Processing Lag (Rapid Fall Rate)	Migrated logic to **Raspberry Pi.**	Higher power draw; handled real-time math.

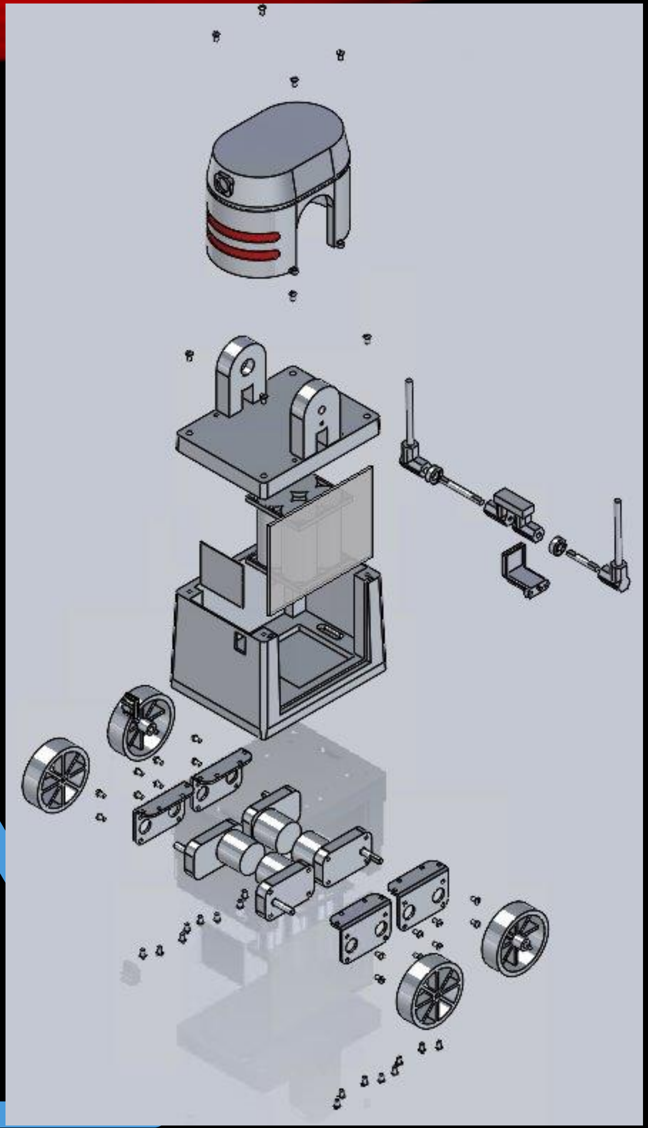
Robot 2: Failure Modes and Effects Analysis (FMEA)

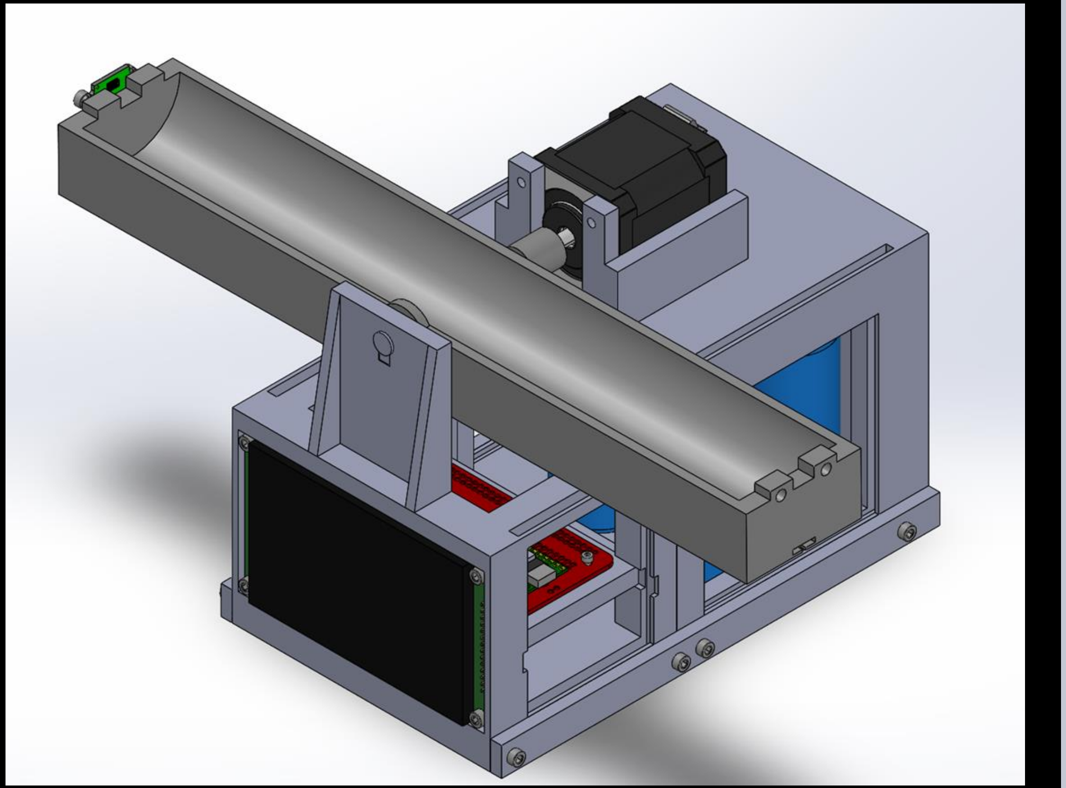
Potential Risk	Engineering Mitigation	Trade-off / Result
Ambient Light Interference	Upgraded to **VL53L0X Time-of-Flight (ToF)** lasers.	Reliable distance tracking despite classroom lighting.
Stepper Motor Skipping Steps	Applied **1/16 micro-stepping**; reduced beam to **290.8 mm.**	Increased holding torque; achieved high **Factor of Safety (FoS).**
Sensor Noise	Integrated **Moving Average Filters** in software.	Achieved **sub-5.0 second settling time** target (ER7).
Mechanical Slop/Lag	Scrapped edge-pivot for **Direct-Drive center mount.**	Isolated motion to a single rotational axis; simplified math.

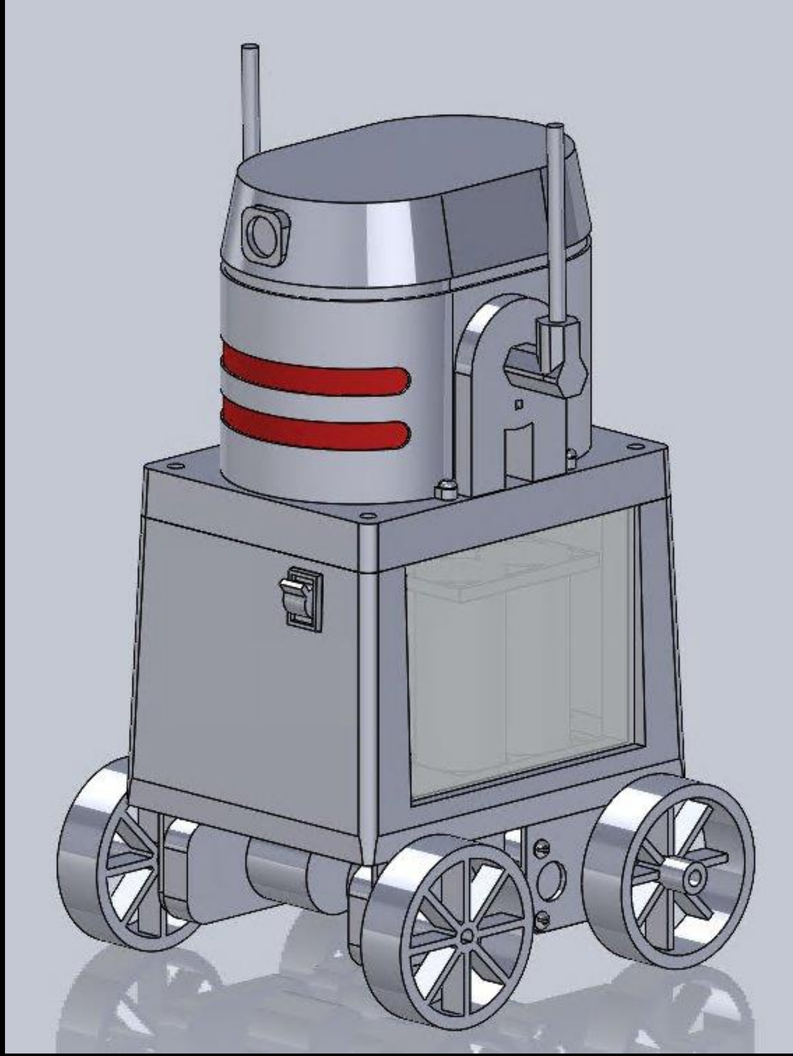
FINAL DESIGNS

So what does it look like today?

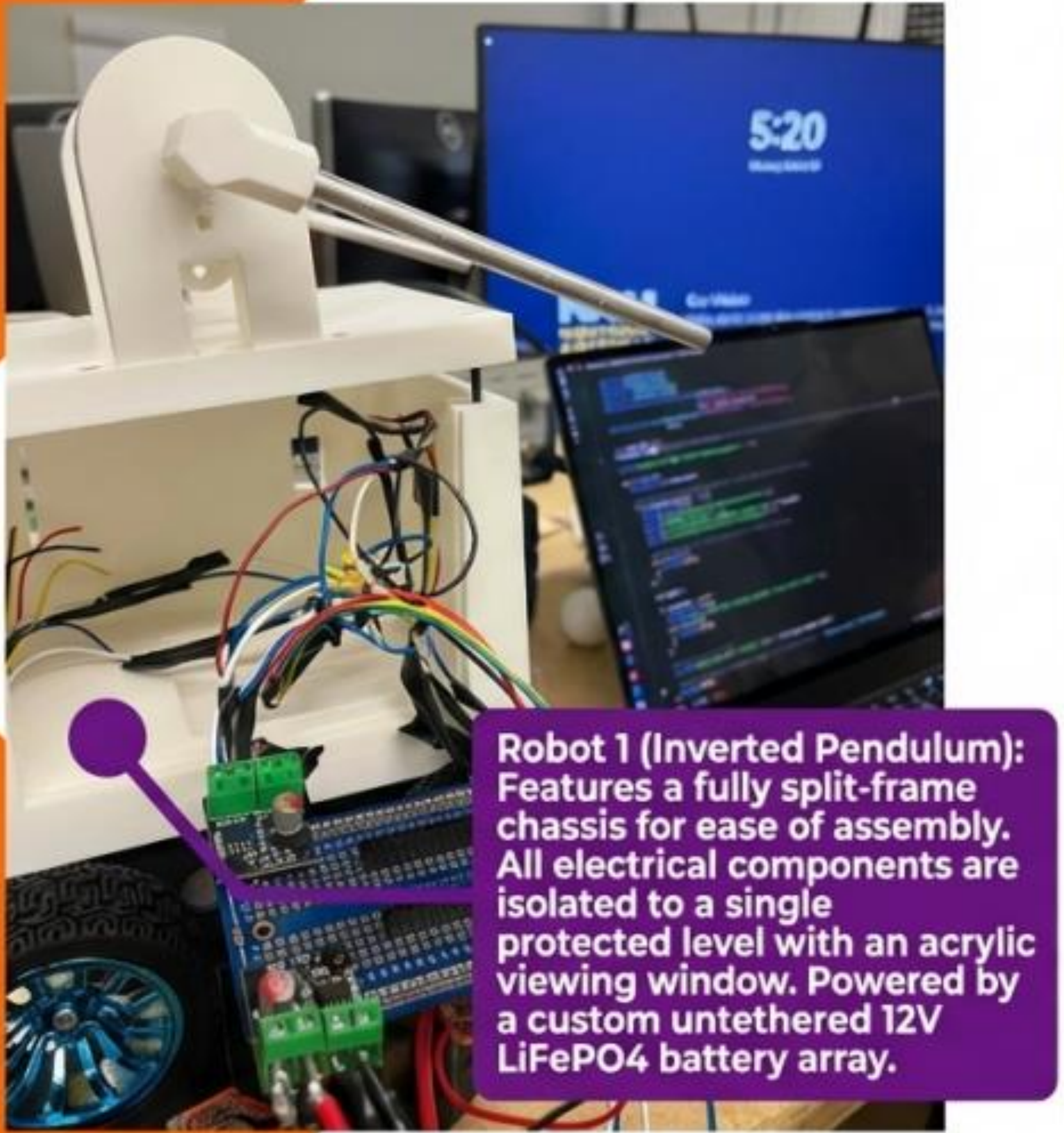
Final CAD



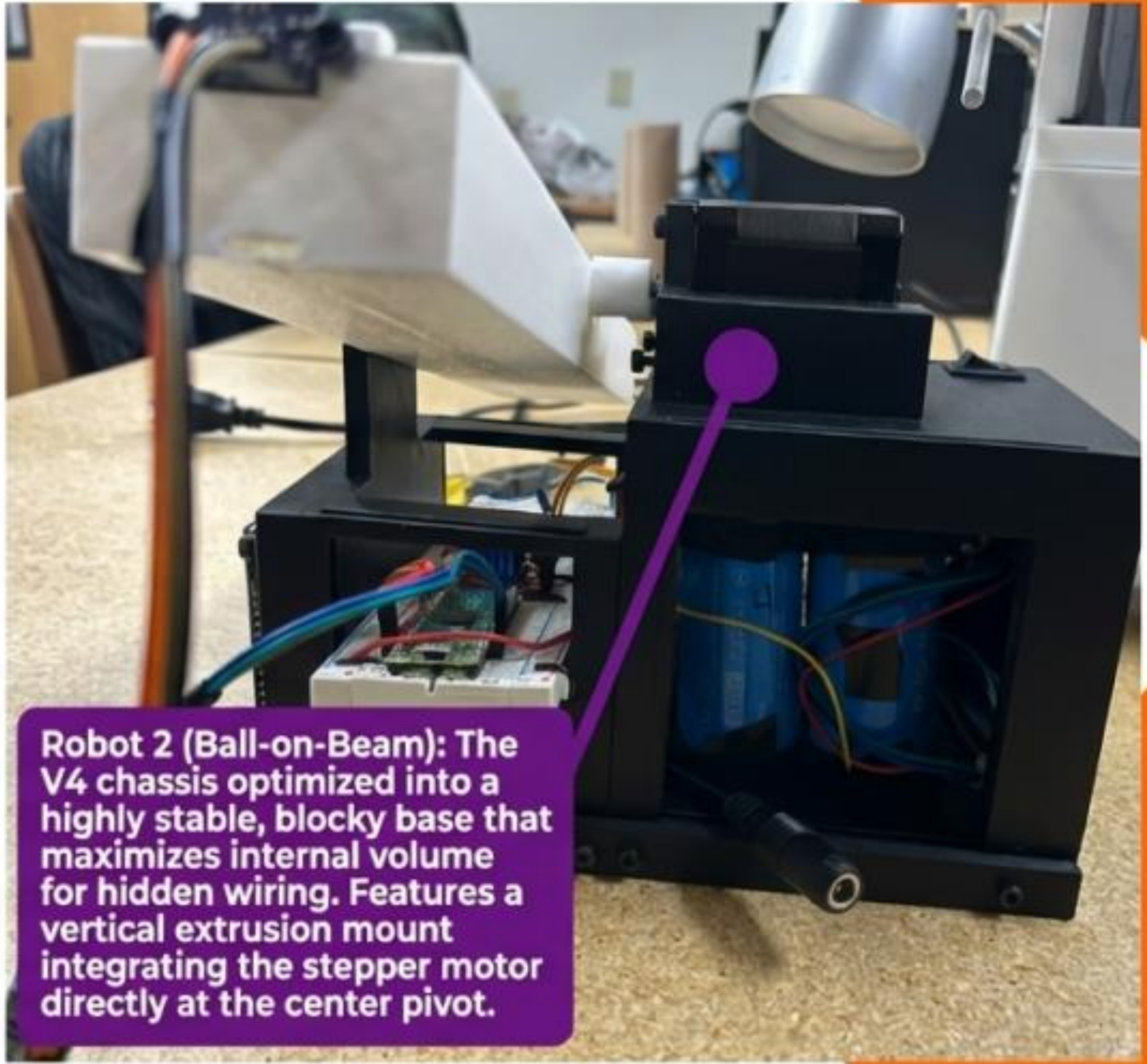




Final Builds Both Robots



Robot 1 (Inverted Pendulum): Features a fully split-frame chassis for ease of assembly. All electrical components are isolated to a single protected level with an acrylic viewing window. Powered by a custom untethered 12V LiFePO4 battery array.



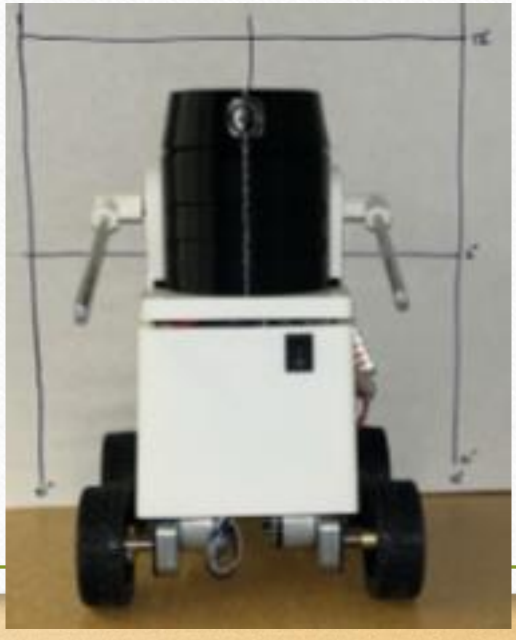
Robot 2 (Ball-on-Beam): The V4 chassis optimized into a highly stable, blocky base that maximizes internal volume for hidden wiring. Features a vertical extrusion mount integrating the stepper motor directly at the center pivot.

Testing

Does it work?

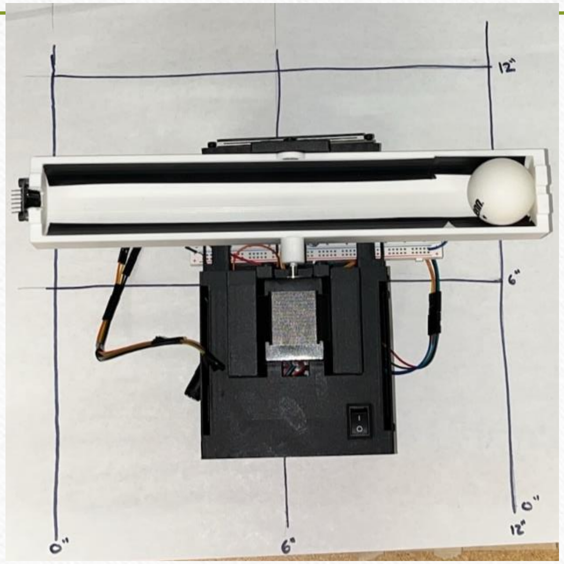
Testing Results – Robot One

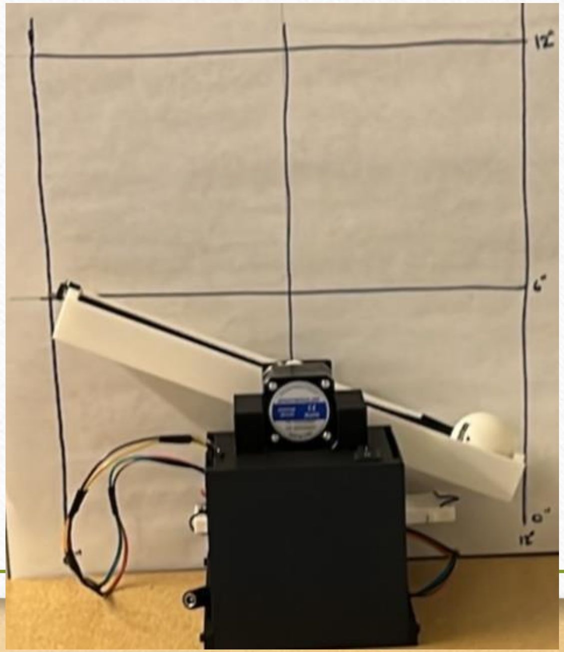
Test/Exp.	Linked Requirement	Objective	Actual Result	Status
EXP1: Drop Test	Survivability (ER5)	36-inch vertical fall	0% structural failure	**PASS**
EXP2: Battery	Runtime (ER2)	> 30 minutes run	~1.4 hours achieved	**PASS**
EXP3: Physical	Safety (ER1/ER9)	< 12" cubed / 0.65" pinch	7" x 7.5" x 11"	**PASS**
EXP5: PID	Settling Time (ER7)	< 5.0s recovery	Recovered in < 5.0s	**PASS**
EXP7: BOM	Mfg. Cost (ER6)	< $500 per unit	$241.90 per unit	**PASS**



Testing Results – Robot Two

Test/Exp.	Linked Requirement	Objective	Actual Result	Status
EXP2: Battery Endurance	ER2 (Runtime)	> 30 minutes	**~1.4 hours**	**PASS**
EXP3: Physical Specs	ER1 (Dimensions)	< 12" × 12" × 12"	**8.5” × 12” × 5.5”**	**PASS**
EXP4: E-Stop / UI	ER10 (Safety)	< 1.0s cutoff	**Instant (0 seconds)**	**PASS**
EXP5: PID Settling	ER7 (Balance)	< 3.0 seconds	**< 5.0 seconds**	**PASS**
EXP6: ToF Accuracy	ER3 (Sensing)	< 5% error margin	**< 5% margin**	**PASS**





Future Work

What’s left to do?

On The Road To The Classroom

Hardware Refinement

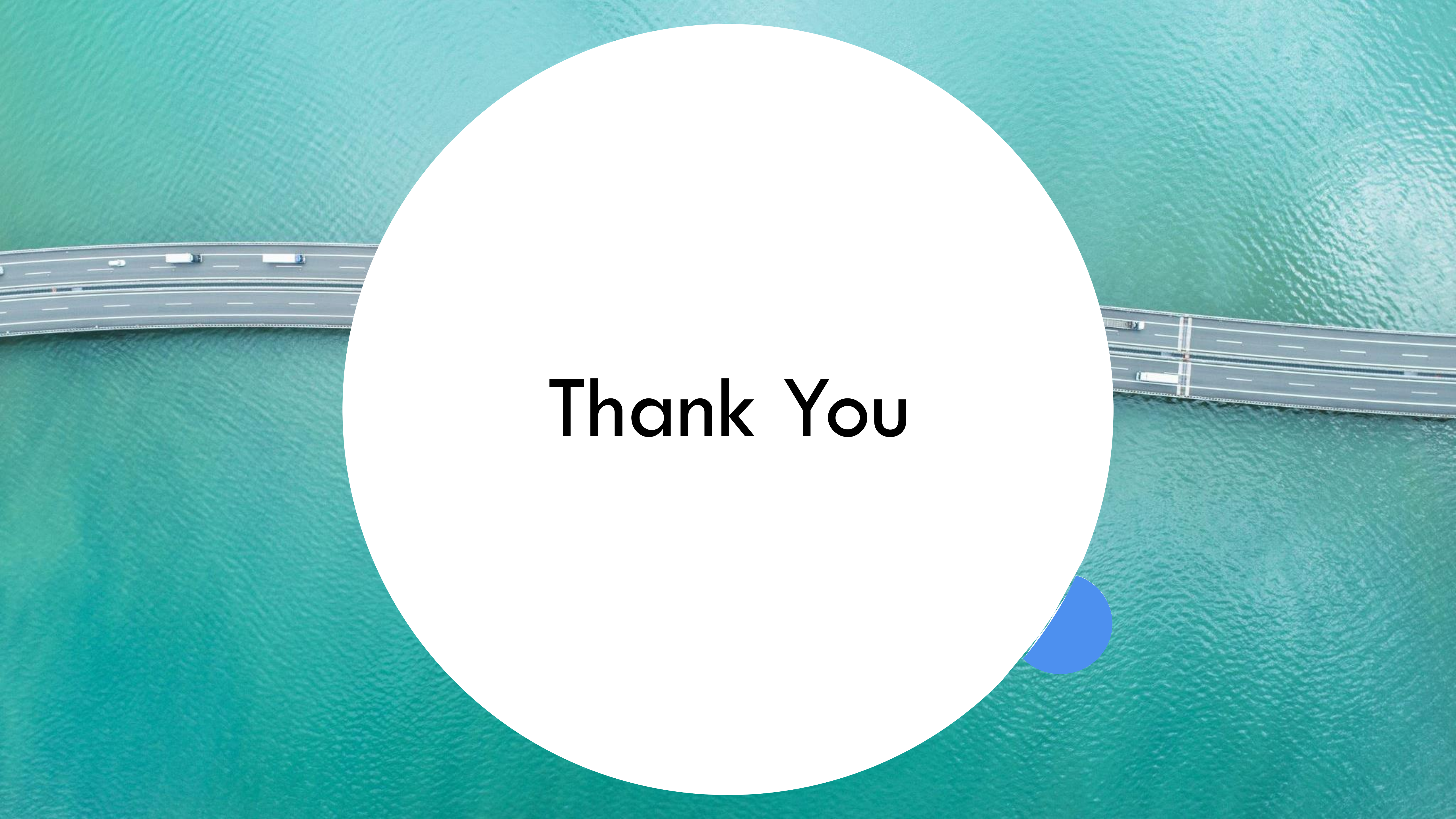
Procure and implement dedicated LiFePO4 Battery Management System (BMS) hardware to guarantee cell balancing and maximize K-12 electrical safety.

Software Polish

Apply a 3-point moving average filter to the Time-of-Flight sensor to eliminate final micro-oscillations in the Ball-on-Beam system.

UI/UX Upgrades

Upgrade the interactive touchscreen displays to further boost student engagement, allowing kids to manipulate PID values and watch the math alter the physical world in real-time.



Thank You

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