Robotics Traveling Van

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ME 476C Sec.2

Project Overview

- **Sponsor:** Dr. Michael Shafer – Northern Arizona University
- **Objective:** Design two portable educational robots to demonstrate **control systems** and **feedback theory** for K–12 students
- **Robots:**
  - **Robot #1 – Inverted Pendulum:** Demonstrates stability and PID control in a self-balancing system.
  - **Robot #2 –** A More **Controls-Based** Robot of our choosing that demonstrates controls in action

Why This Project Matters

- Bridges classroom learning with hands-on robotics.
- Encourages early exposure to engineering design and control systems.
- Robots are designed to be:
  - Safe, portable, and durable.
  - Interactive, allowing students to tune or see real-time responses

Andres & Colin

Robot #1

Inverted Pendulum Robot

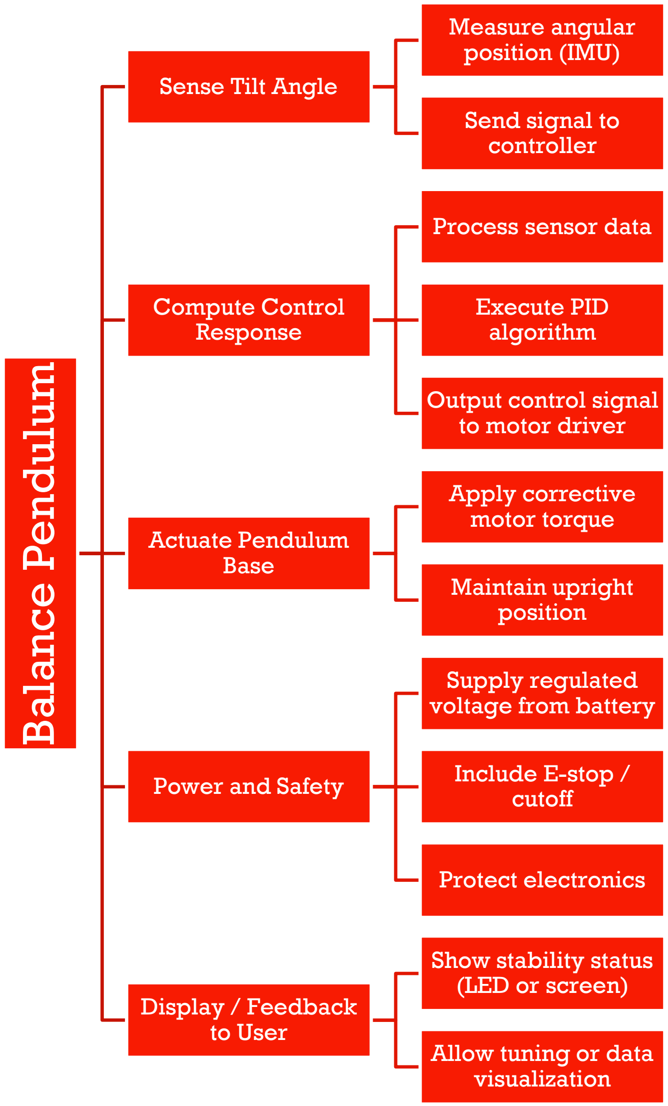
Robot #1 Black Box Model

- Electrical power (battery voltage)
- Sensor data (angle from IMU)
- User input (setpoint / on–off switch)
- Environmental disturbance (push / bump)

- Potentiometer or IMU
- PID controller
- Drivers/Motor Actuation
- Code/Program

- Controlled motor torque and stable upright motion
- Real-time angle correction / position data
- Visual feedback (LED / screen indicating balance)
- Corrective response restoring balance

Robot #1 Functional Decomposition



Morphological Matrix

Robot #1 Concept Generation

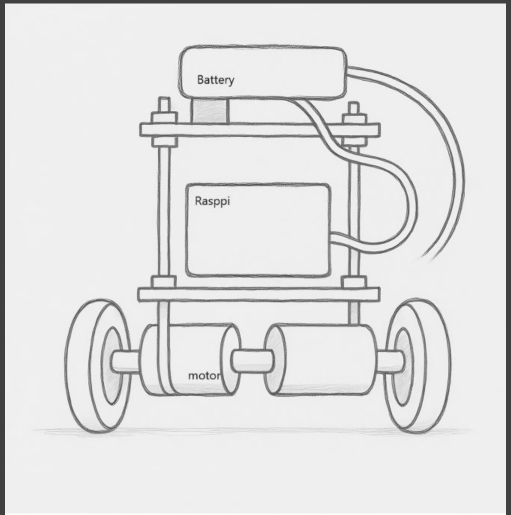
- Primary concept generation from customer request of pendulum robot
- Team members researched and sketched one robot idea based of customer requirements, later engineering requirements
- Individual components were decided upon based on a few criteria
  - Capability to satisfy engineering requirements
  - Economic vs. Durability considerations
  - Build complexity and manufacturing time

Customer Reqs: Mass producable, interactive, battery powered, classroom size

Engineering Reqs: Manufacturing cost, touchscreen, power source, operating space

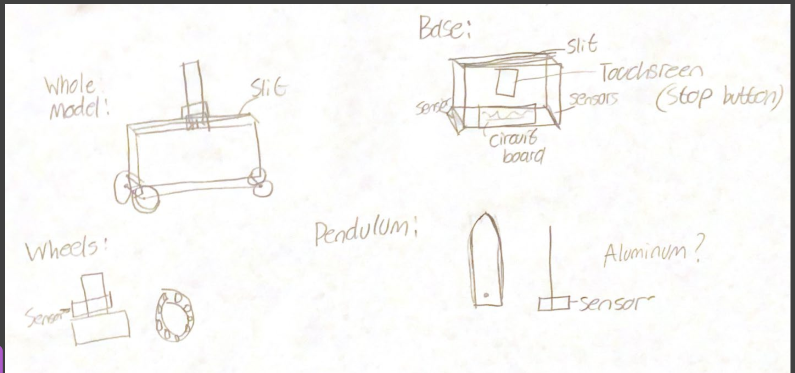
Feature/ Function	2-Wheel, Multi-Axis (A)	Wide Base, 2D Arm (B)	U-Shaped Arm, 4-Wheel (C)	Slit Design, Aluminum (D)	Kart w/ Cage, Touchscreen (E)
Base Type	2-wheeled	4-wheeled wide base	4-wheeled	4-wheeled	4 wheeled – kart style
Pendulum Type	Multi-Axis (robot body itself)	2D Pendulum	Solid U-shape, single axis	Inverted pendulum	Inverted pendulum
Stabilization Axis	Multi-Axis (linear and rotational)	2D	Single Axis	Single Axis	Single Axis
Touchscreen	No	Yes	No	Yes	Yes
Material Notes	Aluminum	3D printed	3D printed	Aluminum	3D printed
Special Features	Vertical battery mount	Wide base	Cage style	Slit for pendulum axis	Roll cage for durability

2-wheeled design, multi axis stabilization



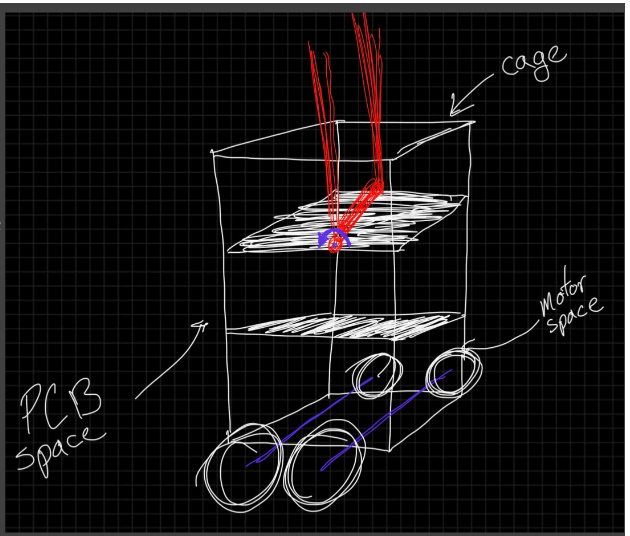
A

Slit design for single axis, 4 wheeled system

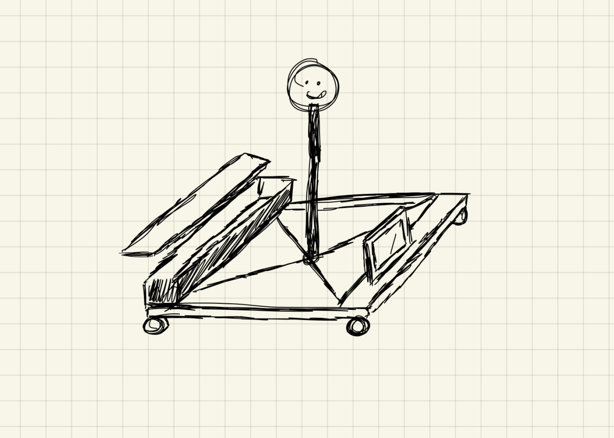


D

Solid U-shape pendulum arm, single axis



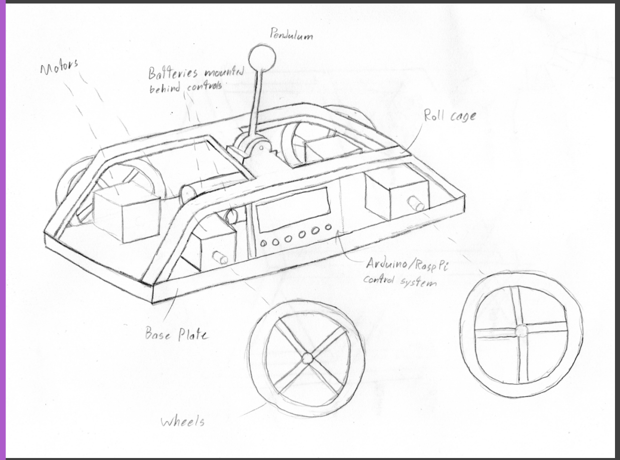
C



B

Wide base, 2D pendulum arm with touchscreen

Kart design, inverted pendulum on single axis, touchscreen



E

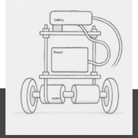
Robot #1 Concept Evaluation

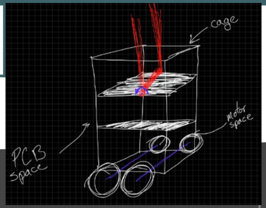
- Educational component not quantifiable as of yet

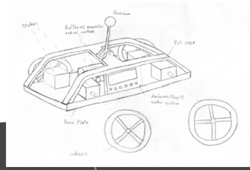
- With prototype, team and customer will meet to frame educational parameters and applications
  - Circuit diagrams, adjustable PID values, robot touchscreen

- Major Design Considerations
- 1. System controller
- 2. Interactive
- 3. Complexity
- 4. Academic setting

Top 3 Robot Options	WEIGHT 1-5	Robot Option A		Robot Option C		Robot Option E	
		BASE SCORE	WEIGHTED	BASE SCORE	WEIGHTED	BASE SCORE	WEIGHTED
Base Type	3	3	9	5	15	5	15
Pendulum Type	4	2	8	5	20	5	20
Stabilization Axis	3	3	9	4	12	4	12
Touchscreen	2	1	2	3	6	4	8
Material Notes	5	3	15	4	20	4	20
Sensor	1	3	3	4	4	3	3
Power	3	3	9	5	15	3	9
		TOTAL WEIGHTED SCORE	55		92		87







Pugh Chart - Evaluation

Team Member #1 Engineering Calculations

Equations

- $V = \sqrt{2gh}$
- $F_{imp} = \frac{mv^2}{2(\Delta t)}$
- $h \geq \sqrt{\frac{6FL}{b\sigma_{flex}}}$

Variables

- m = 3 [kg]
- g = 9.81 [m/s^2)
- h = 0.762 [m]
- L = 0.254 [m]
- b = 0.127 [m]
- Δt = 0.005 [s]

Flexural Strength Values

- σ_{flex} PLA = 97 [Mpa]
- σ_{flex} TPLA = 83 [Mpa]
- σ_{flex} ABS = 60 [Mpa]
- σ_{flex} PC = 89 [Mpa]
- σ_{flex} PETG = 75 [Mpa]
- σ_{flex} N = 75 [Mpa]

Minimum Plastic Thickness

- h_{min} PLA = 23.6 mm
- h_{min} TPLA = 25.5 mm
- h_{min} ABS = 29.9 mm
- h_{min} PC = 24.59 mm
- h_{min} PETG = 26.8 mm
- h_{min} N = 26.8 mm

Equation for the cart (horizontal motion):

- $(\boldsymbol{M} + \boldsymbol{m})\ddot{\boldsymbol{x}} + \boldsymbol{ml}\ddot{\boldsymbol{\theta}}\,\mathbf{cos}(\boldsymbol{\theta}) - \boldsymbol{ml}\dot{\boldsymbol{\theta}}^2\,\mathbf{sin}(\boldsymbol{\theta}) = \boldsymbol{f}$

Equation for the pendulum (rotational motion):

- $\boldsymbol{l}\ddot{\boldsymbol{\theta}} + \ddot{\boldsymbol{x}}\,\mathbf{cos}(\boldsymbol{\theta}) - \boldsymbol{gsin}(\boldsymbol{\theta}) = \mathbf{0}$

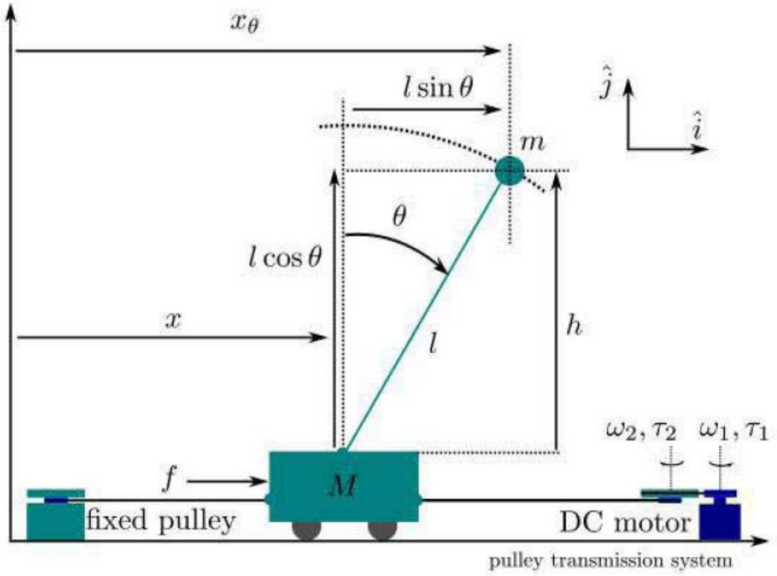
Continuation of Presentation 1 Calculations

Variables

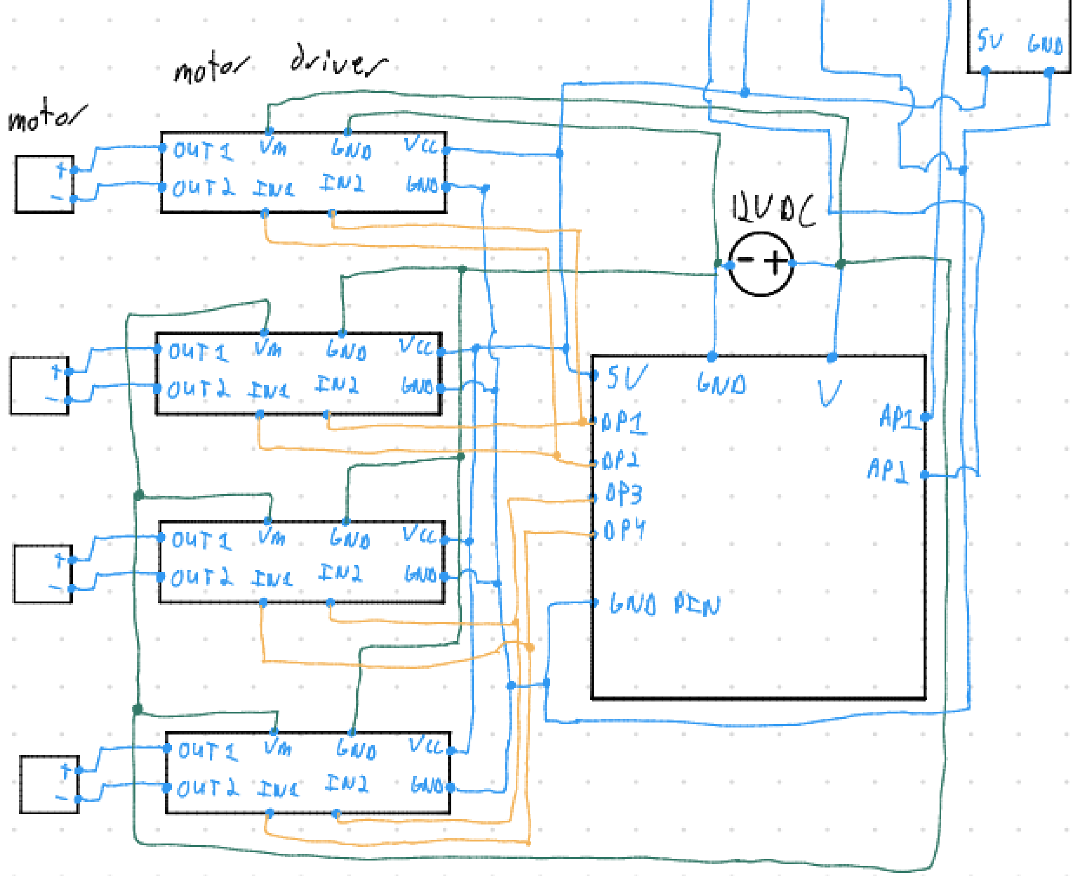
- M = 3 [kg] (Cart Mass)
- m = 0.06 [kg] (Pendulum Mass)
- l = 0.06 [m] (Pendulum Length)
- g = 9.81 [m/s^2] (Gravity)
- θ = 135° = 2.356 [Rads] (Initial Angle)
- $\dot{\theta}$ = 0 [Rad/s^2] (Angular Velocity)
- f = 30.0 [N] (applied Force)

After Solving:

- $\ddot{x}$ = 9.998 [m/s^2] (Cart Acceleration)
- $\ddot{\theta}$ = 233.44 [rad/s^2] (Angular Acceleration)



Team Member #2 Engineering Calculations: Ohm's Law



- The circuit needs to be able to power all system elements and continuously run for 60 minutes

Component	Voltage	Current
DC Motor w/ encoder	11.1V ~ 12V/each	250 mA/each
Encoder/Tracking	5V	30 mA
Potentiometer	5V	1mA
Arduino Uno	5V	70mA
Power Source?	-	-
Motor Driver	11.1V ~ 12V	From DC motor

$$P_{total} = \sum_{i=1}^{n} (V_i \times I_i)$$

$$C_{battery} = \frac{I_{total} \times t_{runtime}}{\eta}$$

Credit to Mr. Andy Babcock (EE)

Team Member #2

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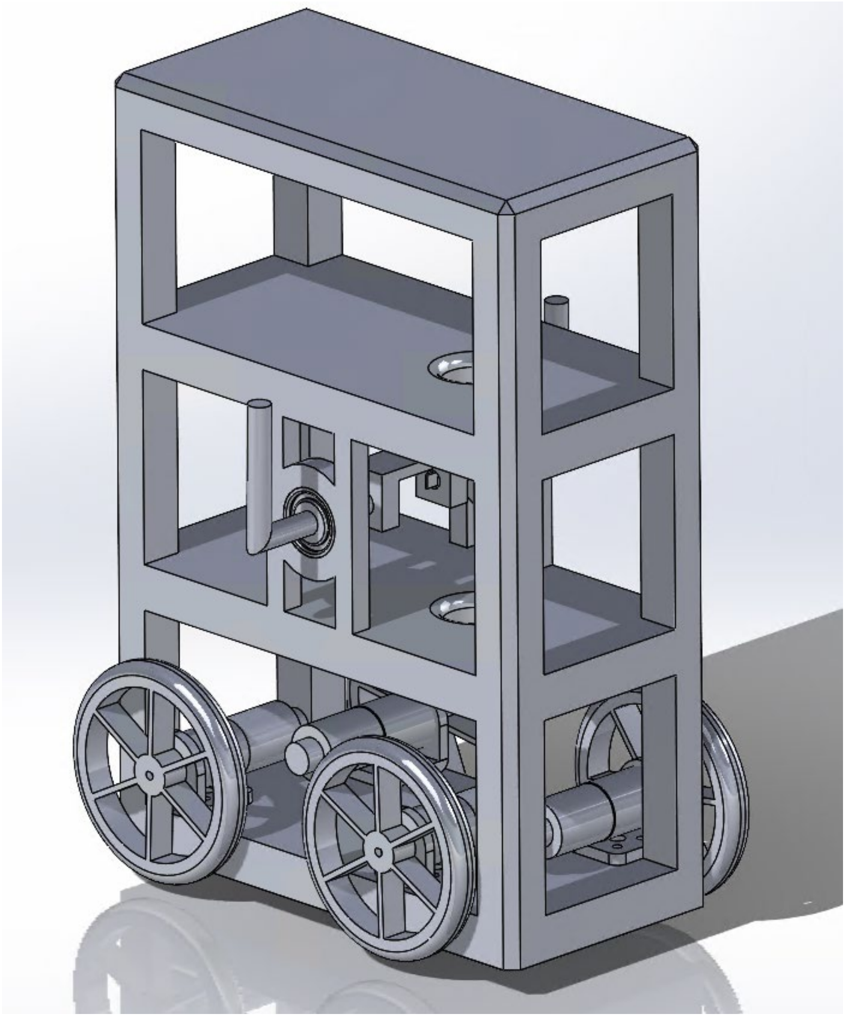
Battery Options

Baterry Options	Runtime	Nominal Voltage	Current Capacity
A. 3S Li-ion Pack (18650 cells, 3 × 4.2 V)	**100 mins**	**11.1 - 12.6 V**	**2.6 Ah**
B. 3S LiPo RC Pack	90 mins	11.1 - 12.6 V	2.2 Ah
C. 12 V Sealed Lead-Acid (SLA)	55 mins	12 V	1.3 Ah

- Max votlage for the system = 12V
- Total continuous current for the system = 1.36 A
- For aproximately 60 minutes of runtime...

Robot #1 Concept Selection

- Final Design Decision: Vertical 4-Wheel Frame design with Solid U-Shaped Pendulum
  - Frame design provides best balance between satisfying engineering requirements and appealing to k-12 students



Bill of Materials – Pendulum Robot Prototype #1

Component	Quantity	Unit Price (USD)	Component Price (USD)
DC12V DIY Encoder Gear Motor	4	15.73	62.92
Polymaker PLA PRO Filament 1.75mm 1kg	1	24.99	24.99
10Pcs WH148 Potentiometer 5K Ohm Variable Resistors	1	6.59	6.59
In case above Potentiometers are out of stock purchase below			
HiLetgo 20pcs WH148 Single-Joint Potentiometer 5K	1	9.29	9.29
ELEGOO UNO R3 Board ATmega328P with USB Cable(Arduino-Compatible) for Arduino	1	16.99	16.99
UL Listed 12V 2A 10FT AC DC Power Supply Adapter with Switching Adapter	1	9.99	9.99
Teyleten Robot DRV8871 Motor Driver DC Motor Driver H-Bridge PWM Driver Module 3.6A 3pcs	2	13.88	27.76

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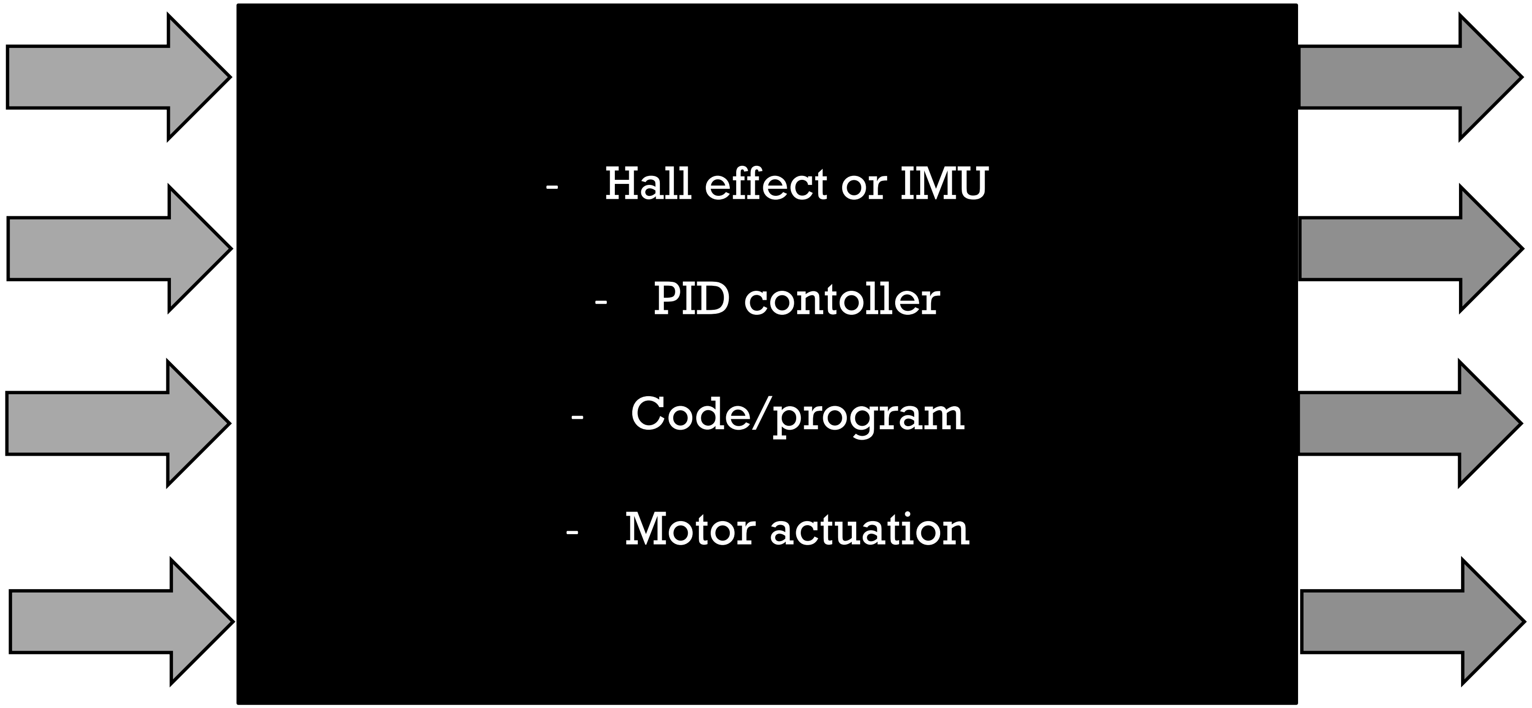
Robot #2

Controls-Based Robot

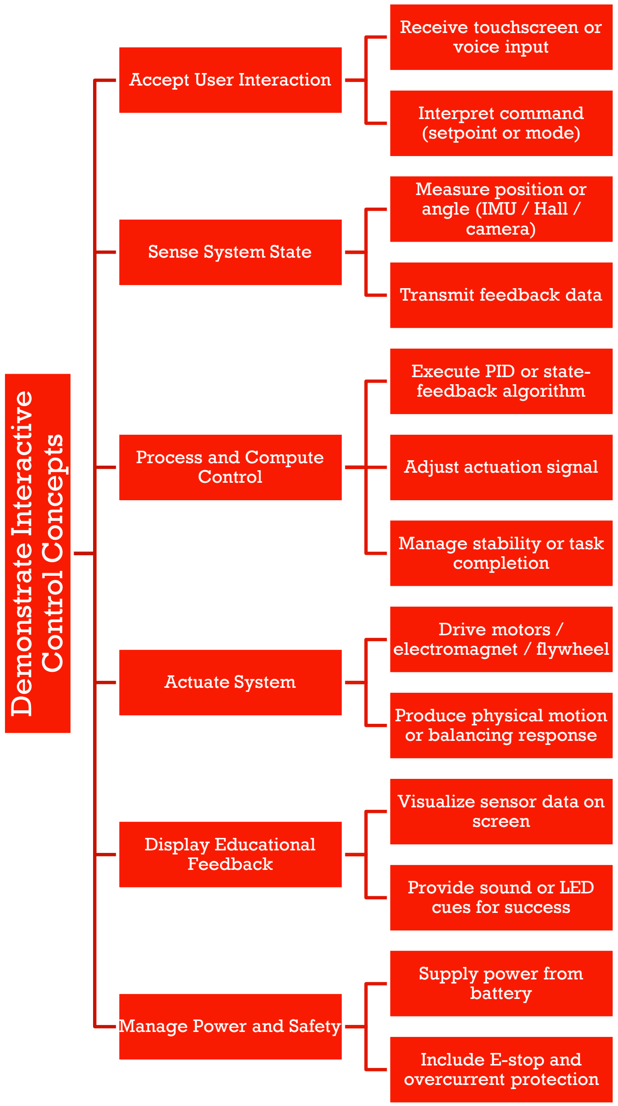
Robot #2 Black Box Model

- Electrical power (battery source)
- User input (touchscreen, voice command, or physical interaction)
- Sensor data (IMU, Hall sensor, or camera)
- Environmental disturbance (student interaction or external force)



- Actuator motion (balance, levitation, or object control)
- Educational feedback (visuals, movement, or sound)
- Real-time corrective response demonstrating control behavior
- Stabilized or reactive motion that maintains performance

Robot #2 Functional Decomposition



Robot #2 Concept Generation

Step 1
- Focused on Customer Requirements

Step 2
- Incorporated Engineering Requirements

Step 3
- Broke the Design into Functional Components

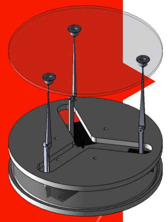
Step 4
- Created a Morphological Chart

Step 5
- Developed Concrete Concept Directions

Category	Option A	Option B	Option C
Educational Task *(Top-Level)*	Maintain a state (balance, hover, stabilize)	Complete a challenge (e.g., hold or center a ball)	Play a game (goal, scoring, or timed objective)
Interactivity Mode *(Top-Level)*	Physical interaction (students try to disturb / balance it)	Cooperative play (students control or compete)	Observation-based challenge (tune or predict behavior)
Demonstration Style *(Top-Level)*	Stationary tabletop demo	Mobile wheeled base	—
Visualization / Feedback *(Top-Level)*	On-screen data plots (angle, position, error)	—	—
Base / Structure *(Sub-Assembly)*	Stationary plate or frame	Wheeled chassis	Enclosed cube (internal actuation)
Actuation *(Sub-Assembly)*	Servo motors (tilt or angle control)	DC motors (mobility / rotation)	Electromagnet or reaction wheel (levitation or balance)
Sensors *(Sub-Assembly)*	IMU / Gyroscope (orientation feedback)	Camera / IR sensor (object tracking)	Hall sensor (magnetic height sensing)
Controller Hardware *(Sub-Assembly)*	Arduino (Uno / Nano / Giga + touchscreen shield)	Raspberry Pi (for vision or advanced UI)	—
Safety Features *(Sub-Assembly)*	E-stop / power cutoff	Software safety limits	—
Power Source *(Fixed Constraint)*	Rechargeable battery pack (Li-ion with regulator)	—	—

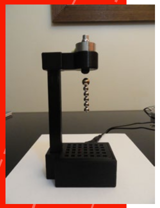
Robot #2 Morphological Chart

Robot #2 Potential Concepts



Ball-on-Plate Robot

- **Educational Task:** Complete a challenge (keep the ball centered)
- **Interactivity Type:** Students move the ball by tilting or touching; robot re-centers automatically
- **Demonstration Style:** Stationary tabletop demo
- **Base / Structure:** Stationary plate supported by servo linkages
- **Actuation:** Dual-axis servo motors to tilt plate
- **Sensors:** IMU (plate angle) + camera/IR (ball position tracking)
- **Controller Hardware:** Arduino with touchscreen interface
- **Safety Features:** Power cutoff + software motion limits



Magnetic Levitation Robot

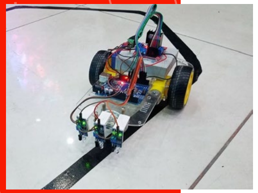
- **Educational Task:** Complete a challenge (levitate and stabilize a steel ball)
- **Interactivity Type:** Students adjust magnetic field strength or height target using touchscreen or voice
- **Demonstration Style:** Stationary tabletop demo with clear acrylic housing
- **Base / Structure:** Stationary frame with electromagnet assembly
- **Actuation:** Electromagnet coil
- **Sensors:** Hall-effect sensor (ball height feedback)
- **Controller Hardware:** Arduino with touchscreen + PID loop
- **Safety Features:** Overcurrent limit for coil + auto power cutoff

Reaction Wheel Robot

- **Educational Task:** Maintain a state (balance upright)
- **Interactivity Type:** Students try to push or knock the robot; it self-corrects using internal flywheels
- **Demonstration Style:** Stationary tabletop or enclosed cube
- **Base / Structure:** Enclosed cube housing flywheels and electronics
- **Actuation:** Reaction wheel assembly (2–3 internal flywheels)
- **Sensors:** IMU/Gyroscope (orientation feedback)
- **Controller Hardware:** Arduino or Nano + IMU + touchscreen display
- **Safety Features:** Emergency stop + torque limits

Hockey Robot

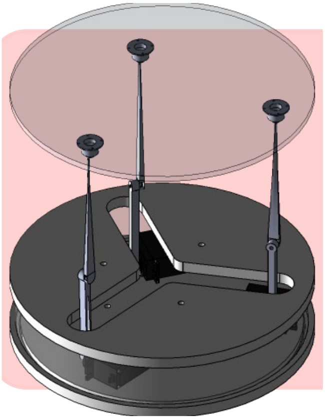
- **Educational Task:** Play a game (aim and shoot pucks into a goal)
- **Interactivity Type:** Students directly play against or with the robot
- **Demonstration Style:** Mobile wheeled base with puck-shooting arm
- **Base / Structure:** Wheeled chassis with servo arm
- **Actuation:** DC motors for drive + servo for shooting
- **Sensors:** IR camera for goal detection + limit switches
- **Controller Hardware:** Arduino or Raspberry Pi for image tracking
- **Safety Features:** E-stop + physical guards around moving parts

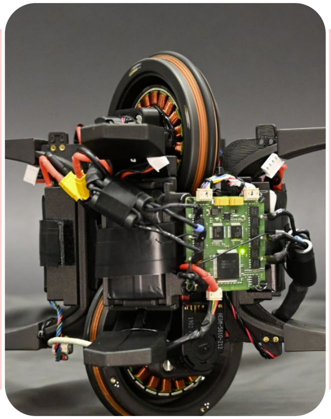


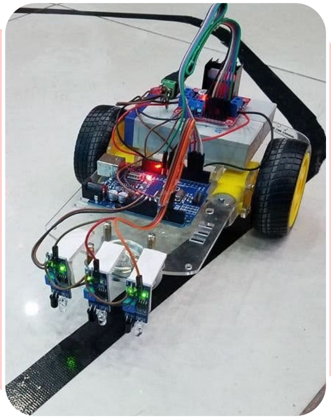
Line-Following Robot

- **Educational Task:** Complete a task (autonomous path tracking)
- **Interactivity Type:** Minimal — students observe the robot following a preset path
- **Demonstration Style:** Mobile wheeled chassis
- **Base / Structure:** Lightweight mobile platform
- **Actuation:** Dual DC motors for movement
- **Sensors:** Line sensors (infrared array)
- **Controller Hardware:** Arduino Uno
- **Safety Features:** Basic power cutoff

Robot #2 Concept Pros and Cons







Ball-on-Plate Robot

Advantages:

1. Highly visual and interactive, students can see real-time feedback as the ball recenters.
2. Demonstrates two-axis feedback control (PID in both X and Y).
3. Compact and safe tabletop demo for K–12 outreach.
4. Excellent teaching tool for stability and control theory.

Disadvantages:

1. Requires precise calibration of both IMU and camera sensors.
2. Mechanically more complex due to dual-axis servo setup.
3. Sensitive to vibration and surface alignment.

Magnetic Levitation Robot

Advantages:

1. Strong "wow" factor, levitation visibly engages students.
2. Demonstrates electromagnetic principles and feedback control.

Disadvantages:

1. Magnetic-field control is nonlinear and can be unstable without precise tuning.
2. Requires careful design to prevent overheating of the coil.
3. Limited range of motion; confined to one axis.

Reaction Wheel Robot

Advantages:

1. Demonstrates angular-momentum control, advanced yet visual.
2. Physically interactive, students can push it and watch it self-correct.
3. Compact, durable, and safe for classroom demonstrations.
4. Represents a higher-order control system (PID with inertia coupling).

Disadvantages:

1. Requires precise balancing of internal flywheels.
2. Needs high-speed motor control; component cost is higher.

Hockey Robot

Advantages:

1. Very interactive, students can play a game against it.
2. Combines image tracking, motion, and control for learning.
3. Visually engaging and fun demonstration.
4. Uses common sensors (IR camera) for educational teaching.

Disadvantages:

1. More electrical engineering focused.
2. Harder to keep within outreach safety limits.
3. Requires larger space; not easily portable.
4. Focus leans more on competition than control theory.

Line-Following Robot

Advantages:

1. Simple, low-cost, and reliable.
2. Easy to reproduce for outreach kits.
3. Demonstrates basic feedback control (line detection and correction).

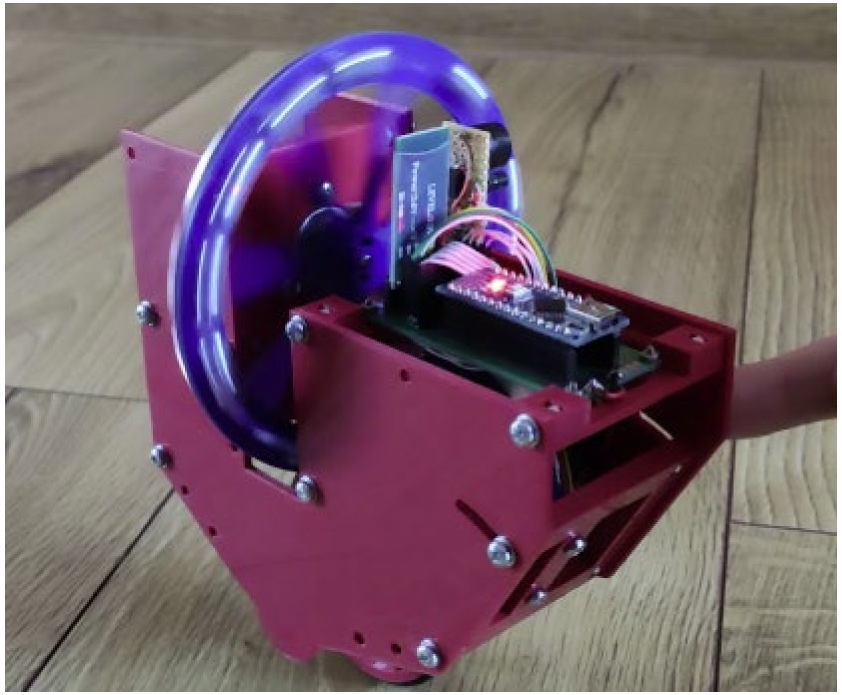
Disadvantages:

1. Minimal interactivity, students only observe.
2. Educational depth limited; little hands-on engagement.
3. Lacks versatility or modular learning opportunities.

Reaction Wheel Calculations

Assumptions (demo-sized cube):

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



Team Member #3 Engineering Calculations

Equations:

$$J_w = \frac{1}{2} m_w {r_w}^2$$

$$\tau_{grav} = mgh\theta$$

$$\alpha_w = \frac{\tau_{grav}}{J_w}$$

Results:

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

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

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

This means that wheel acceleration of $171\ \frac{rad}{s^2}$ counteracts gravity at a 5° lean for this size robot

Ball-on-Plate (Ball Stabilizer System) Calculations

Team Member #4 Engineering Calculations

- Equilibrium of plate (a=0)
- Equilibrium at each joint

Lagrange- Motion for mechanical systems

$$Q_i^* = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} \qquad i \in \{1, 2, 3, 4\}$$

$$L = E_{\mathrm{kin}} - E_{\mathrm{pot}}$$

$$Q_1^* = M_{\mathrm{f},1} + M_{\mathrm{M},1}$$

$$Q_2^* = M_{\mathrm{f},2} + M_{\mathrm{M},2}$$

$$Q_3^* = F_{\mathrm{f},1} \quad Q_4^* = F_{\mathrm{f},2}$$

External force on each joints.

No external force except friction directly on the ball.

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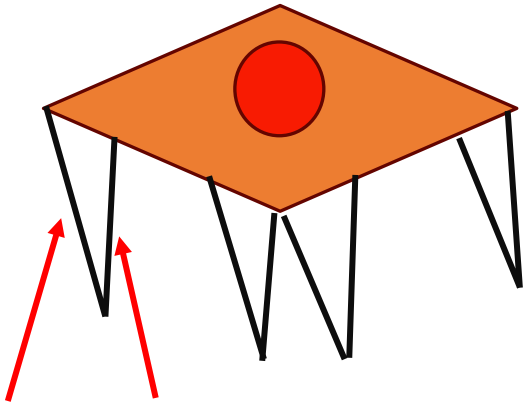
Q= Joints Forces = 1.5, 1.2, -0.2, -0.10 [N•m]
E_{kin}= Kinetic Energy
E_{pot}= Potential Energy
M_M= Motor Torque
M_f= Frictional Force

k_M[torque constant]*I[current])=0.8508 N m/A*10 A = 8.51 Nm
*If the current increases, then the torque increases. Helps determines how much energy is needed for the motor to rotate.



Two Joints = Truss

Assumptions
- Two coaxial electromagnets, gap G = 20 mm
- Coil: N = 800, area Aeff = 3.14e-4 m^2, correction gap g0 = 0.5 mm
- Ball: steel sphere m = 0.033 kg, weight mg = 0.323 N
- Max coil current <= 0.8 A

Team Member #5 Engineering Calculations

Equation:

$$F = \frac{KI^2}{(g+g_0)^2}, \quad K = \frac{\mu_0 N^2 A_{\text{eff}}}{2}$$

$$\frac{KI_U^2}{(G-h+g_0)^2} - \frac{KI_L^2}{(h+g_0)^2} = mg$$

Results

Stable levitation height: h ≈ 7–15 mm

Example operating points:

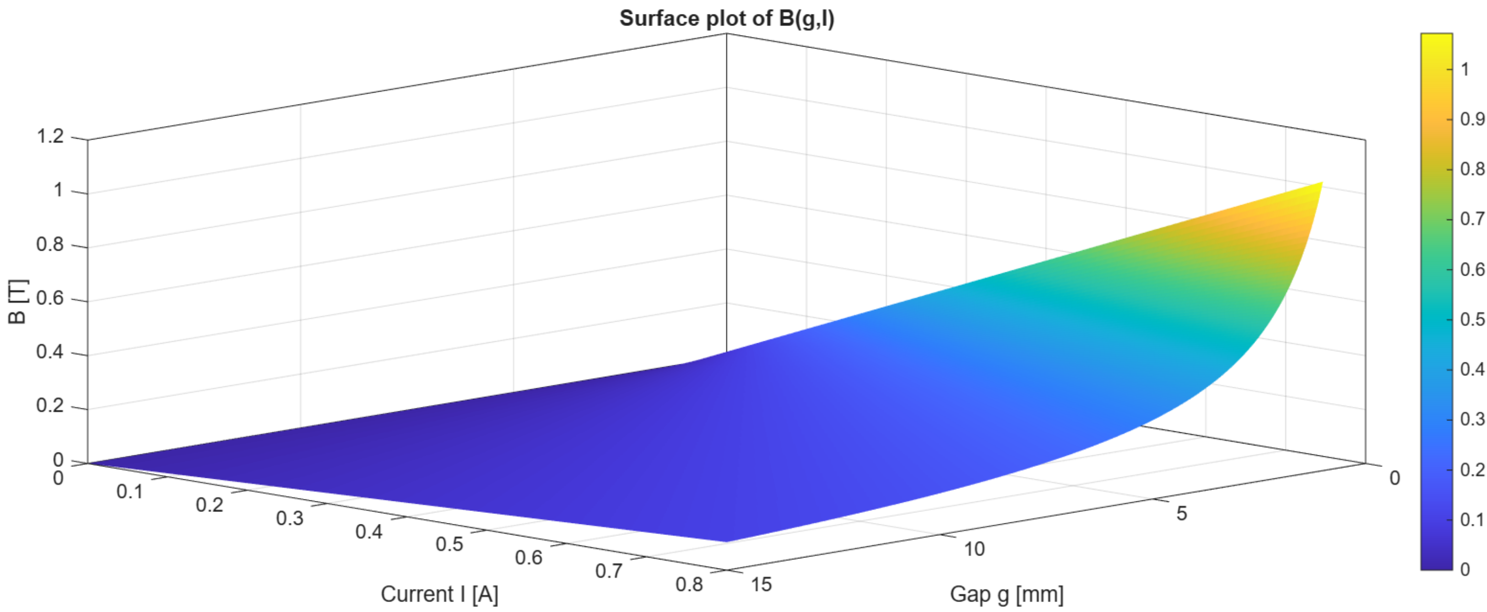
h = 7 mm : Iu ≈ 0.79 A, Il ≈ 0.22 A

h = 9 mm : Iu ≈ 0.69 A, Il ≈ 0.31 A

h = 15 mm: Iu ≈ 0.36 A, Il ≈ 0.64 A

Peak flux density Bmax ≈ 0.06 T << Bsat

Power consumption P ≈ 4–5 W (safe thermally)



Customer Requirement	Weight	Ball-on-Plate	Maglev	Reaction Wheel	Hockey Robot	Line Robot
Interactive for K–12 Students	0.25	9	8	8	7	4
Educational / Demonstrates Control Concepts	0.20	9	9	7	6	5
Kid-Friendly / Safe	0.10	8	7	9	7	8
Durable for Travel	0.10	7	8	9	7	8
Mass Produce	0.10	7	7	8	6	9
Affordable / Low Cost	0.10	8	7	7	8	9
Portable / Compact	0.15	9	9	8	6	9
Weighted Total (0–10)	1.00	8.25	7.90	8.05	6.95	7.50
Rank (1 = Best)		1	3	2	5	4

Robot #2 Decision Matrix A – Customer Requirements

Engineering Requirement	Ored	Ball-on-Plate	Maglev	Reaction Wheel	Hockey Robot	Line Robot
Dimensions / Size Limit	0.10	8	9	9	7	9
Power Efficiency / Battery	0.10	8	6	7	7	9
Controller Compatibility (Arduino/Pi)	0.15	9	8	8	7	8
Safety (CPSC Guidelines)	0.10	8	8	9	7	8
Drop Test / Durability	0.10	7	8	9	7	8
Manufacturing Cost	0.15	8	7	7	8	9
Programming Diagrams	0.15	9	9	8	6	5
Integration with EE Subsystems	0.15	8	7	9	7	7
Weighted Total (0–10)	1.00	8.25	7.75	8.15	7.25	7.95
Rank (1 = Best)		1	3	2	5	4

Robot #2 Decision Matrix B – Engineering Requirements

Robot #2 Concept Selection

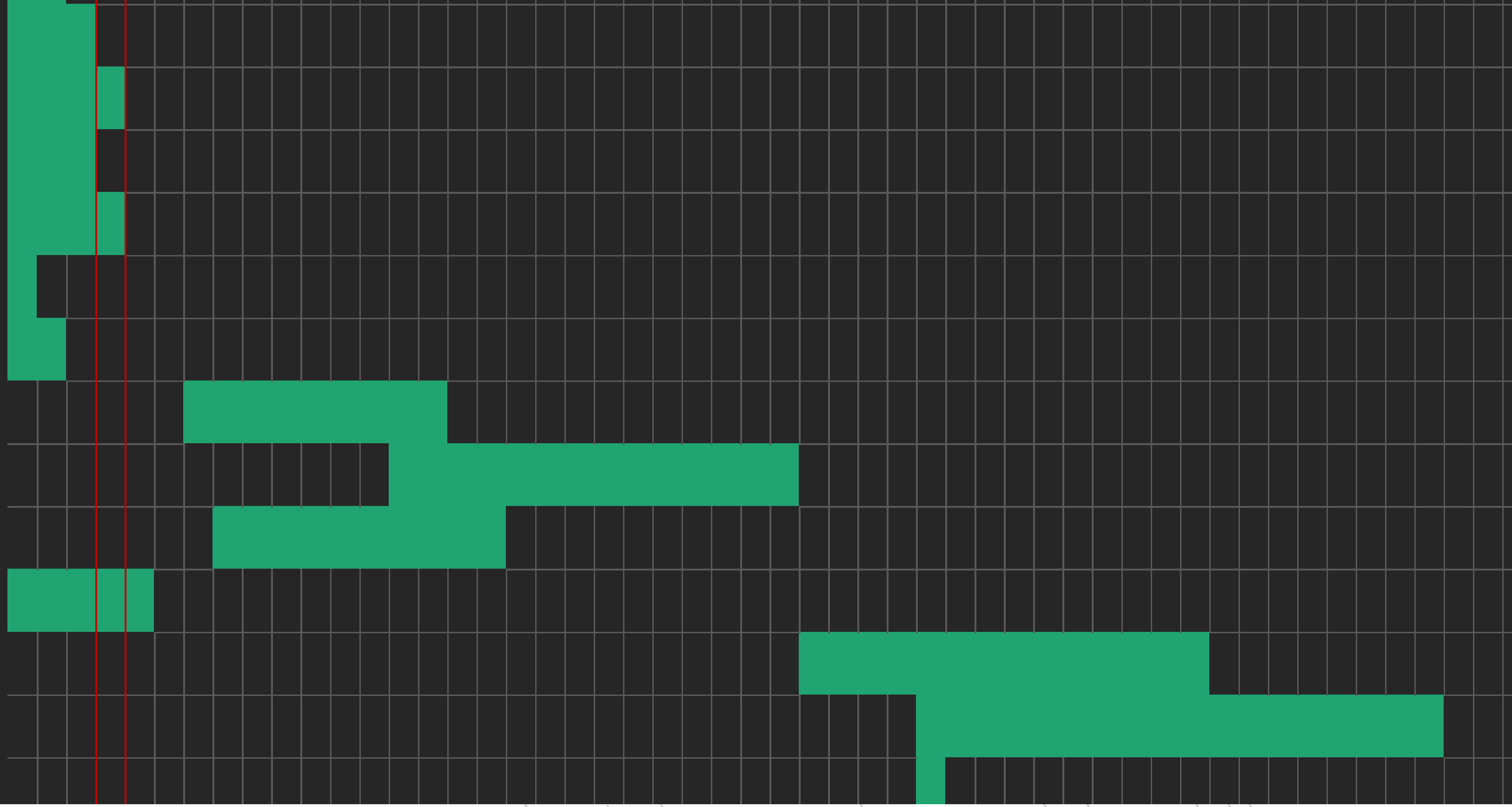
After comparing these concepts, our sub team found that our top 3 were Ball-on-Plate, Magnetic Levitation, and the Reaction Wheel as they best align with our project goals.

- Ball-on-Plate System offers strong educational value with clear feedback visualization. It allows students to see how control algorithms keep a moving object stable.
- Magnetic Levitation Demonstrator has a strong "wow" factor and demonstrates rapid real-time control response, though it may require faster electronics.
- Reaction Wheel Stabilizer is highly educational but may exceed current schedule constraints due to more advanced control theory and precise hardware requirements.

Andres, Freddy, Ziyi

Project Financials and Schedule

Engineering calcs & validation	On Track	All	50%	10/6/2025	3
Concept evaluation (Pugh/decision/FoS)	On Track	Andres	0%	10/6/2025	4
Concept Selection (rough CAD, sub assemblies)	On Track	Colin	0%	10/6/2025	3
Schedule (Ghantt)	On Track	Andres	10%	10/6/2025	4
Budget	On Track	Ziyi	20%	10/6/2025	1
BoM	On Track	Colin	100%	10/6/2025	2
Peer Eval 2	On Track	All	50%	10/12/2025	9
Report #1	On Track	All	33%	10/19/2025	14
Website Check #1	On Track	Andres	23%	10/13/2025	10
Prototype #1	On Track	Andres & Colin	20%	10/1/2025	10
Analytical Analysis Memo	On Track	All	0%	11/2/2025	14
Presentation 3	On Track	All	0%	11/6/2025	18
Peer Eval 3	On Track	All	0%	11/6/2025	1



Schedule

Robot 1: On track!
Robot 2: slightly behind, but okay

Budget

- Allocation

Robot #1 Prototype: 1500 USD

Robot #2 Prototype: 1500 USD

Adjustments & Redesign: 2000 USD

- Robot #1 Prototype

Motors, drivers, controller, sensors

Total ≈ 1500 USD (see BOM previous slide)

- Robot #2 Prototype

Similar scale, parallel development

Budget reserved: 1500 USD

- Adjustments & Redesign

Materials upgrade (stronger shell, lighter frame)

Electronics replacement (drivers, sensors)

Contingency for testing iterations

Reserved: 2000 USD

Update On Fundraising

Reached out to American Society of Mechanical Engineers

Started talking with other officers to ensure we would be allowed to use their bank account

Will allow us to start collecting funds from GoFundMe and Panda Express

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