Course: ME-486C: Mechanical Engineering Design II
Project: Robotics Traveling Van
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Client: Dr. Shafer

1. Design Requirements Summary

This section summarizes the updated Customer Requirements (CR) and Engineering Requirements (ER) derived from the project's Quality Function Deployment (QFD) matrix. These requirements have been adjusted to reflect the current physical specifications of the Inverted Pendulum and Ball-on-Beam systems.

Customer Requirements (CRs)

CR1: Operating Space (System must fit within standard desk boundaries)
CR2: Battery Powered (System must be untethered)
CR3: Active Dynamic Balancing (System must autonomously maintain equilibrium)
CR4: Kid-Friendly (System must be physically safe for K–12 students)
CR5: Durability (System must withstand typical classroom handling)
CR6: Inexpensive (System must be cost-effective for mass production)
CR7: Interactive Interface (System must have a user-accessible touchscreen)
CR8: Educational Props (System must serve as a tangible teaching tool)

Engineering Requirements (ERs)

ER1: Overall Dimensions (Target: < 12 in × 12 in × 12 in)
ER2: Power Source / Run Time (Target: > 30 minutes continuous dynamic operation)
ER3: Control Hardware (Target: Raspberry Pi integrated)
ER4: Electrical Safety (Target: Qualifies under U.S. CPSC guidelines)
ER5: Drop Test (Target: 36 in / 3-foot drop test)
ER6: Manufacturing Cost (Target: < $500 per unit)
ER7: PID Settling Time (Target: < 5 seconds)
ER8: Sharp Edge Radii (Target: Qualifies under U.S. CPSC guidelines)
ER9: Pinch Clearance (Target: Qualifies under U.S. CPSC guidelines)
ER10: Emergency Stop (Target: Yes, integrated mechanism)
ER11: Visual Feedback Interface (Target: Yes, functioning touchscreen GUI)

2. Top Level Testing Summary

The following table lists all tests to be performed and maps them to the relevant Design Requirements.

Experiment/Test	**Applicable Robot**	**Relevant DRs**	**Testing Equipment Needed**	**Other Resources**
EXP1 – Chassis Drop Test	Robot 1 (Inverted Pendulum)	ER5, CR4, CR5	3-foot measuring tape, camera	Hard classroom floor surface
EXP2 – Battery Endurance	Robot 1 & Robot 2	ER2, CR2	Stopwatch, digital multimeter	Fully charged LiFePO4 batteries
EXP3 – Physical Safety & Dimensions	Robot 1 & Robot 2	ER1, ER4, ER8, ER9, CR1, CR4	Calipers, CPSC safety gauge	Lab workspace
EXP4 – Interface & Control Verification	Robot 1 & Robot 2	ER3, ER7, ER10, ER11, CR3, CR7, CR8	Raspberry Pi logic analyzer	Touchscreen GUI
EXP5 – Bill of Materials (BOM) Audit	Robot 1 & Robot 2	ER6, CR6	Excel BOM spreadsheet	Financial purchasing receipts

3. Detailed Testing Plans

EXP1 – Chassis Drop Test (Robot 1 Only)

Test/Experiment Summary

Tests the 3D-printed chassis durability (ER5). Equipment includes measuring tape and a camera. The isolated variable is dropping height, and the calculated variables are structural fracture points.
(Note: Robot 2 excludes pending client approval.

Procedure

1. Mark is exactly 36 inches from the floor.
2. Hold unpowered Robot 1 at the marked height.
3. Release and record impact.
4. Inspect for fractures.

Results (Expected)

We expect the chassis to remain intact.
At 36 inches (0.914 meters), using $v = \sqrt{2gh}$, the anticipated impact velocity is 4.23 m/s

Conclusion

Passing this test verifies ER5 (36-inch Drop Test) and directly proves it satisfies CR4 (Kid-Friendly) and CR5 (Durability).

EXP2 – Battery Endurance (Robot 1 & Robot 2)

Test/Experiment Summary

Verifies runtime (ER2) using the LiFePO4 batteries. Equipment includes a stopwatch and multimeter. The isolated variable is continuous runtime.

Procedure

1. Charge the 12V battery array.
2. Power the robot and engage PID loops.
3. Record voltage every 5 minutes until shutdown.

Results (Expected)

We expect greater than 30 minutes of continuous operation.
Using $t = C / I$ with a 7200 mAh capacity and 5 A continuous draw, the theoretical runtime is approximately 1.44 hours.

Conclusion

Passing this test verifies ER2 (Power Run Time) and directly proves the system satisfies CR2 (Battery Powered).

EXP3 – Physical Safety & Dimensions (Robot 1 & Robot 2)

Test/Experiment Summary.

Verifies volumetric and weight constraints (ER1, ER8) and mechanical safety (ER4, ER8, ER9). Equipment includes calipers and measuring tools

Procedure

1. Measure length × width × height.
2. Use calipers to inspect exterior radii and moving-part clearances for pinch hazards.

Results (Expected)

Static dimensions must remain under 12 in × 12 in × 12 in.
Clearances must comply with CPSC safety standards.

Conclusion

Passing this dimensional audit verifies ER1, ER8, and ER9, fulfilling CR1 (Operating Space) and ensuring the system is CR4 (Kid-Friendly).

EXP4 – Interface & Safety Verification (Robot 1 & Robot 2)

Test/Experiment Summary

Verifies the user-facing control mechanisms (ER10, ER11).

Procedure

1. Boot the Raspberry Pi GUI.
2. Trigger the Emergency Stop to verify complete motor power cutoff.
3. Verify the GUI registers physical touch inputs.

Results (Expected)

Emergency Stop must sever power instantly (0 seconds).
The touchscreen must correctly register user inputs for adjusting system variables.

Conclusion

A functional user interface and Emergency Stop verify ER11 and ER12, explicitly satisfying CR7 (Interactive Interface).

EXP5 – PID Stability & Settling (Robot 1 & Robot 2)

Test/Experiment Summary

Tests the core control loop governing the system's ability to actively balance (ER7). Equipment includes a stopwatch and a protractor or ruler. The isolated variable is the physical perturbation, and the calculated variable is settling time.

Procedure

1. Place the powered robot on a level surface.
2. Introduce a physical perturbation (10° push for pendulum, 2-inch displacement for ball).
3. Record the time required to return to equilibrium.
4. Repeat 5 trials and compute the average settling time.

Results (Expected)

The system is expected to return to a stable state in under 5 seconds for both platforms.

Conclusion

Achieving sub-5-second settling times verifies ER7 (PID Settling Time) and provides definitive proof that the system satisfies CR3 (Active Dynamic Balancing).

EXP6 – ToF Sensor Calibration (Robot 2 Only)

Test/Experiment Summary

Tests the accuracy of the Time-of-Flight (ToF) distance sensor (ER3). Equipment includes a measuring tape and a flat reference block.

Procedure

1. Place a reference block on the beam at measured 5-inch intervals.
2. Record the sensor's digital output at each position using the Raspberry Pi.
3. Calculate percentage error relative to actual distance.

Results (Expected)

The sensor must report position with less than 5% error across the beam length.

Conclusion

Validating sensor accuracy verifies ER3 (Control Hardware) and ensures the system functions effectively as CR8 (Educational Props).

EXP7 – Bill of Materials (BOM) Audit (Robot 1 & Robot 2)

Test/Experiment Summary

Verifies the unit cost (ER6) through financial auditing.

Procedure

1. Compile all material and electronics receipts.
2. Calculate the per-unit cost.
3. Find 1-2 comparable robots on the market, calculate percent savings for equal performance.

Results (Expected)

The calculated per-unit cost must be less than $500 USD.

Acromegaly Linear Inverted Pendulum vs. Robot 1: Inverted Pendulum

The inverted pendulum that's on the market; Acromegaly Linear Inverted Pendulum (A.1), is designed for learning about feedback controls using an unstable non-linear system that balances itself. This robot retails minimum $10,000 per unit [1], and it functions as an open source, and it is compatible with MATLAB, LabVIEW, and Python. [2] As for Robot 1, it costs about $682.23 per unit (A.2), which has a 93.18% saving per unit cost compared to the robot that is on the market.

Acromegaly Ball on Beam vs. Robot 2: Ball on Beam

The ball on beam that's on the market; Acromegaly Ball on Beam (A.3), is a robot that introduces the fundamentals and principles of controls with automatic controls. One unit for this robot is approximately $6, 000 to $12,000, and this ball on beam has one degree of freedom located on one end of the beam [1] [3]. For Robot 2, the total cost for one unit is $314.86 (A.4), the percent saving compared to the robot that is on the market ranges from 94.75% to 97.38% per unit cost.

Conclusion

Passing this audit verifies ER6 (Manufacturing Cost) and definitively proves the system satisfies CR6 (Inexpensive).

4. Specification Sheet Preparation

Customer Requirement Summary Table

Customer Requirement	CR met? (✓/X)	Client Acceptable (✓/X)
CR1 – Operating Space	✓	✓
CR2 – Battery Powered	✓	✓
CR3 – Active Dynamic Balancing	✓	✓
CR4 – Kid-Friendly	✓	✓
CR5 – Durability	X	✓
CR6 – Inexpensive	✓	✓
CR7 – Active Interface	X	✓

Engineering Requirement Summary Table

Engineering Requirement	Target	Tolerance	Measured/Calculated	ER met? (✓/X)	Client Acceptable (✓/X)
ER1 – Dimensions	12 in × 12 in × 12 in	+1 in	R1: 7” × 7.5” × 11” (+8”) R2: 8.5” × 12” × 5.5” (+2” at)	✓	✓
ER2 – Power Run Time	30 min	−5 min	Not Tested		
ER3 – Control Hardware	Raspberry Pi	N/A	Included	✓	✓
ER4 – Electrical Safety	CPSC Qualified	N/A	Not Tested		
ER5 – Drop Test	36 in	−2 in	Not Tested		
ER6 – Manufacturing Cost	$500	+$50			

ER7 – PID Settling Time	5 sec	+2 sec	**X/✓**	**X**	**X**
ER8 – Sharp Edge Radii	CPSC Qualified	N/A	None	✓	✓
ER9 – Pinch Clearance	CPSC Qualified	N/A	Acceptable 0.65″	✓	✓
ER10 – Emergency Stop	Yes	N/A	✓	✓	✓
ER11 – Visual Feedback	Touchscreen	N/A	**X**	**X**	**X**

5. QFD

The attached Quality Function Deployment (QFD) matrix links Engineering Requirements to Customer Requirements, demonstrating that satisfying engineering targets ensures fulfillment of customer needs.

For example, validating the 36-inch drop test (ER5) and safety compliance (ER9, ER10) confirms the system meets Durability (CR5) and Kid-Friendly Safety (CR4). Additionally, verifying the per-unit cost below $500 (ER6) ensures the Inexpensive (CR6) requirement is satisfied.

6. Citations

[1] Acrome Robotics, “Lab Packages,” *Acrome*, Accessed: Apr. 7, 2026. [Online]. Available: https://acrome.net/lab-packages#packages

[2] Acrome Robotics, “Linear Inverted Pendulum,” *Acrome*, Accessed: Apr. 7, 2026. [Online]. Available: https://acrome.net/product/linear-inverted-pendulum

[3] Acrome Robotics, “Ball and Beam,” *Acrome*, Accessed: Apr. 7, 2026. [Online]. Available: https://acrome.net/product/ball-and-beam

7. Appendix

A.1

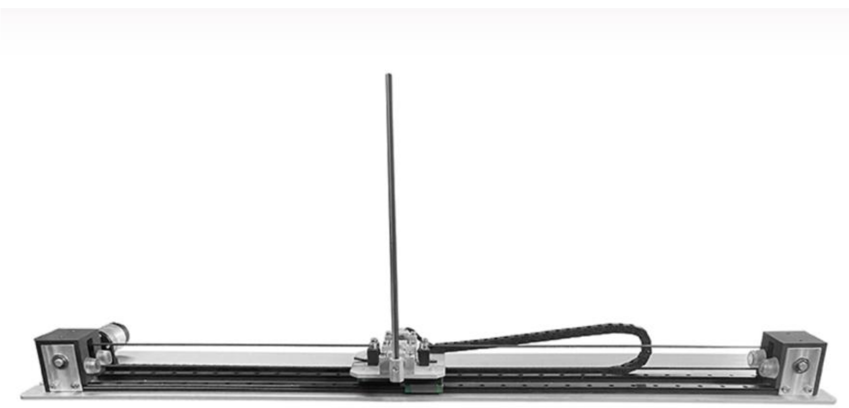

Figure 3: Acromegaly Linear Inverted Pendulum [1]

A.2

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

Figure 2: Robot 1's bill of materials (BOM) with the cost of one unit with the names of the items integrated in the robot listed.

A.3

Figure 3: Acromegaly Ball on Beam [1]

A.4

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

Figure 4: Robot 2's bill of materials (BOM) with costs of one unit and the total of five units with the names of the items that are integrated in robot 2 listed.