University of California, Irvine
Henry Samueli School of Engineering
Department of Mechanical and Aerospace Engineering

MAE151B Mechanical Engineering Design II
Final Design Binder

Rocker-Bogie Stair-Climber

"The 1000 Yard Stair"

Team 28

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Sponsor: Mohamed Shorbagy
March 2026

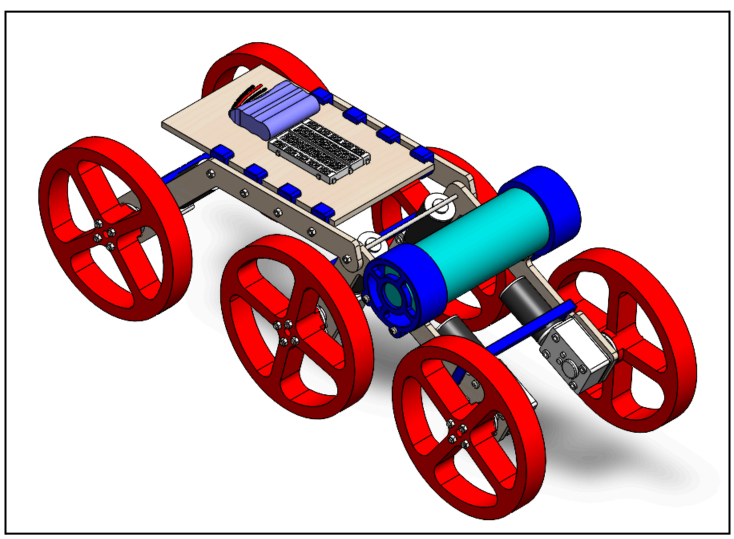
Executive Summary

The 1000 Yard Stair is a six-wheeled rocker-bogie stair-climbing vehicle designed and built by Team 28 for the MAE 151B Mechanical Engineering Design II competition at the University of California, Irvine. The project was sponsored by Mohamed Shorbagy, a PhD candidate in the Department of Mechanical and Aerospace Engineering, who tasked the team with designing a ground-based robot capable of climbing the 19-step Engineering Gateway staircase while transporting a standard water bottle. The competition objective was to complete the climb faster than the other competing teams.

Design Process:
The team began by researching existing stair-climbing propulsion methods, evaluating transformable wheels, linkage legs, and tank treads before ultimately selecting the six-wheeled rocker-bogie architecture through a structured trade study. The rocker-bogie design was chosen for its superior force distribution, tire contact surface area, and practical manufacturability within the project timeline and budget. The chassis was fabricated from laser-cut plywood and connected by M4 threaded rods, with all structural support components including chassis grips, brackets, and the bottle carriage caps 3D printed in PETG. Six BRINGSMART 12V 27 RPM worm gear motors, one per wheel, were selected based on a SolidWorks motion study that identified a peak torque demand of approximately 18 kg·cm at the middle wheel during Phase 2 of the climb. Applying a factor of safety of 2.0 yielded a minimum required motor torque of 36 kg·cm, which the selected motors satisfied with a rated torque of 50 kg·cm. Custom 7-inch diameter PETG wheels were designed and 3D printed after no commercially available wheel satisfied the required diameter, hub interface, and weight constraints simultaneously. All six wheels were dip-coated in Plasti-Dip rubber compound to achieve the rubber-on-concrete static friction coefficient required for traction on the stair surface.

Final Design:
The final design retained the rocker-bogie chassis geometry, with the addition of 3D printed chassis grips to address lateral plywood flexibility, center brackets to prevent inward chassis collapse and mount the electronics plate, and a hard stop at the central pivot joint to prevent the rocker from exceeding its safe articulation range. The originally planned microcontroller-based electrical system consisting of an ESP32, L298N motor drivers, and Bluetooth remote control was removed after repeated integration failures during testing and replaced with a direct battery-to-motor wiring configuration to ensure competition reliability. The final prototype measured 25 3/16 inches in length, 9 5/8

CAD Model of Rocker-Bogie Stair Climber



inches in width, and 8 1/8 inches in height, with a total weight of 4,840.4 grams and a measured battery voltage of 11.37V.

Competition Results:
The rover successfully completed the full 19-step Engineering Gateway staircase climb during the competition, transporting the water bottle payload without displacement or spillage and with no chassis-to-stair contact events. The best recorded run time was approximately 82 seconds, within the marginal value of 120 seconds established in PR-1. Team 28 placed 2nd in the class competition.

Lessons Learned and Future Recommendations:
Due to overcompensating the factor of safety using a value of 2.0 and tradeoff for motors between their torque and speed, our rover resulted in being much slower than what it could have been. By having an actual weight very close to the expected value of 4 kg based on the motion studies and simulations, we chose a torque much higher than what we needed which cost much speed in the process. For future projects involving accurate measurements such as weight, we suggest calculating with a lower factor of safety such as 1.5 to prioritize other important factors such as speed while still providing sufficient margin of error.

Team 28 (from left to right): Kainoa Crow (Electronics Specialist), Alan Duong (Systems), Nolan Hahn (Team Lead/CAD Designer), Matthew Scott (Physics Analyst)

Table of Contents

List of Figures

List of Tables

Part One: Problem Definition

1.1 Background

The increasing popularity of delivery robots such as the Starship wheeled rovers that deliver food for students across campus, there is an increasing demand for these robots to be able to efficiently travel anywhere across multiple terrain to provide the most convenient service possible. To do this, the sponsor of this project Mohamed Shorbagy tasked Team 28 to design a robot that is capable of climbing Engineering Gateway's stairs at UCI while carrying a standard water bottle that can easily be inserted and removed. The project is held as a competition where competing teams each design a robot that accomplishes this task through only ground movement.

The project sponsor is a PhD candidate specializing in research on aerodynamics, theoretical modeling, computational simulation, and control design. The competition awards the fastest robot that can climb the steps which is also improved with the design of the chassis similar to that of aerodynamics. The need to analyze the different physics applied during the motion of the robot for each step using simulation software and physics models is also relevant to the sponsor's field of study.

The sponsor's dream design solution will quickly transport the water bottle up the stairs. The measure of effectiveness for the design will be its speed which is the only criteria for the ideal design. This could mean that the ideal design has a light chassis or has powerful motors. Qualities like these can contribute to a faster water bottle transport system and match the sponsor's dream solution. Though, further research is required to fully understand the problem and proceed to possible solutions.

1.2 Project Objectives

The project objectives establish the overarching goals that guided all decisions throughout the project lifecycle. These objectives were derived from stakeholder needs, competition requirements, and educational goals.

DO-1: Design and Build a Functional Stair-Climbing Vehicle

- Develop a complete, operational rocker-bogie suspension vehicle capable of reliably navigating the 19-step Engineering Gateway staircase. The vehicle must demonstrate:
    - Successful climb of all 19 steps without human intervention during the operation
    - Ground-based locomotion (no flying or non-climbing methods)
    - Robust mechanical design that withstands repeated testing and demonstration cycles
    - Integration of mechanical, electrical, and control subsystems into a cohesive functional system

DO-2: Achieve Optimal Climbing Speed

- Optimize the vehicle's climbing performance to minimize total climb time while maintaining reliability. Speed optimization considerations include:
    - Motor power and torque selection for maximum propulsion without overheating
    - Wheel diameter optimization for obstacle clearance and rolling efficiency
    - Rocker-bogie geometry tuning for rapid weight transfer and minimal hang-up time
    - Trade-off between theoretical maximum speed and practical reliability

DO-3: Transport Water Bottle Securely

- Design a payload mounting system that secures a standard water bottle throughout the entire climb without displacement, spillage, or damage. Requirements include:
    - Secure attachment prevents bottle movement during climbing transitions
    - Protection from excessive vibration, tilting, or impact forces
    - Easy manual loading and unloading between runs
    - Minimal added weight and center of gravity impact

DO-4: Win the Competition

- Achieve the fastest successful climb time among competing teams (Teams 26, 27, 28) through:
    - Superior mechanical design and component selection
    - Thorough testing and optimization before competition day
    - Risk mitigation to ensure a high success probability
    - Contingency planning for failure modes

DO-5: Demonstrate Systematic Engineering Design Process

- Apply and document a comprehensive engineering design methodology, including:
    - Rigorous problem definition with stakeholder needs analysis
    - Thorough review of existing solutions and design space exploration
    - Physics-based requirements derivation and verification planning
    - Multiple concept generation with structured evaluation and selection
    - Detailed analysis supporting all design decisions
    - Iterative prototyping with test-driven design refinement
    - Comprehensive documentation suitable for professional engineering practice

1.2.1 Stakeholders Needs and Expectations

This section identifies the specific needs and expectations of each stakeholder group in numbered list format. These needs inform the project requirements and success criteria.

Mohamed Shorbagy (Sponsor)

Table 1: Mohamed Shorbagy (Sponsor) SN of Rover

Need/Expectation	Success Criteria
SN-1	Successful demonstration of stair-climbing capability on Engineering Gateway stairs with complete water bottle transport
SN-2	Comprehensive engineering documentation including problem definition, conceptual designs, detailed analysis, and verification testing
SN-3	Physics-based models and calculations supporting all design decisions and component selections
SN-4	Regular progress updates through weekly sponsor meetings and quarterly presentations
SN-5	Adherence to project timeline with completion of milestones by specified deadlines
SN-6	Professional-quality Design Binder documentation following MAE 151A guidelines
SN-7	Demonstration of systematic engineering design process from problem definition through verification

Team 28

Table 2: Team 28 TN of Rover

Need/Expectation	Success Criteria
TN-1	Clear project requirements and success criteria from sponsor
TN-2	Development of practical skills in CAD modeling, electronics integration, physics analysis, and systems engineering
TN-3	Portfolio-quality project demonstrating technical competence for future employment
TN-4	Fair evaluation criteria and constructive feedback throughout design process
TN-5	Technical guidance from sponsor on complex engineering challenges
TN-6	Educational experience in mechanical engineering design, systems integration, and project management
TN-7	Access to fabrication facilities, tools, and technical resources

MAE Department

Table 3: MAE Department DN of Rover

Need/Expectation	Success Criteria

DN-1	Student learning outcomes aligned with MAE 151A/B course objectives
DN-2	Demonstration of systematic design methodology and engineering analysis
DN-3	Professional documentation suitable for archival and future reference
DN-4	Safe project execution with proper risk assessment and mitigation
DN-5	Completion of all course deliverables including presentations, reports, and demonstrations
DN-6	Efficient use of departmental resources and facilities
DN-7	Projects that enhance department reputation and student capabilities
DN-8	Comprehensive evaluation data for course assessment and continuous improvement

Engineering Gateway Facility

Table 4: Engineering Gateway Facility EN of Rover

Need/Expectation	Success Criteria
EN-1	No damage to stairs, railings, or surrounding infrastructure during testing
EN-2	Safe testing procedures with proper supervision and safety protocols
EN-3	Proper cleanup and restoration of testing area after each session

Future MAE 151A Students

Table 5: Future MAE 151A Students PN of Rover

Need/Expectation	Success Criteria
PN-1	Thorough documentation of design process, decisions, and rationale
PN-2	Lessons learned and recommendations for future improvements
PN-3	Accessible technical information on component selection and performance
PN-4	Identification of technical challenges and effective solutions
PN-5	Budget breakdown and cost analysis for project planning

Competition Judges and Competing Teams

Table 6: Competition Judges and Competing Teams CN of Rover

Need/Expectation	Success Criteria

CN-1	Fair and transparent competition rules and judging criteria
CN-2	Level playing field with consistent testing conditions for all teams
CN-3	Demonstration of innovation and engineering excellence
CN-4	Reliable and repeatable performance during competition demonstration
CN-5	Technical presentations showcasing design rationale and analysis

1.3 Project Research

During our initial analysis of the design challenge, we found the propulsion system to be the most impactful on the overall design. Without a propulsion system, we would not be able to climb the stairs regardless of the performance of the other subsystems. Therefore, we began researching already existing solutions centered around propulsion for overcoming defined obstacles. The geometrical challenges with such a system would later be explored and the remaining subsystems would be designed around the propulsion once it was realized.

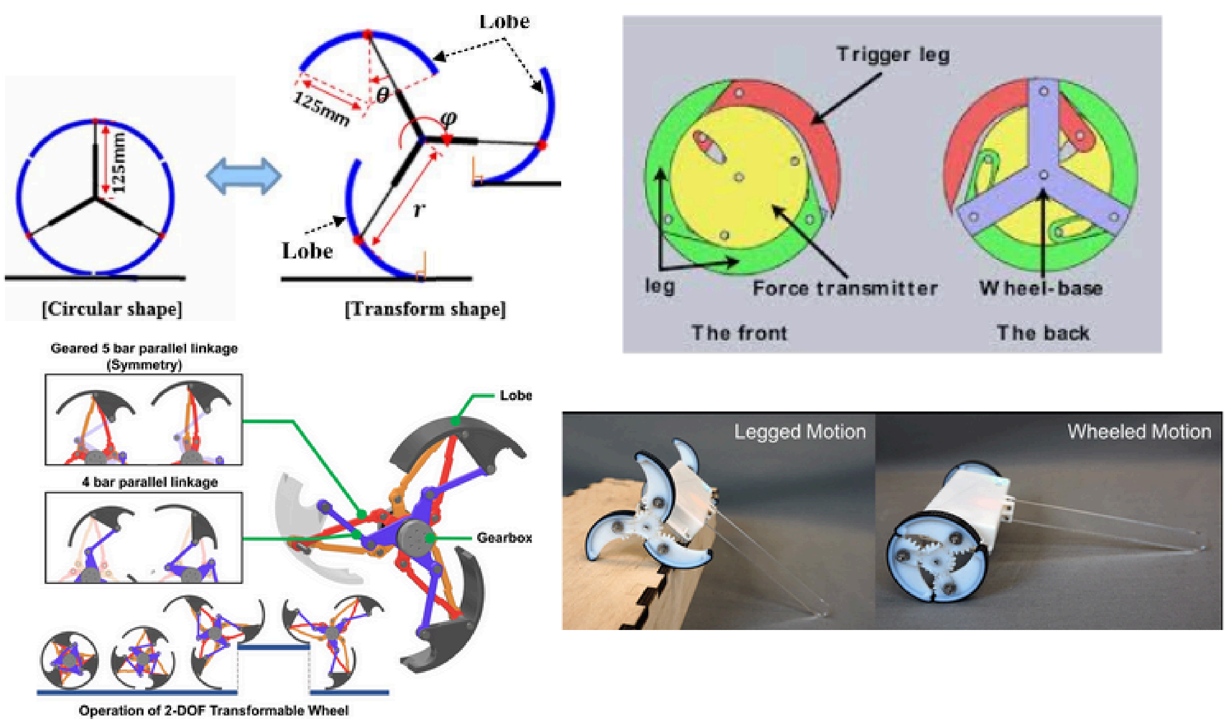


Figure 1: Transformable Wheel Variants with Expansions of Slider Crank (Upper Right), Linkage System (Bottom Left), and Gear System (Bottom Right)

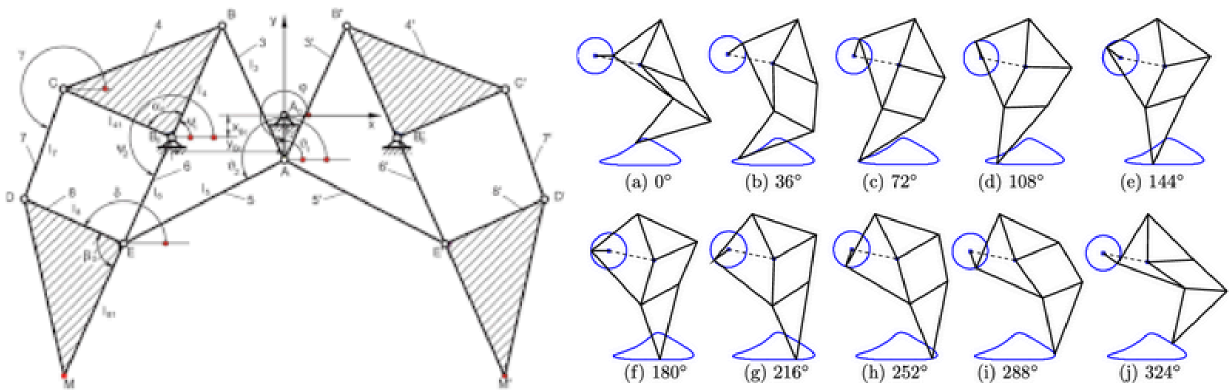


Figure 2: Jansen Linkage Leg System Design and Motion Path Diagram

Figure 3: Liftkar Handicap Assistance Robot Traveling on Stairs Using Tank Treads

	Pros	Cons
Transformable Wheel	- Can alter radius at any point and time - Has speed of a regular wheel	- Uses servo and motor for each wheel - Many parts for each wheel
Linkage Legs	- Capable of efficient organic movement - Can be made of a light frame	- Many moving joints - Complex geometry synthesis
Tank Treads	- Treats stairs as a ramp - Smooth linear travel	- Struggles with initial incline - Needs to be long enough to touch multiple stairs

Table 7: Pros & Cons of Design Solutions

To determine an adequate propulsion system, we researched three different types of propulsion. We organized these ideas into the pros and cons table above to examine the possible benefits and drawbacks of using them in our project. Transformable wheels would give us the ability to alter the geometry of our wheels at any point in time, which is particularly beneficial when having optimal configurations for different climbing phases. While circular wheels may struggle with stair climbing in comparison to spoked wheels, spoked wheels would be slower on flat surfaces. Transformable wheels would have given us the ability to switch between both. Linkage legs would provide the most efficient and organic movement for the stairs with a possibly lighter frame. However, both transformable wheels and linkage legs add much complexity to the project as either additional motors or complex geometrical accommodations are needed. The use of tank treads could have been a way to achieve similar flexibility in a simpler fashion. Treads can overcome flat ground and stairs smoothly with the assistance of gears for tension, but a significantly larger vehicle would have to be constructed.

With the three propulsion methods that we initially researched, we would later devise and find new combinations of propulsion and chassis designs ranging in complexity. All of these concepts would later be compiled into trade studies when beginning conceptual designs.

1.4 Design Requirements

The design requirements define all quantifiable criteria the stair-climbing vehicle must satisfy to be considered successful. Requirements are organized into four categories: Functional, Performance, and Design. Each requirement includes a unique identifier, description, specification, ideal and marginal values, units, importance level, verification method, and comments. Figure 4 presents the design attributes objectives tree illustrating the hierarchical relationship between project goals, design objectives, and derived requirements.

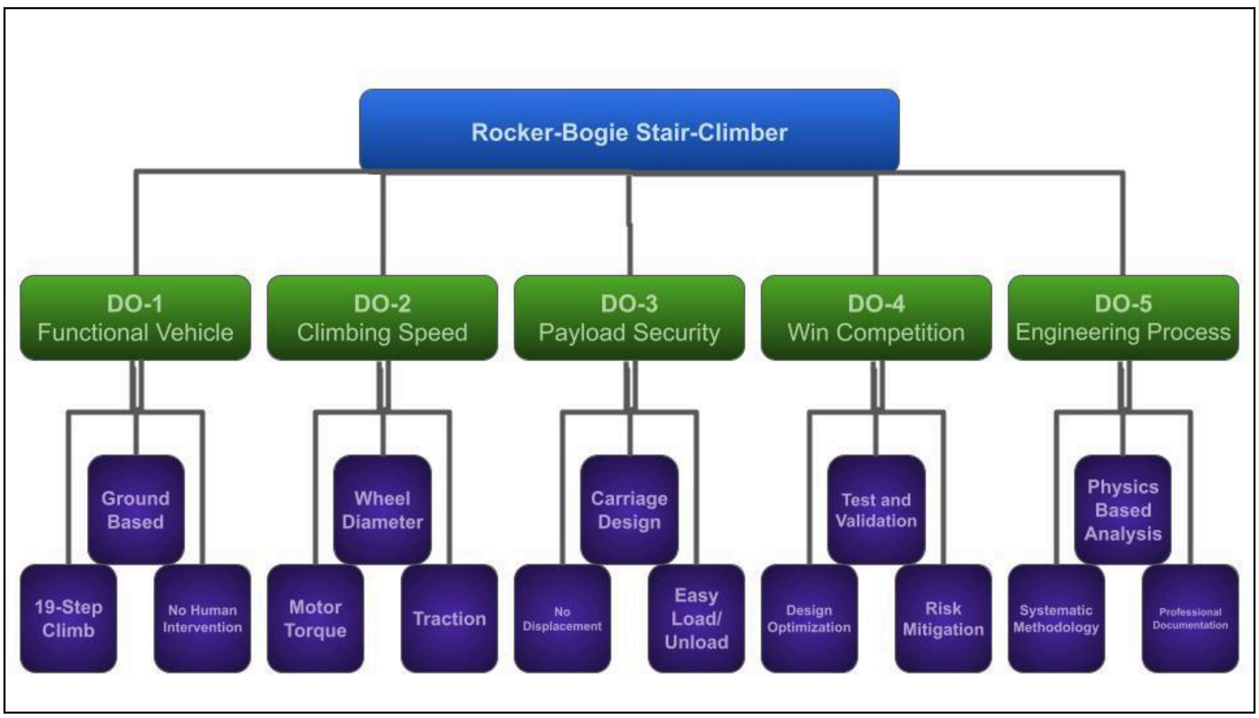


Figure 4: Design Attributes Objectives Tree

1.4.1 Design Attributes Table

The Design Attributes Table below maps each design objective to its measurable attributes and links them to the corresponding formal requirements. This traceability ensures that every high-level project goal is directly supported by at least one quantifiable requirement that can be verified through testing.

Design Objective	Design Attribute	Metric	Requirement Link
DO-1: Functional vehicle	Stair climbing capability	Climbs all 19 EG steps	FR-1
DO-1: Functional vehicle	Locomotion type	Ground contact only	FR-2
DO-2: Climbing speed	Climb time	≤120 seconds	PR-1
DO-2: Climbing speed	Motor speed	≥20 RPM	PR-6
DO-3: Payload security	Bottle displacement	≤0.5 inch	PR-2
DO-3: Payload security	Loading time	≤30 seconds	FR-4
DO-4: Win competition	Vehicle weight	≤4 kg	PR-12
DO-4: Win competition	Wheel traction	≤2 slip events	PR-13
DO-5: Engineering process	Documentation	Full design binder	—

Table 8: Design Attributes Table

1.4.1 Functional Requirements

Functional requirements define what the system must do to fulfill its primary mission.

Req ID	Description	Specification	Ideal Value	Marginal Value	Units	Importance	Verification Method	Comments
FR-1	Transport water bottle up stairs	Complete climb of all 19 steps at Engineering Gateway	19 steps	19 steps	steps	Must Have	Demonstration	Must successfully transport bottle from bottom to top of EG stairs
FR-2	Ground-based climbing only	Vehicle must climb stairs using ground contact (no flying)	100% ground contact	100% ground contact	%	Must Have	Observation	All 6 wheels must maintain contact with stair surfaces during climb

FR-3	Autonomous or remote operation	System operates without physical tether or human intervention during climb	Fully autonomous	Remote controlled	-	Must Have	Demonstration	Either mode acceptable; no physical tether allowed
FR-4	Water bottle loading/unloading	Manual loading and unloading permitted	≤ 10 seconds	≤ 30 seconds	seconds	Should Have	Timed test	Time to load bottle into carriage and secure
FR-5	Rocker-bogie articulation	All pivot joints must articulate freely throughout climb	0 binding events	0 binding events	events	Must Have	Physical inspection + climb test	Linkages must move smoothly without jamming

Table 9: Functional Requirements Table

1.4.2 Performance Requirements

Req ID	Description	Specification	Ideal Value	Marginal Value	Units	Importance	Verification Method	Comments
PR-1	Minimize total climb time	Fastest completion time wins competition	≤ 60 seconds	≤ 120 seconds	seconds	Must Have	Timed test on EG stairs	Time measured from start line to top step
PR-2	Maintain payload security	Water bottle must not fall, tip, or displace during climb	0 displacement	≤ 0.5 inch displacement	inches	Must Have	Visual inspection + measurement	Bottle must remain upright and secure throughout
PR-3	Obstacle clearance capability	Climb 5.75-inch step height	≥ 6 inches	≥ 5.75 inches	inches	Must Have	Direct measurement + climb test	Based on EG stair dimensions
PR-4	Ground clearance	Minimum clearance between chassis and stairs	≥ 1.0 inch	≥ 0.25 inch	inches	Must Have	Measurement during climb	Prevents chassis scraping on step edges
PR-5	All-wheel ground contact	All 6 wheels maintain contact during climb	6 wheels	≥ 5 wheels	wheels	Must Have	Visual observation during climb	Ensures traction and stability
PR-6	Motor speed (no-load)	Rotational speed of drive motors	30 RPM	20 RPM	RPM	Should Have	Tachometer or encoder measurement	Affects climb speed

PR-7	Battery runtime	Continuous operation time on single charge	≥ 15 minutes	≥ 5 minutes	minutes	Should Have	Endurance test	Must complete multiple test runs
PR-8	Chassis pitch angle tolerance (Phase 1)	Front wheels climbing first step	63.43° ± 2°	63.43° ± 5°	degrees	Should Have	Protractor measureme nt	Critical climbing geometry
PR-9	Chassis pitch angle tolerance (Phase 2)	Middle wheels climbing	101.8° ± 2°	101.8° ± 5°	degrees	Should Have	Protractor measureme nt	Maximum articulation position
PR-1 0	Chassis pitch angle tolerance (Phase 3)	Rear wheels climbing	27.57° ± 2°	27.57° ± 5°	degrees	Should Have	Protractor measureme nt	Recovery phase geometry
PR-11	Chassis pitch angle tolerance (Phase 4)	Final wheel transition	48.99° ± 2°	48.99° ± 5°	degrees	Should Have	Protractor measureme nt	Completion of step climb
PR-1 2	Maximum vehicle weight	Total system weight including battery and bottle	≤ 3 kg	≤ 4 kg	kilogram s	Should Have	Scale measureme nt	Lighter = faster climb
PR-1 3	Wheel traction	No wheel slippage on concrete stairs	0 slip events	≤ 2 slip events	events	Must Have	Visual observation during climb	Critical for forward progress

Table 10: Performance Requirements Table

1.4.3 Design Requirements

Design requirements specify constraints and standards for the engineering design process and physical implementation.

Req ID	Description	Specification	Ideal Value	Marginal Value	Units	Importance	Verification Method	Comments
DR-1	Wheel diameter	Rocker-bogi e wheel size for obstacle clearance	7.0 ± 0.1 inches	6.5 - 7.5 inches	inches	Must Have	Caliper measurement	Based on 2× wheel diameter clearance rule
DR-2	Rocker arm length (front)	Length of front rocker segment	4.0 ± 0.1 inches	3.5 - 4.5 inches	inches	Must Have	Ruler/caliper measurement	Critical for climbing geometry
DR-3	Rocker arm length (rear)	Length of rear rocker segment	8.0 ± 0.1 inches	7.5 - 8.5 inches	inches	Must Have	Ruler/caliper measurement	Critical for weight distribution

DR-4	Bogie arm length	Length of two-wheel bogie assembly	5.5 ± 0.1 inches	5.0 - 6.0 inches	inches	Must Have	Ruler/caliper measurement	Determines rear wheel spacing
DR-5	Wheelbase (front to rear)	Total chassis length from front to rear wheel	25 ± 1 inches	22 - 28 inches	inches	Must Have	Direct measurement	Must span 1.5-2 steps for stability
DR-6	Chassis width	Distance between left and right wheel assemblies	8.8 ± 0.2 inches	7 - 10 inches	inches	Should Have	Direct measurement	Affects stability and stair navigation
DR-7	Total vehicle height	Maximum height including bottle carriage	≤ 12 inches	≤ 15 inches	inches	Should Have	Direct measurement	Affects center of gravity
DR-8	Motor voltage	Operating voltage for drive motors	12V DC	9-12V DC	volts	Must Have	Multimeter measurement	Standard for selected motors
DR-9	Battery voltage	Nominal battery pack voltage	12V	12V	volts	Must Have	Multimeter measurement	Must match motor requirement s
DR-10	Control system voltage	ESP32 microcontroll er operating voltage	3.3V	3.3V	volts	Must Have	Multimeter measurement	Regulated from 12V battery

Table 11; Design Requirements Table

1.4.4 System Diagrams

System diagrams provide visual representations of the stair-climbing vehicle architecture at multiple levels of abstraction. These diagrams facilitate understanding of system functionality, component relationships, and hierarchical decomposition from high-level mission objectives down to individual physical components.

Black Box Diagram

The black box diagram represents the highest level of system abstraction, showing only the inputs, outputs, and primary function without revealing internal implementation details.

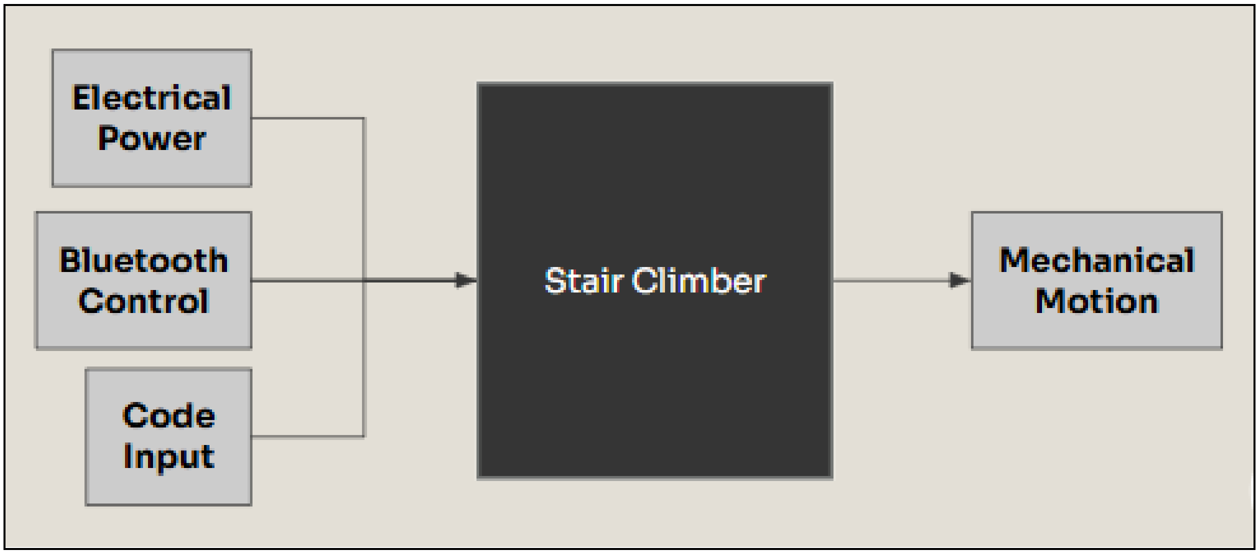


Figure 5: Black Box Diagram of Rover

Gray Box Diagram
The gray box diagram reveals the major subsystems within the black box while maintaining abstraction of component-level details.

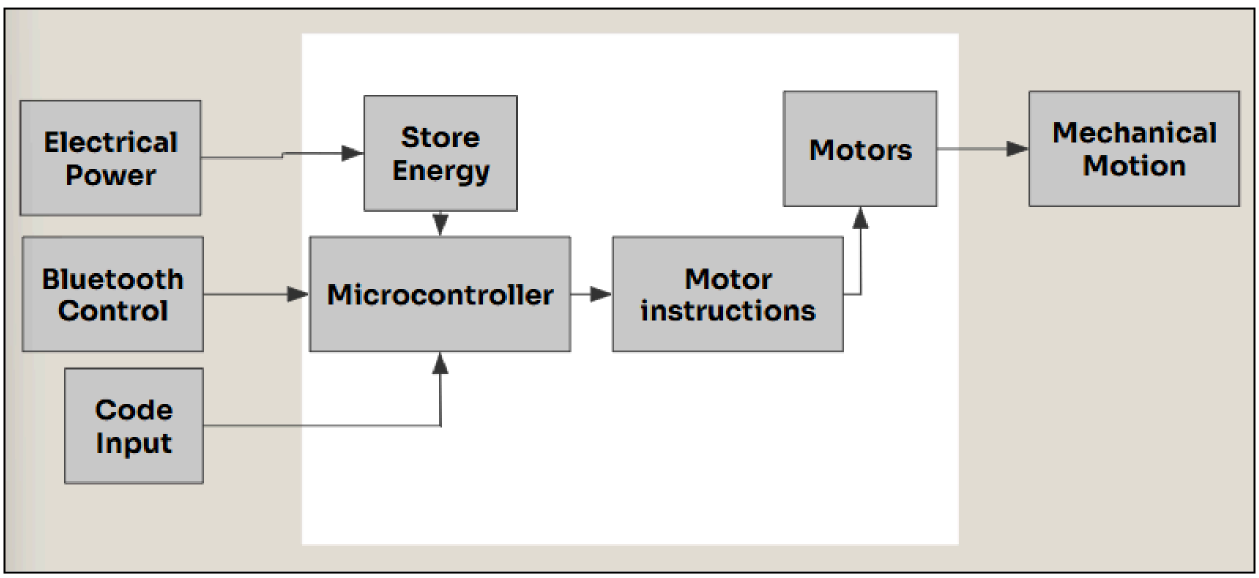


Figure 6: Gray Box Diagram of Rover

Structural Hierarchy Diagram
The structural hierarchy shows the physical breakdown of the system from complete vehicle down to individual components.

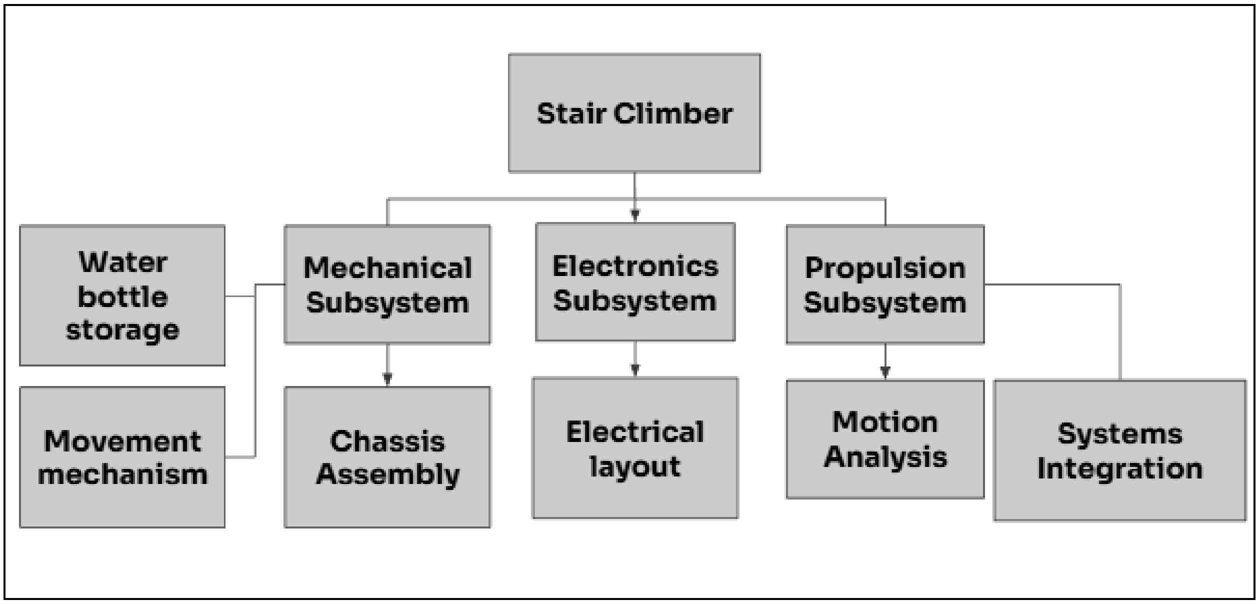


Figure 7: Structural Hierarchy of Rover

1.5 Work Breakdown Structure

The Work Breakdown Structure (WBS) below decomposes the project into four functional work packages assigned across team members.

Software (Kainoa, Matt)

- Write control code for five climbing phases
- Program motor control logic with differential drive for directional corrections
- Add stall detection and emergency stop conditions

Electronics (Kainoa, Nolan)

- Wire motor controllers to ESP32
- Connect six motors to motor controllers
- Integrate 12V battery with voltage regulation system
- Test full electrical system (all motors running, sensor reading data)

Manufacturing (Nolan, Matt)

- Laser cut chassis frame components
- Assemble rocker-bogie linkages and mount motors to chassis
- Apply adhesive to wheels

Testing and Optimization (All Team Members)

- Functional testing: single-step and three-step autonomous climbs
- Full staircase validation: complete 19-step autonomous navigation
- Performance tuning: optimize climb time to ≤90 seconds target
- Repeatability testing: achieve ≥90% success rate over multiple runs
- Final competition preparation and demonstration readiness

1.6 Initial Timeline

The preliminary Gantt chart below was developed at the beginning of Winter Quarter 2026 and outlines the team's planned schedule for fabrication, assembly, testing, and competition preparation across the quarter.

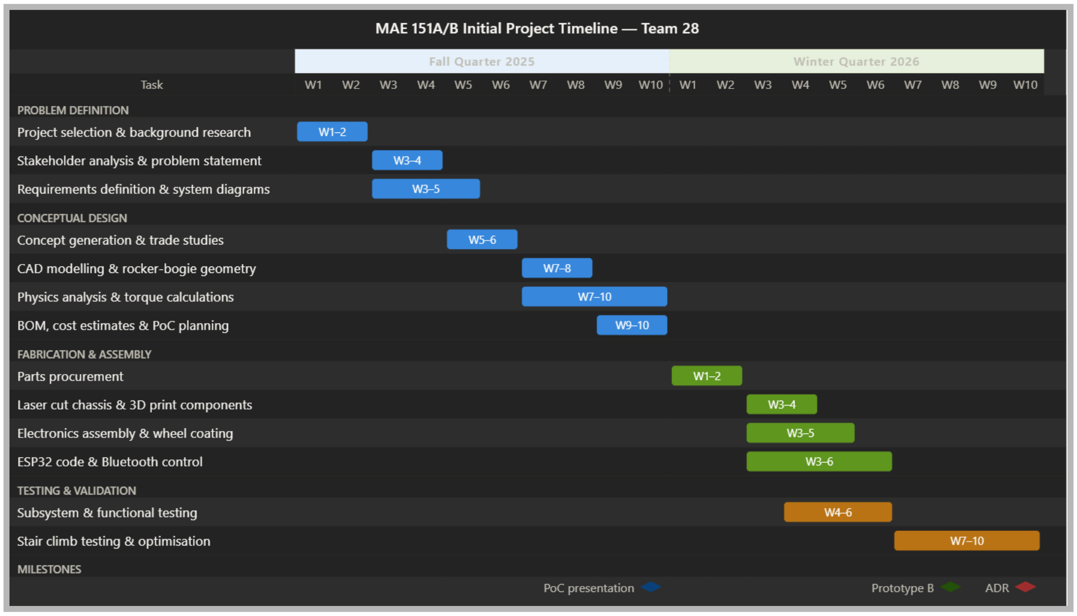


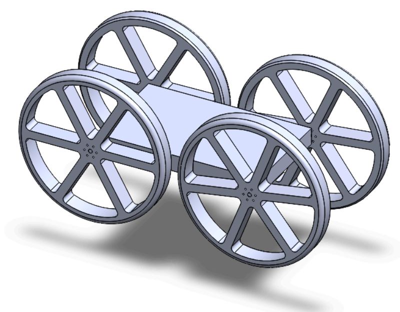
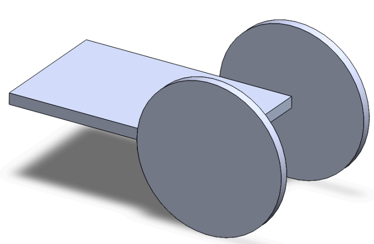
Figure 8: Initial Project Timeline

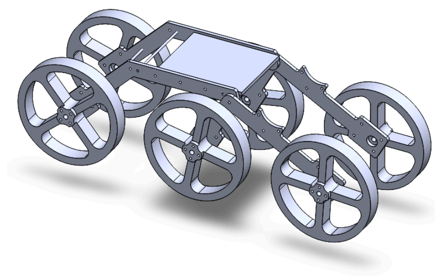
Part Two: Design Process

2.1 Preliminary Designs

After initial research of the three propulsion methods at the start of the project, we developed three additional design concepts that combine chassis subsystems with standard wheels with tires. All of the designs we devised that utilized standard wheels rely on tire friction to grip onto the stairs for the propulsion. These concepts are displayed and explained in the table below.

Table 12: Chassis Subsystem Design Concepts

Chassis Design Concept	Main Components	How It Works
4-Wheeled Car 	● 4 symmetrical wheels ● 1 simple shape chassis	All wheels use traction from tires to roll up stairs using static friction. The movement pattern is front wheels rolling up stairs, then followed by the rear wheels so the whole robot rests on a single step being parallel to the ground before climbing the next step. Other components are housed on a flat plate chassis. Provides phases of robot stability during climbing by ability to fit in a single stair step.
2-Wheeled Plow 	● 2 large symmetrical wheels ● 1 large simple shape chassis	Front wheels significantly larger to stairs use tire friction to roll up the stairs using static friction. Components are placed on a large flat plate which is long enough to always be in contact with the previous 2 steps for balance. Treats the stairs as a smaller obstacle due to proportionally larger wheel size.
6-Wheeled Rocker-Bogie	● 2 front wood segments ● 2 back wood segments ● ~ 6 threaded rods ● 6 symmetrical wheels	All wheels use traction from tires to roll up stairs using static friction. Hinged chassis of front and back wood segments

		allows the robot to climb stairs through each pair of wheels sequentially. Allows for better force distribution among wheels.

These three concepts were devised in response to the high demands of the initially researched propulsions. Although transformable wheels, linkage systems, and tank treads provide efficient climbing methods, each one required a significantly higher complexity in geometrical design or materials required for size. That is why three wheel-based designs were also considered despite their comparable limitations. To determine which design to proceed with and further develop, we conducted a trade study of the six concepts with cost, design time, and weight being weighted the most due to the timeline and budget constraints of the project. The results are shown in the table below with each category having a score range of 1 to 6.

Option	Components	Repairabi lity	Lifespan	Cost	Design Time	Troublesh ooting	Weight	Average
Weights	0.095	0.005	0.05	0.23	0.23	0.16	0.23	1
Transform able Wheels	2	1	1	1	2	2	2	1.715
Linkage Legs	1	2	2	2	1	1	3	1.745
Tank Treads	3	3	3	3	3	3	1	2.54
Rocker-Bogie	4	4	4	5	4	5	5	4.62
2-Wheel Plow	6	5	5	4	5	4	4	4.475
4-Wheel Car	5	6	6	6	6	6	6	5.905

Table 13: Trade Study of Design Solutions

Our rankings revealed that the 4-Wheel Car design was the best for our requirements with a score of 5.905. We then began developing a preliminary design around the concept using Pollolu wheels, which are commercially available wheels with silicone tires. We chose to use an off-the shelf wheel for its professional reliability and to provide more design time for other aspects of the rover instead of manufacturing our own wheels.

	Clearance	Stiffness	Mass	Center of	Manufacturin	Cost	

				Gravity	g		
Weight	0.3	0.25	0.1	0.15	0.1	0.1	Score
Flat plate	2	3	4	3	5	5	3.2
Ladder frame	3	4	3	3	4	4	3.45
Curved frame	5	4	4	4	3	3	4.1
Spaceframe	4	5	4	4	2	2	3.85

Table 14: Trade Study of Chassis Options

Four designs of the chassis were compared to decide which one was best for the stairs. The criteria used in the table gave us a better understanding of how well the chassis type would work with the Pollolu wheels and in the competition. The curved frame was found to be the best option overall with a score of 4.1 due to the expected weight and geometrical properties of avoiding interference with the stairs.

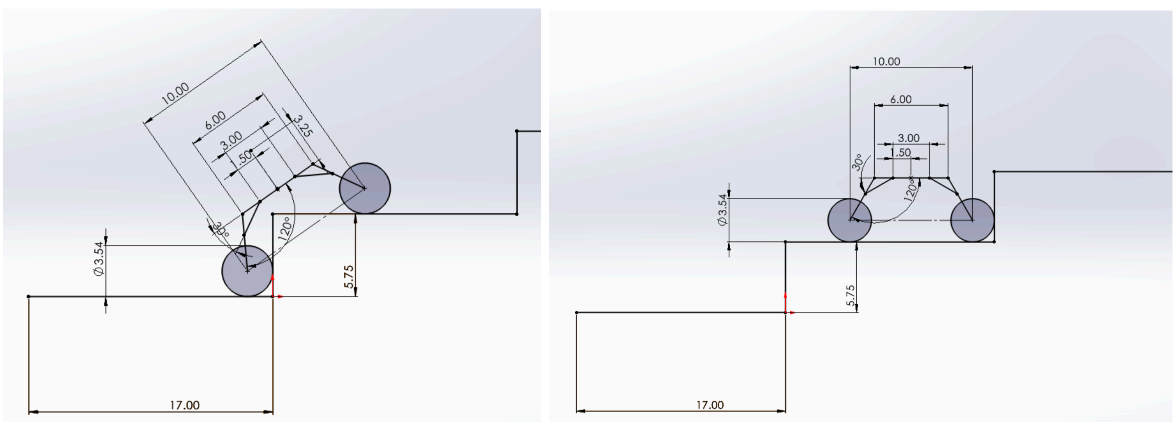


Figure 9 & 10: CAD Drawings of Arched Chassis Climbing Phases

The images above are two phases that we expected the vehicle to go through during the stair climb. They served as our way of understanding the design problem geometrically. Although our study of chassis designs found the curved chassis to be the best, we decided to go with a hybrid of a flat plate and curved. A flat plate would be less geometrically sound for climbing but easier for mounting electronics. Diagonal features could be added to preserve the flat top and achieve a curved design. Using the dimensions of the Engineering Gateway stairs and diameter of the Pollolu wheels, we added additional measurements to denote the possible outline of our initial design.

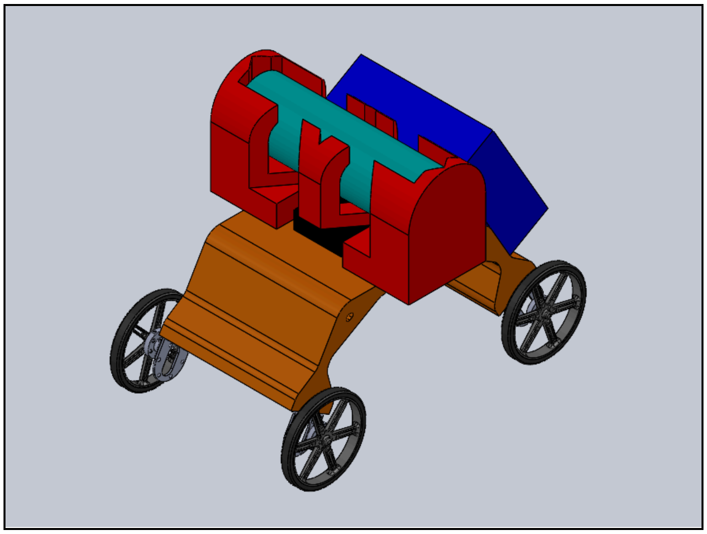


Figure 11: CAD Model of Arched Chassis Design

Component	Optimal Quality	Needed Quantity	Product	Purchase Quantity	Unit Cost	Cost
PETG Filament	Impact and UV Resistance	2	SUNLU PETG 2kg	2	$22.99	$22.99
Wheel	Mounting Holes and Large Diameter	4	Pololu Wheel 90mm x 10 mm	2	$9.49	$18.98
Motor Bracket	37D Motor Compatible	4	Pololu L-Bracket for 37D Motor	2	$11.95	$23.90
Mounting Hub	37D Motor Compatible	4	Pololu Mounting Hub for 6 mm Shaft	2	$12.95	$25.90
						Est. Cost
						$91.77

Table 15: Bill of Materials for Arched Car Design Hardware

Component	Optimal Quality	Needed Quantity	Product	Purchase Quantity	Unit Cost	Cost
Microcontroller	Bluetooth Capable	1	ESP32	3	$15.99	$15.99
Motor	12 V DC Brushed	4	Generic 12V DC 60 RPM	1	$15.89	$63.56
Motor Shield	2 Motors min	1	L298N	4	$9.99	$9.99
Voltage Regulator	12V to 5V DC to DC	1	NOYITO DC to DC	1	$6.99	$6.99
Battery	12V	1	rapthor Rechargeable	1	$20.89	$20.89
Breadboard	Small	1	Breadboard Kit	5	$5.68	$5.68
					Est Cost	
					$123.10	

Table 16: Bill of Materials for Arched Car Design Electronics

Above is an image of our initial CAD design and the initial Bill of Materials. Most of our chassis would be 3D printed out of SUNLU PETG. The electronics housing would be mounted on the face pointing towards the stairs and the water bottle would be mounted in the center. The motors would be attached to metal brackets which would be fixed to the chassis.

Though our sponsor reviewed this preliminary design and strongly recommended making the wheels larger in diameter due to major concerns in the wheels being too small to climb up the stairs. In response, we made a new CAD model using wheels larger in diameter than the step height with the expectation that the wheels would now be 3D printed due to the unavailability of commercial wheels of that size within our budget.

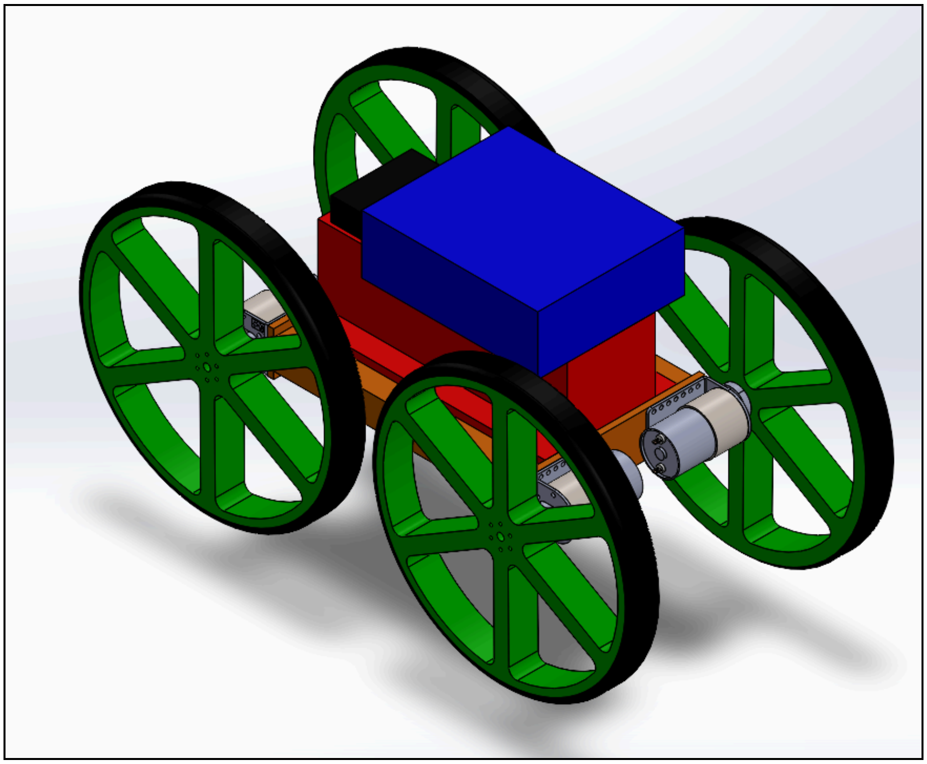


Figure 12: CAD Model of Flat Plate Chassis Design

As shown in Figure 12, this new design switched the chassis to a flat plate as the large wheels no longer risked chassis interference with the stairs. This meant that the chassis could be flat without risking step interference while also making it easier to manufacture and mount items. Though multiple simulations and motion studies in Solidworks with this model consistently displayed the rover slipping on all of the steps due to not having enough tire friction to compensate for the geometry and weight. These simulations never displayed a successful climb with the slipping which convinced us to pivot towards a new design that provided better performance with the larger wheels.

Due to time constraints and familiarity with our original design, we decided to make a new trade study only involving the previous designs using standard wheels as propulsion. The new trade study focuses more on the wheel propulsion and tangibility of the design with the knowledge of the success with the original design.

Table 17: Chassis Subsystem Trade Study

Option	Components	Repairability	Tire Contact Surface Area	Cost	No Chassis-Stair Collision	Force Distribution	Weight	Average
Weights	0.05	0.05	0.2	0.2	0.1	0.2	0.2	1
4-Wheeled Flat Plate	2	2	2	3	2	1	2	2

2-Wheeled Plow	3	1	1	1	1	2	1	1.3
6-Wheeled Rocker-Bogie	1	3	3	2	3	3	3	2.7

Tire contact surface area, cost, force distribution, and weight were weighted the most in the trade study due to these factors contributing the most towards tangibility of the design climbing the stairs while still being within budget. Based on the trade study, the 6-wheeled rocker-bogie design was considered as the best choice for the project with a score of 2.7. Compared to the other two chassis concepts, the rocker-bogie is able to aid climbing the best due to the propulsion method of tire static friction. The need for the tire traction to grip on the stairs in order to roll over them means that the traction is improved with increased contact surface area with the tires to the stairs and decreased opposing forces of the robot working against the friction such as overall weight when the wheels are lifting the robot. Due to the rocker-bogie using the most wheels out of the concepts and having a hinged chassis, the tires have as much surface area as possible and the weights and other opposing forces are separated into segments so that each wheel is only opposed by a single segment of the robot. The bottle storage system was not considered in trade study due to the climbing method being more important to satisfy requirements and was designed after first determining chassis design. For the storage system, it was decided for 2 bottle carriage caps attached to both of the front chassis segments with each one encasing the water bottle that could be attached through screws and regular nuts for ease of removal. The carriage system is placed in the front of the robot to use the weight to prevent the front segment of the robot from flipping over during travel and preventing the climbing motion.

2.2 Critical Design

2.2.1 Critical Design Overview

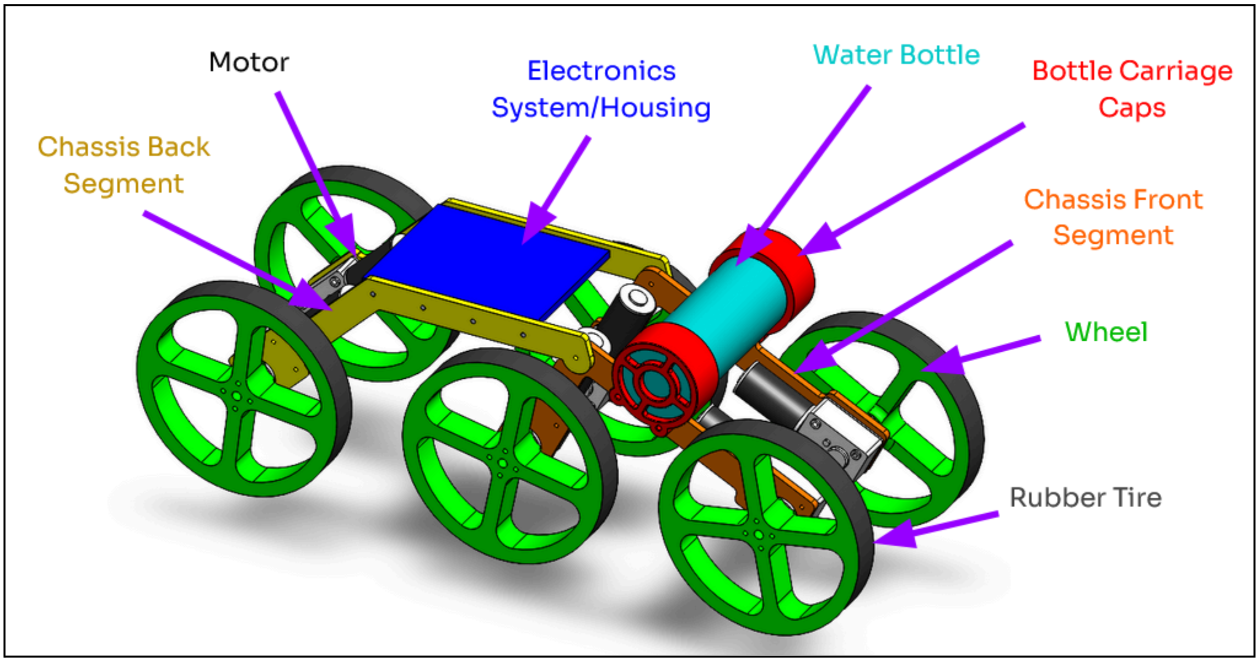


Figure 13: Preliminary 6-Wheeled Rocker-Bogie Design. Design uses hinged chassis and tire friction to crawl up stairs segment by segment.

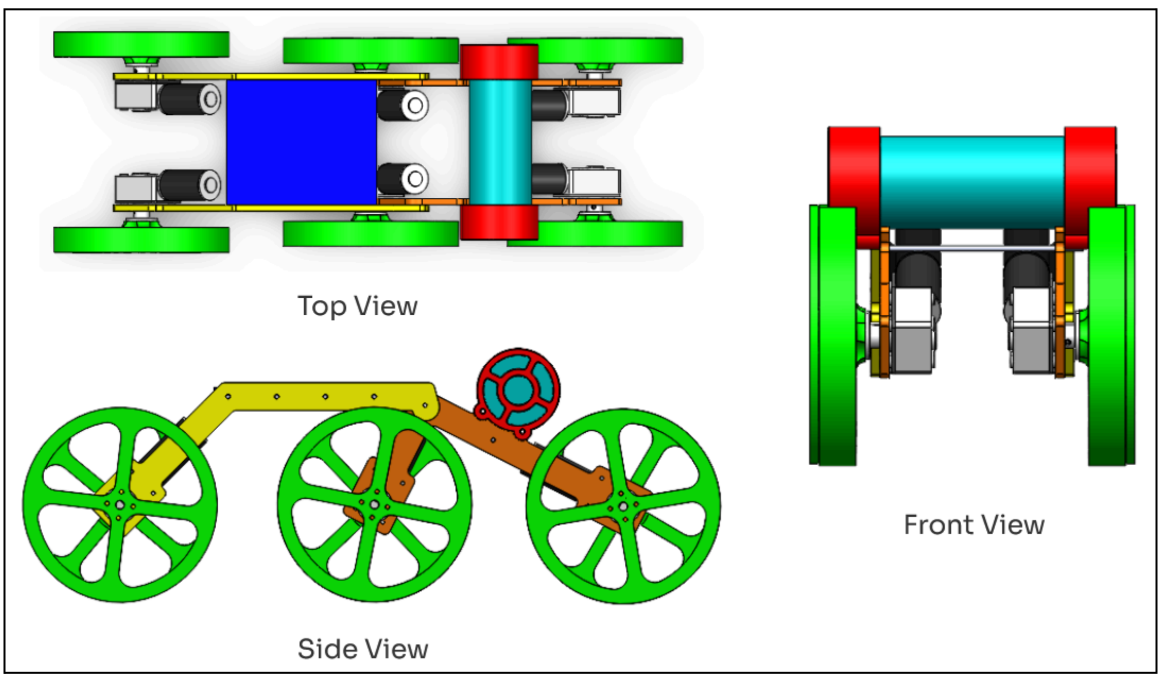


Figure 14: Orthographic Views of Preliminary Design. Overall height from highest point of bottle carriage cap to lowest point of wheels is 11.606 in. Overall length from the farthest lateral point of both front and back wheels is 25.102 in. Overall width from both edges of both wheel thicknesses is 8.799 in.

After deciding to now pursue the rocker-bogie design, a new CAD model was created and analyzed as our critical design. As displayed in Figures 13 and 14, the remote controlled stair climber robot uses a 6-wheeled rocker-bogie design that uses static friction from tire traction to crawl up the stairs. In combination with the 2 segment hinged chassis, the tires allow each wheel pair to roll up the stairs sequentially while disturbing the overall opposing forces among both the chassis segments and wheels for ease of climbing. Each wheel is mounted to its own motor which is wired into the circuit of the electronics subsystem controlled by an EPS 32 chip, which allows bluetooth control of the robot through common devices such as a phone or game controller. The water bottle is also stored in the chassis through 2 bottle carriage caps on the sides of the chassis front. The caps are attached using standard screws and nuts for a secure hold on the bottle during climbing while still being easy to remove.

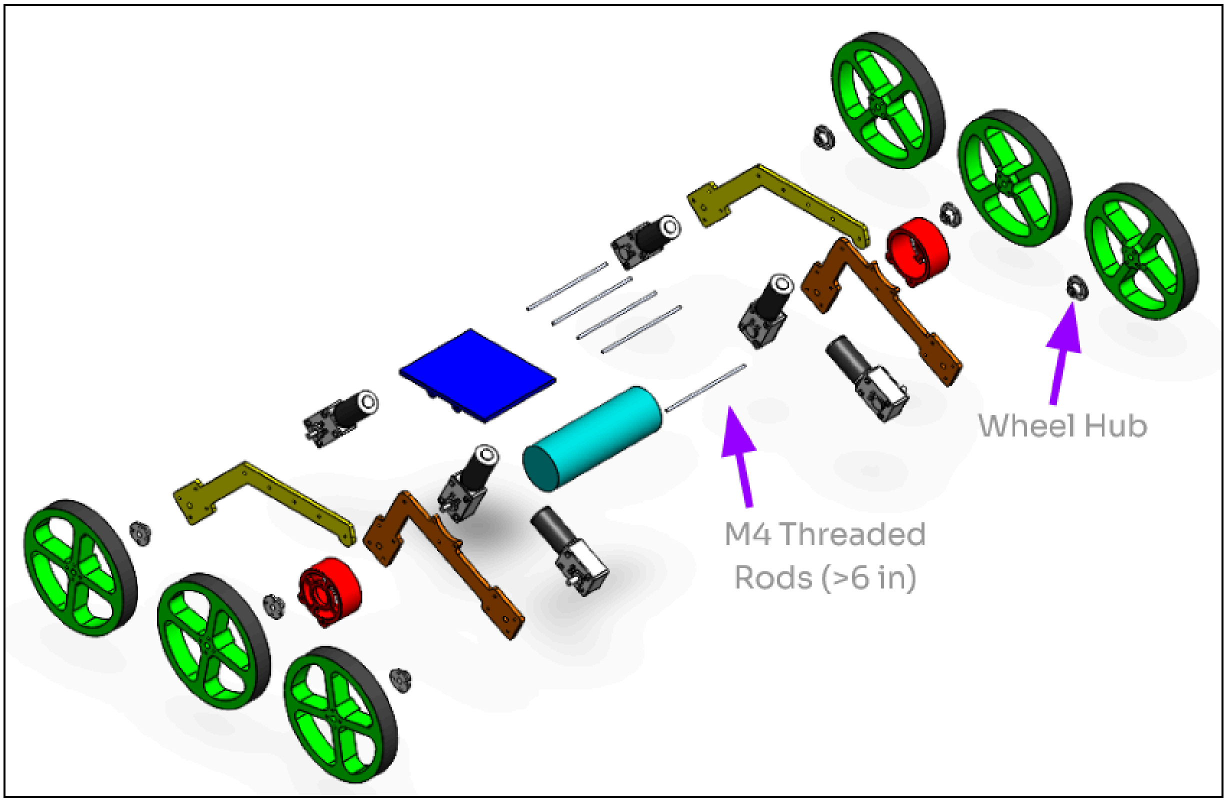


Figure 15: Exploded View of Preliminary Design. Wheels are mounted to motors using 8 mm wheel hubs and left and right chassis assemblies are connected through M4 threaded rods of minimum length 6 in.

Figure 15 depicts the wheels being mounted to the motors through wheel hubs to lock them into the motor rotation. Additionally, the left and right subassemblies of the chassis are connected by threaded rods for lesser overall weight which are also used to attach the electronics subsystem at the top once the housing for it is fully designed.

2.2.2 Component Analysis

Torque and Motor Selection Analysis

Component analysis was conducted using a SolidWorks motion study simulating the rover traversing the Engineering Gateway stairs at a constant motor speed of 27 RPM, from which the required torque per motor was derived. A rubber-on-concrete coefficient of friction value was sourced from an engineering reference table to validate that the Plasti-Dip rubber wheel coating would provide sufficient traction for forward propulsion without slipping. Estimated overall weight of the rover of 4 kg was used when running the simulation.

Figure 16: SOLIDWORKS Motion Analysis Motor Torque Graphs

Material	Against Material	Static Coefficient of Friction	
		Dry Contact	Lubricated Contact
Aluminum	Aluminum	1.10 -1.35	.30
Aluminum-Bronze Alloy	Steel	.46	-
Aluminum	Steel	.61	-
Brake (Composite)	Cast Iron	.40	.21 (wet)
Brass	Steel	.50	.19
Brass	Cast Iron	.28	
Brick	Wood	.60	-
Bronze	Cast Iron	.21	-
Bronze Sintered	Steel	-	.12
Bronze	Steel		.16
Cadmium	Cadmium	.50	.05
Cadmium	Chromium (Chrome)	.40	.35
Cadmium	Steel, Mild	.46	
Carbon	Carbon	.15	.12 - .14
Carbon	Steel	.14	.12 - .14
Cast Iron	Cast Iron	1.1	.08
Cast Iron	Copper	1.05	-
Cast Iron	Oak Wood	.485	.08
Cast Iron	Steel	.40	.21
Cast Iron	Zinc	.85	-
Chromium (Chrome)	Chromium (Chrome)	.41	.34
Colbalt (70°C)	Cobalt	.3	-
Concrete	Rubber	1.0	.30 (wet)

Table 18: EngineersEdge Coefficient of Friction Table

The motion study identified the middle wheel during Phase 2 as the highest torque demand point, with a peak value of approximately 18 kg·cm. Applying a factor of safety of 2.0 yielded a minimum required motor torque of 36 kg·cm. The BRINGSMART 12V 27 RPM worm gear motors were selected with a rated stall torque of 50 kg·cm, satisfying the minimum requirement with an additional margin above the safety factor threshold.

Rocker-Bogie Geometry Analysis

The rocker-bogie chassis geometry was designed around the specific dimensions of the Engineering Gateway staircase, 5.75 inches in rise and 17 inches in run, to ensure continuous wheel contact and chassis clearance across all four climbing phases. The front rocker arm (4 inches), rear rocker arm (8 inches), and bogie arm (5.5 inches) lengths were derived iteratively in SolidWorks to satisfy two conditions simultaneously: no point of the chassis frame contacts the stair edge during any phase, and a minimum of 5 of 6 wheels remain in contact with a stair surface at all times.

The four critical climbing phases and their corresponding chassis pitch angles are shown in the SolidWorks simulation below. Phase 1 occurs as the front wheels first contact the step edge at 63.43°, Phase 2 represents the maximum articulation point as the front wheels crest the step at 101.8°, Phase 3 captures the middle wheels climbing at 27.57°, and Phase 4 shows the rear wheels completing the step transition at 48.99°. A wheel diameter of 7 inches was selected as it satisfies the general rule that wheel diameter should be at least twice the step height (2 × 5.75 = 11.5 inches circumferential contact arc) while remaining within the weight and torque budget of the selected motors.

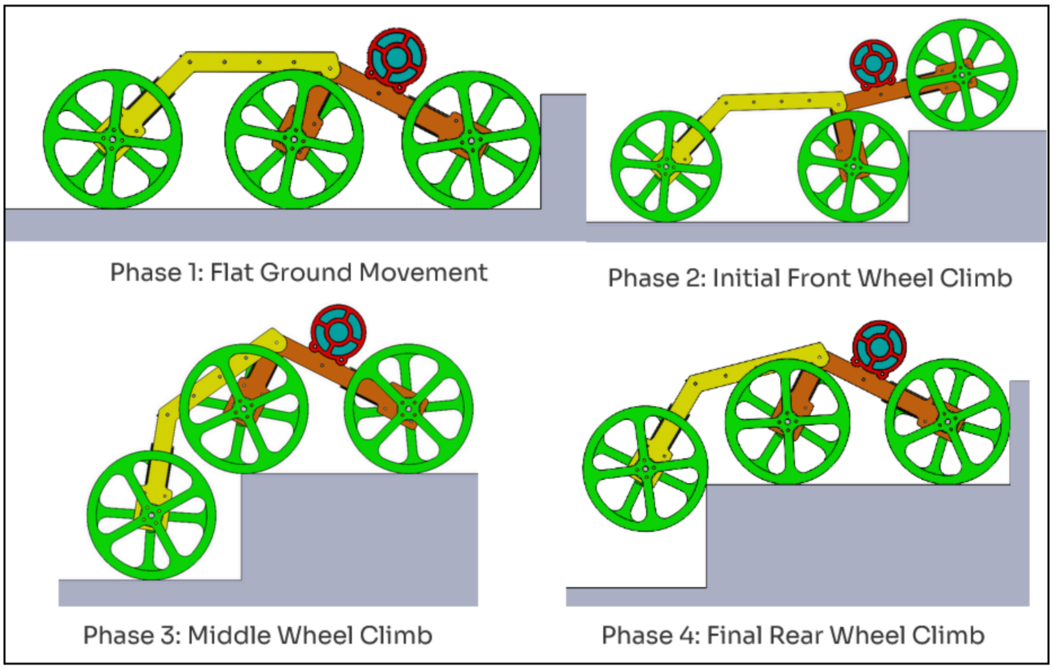


Figure 17: Phases of climbing process

Wheel Selection Analysis

Initial component sourcing identified Pololu 90mm wheels as the baseline commercial solution due to their compatibility with the 37D motor shaft interface and availability within the project budget. However, upon evaluating the rocker-bogie geometry requirements, no commercially available wheel satisfied the necessary criteria simultaneously: a 7-inch (177.8 mm) diameter for step clearance, lightweight, and the ability to connect to wheel hubs. As a result, the team elected to design and manufacture custom wheels.

PETG (Polyethylene Terephthalate Glycol) was selected as the wheel material over alternatives such as PLA and ABS. PETG offered a superior combination of impact resistance and UV stability, the latter being a critical consideration given that all stair climb testing and the competition itself were conducted outdoors in direct sunlight. PLA was eliminated due to its low UV and heat resistance, which risked dimensional creep and structural softening during prolonged outdoor use. ABS was eliminated due to its tendency to warp during printing.

While PETG provided the necessary structural properties, its surface friction against concrete was insufficient to guarantee forward traction on the stair surface. To address this, all six wheels were dip-coated in Plasti-Dip rubber compound. Based on the EngineersEdge coefficient of friction reference table, rubber-on-concrete yields a static coefficient of friction of 1.0, well above the minimum required to prevent slipping under the calculated peak motor torque of 18 kg·cm.

2.2.3 Component Testing

Verification Test #1 - Rocker-Bogie Geometry

The objective of this test was to confirm that the rocker-bogie arm geometry, derived from the Engineering Gateway stair dimensions, produced the four theoretical climbing phase angles without chassis-to-stair contact or tip-over. The rover was manually pushed at a slow constant speed through a three-step climb sequence. The following parameters were recorded via video for frame-by-frame analysis:

- Chassis pitch angle at each of the four climbing phases, measured against a reference protractor
- Any chassis-to-stair contact events
- Tip-over events
- Structural failures or pivot joint binding

Acceptance criteria required successful completion of all three steps, zero tip-over or structural failure events, pitch angles within ±5° of the four theoretical values (63.43°, 101.8°, 27.57°, 48.99°), and chassis clearance maintained above 0.25 inches throughout all phases.

Results: The rover successfully completed the three-step climb without tip-over, structural failure, or chassis-to-stair contact. Pitch angles measured at the four climbing phases were 60°, 105°, 35°, and 55°, yielding deviations of 3.43°, 3.2°, 7.43°, and 6.01° from theoretical values respectively. Phases 1 and 2 fell within the ±5° marginal tolerance. Phases 3 and 4 exceeded the marginal tolerance, attributed to manual push speed variability and lateral drift during testing rather than a geometric design flaw, as chassis clearance was maintained throughout with no contact events observed. The rocker-bogie geometry was confirmed as mechanically feasible and cleared for final fabrication.

Verification Test #2 - Wheel Traction

The objective of this test was to verify that the Plasti-Dip rubber wheel coating provided sufficient static friction against a concrete stair surface to propel the vehicle forward without slipping. This test was conducted independently from the geometry validation to isolate traction performance as a standalone variable. A single 5.75-inch concrete step was used as the test surface. The rover was placed with its front wheels against the step face and driven under motor power, while the following parameters were observed:

- Presence of wheel slip events at the stair contact surface
- Ability of the front wheels to initiate and complete the step-over transition under motor torque

- All-wheel ground contact during the climb transition

Acceptance criteria required zero wheel slip events on the concrete surface, successful front wheel step-over under motor power alone, and a minimum of 5 of 6 wheels maintaining contact with a stair surface during the transition.

Results: No wheel slip events were observed during the single-step motorized climb. The front wheels initiated and completed the step-over transition under motor power without manual assistance, confirming that the Plasti-Dip coating achieved sufficient rubber-on-concrete static friction. All 6 wheels maintained stair contact throughout the transition, satisfying the all-wheel contact acceptance criterion. Traction performance was validated, and no modifications to the wheel coating process were required prior to final assembly.

2.2.4 FMEA

A Failure Mode and Effects Analysis was conducted to identify potential failure modes across all subsystems and prioritize corrective actions before final fabrication. Each failure mode was assigned Severity (SEV), Occurrence (OCC), and Detectability (DET) scores, which were multiplied to produce a Risk Priority Number (RPN) used to rank overall risk. The results are summarized in the table below.

Process	Failure Mode	Failure Effect	SEV	Causes	OCC	Process Controls	DET	RPN	Further Actions
Secure water bottle	Slide or fall off	Competition failure	9	Improper design or assembly	1	3D print new design	1	9	Works geometrically. Test via trials up the stairs
Chassis breaks	Impact or competition stresses	Poor competition performance	8	Improper handling or assembly	1	Laser cut new chassis	1	8	Works geometrically. Test via trials up the stairs
Chassis segments misaligned	Unsymmetrical force distribution	Potential minimal performance impact	3	Vibration or improper assembly	2	Inspect and adjust	1	6	Should not be an issue
Improper wiring	Loss of electrical response	Loss or insufficient motor torque	8	Misplaced wiring or component	1	Test and follow schematic	1	8	Incorrect wiring can easily be fixed
Insufficient motor torque	Slow or no rotation over the stairs	Competition failure	10	Lack of power or excess load	4	Keep load specs near simulation	4	160	Ensure minimal deviation from the simulated design
Insufficient friction from rubber coating	Slow or no rotation over the stairs	Competition failure	10	Inadequate rubber coat	2	Add new coat or remake wheel	6	120	Good coat can mitigate the risk. New coat or wheel can be made
Parts over budget	Additional/replacement parts exceed budget	Parts sold or personal money used	7	Part broken or unaccounted for	2	Careful handling and follow BOM	2	28	Should not be an issue if no parts break unexpectedly

Table 19: Failure Mode and Effects Analysis Table

2.2.5 Compliance Table

The compliance table below documents the verification status of all project requirements against their specified target values. Requirements were verified through a combination of physical measurement, component testing, verification tests, and the final competition demonstration. Requirements associated with the control system are marked N/A following the decision to simplify the electrical system to a direct battery-motor wiring configuration in the final design.

Req ID	Type	Description	Target Value	Verification Method	Status	Comments
FR-1	Functional	Transport water bottle up all 19 stairs	19 steps	Competition demonstration	Verified	Successfully completed during competition
FR-2	Functional	Ground-based climbing only	100% ground contact	Observation	Verified	All 6 wheels maintained ground contact
FR-3	Functional	Remote operation	Remote controlled	Demonstration	N/A	Direct wiring implemented; control system removed from final design
FR-4	Functional	Water bottle loading/unloading	≤30 seconds	Timed test	Verified	Carriage cap design allows quick load/unload
FR-5	Functional	Rocker-bogie articulation	0 binding events	Physical inspection + climb test	Verified	All pivot joints articulated freely throughout climb
PR-1	Performance	Total climb time	≤120 seconds	Timed test on EG stairs	Verified	Climb completed within marginal value
PR-2	Performance	Payload security	≤0.5 inch displacement	Visual inspection	Verified	Bottle remained secure throughout climb
PR-3	Performance	Obstacle clearance	≥5.75 inches	Direct measurement + climb test	Verified	7-inch wheel diameter satisfies clearance requirement
PR-4	Performance	Ground clearance	≥0.25 inch	Measurement during climb	Verified	Confirmed via geometry testing
PR-5	Performance	All-wheel ground contact	≥5 wheels	Visual observation	Verified	All 6 wheels maintained contact during climb
PR-6	Performance	Motor speed (no-load)	≥20 RPM	Direct measurement	Verified	BRINGSMART motors rated 27 RPM no-load
PR-7	Performance	Battery runtime	≥5 minutes	Endurance test	Verified	Battery sustained multiple full staircase runs
PR-8	Performance	Chassis pitch angle Phase 1	63.43° ± 5°	Video measurement	Verified	Measured 60° during testing
PR-9	Performance	Chassis pitch angle Phase 2	101.8° ± 5°	Video measurement	Verified	Measured 105° during testing

PR-10	Performance	Chassis pitch angle Phase 3	27.57° ± 5°	Video measurement	Partial	Measured 35°; outside marginal tolerance, attributed to manual push variability
PR-11	Performance	Chassis pitch angle Phase 4	48.99° ± 5°	Video measurement	Partial	Measured 55°; outside marginal tolerance, attributed to manual push variability
PR-12	Performance	Maximum vehicle weight	≤4 kg	Scale measurement	Verified	Final assembly within weight budget
PR-13	Performance	Wheel traction	≤2 slip events	Visual observation	Verified	No slip events observed during traction test
DR-1	Design	Wheel diameter	7.0 ± 0.1 inches	Caliper measurement	Verified	Confirmed during PoC
DR-2	Design	Rocker arm length (front)	4.0 ± 0.1 inches	Ruler measurement	Verified	Confirmed during PoC
DR-3	Design	Rocker arm length (rear)	8.0 ± 0.1 inches	Ruler measurement	Verified	Confirmed during PoC
DR-4	Design	Bogie arm length	5.5 ± 0.1 inches	Ruler measurement	Verified	Confirmed during PoC
DR-5	Design	Wheelbase	25 ± 1 inches	Direct measurement	Verified	Confirmed during PoC
DR-6	Design	Chassis width	8.8 ± 0.2 inches	Direct measurement	Verified	Confirmed during PoC
DR-7	Design	Total vehicle height	≤15 inches	Direct measurement	Verified	Confirmed during PoC
DR-8	Design	Motor voltage	12V DC	Multimeter	Verified	Battery voltage confirmed 12V
DR-9	Design	Battery voltage	12V	Multimeter	Verified	Confirmed prior to competition
DR-10	Design	Control system voltage	3.3V	N/A	N/A	Control system removed from final design
E-1	Electrical	Battery voltage	12V	Multimeter	Verified	—
E-2	Electrical	Motor operation	27 RPM	Direct measurement	Verified	Confirmed on all 6 motors
E-3	Electrical	ESP32 / converter / L298N voltages	3.3V / 5V / 12V	N/A	N/A	Direct battery-motor wiring implemented; microcontroller removed from final design

Table 20: Compliance Table

2.3 Final Design

2.3.1 Final Design Overview and Specifications

The final design is the same as the critical design with the additions of the electronics plate, brackets, and chassis grips while also having a reduced circuit compared to the previous version. The circuit is a simplified version by only being composed of the battery, breadboard, and motors. The added components helped in both chassis stability and creating a place to secure the electronics. The specifications of the final prototype include a length of 25 $\frac{3}{16}$ inches, width of 9 ⅝ inches, height of 8 ⅛ inches, weight of 4840.4 grams, wheel diameters of 7-7 ⅛ inches, battery voltage of 11.37 V, and current of over 10 A. The remainder of this section depicts CAD images of the final design and drawing files for all manufactured components.

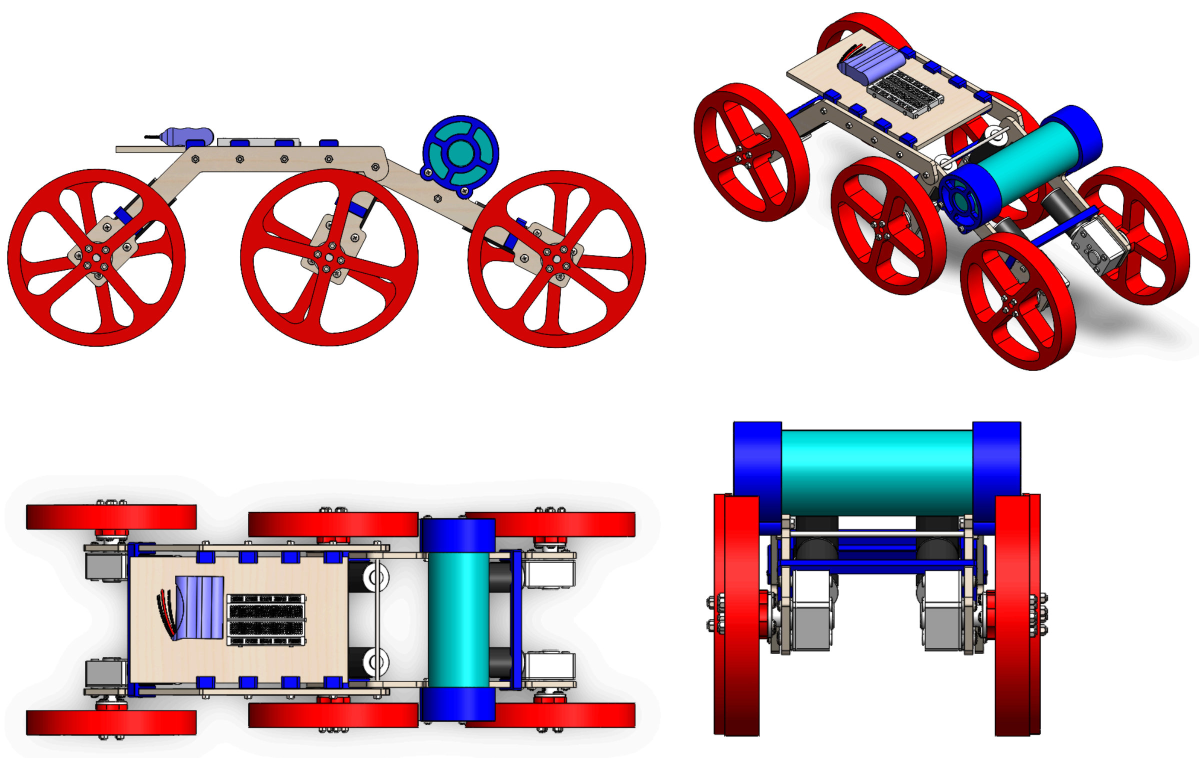


Figure 18: Orthographic Views of Final Design

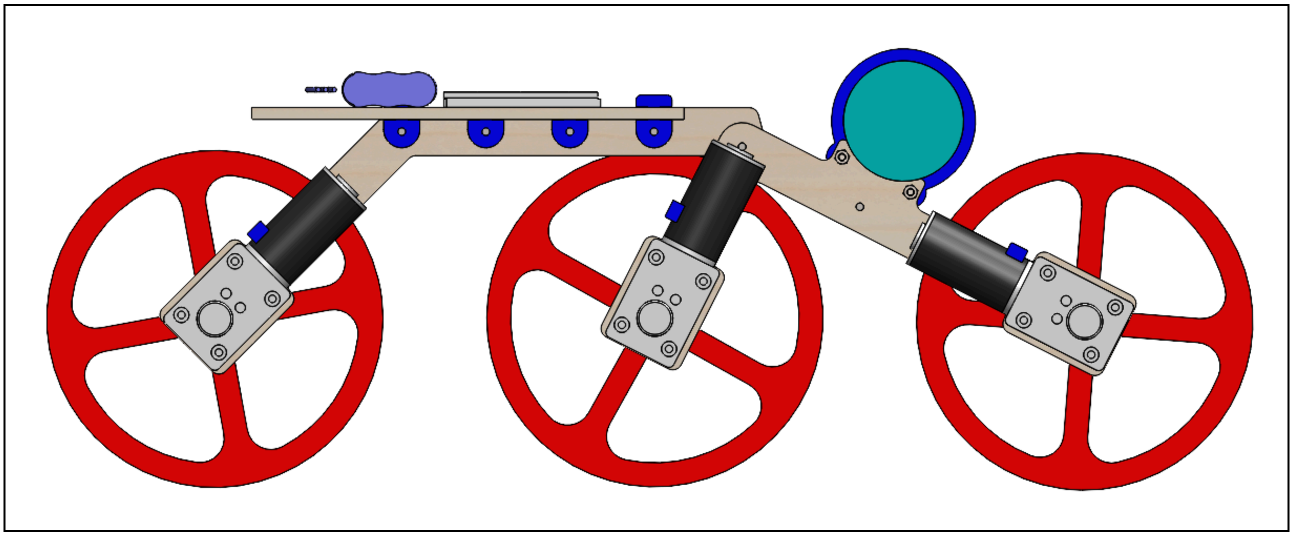


Figure 19: Section View of Final Design

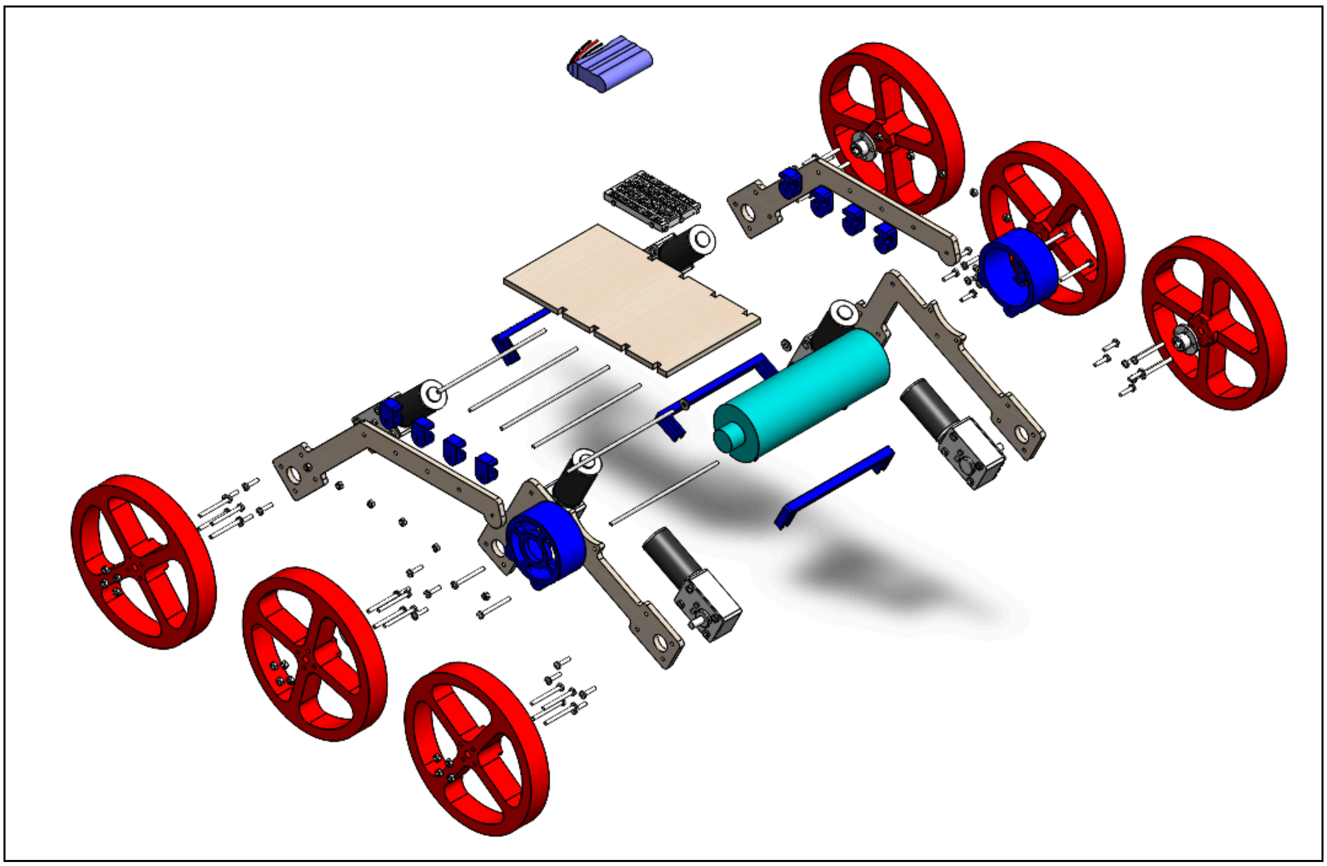
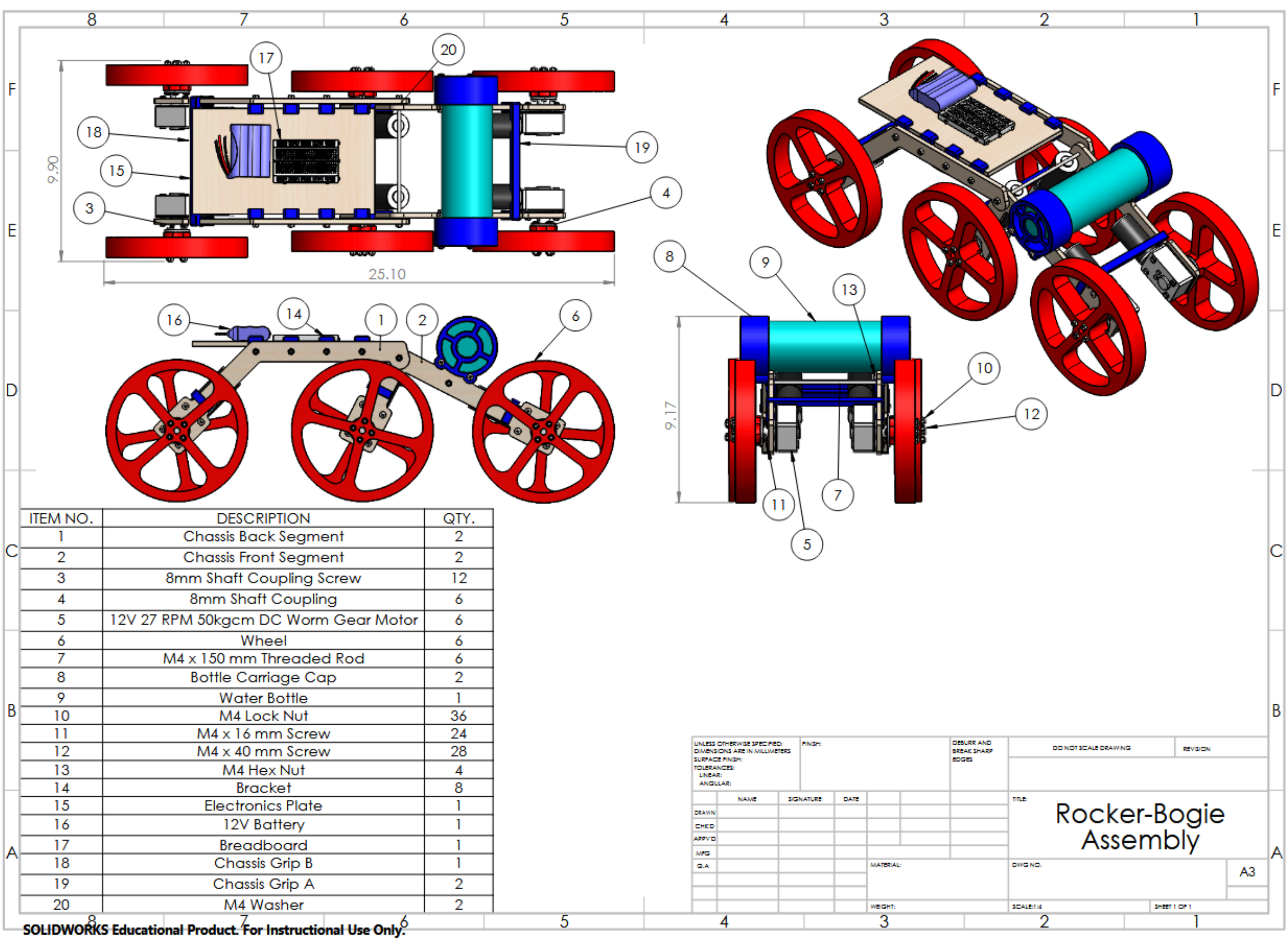


Figure 20: Exploded View of Final Design



ITEM NO.	DESCRIPTION	QTY.
1	Chassis Back Segment	2
2	Chassis Front Segment	2
3	8mm Shaft Coupling Screw	12
4	8mm Shaft Coupling	6
5	12V 27 RPM 50kgcm DC Worm Gear Motor	6
6	Wheel	6
7	M4 x 150 mm Threaded Rod	6
8	Bottle Carriage Cap	2
9	Water Bottle	1
10	M4 Lock Nut	36
11	M4 x 16 mm Screw	24
12	M4 x 40 mm Screw	28
13	M4 Hex Nut	4
14	Bracket	8
15	Electronics Plate	1
16	12V Battery	1
17	Breadboard	1
18	Chassis Grip B	1
19	Chassis Grip A	2
20	M4 Washer	2

Figure 21: Assembly Drawing of Final Design

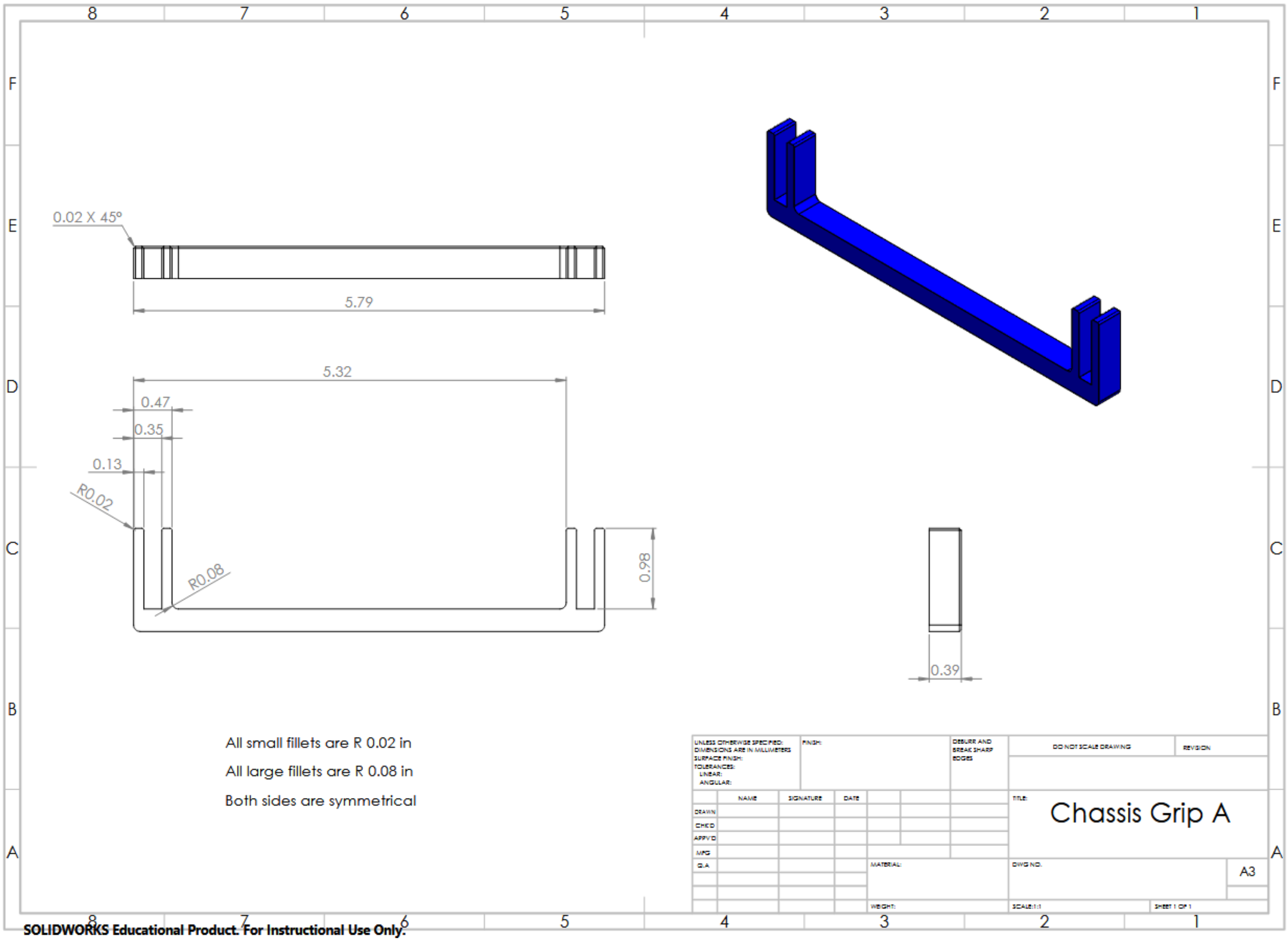


Figure 22: SolidWorks Drawing of Chassis Grip A (3D Printed)

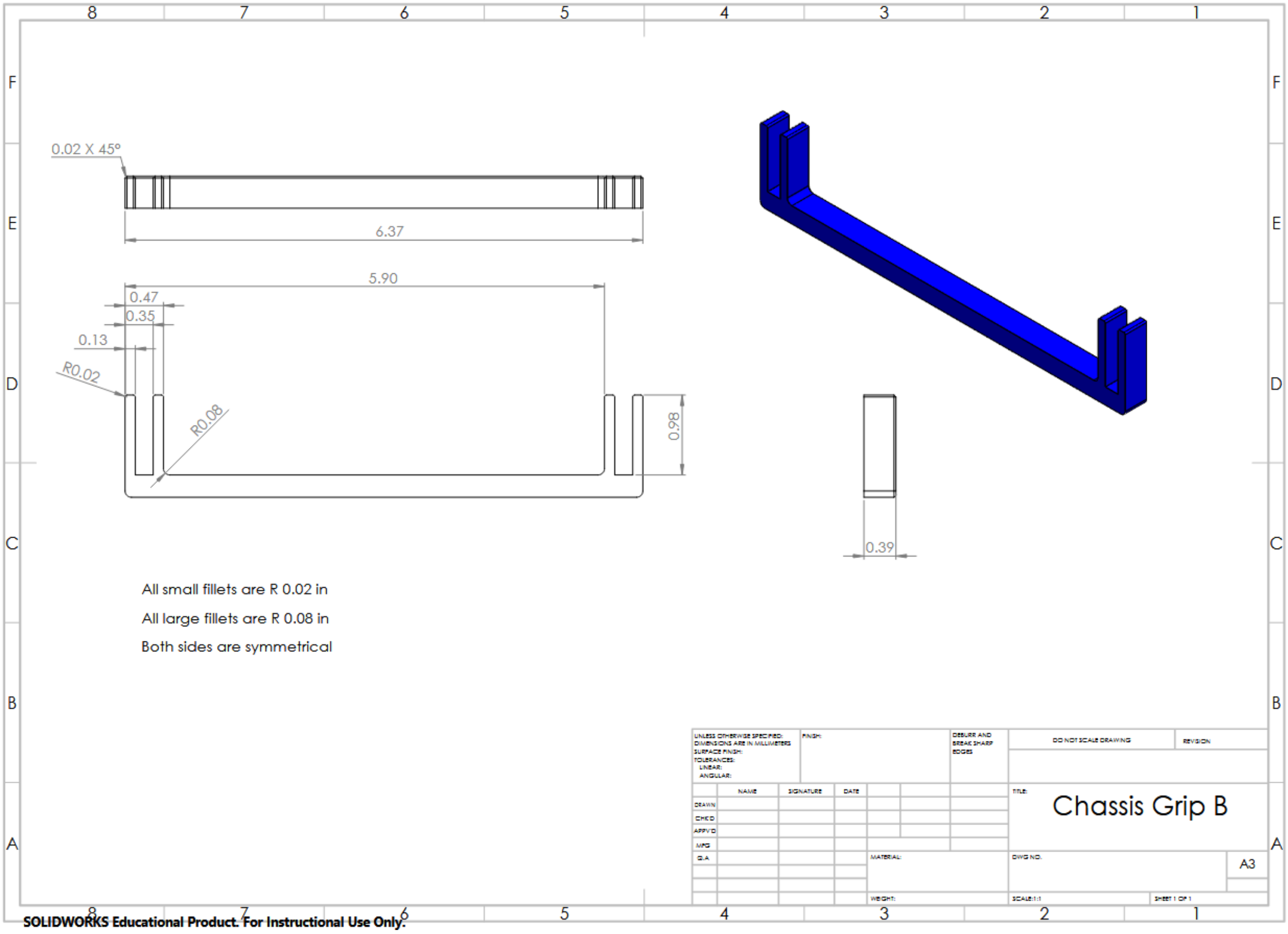


Figure 23: SolidWorks Drawing of Chassis Grip B (3D Printed)

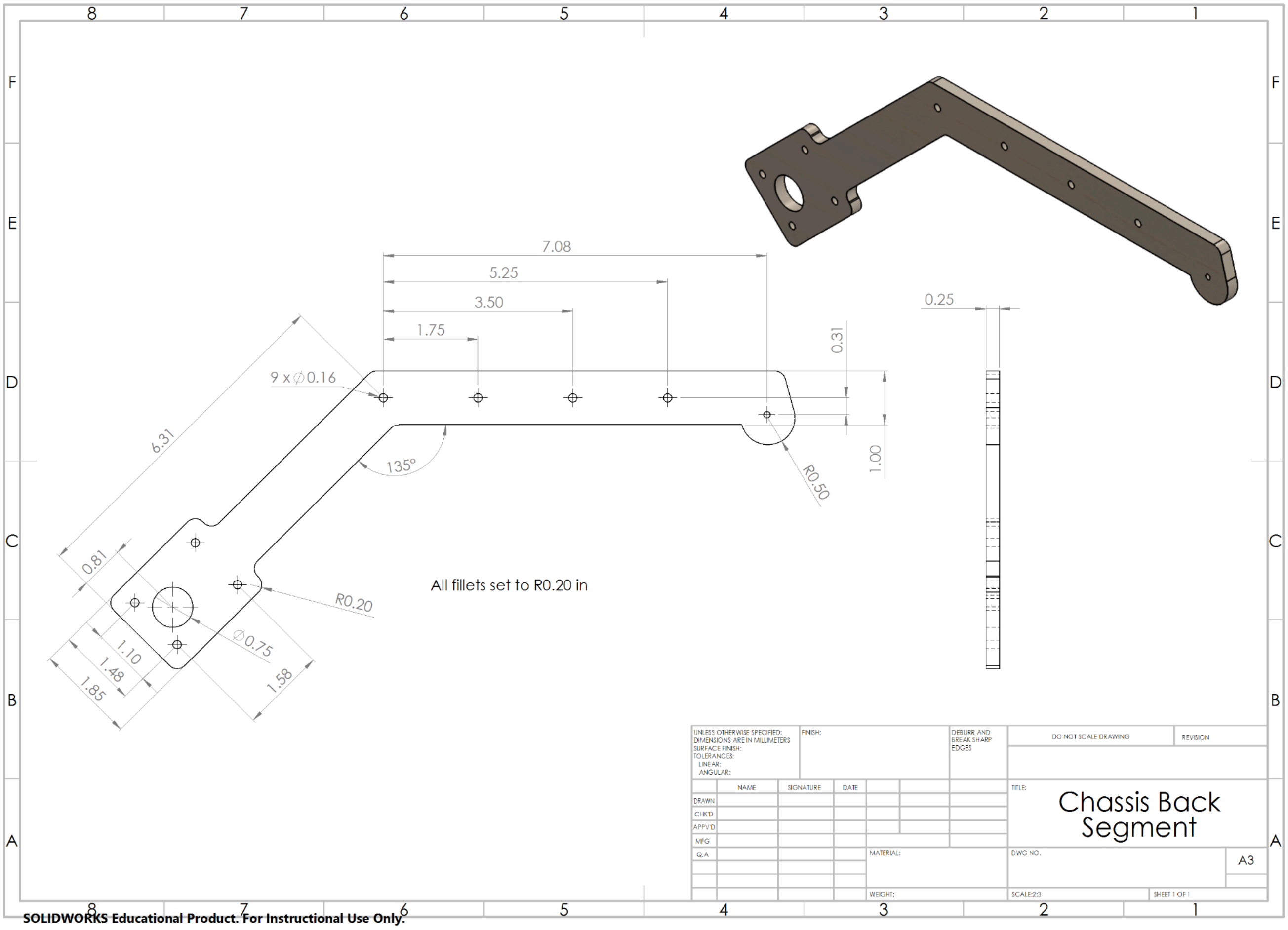


Figure 24: SolidWorks Drawing of Chassis Back Segment (Laser Cut)

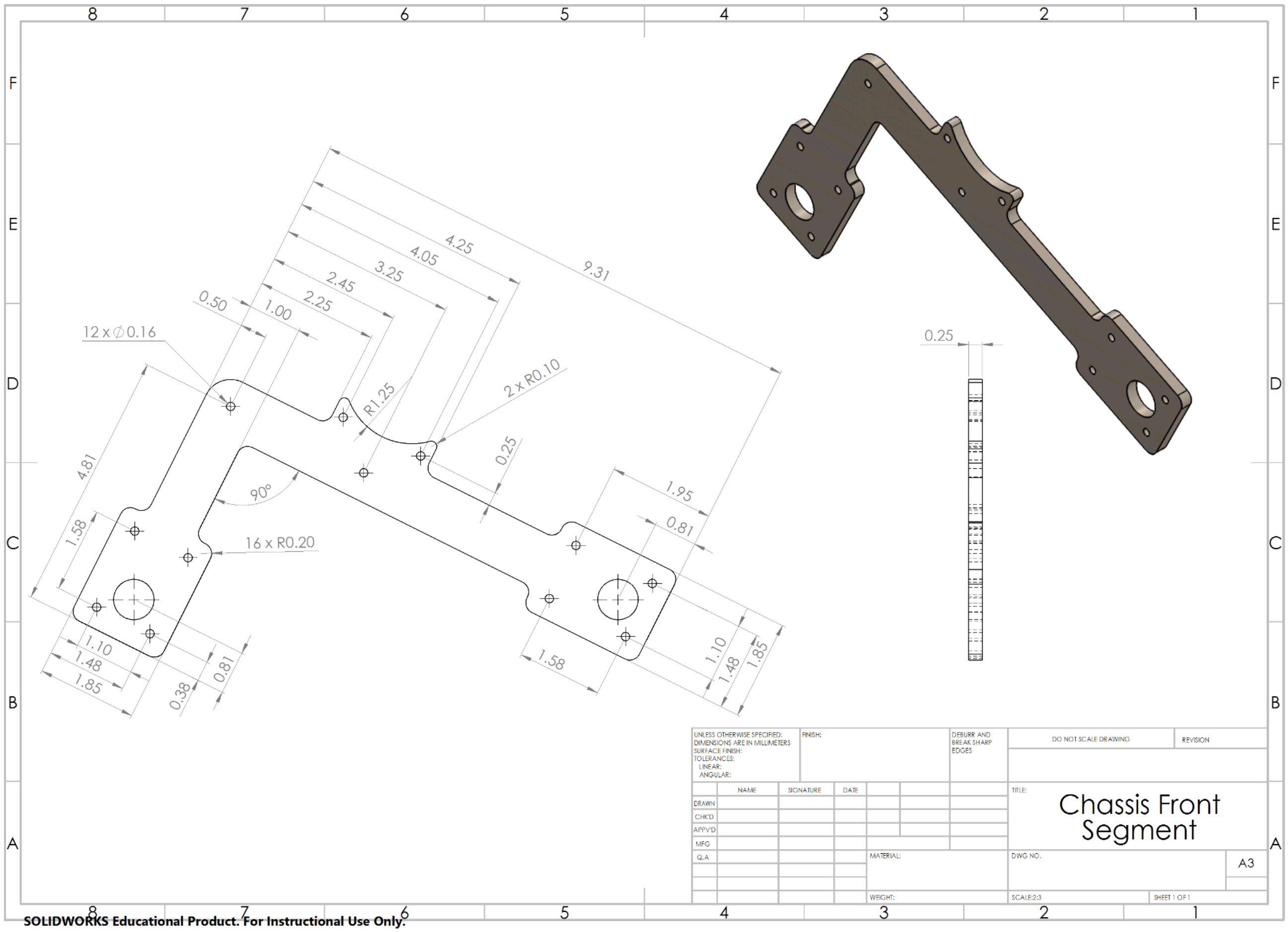


Figure 25: SolidWorks Drawing of Chassis Front Segment (Laser Cut)

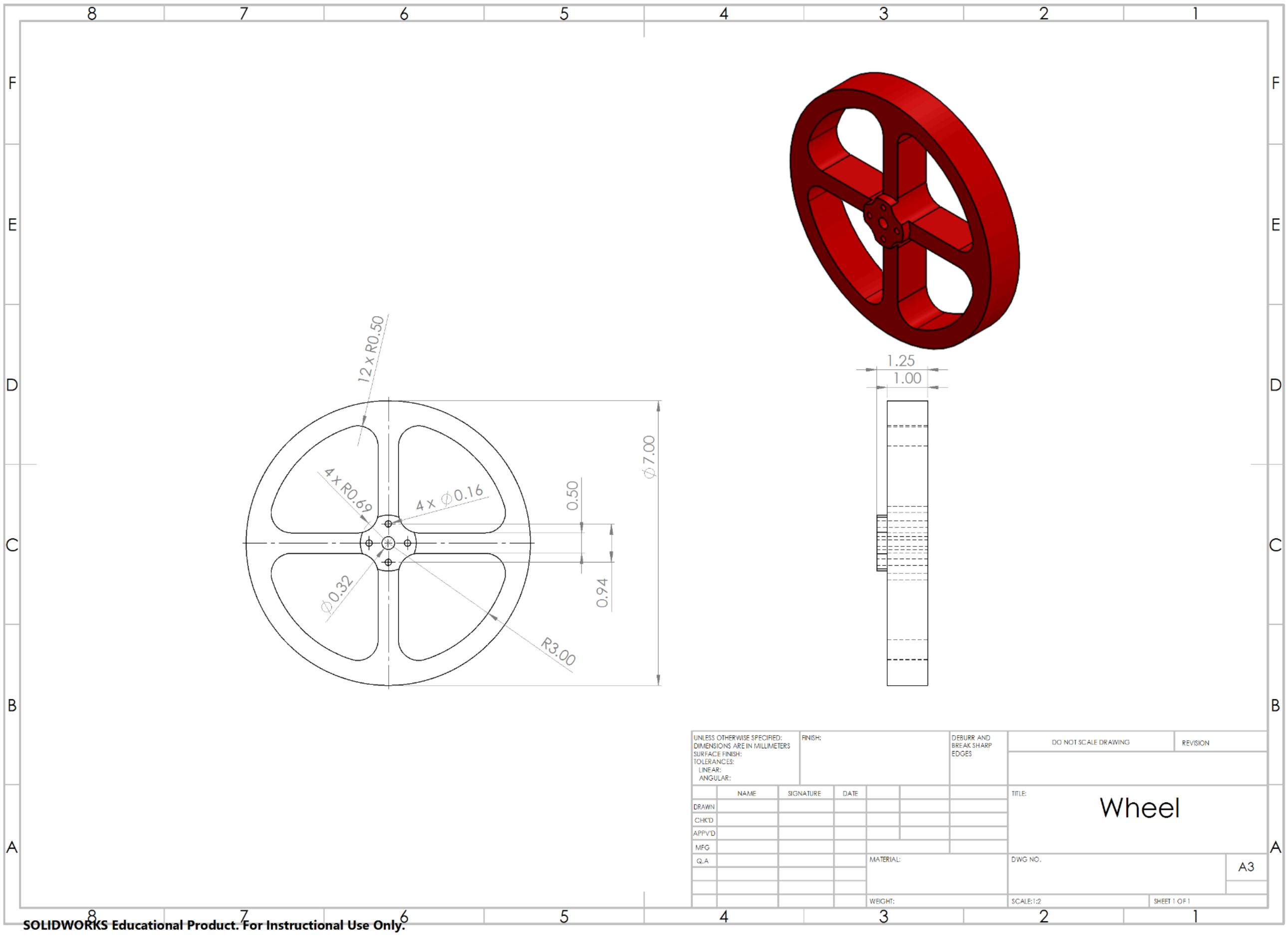


Figure 26: SolidWorks Drawing of Wheel (3D Printed)

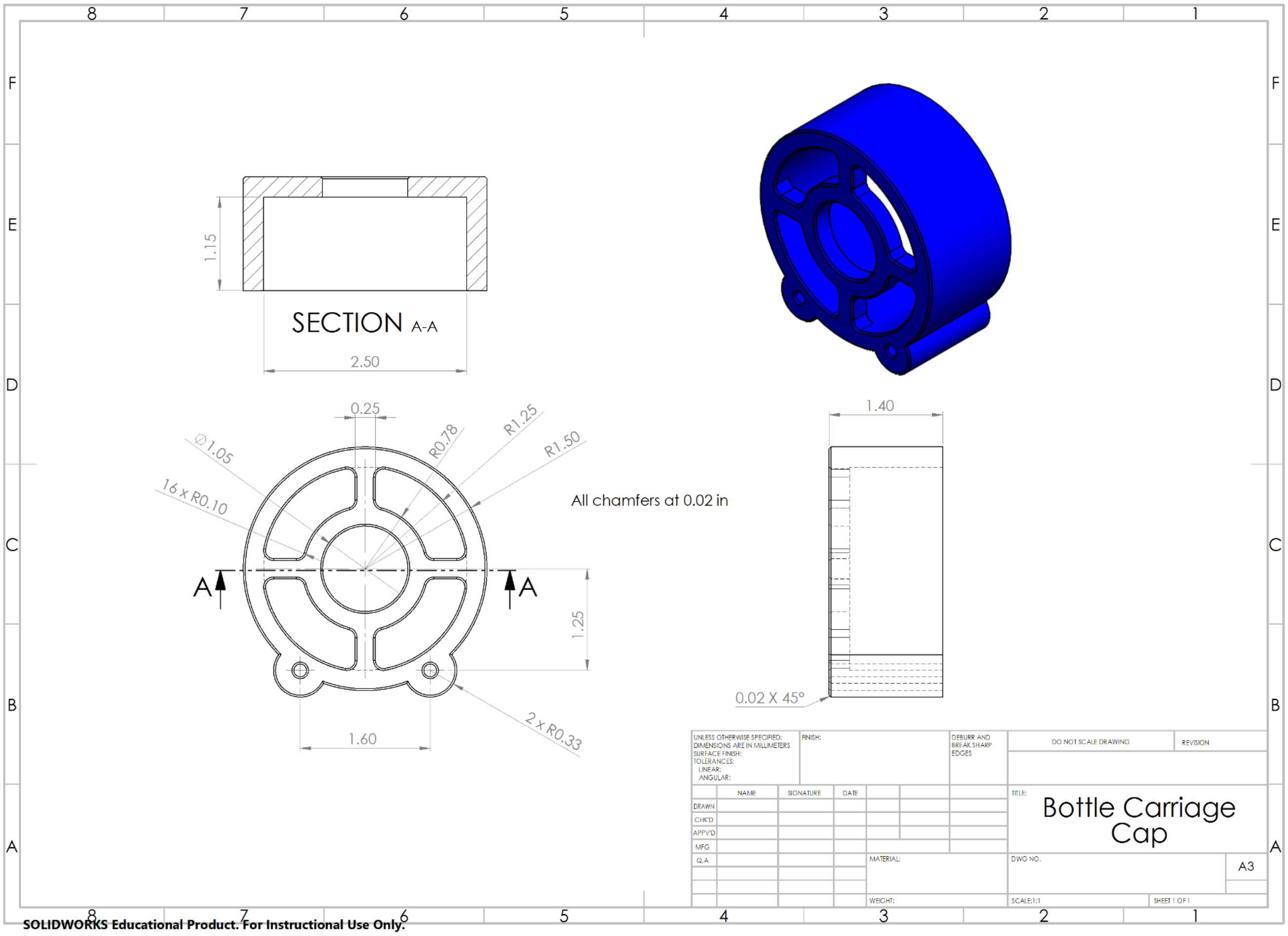


Figure 27: SolidWorks Drawing of Bottle Carriage Cap (3D Printed)

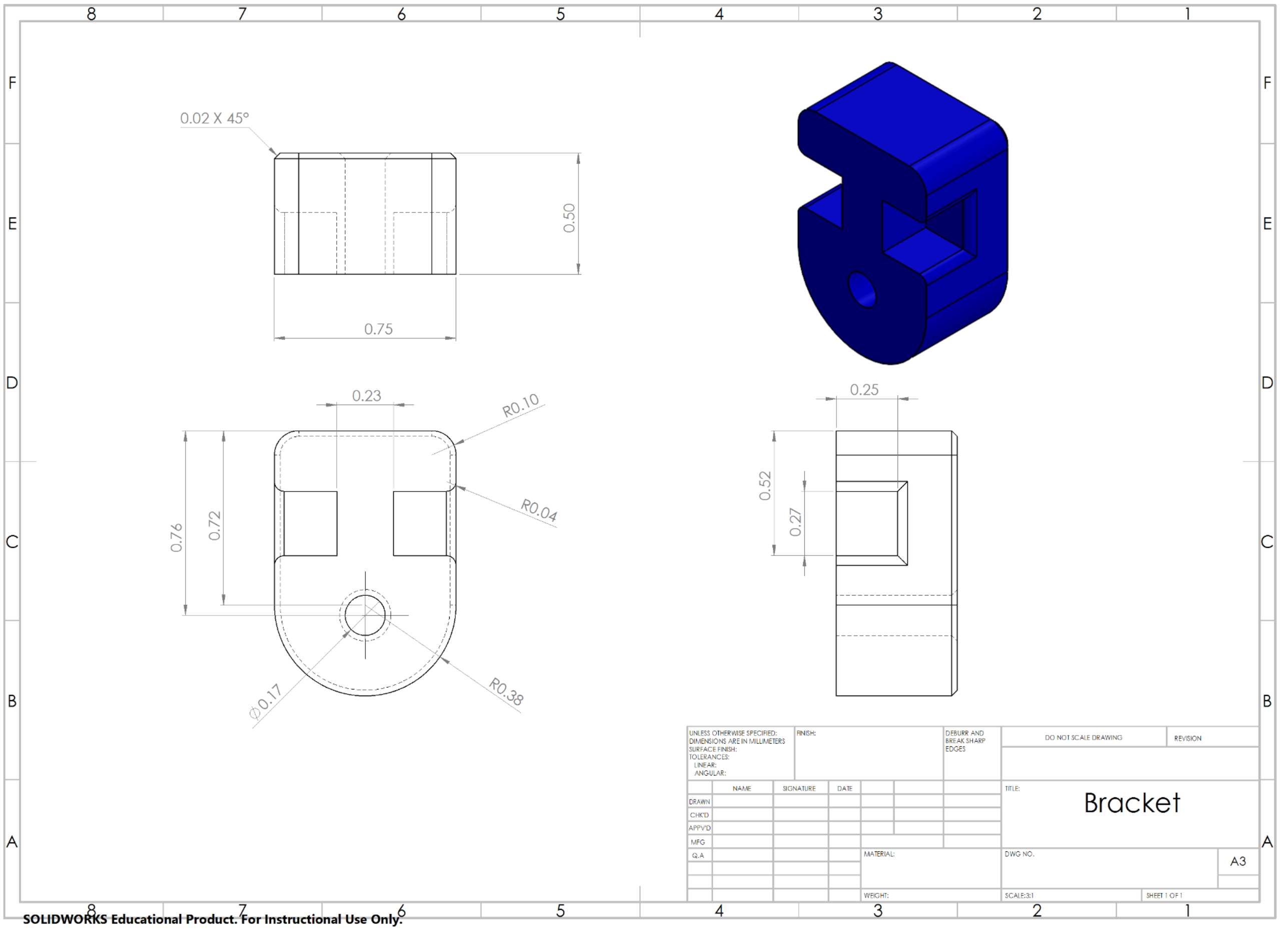


Figure 28: SolidWorks Drawing of Bracket (3D Printed)

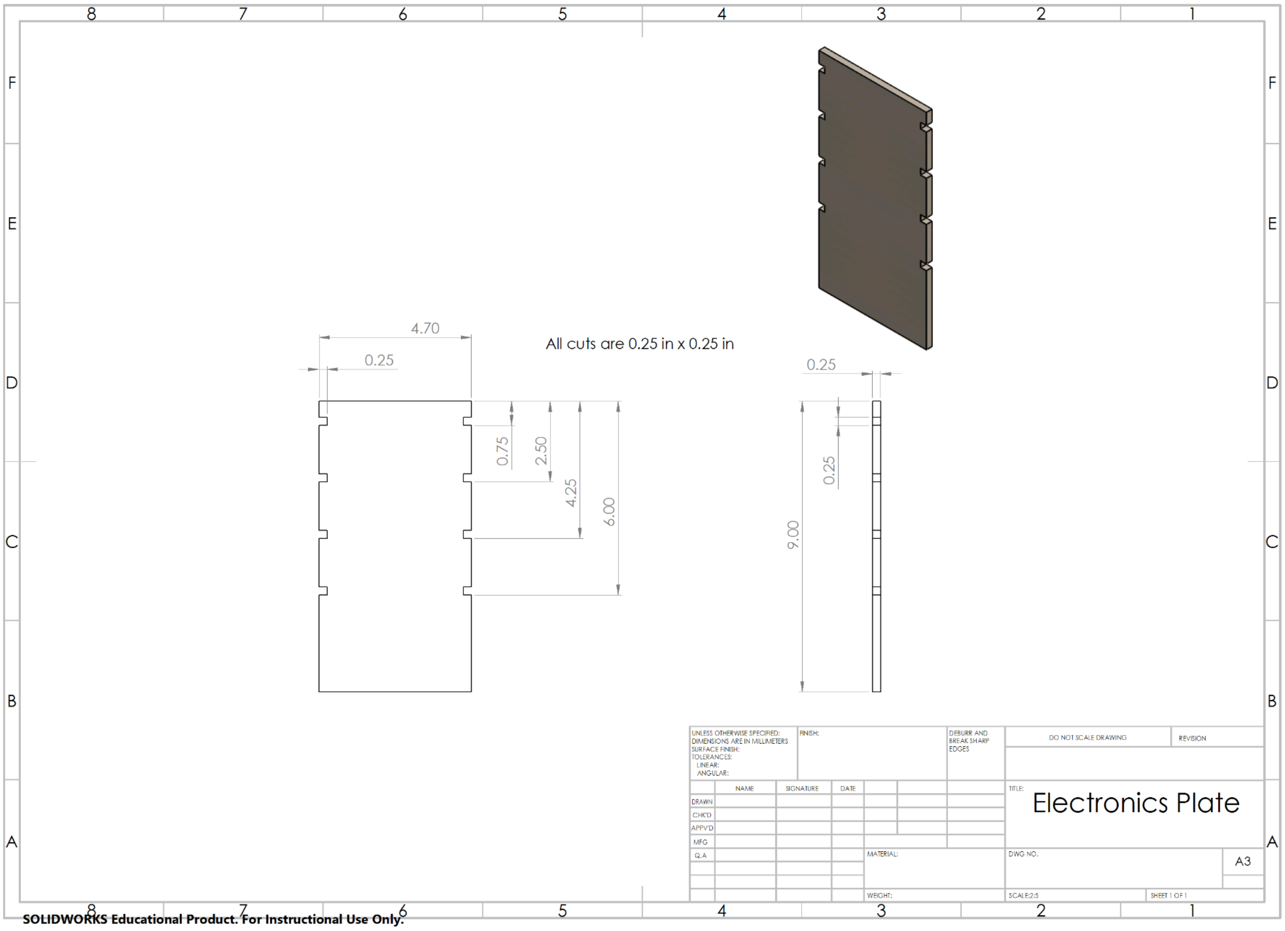


Figure 29: SolidWorks Drawing of Electronics Plate (Cut with Bandsaw)

2.3.2 Design Validation

Validation of the final design was performed by running the assembled rover up the full Engineering Gateway staircase. During the competition with the other stair-climbing teams, the rover successfully completed the climb from the bottom to the top step, while transporting the water bottle payload without any displacement or spillage. There were no chassis-to-stair contact events, and all six wheels maintained ground contact throughout the full climb. The best recorded run of the rover from touching the lowest step to finishing the climb of the furthest step was approximately 82 seconds.

The validation run confirmed that the rocker-bogie design procured during the critical design phase was capable of climbing the Engineering Gateway stairs. The Plasti-Dip coating helped provide sufficient traction across all of the 19 steps without any slip events observed. The water bottle carriage cap retained the payload securely through all four climbing phases, including the high-pitch-angle Phase 2 transition, which represents the maximum articulation and greatest risk of payload displacement.

The vehicle completed the climb within the marginal value of 120 seconds established in PR-1, satisfying the performance requirement for competition. The validation run is considered a full-system success: all Must Have requirements (FR-1, FR-2, FR-5, PR-2, PR-3, PR-4, PR-5, PR-13) were demonstrated to be met in a single uninterrupted climb under real staircase conditions.

2.3.3 Uncertainty and Error Analysis

Traction Coefficient Uncertainty

The coefficient of friction value from the EngineersEdge engineering reference table of 1.0 was used to confirm that the rubber-on-concrete contact would provide sufficient traction under the calculated peak motor torque. This value represents the nominal dry contact condition, while in practice, the coefficient of friction for rubber on concrete varies with surface texture, dust/particles, moisture, and normal force distribution among the six wheels. The actual coefficient experienced by the Plasti-Dip coated wheels on the Engineering Gateway concrete surface may differ from the tabulated value by an estimated ±0.1 to ±0.2. Despite initial motion analysis simulations being completed using this theoretical value, it is not considered to pose a design risk, as the rover completed the climb and satisfied the traction requirement. Zero wheel slip events were observed during the full competition run, showing adequate traction in field conditions.

Battery and Electrical System Uncertainty

The direct battery-to-motor wiring configuration, while effective at eliminating control system complexity, introduced a significant and underestimated source of uncertainty: unregulated current draw under load. With all six motors wired in parallel directly to the 12V battery and no motor driver or current-limiting circuitry in the system, each motor drew its full operating current simultaneously during stair climbing, particularly during high-torque transitions such as Phase 2, where peak demand across all six motors occurred concurrently. This produced sustained high-current conditions in the wiring harness that the wire gauge and connector ratings were not sized to handle continuously.

The thermal consequences of this design were observed progressively during repeated test runs. The failure mode culminated in the complete thermal failure of one of the recharge cable wires, which burned through entirely and rendered the battery unable to be recharged for the remainder of testing.

The key sources of uncertainty in the electrical system were the actual peak current draw under combined motor load, which was estimated from motor specifications rather than measured directly, and contact resistance at crimp and solder joints. These uncertainties underscore the risks of the simplified direct-wiring approach adopted late in the design process. Future design iterations should reimplement a proper electrical system, dedicated motor drivers for current regulation, and a microcontroller-based software architecture with PWM speed control and fault protection.

Chassis Pitch Angle Measurement Uncertainty

Pitch angles at the four climbing phases were measured by reviewing slow-motion video footage frame-by-frame against a reference protractor held adjacent to the chassis. This method introduces several error sources. The protractor was hand-held and subject to parallax error, estimated at ±2–3°. The specific frame selected as the "peak" of each phase is subjective, as the transition between phases is continuous rather than discrete, introducing an additional ±2° of reading uncertainty. Combined, total measurement uncertainty for the pitch angle readings is estimated at ±4–5°.

Phases 1 and 2 yielded measured values of 60° and 105°, deviating from theoretical values of 63.43° and 101.8° by 3.43° and 3.2° respectively, both within the ±5° marginal tolerance. Phases 3 and 4 measured 35° and 55°, deviating from 27.57° and 48.99° by 7.43° and 6.01°, both outside the marginal tolerance. These deviations are consistent with the identified sources of measurement error combined with manual push speed variability during the three-step geometry test, which introduced dynamic effects not present in the quasi-static SolidWorks simulation. To mitigate the risk of the rocker assembly flipping beyond its intended articulation range during climbing, a 3D printed hard stop was incorporated at the central pivot joint, physically limiting the maximum rotation angle of the front rocker segment. This ensured that even under dynamic conditions where pitch angles deviated from theoretical values, the chassis could not exceed a safe articulation limit. No chassis-to-stair contact events were recorded during either the geometry test or the full validation run, confirming that the geometric design intent was achieved in practice despite the out-of-tolerance angle readings.

2.3.4 Design Optimization

Several design optimizations were identified and implemented during the fabrication and testing phases that helped improve rover reliability and performance.

Wheel Coating Optimization

Custom PETG wheels were designed and 3D printed, with Plasti-Dip rubber dip-coating applied to provide sufficient rubber-on-concrete traction. However, repeated full staircase test runs gradually wore down the Plasti-Dip coating, and traction performance began to degrade noticeably as the rubber layer thinned. To address this, all six wheels were recoated with a fresh layer of Plasti-Dip. This optimization restored traction performance to its original level and highlighted the importance of coating maintenance as a recurring requirement for any future design using this wheel treatment.

Chassis Grip Stabilization

During testing, the laser-cut plywood chassis halves exhibited lateral flexibility under load, causing the left and right sides of the front rocker segment to flex independently. This resulted in the left and right front wheels climbing at slightly different rates, placing asymmetric stress on the pivot joints and risking chassis deformation or failure over repeated runs. To correct this, 3D printed grips were added along the outer edges of both chassis segments to laterally stiffen the plywood and constrain the left and right sides from flexing relative to one another. The clips tied the two sides of each chassis half together, ensuring the front wheels climbed in unison and reducing the asymmetric loading that had been observed during earlier test runs. These grip unintentionally also provided a robust place to grab onto the rover when transporting it between locations without worry of failure.

Electronics Board Chassis Brackets

A related flexibility issue was identified at the center of the chassis, where the two plywood halves connected by the threaded rod crossmembers were susceptible to inward collapse under the compressive loads generated during climbing. To address this, 3D printed brackets were added at the midpoint of the chassis, fastened directly to the existing chassis screws. These brackets served a dual purpose: preventing the chassis sides from collapsing inward under load, and providing a stable mounting platform for the electronics plate. This added both structural rigidity and a cleaner electronics integration solution compared to the preliminary design, which had no dedicated internal bracing.

Electrical System Simplification

The preliminary design planned a full control architecture including an ESP32 microcontroller, L298N motor drivers, and Bluetooth remote operation. During integration testing, this system encountered repeated reliability failures, including startup pins causing binding, frying 2 different ESP32s, and insufficient power. With competition day approaching, the team elected to remove the electronics entirely and wire all six motors directly to the 12V battery. This eliminated all known electrical failure modes and produced a successful full 19-step competition climb. However, this simplification should be treated as a one-time competition contingency rather than a permanent design direction, and future iterations should reintegrate a proper microcontroller-based architecture with dedicated motor drivers and software control.

2.3.5 Detailed Bill of Materials

Level	Item Number	Description	Category	Needed Quantity	Purchase Quantity	Lifecycle Phase	Cost (ea.)	Cost (tot,)
2	100-001-001	Microcontroller	Electrical	1	3	Production	$ 15.99	$ 15.99
2	100-001-002	Motor	Electrical	6	1	Production	$ 31.22	$ 187.32
2	100-001-003	Motor Shield	Electrical	3	4	Production	$ 9.99	$ 9.99
2	100-001-004	Magnetometer	Electrical	1	2	Production	$ 7.99	$ 7.99
2	100-001-005	Voltage Regulator	Electrical	1	1	Production	$ 6.99	$ 6.99
2	100-001-006	Battery	Electrical	1	1	Production	$ 19.99	$ 19.99
2	100-001-007	Breadboard	Electrical	1	5	Production	$ 7.49	$ 7.49
3	200-001-001	PETG 3D Printing FIlament	Structural	2	4	Production	$ 36.09	$ 36.09
2	200-002-001	Chassis	Structural	1		Development		
2	200-002-002	Bottle Carriage	Structural	1		Development		
2	300-001-001	Wheel	Mechanical	4		Development		
2	200-001-003	Threaded Rod	Structural	6	1	Production	$ 6.00	$ 36.00
2	300-002-002	Wheel Hubs	Mechanical	6	4	Production	$ 7.99	$ 15.98
3	200-001-004	M4 Screws and Nuts	Structural	42	100	Production	$ 20.63	$ 20.63

2	300-001-002	Wheel Rubber Coating	Mechanical	1	1	Production	$ 16.49	$ 16.49
							Est. Total Cost:	$ 380.95

Table 21: Detailed Bill of Materials

2.3.6 Cost Analysis

Estimated Costs per Assembled Design			
Category	POC Design	Final Design	Description
Chassis Materials	$34.62	$34.62	All 3D printed and plywood components and fasteners used to make the chassis.
Wheel Materials	$18.04	$18.04	3D printed components used to make the wheels.
Manufacturing	$18.25	$18.25	Cost of laser cutting and applying rubber coating
Electronics	$245.10	$207.31	Cost of electronics used
Total Estimated Cost	$316.31	$278.22	

Table 22: Estimated Cost Table

The costs above were estimated using the unit prices from the Bill of Materials. They represent the cost of only the components used in the design and exclude the unused. Shipping costs and tax are also not included.

2.3.7 Process Flowchart

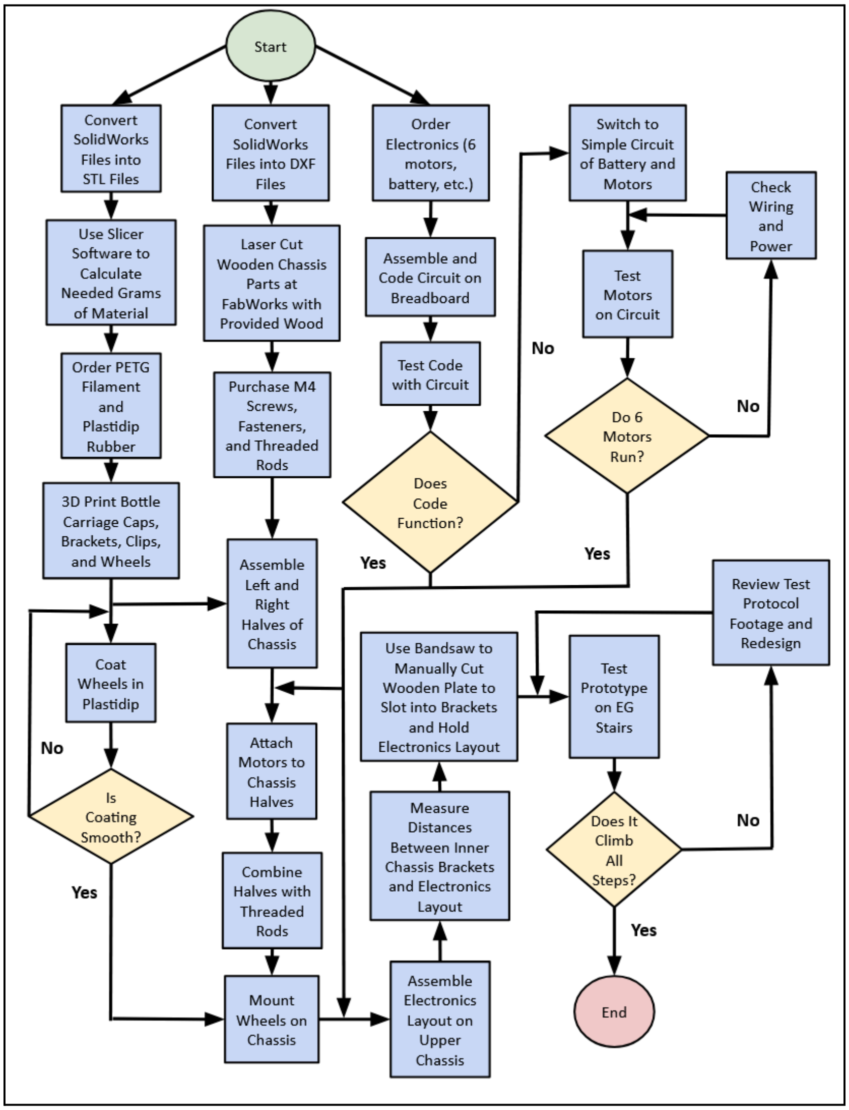


Figure 30: Flowchart Diagram

2.4 Conclusions

Throughout the course of this project, our team developed a vehicle that would be capable of carrying a water bottle up the Engineering Gateway (EG) stairs and could complete the task faster than the other teams. After extensive research, design, and testing, we developed a solution that could complete the task by satisfying the needs of our sponsor, Mohamed Shorbagy. We created a vehicle with a rocker-bogie chassis using plywood, threaded rods, and 3D printed supports. We used high torque DC motors to power custom wheels that were 3D printed and coated with a Plastidip rubber layer. In the end, the engineering design efforts of our team helped us create a stair climber that could overcome the EG stairs and participate in the competition. After using too large of a value for factor of safety with the actual weight being very close to the estimated weight, the wheels would've been able to climb at faster speeds without failure. Future design recommendations for this project would be to lower the factor of safety to values such as 1.5 in order to favor more speed over torque when selecting motors while still providing margin for error. Regardless, our design decisions still produced a design that satisfied our expectations and requirements.

2.5 Final Timeline

The final Gantt chart below documents the actual project timeline followed by Team 28 across Fall Quarter 2025 and Winter Quarter 2026. Compared to the initial planned timeline, the fabrication phase shifted earlier into Fall Quarter as the team prioritized completing mechanical components before the start of Winter Quarter. Electronics integration consumed a significant portion of Winter Quarter as repeated ESP32 and L298N failures required extensive troubleshooting, ultimately leading to the decision to simplify the electrical system in Week 8. Iterative design additions including chassis braces, clips, and wheel recoating extended fabrication activity through Week 9, overlapping with the testing and optimization phase. The final validation run was completed in Week 10 of Winter Quarter, meeting the competition deadline.

Figure 31: Final Project Gantt Chart

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Appendices

Proof of Concept Videos
- Includes videos of our proof of concept trials

MAE151A_Bogie4
- SolidWorks files of our Rocker-Bogie CAD model

MAE151_BOM_Team28.xlsx
- Team 28's Bill of Materials excel

MAE 151A Team 28 PoC Presentation
- Proof of concept presentation

Compliance Table and Testing Plans - Team 28
- Compliance Table and Proof of Concept Testing plans

TradeStudy
- Trade Study for MAE 151A

Electronics Trade Study.xlsx
- Trade studies of different components

Problem Definition Presentation - Team 28
- Problem Definition Presentation

Critical Design Presentation - Team 28
- Critical Design Presentation

Prototype B Presentation - Team 28
- Prototype B Presentation

MAE 151B Meeting Notes
- Meeting notes with sponsor and team

Sponsor Meeting Presentations:
- Sponsor meeting presentations for MAE 151A and MAE 151B\

Successful Climbing Videos
- Videos of all full runs up EG stairs