Team 5 MAE 2020 Spring Racer Project Report

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1. Introduction

The goal of this project was to design and 3D-print a high-performance vehicle capable of earning the maximum possible points on an obstacle course while adhering to strict design and material constraints. The design objectives focused on optimizing speed, stability, and energy efficiency, ensuring that all components functioned reliably under real-world testing conditions.

The vehicle could be powered using one or more of three energy sources:

- Gravitational potential energy from a ramp up to 42" high
- Mechanical energy stored in one to three springs
- Electrical energy stored in a 10 F supercapacitor charged to 5 V, which drives a small coreless brush motor with an attached propeller. A switch allows precise timing of energy delivery.

Key design and project constraints included:

- The combined mass of ABS model and SR-30 support material for all 3D-printed parts must not exceed 200 grams
- The vehicle must fit within a bounding box of 12” × 8” × 4”. Wheels may spin immediately, but all other components must remain within the envelope until motion begins
- The design must incorporate at least two sets of meshing gears that move automatically together during the vehicle’s trajectory
- All SolidWorks models must use IPS as the base standard, though specific dimensions may be entered in millimeters when convenient

This project provided an opportunity to apply principles of mechanical design, CAD modeling, and iterative prototyping while balancing material constraints and functional performance.

2. Design Process

2.1 Problem Definition

The objective of this project was to design, fabricate, and validate a 3D-printed vehicle capable of maximizing point accumulation on a 60-feet long obstacle course under a prescribed set of mechanical, electrical, and material constraints. While stationary, the vehicle was required to fit within a 12” × 8" × 4" bounding volume while remaining fully self-supporting. All methods to gain or lose points are listed below:

Instance	Change in Points
Clear Carpet Section	+100
Clear Speed Bump	+100

Clear Spinner Target	+200
Clear Short Jump	+300
Clear Long Jump	+500
Clear Loop	+800
Pick up Hitchhikers	1x=+100, 2x=+200, 3x= 400, 4x=+800, 5x=+1600, or 6x=+3200
Cross finish line (60')	+200
Ramp handicap	-10 per inch up (42 max)
Fall off track	-200
> 200-gram ABS / SR-30 support material used	-300
Break or leave adhesive on stock component	-200 per component

Figure 1: Points Table

Some other ways to earn points are by hitting the far wall past the finish line, having the lightest design (including stock components), using the least ABS and SR-30 material in the entire printing process, having the fastest velocity at the 10-foot mark, and two subjective categories for the most ingenious and elegant design respectively. All these subcategories earn the rightful team an extra 500 bonus points.

The vehicle was required to incorporate a minimum of two automatically meshing gear interfaces and could be powered by one or more of the previously mentioned energy sources. Notable constraints were the strict limits on spring extension (up to 12-inches), a prohibition on modification of stock components, and a maximum allowable usage of 200 g of ABS and SR-30 support material (300 g absolute maximum). Although ABS fabrication was permitted, all prototypes and final components for this vehicle were fabricated using PLA on personal printers, resulting in zero consumption of ABS or SR-30 material.

2.2 Research and analysis

Initial research and analysis focused on understanding the physical limitations and performance tradeoffs imposed by the competition rules. General hand calculations were done to estimate the mechanical energy available from the springs and to evaluate how spring extension length, mass distribution, and gear and spool diameter would affect vehicle acceleration and range.

Spring energy calculations were based on a nominal spring constant of approximately 0.877 lbf/in (given) at different adjustments between the resting (3 in rest) and maximum lengths. These calculations informed decisions regarding spring placement, transmission layout, and allowable chassis geometry. Electrical energy availability from the 10 F supercapacitor charged to 5.0 V was also examined to estimate motor runtime and expected propulsive contribution from the propeller system at different overall weights.

While frictional losses, wheel traction, and weight distribution on the foam-based track surface were recognized as significant contributors to vehicle stability and repeatability, these effects were treated as nominal during the early analytical phase due to uncertainty in surface conditions and material properties. Instead of attempting to more precisely model these variables, the design strategy was to stand on conservative assumptions and adjustability, allowing their effects to be mitigated through testing and iterative refinement rather than detailed analytical predictions.

2.3 Concept generation

We agreed that we would go for a fast and light vehicle with the main goal of going through the loop. Our designs were based on making a light and compact car that would hopefully use all three springs to give us an advantage over other teams to become the fastest.

Multiple vehicle concepts were initially sketched out to explore different propulsion strategies and layouts. These concepts varied in terms of primary energy source utilization, gear placement, and intended obstacle engagement. Concepts included gravity-dominated vehicles focused on low rolling resistance, spring-powered designs focused on high initial acceleration; hybrid systems utilized both methods at once.

Each concept was evaluated qualitatively with respect to expected performance, mechanical complexity, manufacturability, and robustness under competition conditions. The goal of this phase was to maximize design diversity while identifying architectures with high scoring potential and manageable technical risk.

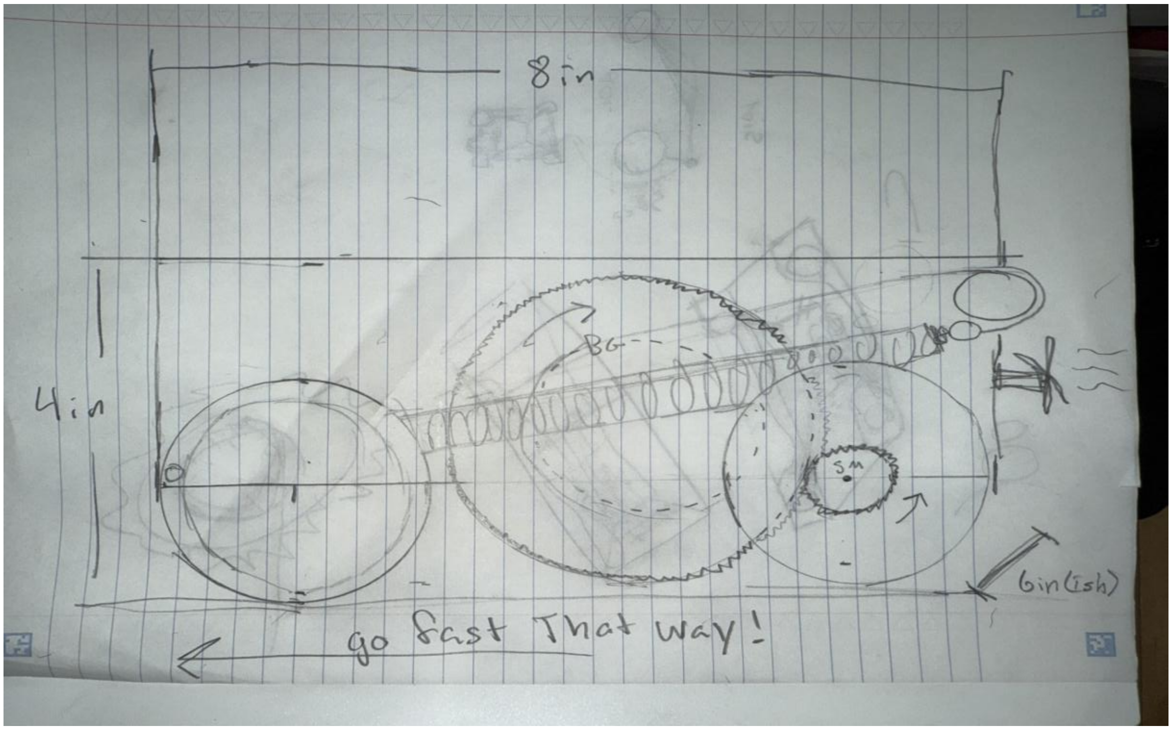

Figure 2: Design Sketch

2.4 Concept selection

The final vehicle concept was selected based on an accumulation of manageable factors related to their evaluations as a team. Concepts that required excessive part counts, extreme tolerances, or complex timing mechanisms were eliminated in favor of more robust designs that could reliably transfer energy from the springs to the wheels.

The chosen design struck a balance between performance potential and implementation risk, while remaining well-suited for rapid prototyping with PLA. The decision was guided by both calculations and considerations such as ease of assembly, adjustability, and the expected ability to perform consistently on the track.

2.5 Design development

After selecting the final concept, the design was refined in detail using SolidWorks. This phase included optimization of chassis geometry, gear size and teeth ratios, and placement of springs, shafts, bearings, and wheels within the vehicle. Attention was given to alignment of shafts and meshing of gears to minimize friction and prevent binding under load.

Variability inherent in 3D printing was addressed through post-print sanding to achieve precise fits. Additional considerations included material stiffness, weight distribution, and component accessibility, allowing the vehicle to be reliably reset for multiple runs while preserving consistent performance in a short time.

2.6 Prototyping

An initial PLA prototype was fabricated to evaluate the fit, function, and performance of individual subsystems. It focused on rear-axis shaft alignment with the chassis and gear engagement, while later iterations addressed structural geometry and spring attachment. It was made with the intention of versatility should any edits to any components come to pass, such as the wheel-to-bearing adapters and the pulley wheel. This method of prototyping allowed design flaws to be identified early and revised efficiently. Lessons learned from unsuccessful prototypes directly informed subsequent design improvements.

For example, we would try different sizes of spools for the bigger gear to test how much torque we could get before the wheels slip. This would allow us to home in on dimensions that would let us get the maximum amount of power transferred into the wheels.

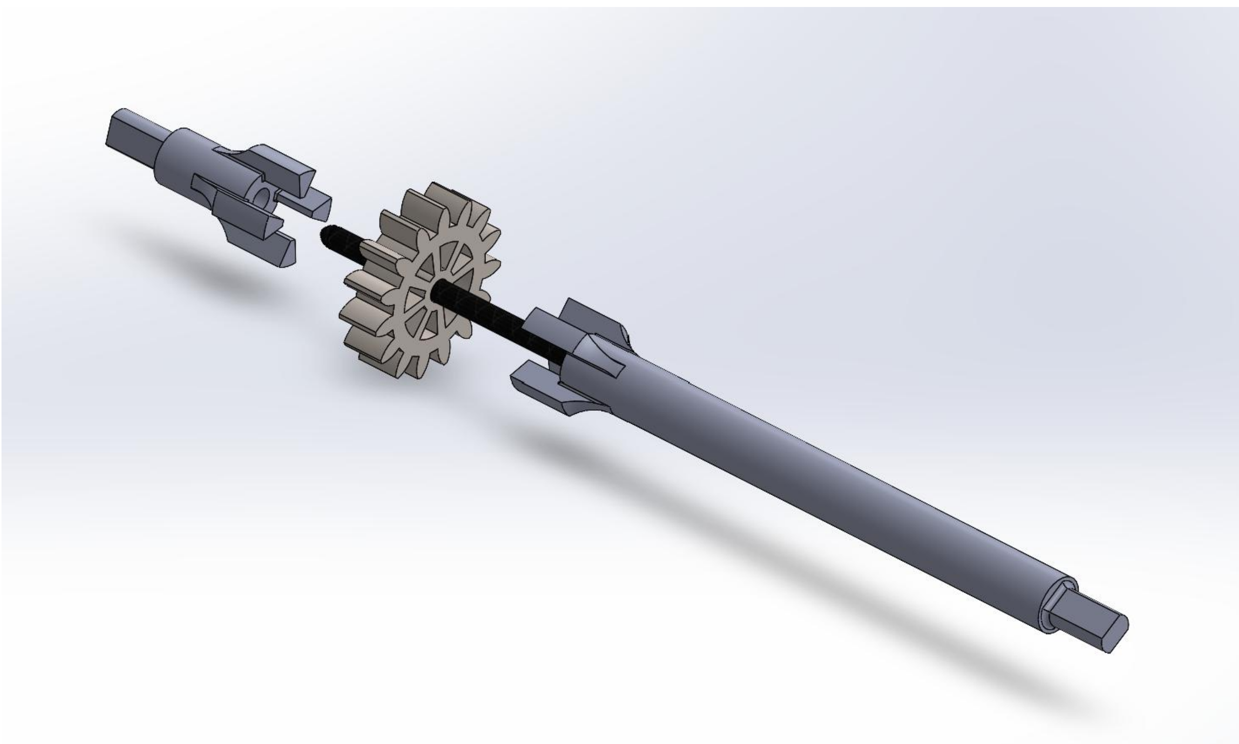

Figure 3: Rear Wheel Axle Assembly

2.7 Evaluation and testing

The vehicle was evaluated through iterative testing with particular emphasis on straight-line stability and minimizing wheel slip during initial acceleration. Early testing indicated that the high torque generated at spring release could lead to wheel slip and unintended yaw.

To address these issues, testing focused on assessing the effects of gear ratio selection, wheel alignment, and mass distribution on initial traction. Rolling tests were then conducted to observe vehicle behavior immediately after release, with attention to deviations from straight-line motion and evidence of wheel spin.

Results from these tests informed adjustments to rear axle shaft alignment, and weight placement to improve traction at launch. Subsequent testing demonstrated noticeable improvements in straight-line tracking and a reduction in wheel slip; however, these effects were not fully eliminated. While initial acceleration became more consistent and usable energy transfer increased, some degree of slip and directional deviation remained under high-torque conditions immediately following the springs' release.

2.8 Design optimization

Based on testing results, the design was optimized to improve performance. The initial car chassis was found to have unnecessary mass on the sides of the frame and was removed in the proceeding chassis design. Additionally, initial testing showed high initial torque which was combated by making a smaller spool which would wind up more string and in return create release the springs at a slower pace and allowing the energy to be preserved over time rather than being released all within the first second of launch. Improving alignment of rotating components was also optimized to minimize frictional interfaces.

Each modification was evaluated to ensure that it improved listed performance metrics without introducing new failure modes such as friction between iterated parts.

2.9 Implementation

The final vehicle was assembled after confirming that all design requirements and competition rules were met. Assembly procedures emphasized consistency, rule compliance, and ease of inspection. The completed vehicle was verified to be fully functional and ready for competition testing.

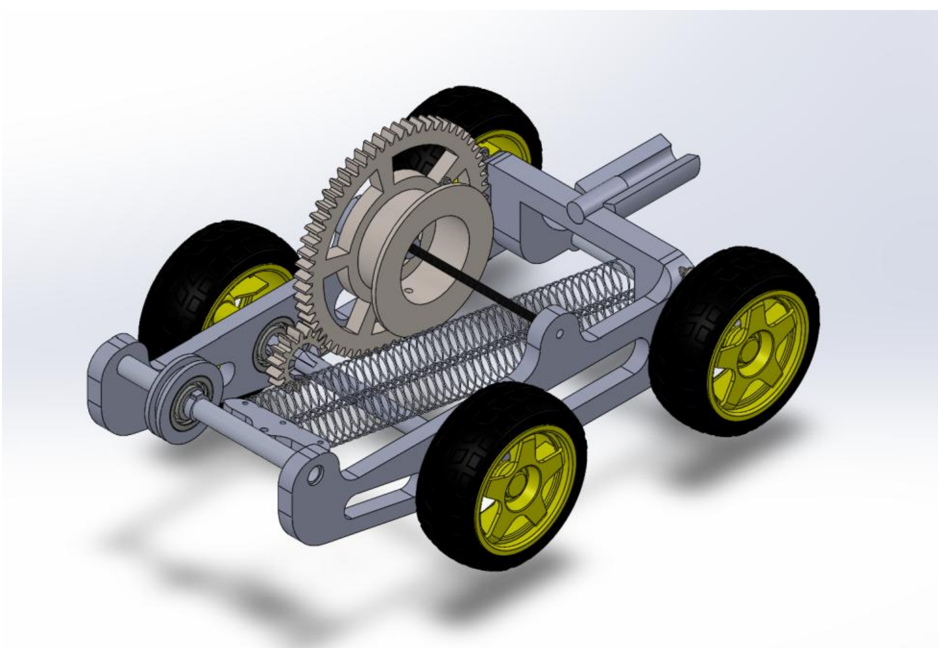

Figure 4: Full Car Assembly

2.10 Presentation and maintenance

The vehicle was prepared for competition with attention to accessibility of components and the ability to quickly reset and repeat runs by rewinding the spring mechanism. Design features allowed for straightforward disassembly, with all components remaining unaltered and connected only through mechanical interfaces.

3. Materials and Components

The design and fabrication of the vehicle required careful selection and integration of both 3D-printed parts and stock components to achieve reliable performance, structural integrity, and efficient energy transfer. All 3D-printed components were fabricated from PLA, which provided strength, ease of printing, and dimensional stability for both prototyping and final assembly. Stock components contributed essential functionality in energy storage and vehicle motion. The components used in the vehicle are listed below:

- 3D-Printed Parts (PLA)
    - Chassis
    - Large gear with integrated spool (90 mm pitch ⌀)
    - Small gear on the rear shaft (22.5 mm pitch ⌀)
    - Wheel adapters (one per wheel)
    - Aluminum Bar Clips
    - Pulley
    - Adapters
        - Wheel-Axle
        - Gear-Bearing-Axle
        - Bearing-Carbon Rod
- Stock Components
    - Yellow plastic wheels with rubber tires (x4)
    - 608 ball bearing, ID = 8mm, OD = 22 mm (x6)
    - Carbon fiber rods, 1/8” x 4” (x2)
    - Aluminum tubes, 5/16” x 4” (x2)
    - Springs, nickel-plated steel, 3” rest length (x2)
    - 10 F supercapacitor charged to 5.0 V (x1)
    - Coreless DC brush motor with propeller (x1)
    - SPTD limit switch (x1)
    - Paracord, 1/8” x 24” (x2)
    - 6-32 machine screws, ½” (x4), 1” (x1)

These components were carefully integrated to form a functional vehicle, with 3D-printed parts providing custom structural elements and energy transmission components, including a spring-driven spool and gear system, while stock components supplied key mechanical and electrical functions required for motion and energy transfer.

Our team did not print any ABS parts in the MILL.

4. Fabrication and Assembly

When 3-D printing, we had to balance layer line placement and accuracy of printed parts. One example of this is how it changed the design of our back wheel axle. To simplify the gear and axle assembly and avoid slipping, we decided to 3-D print them as one part instead of putting a gear over a carbon fiber rod. Although we initially ran into the problem where the rod and gear had to be printed at different orientations for maximum layer line strength and gear teeth precision. To combat this, we split the assembly into three different 3-D printed parts that would snap fit into each other. We ended up adding the carbon fiber rod into the 3-D printed axel anyways to add stability and rigidity (Figure 3). There was an issue with stability in our car during the initial testing phase. To remedy this, we decided to CAD and print clips for the aluminum bar to hold certain pieces, such as the spool for the rope, in place for consistent placement and decrease the chance of slipping. The pieces were light and removable. They were able to accommodate multiple placement shifts.

Our chassis was split into three different parts to minimize 3-D printing time and get rid of the use of support material while also enhancing strength by choosing proper orientation for layer line placement. We used holes with tight tolerancing to be able to thread the machine screws though the holes to have a very secure hold that wouldn't need nuts.

5. Testing and Performance

Final testing for the car was done using the ramp to get assistance for speed. One of the first things that was noticed was that the car would not always go in a straight line, veering off and colliding with the barriers. This was partly due to the one of the wheels in the back losing traction once the springs were released due to the high rotational speed. We attempted to address this issue by initializing the car at an angle at the start. This fixed some of our problems and during one of the test runs; our car went the first 10 feet and cleared the following carpet section.

During the actual testing, we found out that we had used the diameter for the wheels (we had used the diameter without the rubber wheels) and so for our car to fit the 4-in height limit, the rubbers were removed. This had a negative impact on our performance because due to slippage of the wheels and so the car had no traction and did not score any points at all. Human errors occurred during the assembly and measurement of the CAD model, and last-minute variations impacted the car's actual height.

6. Optimization and Improvements

Some notable improvements to be made with the current design would be to address the volatility in trajectory while also looking at energy transfer rates. The car's path was altered due to a mixture of weight distribution and car gyration. The parallel gear system was placed offset (right) from the center of the chassis, and the springs sat on the left of the gear. The larger, heavy gear would cause the entire system to kick up temporarily at times; when this happened, due to the offset of the gear and springs, a clockwise yaw was induced.

To combat this, a new design would change the ratio of gears to be more negative than what was used in the final design. This change would allow the springs to be released at a slower rate to prevent kicking. Moving the gear to the absolute center of mass along the length of the car would also decrease deviation should there still be a slight jump on release. One spring would be placed on each side of the gears so that forces may be distributed across the entire car's width / axles.

7. Project Management

Keeping the project on-track was followed by a general outline created through a Gantt chart. This chart listed the team and all subsequent members, while clearly labeling tasks for each member to work on throughout the course of the project. (Days worked on were from November 23rd to December 14th, not including the time that each member takes personally to complete their team evaluation.) Tasks are listed in rows and dates are listed in columns; important due dates are boxed in red with the time due inside of the box. This project was split into four phases: (1) Planning and Initial Design, (2) Iterations, (3) Finalization and Testing, (4) Final Submissions.

Phase 1 (Nov. 23 – Nov. 25) was the general planning and agreement for the team's goals to hit. Speed of the assembly was prioritized mainly.

Phase 2 (Nov. 26 – Dec. 8) worked out small aspects of the design to make everything "work", such as tolerances between all the parts and the implementation of adaptors and clips.

Phase 3 (Dec. 6 – Dec. 10) focused on starting this final report early while making final adjustments for testing at 11:00 A.M. on December 10th.

Phase 4 (Dec. 11 – Dec. 19) is currently prioritizing an adequate final report submission, a submission of CAD files with proper naming scheme, and performing team evaluations.

While each member was assigned various roles based on their strengths, others were encouraged to help when they had the time to spare. From phase 1, which was mainly measuring stock components and getting an initial design, near-daily meetings were held to work on the design as a team. Over the course of the entire project, every team member made it to these meetings and would adapt to small roles for the day. For example, if it was concluded that several small parts or clips were needed for the design, each team member would break off and meet back in ~15 minutes with their design to be peer reviewed. Larger models, such as the chassis, would be made between 2 or 3 people cross-checking the modeling process. All members were present for the final day of testing.

8. Conclusion

This project was an insight into what is required as a team and an engineer to complete a job for a client under time and material constraints. It required communication, time, adaptation, and independence from each member to strive closer to the impossible goal of a perfectly optimized product throughout the process. Having strict deadlines was also a key aspect to the project's completion, relying on time for parts to print and meeting deadlines. The car received a score of 0 during the final testing, since it did not violate any rules but did not earn any points. The tires were required to be removed for our tests due to an error in CAD assembly which made the car slightly taller than the 4” maximum height. This increased slipping and reduced traction of the car in contact with the track. Possible changes could have been to take point deduction (keeping the tires on the car) and committing to doing the track with the hope of scoring positive points. Further testing under a later deadline would yield iterations mentioned in section 6 of this report. Much was learned through pursuing the design process and iterating on different pieces of our car until considered presentable for the final design. Every member provided valuable insight into the design process and worked to complete tasks quickly to account for varying print times.