SPRING-POWERED ELEVATOR PROTOTYPE

POLE-CLIMBING "SPACE ELEVATOR" MECHANISM

FAISAL A

Contents

1. Project Summary

The **Spring-Powered Elevator Prototype (Pole-Climbing "Space Elevator" Mechanism)** project focused on the design, fabrication, and testing of a purely mechanical system capable of climbing a vertical steel pole using energy stored in a constant-force coil spring. The project was conducted between September and December 2018 as part of a team-based mechanical engineering design course, with performance evaluated through a competitive pole-climbing demonstration.

The primary objective was to develop a lightweight and simple mechanism that could climb a **7 ft (84 in)** vertical pole as quickly and reliably as possible while adhering to strict constraints on materials, mass, and allowable energy input. Only supplied materials were permitted, the entire mechanism was required to climb the pole without leaving components behind, and no electrical or motorized systems were allowed.

The final design employed a wheel-based climbing approach driven by a two-stage gear train optimized to convert the limited output of the constant-force spring into sufficient torque at the drive roller. Components were designed in SolidWorks and manufactured using a combination of CNC machining (MDF components) and FDM 3D printing, with iterative refinements made to address friction, weight, and manufacturability within the limited project timeframe.

During the competition, the prototype successfully climbed **62 in (5.17 ft)** of the pole—approximately **81% of the total height**—in approximately **0.6 seconds**, achieving **first place** among all teams. Notably, it was the only mechanism to surpass the halfway mark. The completed system had a total mass of **169 g**, meeting all project constraints.

2. Problem Statement

Background & Motivation

The concept of a space elevator proposes transporting payloads along a stationary vertical structure rather than relying on conventional propulsion systems. While full-scale space elevator implementations remain impractical due to material and environmental limitations, the underlying engineering challenge of efficiently climbing a vertical structure using limited onboard energy has direct relevance to real-world applications such as inspection devices, maintenance systems, and constrained-environment robotics.

In this project, a vertical steel pole served as an analogue for a space elevator cable. The core engineering problem was to design a **purely mechanical pole-climbing mechanism**, powered only by a constant-force coil spring, that could reliably ascend the pole within a fixed time window. The system was required to maximize climbing height and speed while operating under strict limitations on mass, materials, available energy, and development time.

Team Contribution & Project Context

The Spring-Powered Elevator Prototype was completed as a team-based mechanical engineering design project. All teams were provided with an identical, limited set of materials and were required to design, fabricate, and test a working prototype within the academic term. Final performance was evaluated during a competitive demonstration in which each mechanism was given a ten-minute window to attempt multiple climbs of a 7 ft vertical steel pole.

The project required the application of the full engineering design process, including problem definition, concept generation, mechanical analysis, detailed design, manufacturing, testing, and iterative refinement. The team collaboratively conducted mechanical concept selection, gear-train configuration and torque–distance trade-off analysis, CAD modeling using SolidWorks, CAM preparation and CNC machining using MasterCAM, and design iteration based on testing and competition performance.

3. Assumptions & Constraints

The design and development of the Spring-Powered Elevator Prototype were governed by a set of explicit assumptions and constraints defined by the project outline and competition rules. These limitations strongly influenced concept selection, mechanical design decisions, and overall system performance.

A primary constraint was **time**. The project was conducted over an approximately two-month period, from early September to early December 2018, encompassing concept development, detailed design, manufacturing, testing, and final competition. Limited access to machining and rapid prototyping facilities further constrained the number of feasible design iterations.

Material and manufacturing constraints were also significant. Only the materials supplied by the department were permitted for structural and mechanical components, including MDF boards, a fixed quantity of 3D-printable filament, a constant-force coil spring, dowel pins, elastics, and fasteners. The total mass of the completed mechanism could not exceed the mass of the supplied materials, excluding adhesives and paint. No electronic components, motors, or external power sources were allowed.

The system was required to operate as a **fully self-contained mechanical mechanism**. The entire device had to climb the pole together, with no components allowed to detach or remain behind. The climbing surface and environment were fixed and could not be modified, requiring the mechanism to accommodate the given steel pole geometry and surface condition.

An additional performance constraint was imposed by the **competition format**. Each team was allotted a ten-minute window to demonstrate its mechanism, during which multiple attempts could be made. The mechanism was required to complete its climb within this time window using the limited energy available from the constant-force spring, whose finite length and force output constrained both achievable torque and total climbing distance.

For design and analysis purposes, it was assumed that frictional losses at contact interfaces could be reduced through surface finishing and alignment but could not be eliminated. It was also assumed that material properties of MDF and FDM-printed components were consistent with typical published values, and that the constant-force spring delivered approximately uniform force over its usable length. These assumptions informed gear ratio selection, torque calculations, and expected climbing performance.

4. Methods / Approach

The design approach for the Spring-Powered Elevator Prototype followed a structured mechanical engineering design process, emphasizing simplicity, efficiency, and rapid iteration under strict constraints. The methodology consisted of concept selection, analytical evaluation, detailed design, fabrication, testing, and iterative refinement.

The project began with preliminary research into existing pole-climbing and wall-climbing mechanisms, with particular focus on wheel-based and inchworm-type systems. Based on the project constraints—specifically the absence of motors, electronics, or additional springs—a wheel-based climbing mechanism was selected due to its mechanical simplicity, smoother motion, and higher potential climbing speed.

A constant-force coil spring was used as the sole energy source. To effectively convert the limited linear spring energy into usable climbing motion, a spring-winding mechanism coupled to a two-stage gear train was developed. Gear ratios were analytically selected to balance torque output and travel distance, ensuring sufficient traction at the drive roller while maintaining the ability to reach the required height.

Mechanical analysis focused on torque transmission, frictional forces, center-of-gravity placement, and normal force generation between the rollers and the pole. The center of gravity was intentionally positioned to create a self-locking moment that pressed the drive roller into the pole, improving traction without the need for additional clamping springs.

Detailed component design was carried out in SolidWorks, with parts optimized for minimal mass and manufacturability using the supplied materials. MDF components were prepared for CNC machining using MasterCAM, while complex geometries such as rollers were produced via FDM 3D printing. Assembly methods prioritized modularity, allowing design changes—such as adjustments to the spring winding radius—to be implemented quickly when performance issues were identified during testing.

Testing and iteration played a critical role in the methodology. Initial prototype trials revealed issues related to friction, torque sufficiency, and reliability. These findings led to design refinements, including an increased spring-winding radius to improve torque output at the cost of reduced travel distance. Final performance was validated during the competition, where the mechanism's real-world behavior was compared against theoretical predictions.

Overall, the adopted methods balanced analytical modeling with hands-on experimentation, enabling the team to converge on a reliable and competitive mechanical solution within the project's limited timeframe.

5. Engineering Design

The final design of the Spring-Powered Elevator Prototype employed a wheel-based climbing mechanism optimized for mechanical efficiency, weight reduction, and reliable pole engagement. The mechanism was primarily driven by a constant-force coil spring, with motion transmitted through a two-stage gear train to the main drive roller. This configuration maximized torque output while adhering to strict mass and material constraints.

5.1 Mechanical Subsystems

The subsystems were selected to maintain consistent contact and normal force throughout the climb while minimizing friction induced by misalignment.

- **Drive System:** A two-stage gear train converted the linear energy of the spring into rotational motion at the main drive roller. The gear ratios were chosen to optimize torque and climbing speed while minimizing slippage.
- **Rollers:** A v-groove FDM-printed drive roller ensured consistent contact with the pole, while two support rollers provided stability and alignment.
- **Spring Winding Mechanism:** The coil spring was secured to a custom MDF roller, allowing controlled energy release. A modular adapter was incorporated to adjust torque delivery in response to frictional resistance.
- **Chassis and Linkages:** The main chassis and connecting arms were machined from MDF, designed to maintain structural integrity while keeping the system lightweight. Rigid linkages ensured proper alignment of drive and support rollers.

5.2 Materials and Fabrication

- **MDF Components:** Chassis, gear supports, and spring roller were CNC-machined from medium-density fiberboard.
- **3D-Printed Components:** Rollers and small structural elements were printed using PLA filament on an FDM printer.
- **Adhesives and Rubber Bands:** Permitted adhesives were used to secure components, and rubber bands provided supplemental clamping to maintain roller contact with the pole.

5.3 Iterative Refinements

The design underwent multiple iterations to address friction, torque delivery, and manufacturability:

- Roller diameter adjustments increased torque output while managing spring travel.
- Gear alignment and shaft positioning were refined to reduce friction losses.
- Modularity allowed rapid adaptation of components in response to performance testing.

5.4 CAD and CAM Integration

All components were modeled in SolidWorks, converted to STL for 3D printing or MasterCAM for CNC machining. G-code generation ensured precise fabrication of each part, allowing the prototype to be assembled efficiently within the project's tight timeframe.

The implemented design achieved a lightweight, mechanically efficient, and reliable climbing system that successfully met the project objectives.

6. Testing & Validation

The Spring-Powered Elevator Prototype was evaluated through a series of practical tests designed to assess its ability to climb a vertical steel pole, as well as to compare its actual performance to theoretical predictions. Testing focused on key performance metrics, including climb height, climb speed, repeatability, and reliability under the constraints of supplied materials and total mechanism mass.

Initial validation involved assembling the prototype and performing incremental test runs to observe the mechanism's engagement with the pole, spring winding, and drive roller functionality. Adjustments were made to optimize tension in the rubber bands, ensure proper alignment of the gear train, and reduce friction at contact points.

During the formal competition test, the mechanism successfully climbed 62 inches (5.17 ft) of the 84-inch pole in approximately 0.6 seconds. This performance was consistent with theoretical calculations predicting partial success for the final design iteration, confirming that the torque delivered by the spring through the two-stage gear train was sufficient to achieve reliable ascent under the specified constraints. The prototype was also the only entry to surpass the halfway point of 48 inches, validating the effectiveness of the wheel-based climbing approach and spring-winding mechanism.

Additional observations included minor slippage of the drive roller and frictional losses in the elastic bands, which were accounted for in subsequent design refinements. Overall, testing and validation demonstrated that the prototype met the primary functional requirements, provided repeatable results, and achieved the intended performance benchmarks under strict material and mass constraints.

7. Results & Discussion

The testing of the Spring-Powered Elevator Prototype revealed several key performance outcomes and insights. The prototype successfully climbed 62 inches (5.17 ft) of the 84-inch pole, achieving approximately 81% of the total height. This result placed the team first in the competition and confirmed that the wheel-based climbing mechanism with a two-stage gear train effectively converted spring energy into sufficient torque at the drive roller.

7.1 Performance Analysis

Climb Height: Achieved 62 in, compared to the theoretical maximum of 69.7 in for the final design iteration. The discrepancy of 7.7 in was attributed to minor roller slippage and incomplete spring winding.

Climb Speed: The ascent took approximately 0.6 seconds, demonstrating rapid energy transfer from the spring to the drive mechanism and confirming the efficiency of the gear train design.

Weight Compliance: The total mass of 169 g met all material constraints, ensuring that performance metrics were evaluated within the intended design boundaries.

7.2 Observed Challenges

Frictional Losses: Elastic bands and roller surfaces introduced friction that slightly reduced effective torque.

Spring Behavior: Over-tensioning or partial buckling of the coil spring occasionally hindered smooth operation.

Assembly Sensitivity: Small component sizes and precise alignment requirements made setup time-consuming and occasionally inconsistent during repeated trials.

7.3 Design Implications

The results highlight the effectiveness of a lightweight, modular, wheel-based climbing system driven by a constant-force spring. Iterative adjustments, such as increasing the spring-winding roller radius, improved torque delivery and reliability but slightly reduced projected travel distance. These observations underscore the trade-offs inherent in constrained mechanical design: balancing torque, friction, component mass, and reliability to achieve optimal performance.

7.4 Key Takeaways

- The two-stage gear train efficiently amplified the spring’s limited output.

- Modularity allowed for quick adjustments to improve reliability during testing.
- Rapid prototyping and CNC machining enabled precise fabrication within the tight project timeline.

8. Conclusions & Recommendations

The Spring-Powered Elevator Prototype successfully demonstrated the design, fabrication, and testing of a purely mechanical pole-climbing system powered by a constant-force coil spring under strict material and weight constraints. The project achieved its primary objective: to create a lightweight, simple mechanism capable of climbing a 7 ft (84 in) steel pole under strict material and weight constraints. The prototype climbed 62 in (5.17 ft), achieving first place in the competition and becoming the only mechanism to surpass the halfway mark.

8.1 Conclusions

The wheel-based climbing design, combined with a two-stage gear train, effectively converted the spring's stored energy into sufficient torque for reliable operation.

Iterative design refinements—such as modifying the spring-winding roller radius—enhanced torque delivery, reliability, and climbing performance.

Rapid prototyping (FDM 3D printing) and CNC machining (MDF components) facilitated precise component fabrication within a limited timeframe.

The project reinforced the value of modularity, mechanical analysis, and careful consideration of friction, torque, and mass in constrained mechanical design challenges.

8.2 Recommendations for Future Work

Gear Ratio Optimization: Adjusting gear ratios could increase torque on the drive roller, potentially enabling full-pole climbs.

Friction Reduction: Additional sanding, lubrication, or surface treatment of rollers and shafts could further reduce frictional losses and improve speed.

Spring Management: Alternative coil spring configurations or improved winding mechanisms may prevent buckling and improve consistency of energy delivery.

Detailed Load Analysis: Incorporating torque, friction, and safety factor calculations could refine component design and enhance performance.

Iterative Testing: Additional design iterations under controlled conditions could identify optimal component dimensions and material configurations for maximum climbing efficiency.

Overall, the project successfully applied the engineering design process, rapid prototyping, and performance evaluation within strict constraints, providing a robust proof-of-concept for mechanical pole-climbing systems.

9. References

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10. Appendices

APPENDIX A – Calculations

Sample spring and gear train calculations for determining torque, revolutions, and projected distance traveled.

Free Body Diagram (FBD) illustrating major forces on the mechanism.

APPENDIX B – Mechanism and Competition

Images and descriptions of mechanism placement, adjustments, and height measurements during the competition.

Documented observations of competition runs and performance metrics.

APPENDIX C – CAD, CAM, and STL Files

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SolidWorks models of initial and final designs.

MasterCAM setup sheets and G-code scripts for CNC machining.

STL files used for FDM 3D printing components.