PROJECT PHASE 4:

Optimization Challenge Report

Prepared for

MEEN 357 - Section 501

Team #10

By

Jacob Hargreaves

Ian Wilhite

David Guess

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Aggie Honor Code: *"On my honor, as an Aggie, I have neither given nor received unauthorized aid on this academic work."*

"None of the members of the team communicated in any way with other teams with regards to specific coding issues with this project."

Signature:	*Jacob Hargreaves*	Date:	*11/29/2024*
	David Guess	Date:	*11/29/2024*
	Ian Wilhite	Date:	*11/29/2024*

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Introduction

The design of an Entry, Descent, and Landing (EDL) system and a rover for a Martian mission is a challenging problem that requires careful consideration of multiple factors.
The goal is to create a system that can safely land on Mars and allow the rover to travel at least 1 kilometer on a single battery charge. This involves optimizing key parameters like landing velocity, rover speed, and energy usage while staying under the $7.2 million budget. To meet these requirements, we had to choose the best combination of components, such as parachutes, motors, batteries, and chassis materials, while making trade-offs between cost, performance, and weight. This project highlights the complexity of designing systems for real-world space exploration missions.

Formulation of the Design Problem

We aim to design an Entry, Descent, and Landing (EDL) system coupled with a rover capable of traversing at least 1 km on a single battery charge over a predefined Martian terrain. The design must balance key performance metrics: speed, cost, and battery efficiency, while adhering to specific constraints. Among these, speed is prioritized, followed by cost considerations. The design solution should:

- **Maximize rover speed** to reduce the total mission duration.
- **Minimize total cost**, ensuring it stays within the $7.2 million budget.
- Optimize battery capacity to achieve sufficient energy per meter (J/m) without excessive weight or cost.

Ensure the system satisfies constraints such as:

- Landing velocity below 1 m/s.
- Rover chassis strength exceeding 40,000 units.
- Mass and geometry limits for all components.

Key decision variables include:

- Parachute diameter, fuel mass, wheel radius, and gear diameter (continuous variables).
- Motor type, battery type, number of modules, and chassis material (discrete variables).

Considered Design Solutions

To address the rover's design requirements, we examined multiple options for key components and materials, considering performance and cost.

1) **Motor Selection**: The six available motor types were evaluated, focusing on their efficiency, torque, and speed capabilities. High-efficiency motors offered a balance of performance and reasonable cost increases. Both torque_he and speed_he motors stood

out as superior options, with the speed_he motor chosen for its ability to maximize rover speed, a primary objective.

2) **Chassis Material**: The three chassis material options—steel, magnesium, and carbon fiber—were compared for cost, strength, and weight. While carbon fiber exceeded budget constraints due to its high cost, magnesium emerged as the optimal choice. Its high specific strength allowed for a lighter chassis, aligning with the weight limits, while maintaining structural integrity and meeting strength requirements.
3) **Battery Configuration**: Various battery types and configurations were analyzed for energy efficiency and cost. PbAcid-1 batteries provided a good energy-to-cost ratio, making them a favorable option. Initial testing started with 10 modules to evaluate performance before editing the configuration.

Final Design Selection

We developed a Python program called value_sweep.py designed to comprehensively analyze the EDL process by systematically compiling and evaluating constraint values across multiple iterations. Our approach involved collecting data for each constraint, sorting iterations by time, and strategically eliminating scenarios that did not work.

Unlike traditional methods that focus on optimizing a single parameter, our approach allowed for simultaneous multi-constraint analysis. This methodology provided a more holistic and nuanced optimization strategy, enabling us to maximize overall performance in ways that would have been impossible with a narrow, single-constraint approach. By examining the complex interplay between different constraints, we gained deeper insights into the system's potential.

The effectiveness of this strategy was evident in the progressive evolution of our value_sweep.py outputs. The data range from our initial analysis to the final iterations demonstrated significant improvements in our understanding and optimization of the EDL process, validating the power of our comprehensive analytical approach.

We used this approach to optimize our design and choose the best one, given the constraints and the parameters we wanted to emphasize.

Numerical Methods Used

Our Python script employs several numerical optimization methods for maximizing objectives and solving constraints. These methods are from the scipy.optimize library and include:

1. **Trust-Region Constrained Algorithm (trust-constr)**:

    - This method solves the optimization problem with constraints and bounds defined using a Nonlinear Constraint object. It iteratively updates the solution while respecting constraints like strength, cost, and battery energy limits.
2. **Sequential Least Squares Programming (SLSQP)**:
    - This method minimizes the objective function with equality and inequality constraints defined via the ineq_cons dictionary. It is also bound-aware.
3. **Differential Evolution**:
    - A global optimization algorithm that explores the search space more thoroughly compared to local optimizers. It handles constraints through a nonlinear constraint and allows population-based exploration.
4. **Constrained Optimization BY Linear Approximations (COBYLA)**:
    - It deals with constraints by linear approximations and can handle inequality constraints without requiring explicit gradient definitions.

Additionally, grid search is employed in the loops to systematically explore the parameter space before optimization, providing initial guesses (x0) for the optimization algorithms. This enhances the likelihood of finding a global maximum.

Description of Final Design

We arrived at our final design by optimizing key aspects of our rover in order to minimize the time while staying within the parameters. The following are key parameters found when designing our rover:

- **Parachute:** We found that minimizing the parachute diameter to 14 m allowed our rover to descend the quickest.
- **Wheel Radius:** Our wheel radius is maximized at almost 0.7 m in order to allow the rover to move the furthest that it can in the least amount of rotations.
- **Speed Reducer (d2):** Additionally, the speed reducer is the smallest that it can be at 0.05 m in order to maximize the number of rotations that the wheel has.
- **Fuel and Chassis Mass:** Our fuel mass and chassis mass are both a bit on the heavier side but light enough to allow the rover to land safely and quickly.

We found that the budget constraint was not one of the key factors to create tough decisions in our design. This is shown in our total cost as we are about $1.25 million under the $7 million budget.

Table 1: Final Optimized Rover Parameters

Parameter	Value	Units
Optimized Parachute Diameter	14.00	m
Optimized Fuel Mass	200.304121	kg
Time to complete EDL Mission	128.786949	s
Rover Velocity at Landing	-0.100512	m/s
Optimized Wheel Radius	0.699995	m
Optimized d2	0.05	m
Optimized Chassis Mass	375.299577	kg
Time to Complete Rover Mission	395.625	s
Time to Complete Mission	524.412	s
Average Velocity	2.436	m/s
Distance Traveled	1000.00	m
Battery Energy per Meter	541.524	J/m
Total Cost	5751017.33	$

Performance Data

The final rover design, optimized by using the COBYLA method, meets all mission requirements while achieving high performance in the Entry, Decent, Landing, and traversal phases. Below is a detailed summary of the performance results.

- **Motor**: The high-efficiency speed_he motor was selected to maximize the rover's speed without significantly increasing energy consumption.
- **Chassis Material**: Magnesium was chosen for its lightweight and high strength-to-weight ratio. The cost was also a very big consideration for this choice
- **Battery**: PbAcid-1 batteries were selected for their reliability and cost efficiency. A configuration of 5 battery modules was used to achieve the necessary energy storage.

Table 2: Chosen Rover Specifications

Parameter	**Chosen Specification**
Motor	*speed_he*
Chassis Material	Magnesium
Battery	PbAcid-1
Number of battery Modules	5
Optimization Method	COBYLA

```
   Normal return from subroutine COBYLA

   NFVALS =   66   F = 5.244124E+02    MAXCV = 0.000000E+00
   X = 1.400003E+01   6.999954E-01   3.752996E+02   5.000000E-02   2.003041E+02
Commencing simulation run...

Ejecting heat shield at        t = 5.9742   [s], altitude = 8000.0000 [m], speed = -428.9329 [m/s]
Turning on rockets at          t = 29.7310  [s], altitude = 1800.0000 [m], speed = -169.9525 [m/s]
Ejecting parachute at          t = 36.4478  [s], altitude = 900.0000  [m], speed = -103.0225 [m/s]
Turning on speed control at    t = 52.4011  [s], altitude = 9.1366    [m], speed = -9.0000   [m/s]
Turning on altitude control at t = 52.4029  [s], altitude = 9.1200    [m], speed = -8.9904   [m/s]
Commencing simulation run...

Ejecting heat shield at        t = 5.9742   [s], altitude = 8000.0000 [m], speed = -428.9329 [m/s]
Turning on rockets at          t = 29.7310  [s], altitude = 1800.0000 [m], speed = -169.9525 [m/s]
Ejecting parachute at          t = 36.4478  [s], altitude = 900.0000  [m], speed = -103.0225 [m/s]
Turning on speed control at    t = 52.4011  [s], altitude = 9.1366    [m], speed = -9.0000   [m/s]
Turning on altitude control at t = 52.4029  [s], altitude = 9.1200    [m], speed = -8.9904   [m/s]
Turning on sky crane at        t = 52.5848  [s], altitude = 7.6000    [m], speed = -7.7247   [m/s]
The rover has landed!
   t=128.7869 [s], rover pos = 0.0000 [m], rover speed = -0.1005 [m/s] (sky crane at h=7.6202, v=-0.000512)

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Figure 1: Rover Mission Timesheet

These results demonstrate the efficacy of the chosen design approach and optimization method. The design success highlights its capability to meet the heavy constraints of the Mars Mission.