UW ME550: Nonlinear Optimal Control
Autumn 2025

A Review of:
Minimum-Landing-Error Powered-Descent Guidance for Mars Landing Using Convex Optimization

By Pranav Ramasahayam and Nick Nuxoll

Contents

Description of the System

- Mars lander using powered-descent, beginning after parachutes are cut
- Land at some target on the surface
  - Minimum fuel if feasible
  - Minimum landing-error if infeasible
- Improve accuracy of landing guidance algorithms for Mars missions
- Convex-optimization approach → guaranteed globally optimal solution in finite time

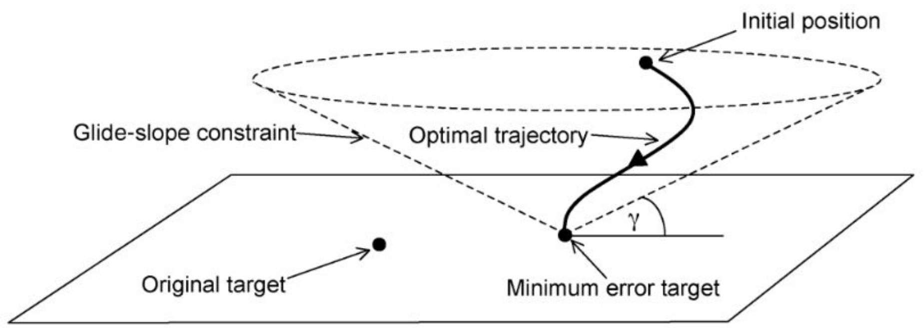
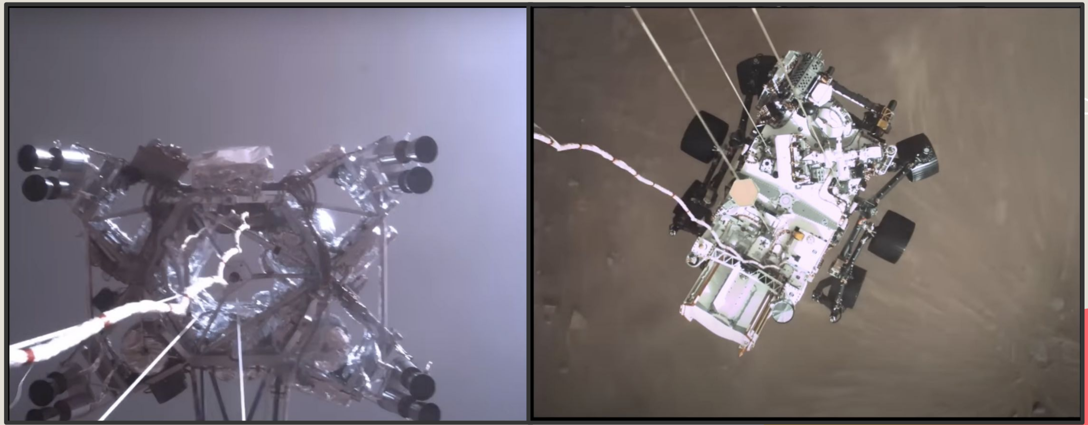


Fig. 1 Glide-slope constraint in minimum-landing-error powered-descent guidance problem. The glide-slope constraint requires the spacecraft to remain in a cone defined by the minimum slope angle γ. In the minimum-landing-error case, the apex of the cone coincides with the landed position of the spacecraft, rather than the original target.

Okay, but why is this important?

G-FOLD Diversion Test - NASA Jet Propulsion Laboratory
YouTube



Perseverance rover touching down on Mars. February 18th, 2021
Image: *JPL-Caltech/NASA*

Minimum-Fuel - Continuous

Cost $$\max_{t_f, T_c(\cdot)} m(t_f) = \min_{t_f, T_c(\cdot)} \int_0^{t_f} \|T_c(t)\| \, \mathrm{d}t$$

subject to

Dynamics $$\ddot{r}(t) = g + T_c(t)/m(t), \quad \dot{m}(t) = -\alpha \|T_c(t)\|$$

Min/Max Thrust $$0 < \rho_1 \leq \|T_c(t)\| \leq \rho_2, \quad r_1(t) \geq 0$$

Glideslope $$\|S_j x(t) - v_j\| + c_j^T x(t) + a_j \leq 0$$
$$j = 1, \ldots, n_s$$

Initial/ Terminal Conditions $$m(0) = m_{\text{wet}}, \quad r(0) = \mathbf{r}_0, \quad \dot{r}(0) = \dot{\mathbf{r}}_0$$
$$r(t_f) = \dot{r}(t_f) = 0$$

Minimum-Fuel - Discrete Convex

Cost $\min_{N,\eta} \omega^T \eta \rightarrow$ **Fuel usage at each time step**

subject to

Max thrust $\|E_u \Upsilon_k \eta\| \leq e_\sigma^T \Upsilon_k \eta, \quad k = 0, \ldots, N$

Min/Max Mass

$$\mu_1(t_k)\left[1 - \{F\mathbf{y}_k - z_0(t_k)\} + \frac{\{F\mathbf{y}_k - z_0(t_k)\}^2}{2}\right]$$
$$\leq e_\sigma^T \Upsilon_k \eta \leq \mu_2(t_k)(1 - \{F\mathbf{y}_k - z_0(t_k)\})$$
$$k = 1, \ldots, N$$

$$\ln(m_{\mathrm{wet}} - \alpha\rho_2 t_k) \leq F\mathbf{y}_k \leq \ln(m_{\mathrm{wet}} - \alpha\rho_1 t_k)$$
$$k = 1, \ldots, N$$

Glideslope

$$\|S_j E\mathbf{y}_k - v_j\| + c_j^T E\mathbf{y}_k + a_j \leq 0$$
$$k = 1, \ldots, N, \quad j = 1, \ldots, n_s$$

Minimum-Landing-Error - Discrete Convex

Cost $\min_{N,\eta} \|E_r y_N\|^2 \rightarrow$ **Distance from origin**

subject to

Max thrust $\|E_u \Upsilon_k \eta\| \leq \mathbf{e}_4^T \Upsilon_k \eta, \quad k = 0, \dots, N$

Min/ Max Mass

$$\rho_1 e^{-z_0(t_k)} \left[1 - (F\mathbf{y}_k - z_0(t_k)) + \frac{(F\mathbf{y}_k - z_0(t_k))^2}{2}\right]$$
$$\leq \mathbf{e}_4^T \Upsilon_k \eta \leq \rho_2 e^{-z_0(t_k)} [1 - (F\mathbf{y}_k - z_0(t_k))]$$
$$k = 1, \dots, N$$

$E_r \mathbf{y}_k \in \mathbf{X}, \quad k = 1, \dots, N$ **Glideslope**

$F y_N \geq \ln m_{\text{dry}}$ **Max Fuel Usage**

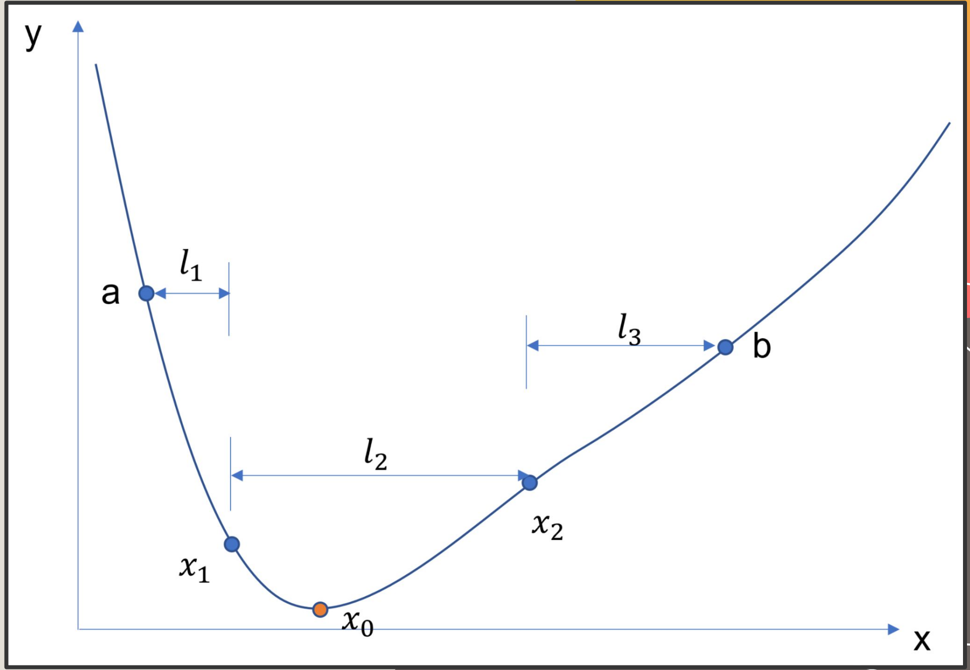
$y_N^T \mathbf{e}_1 = 0, \quad E_v y_N^T = \mathbf{0}$ **Final Alt./Vel. = 0**

Dynamics

$$\mathbf{y}_k = \Phi_k \begin{bmatrix} \mathbf{r}_0 \\ \dot{\mathbf{r}}_0 \\ \ln m_{\text{wet}} \end{bmatrix} + \Lambda_k \begin{bmatrix} \mathbf{g} \\ 0 \end{bmatrix} + \Psi_k \eta \qquad k = 1, \dots, N$$

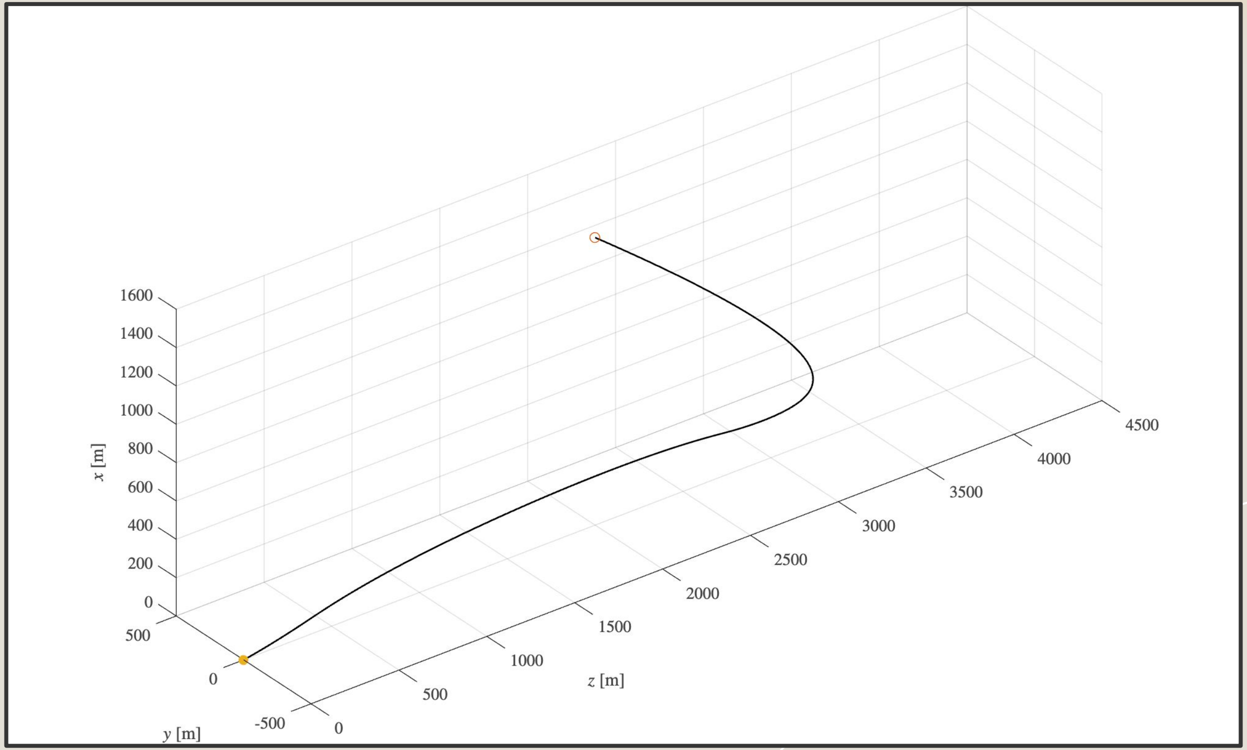
Simulation Methods

- CVX interface in MATLAB to solve second-order cone program
- Optimal fuel/error depends on chosen final time
    - Golden-section search for time
- ~20 seconds from initialization to solution
    - Flight software would use C/C++ → massive speedup
    - Lots of room for optimization in the code still
- Just one part of the larger G-FOLD algorithm



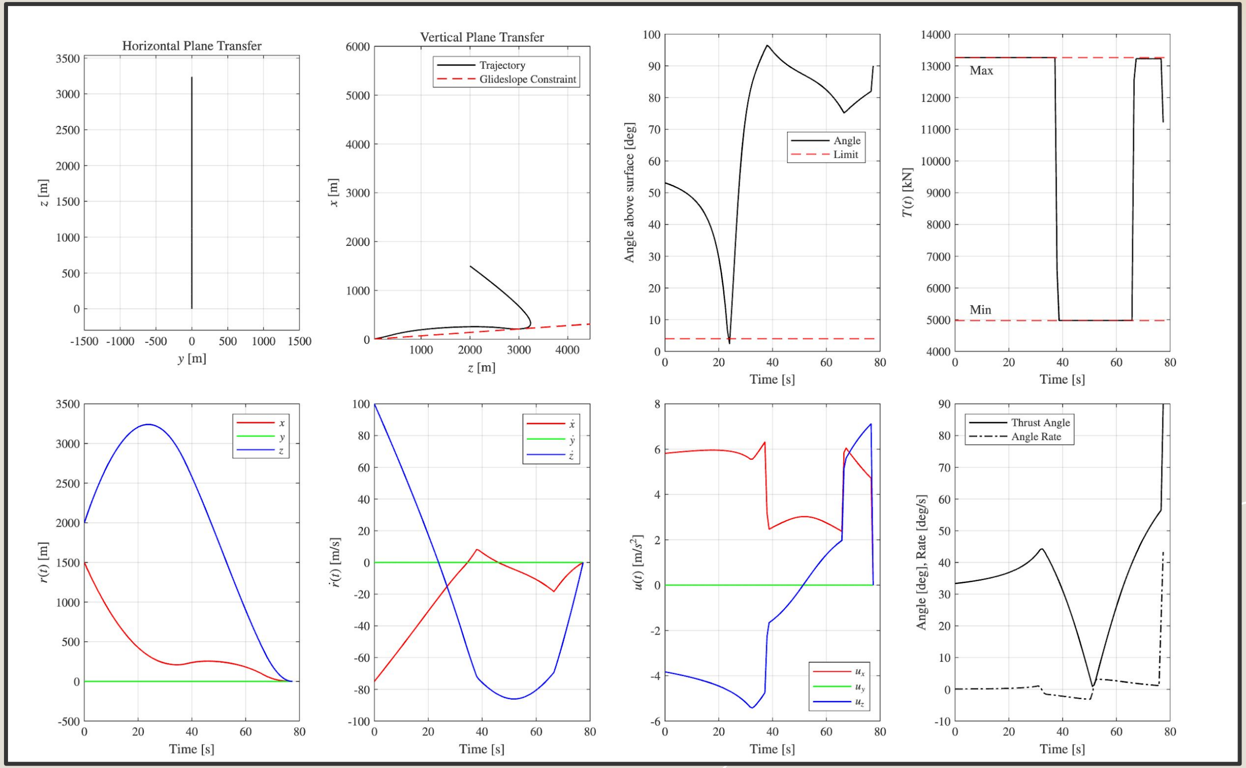
Golden-section search illustration
Yaning Liu, CU Denver

Simulation Results - Fuel



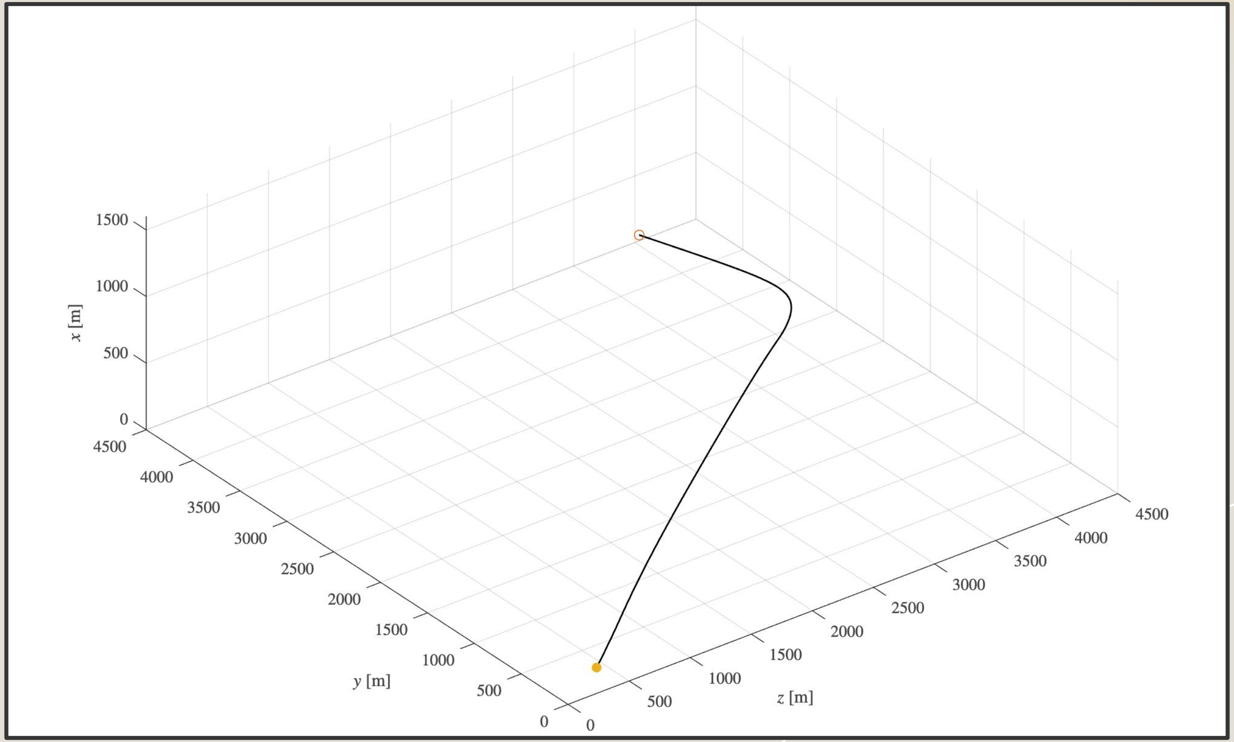
Minimum-Fuel - 3D Trajectory

Simulation Results - Fuel



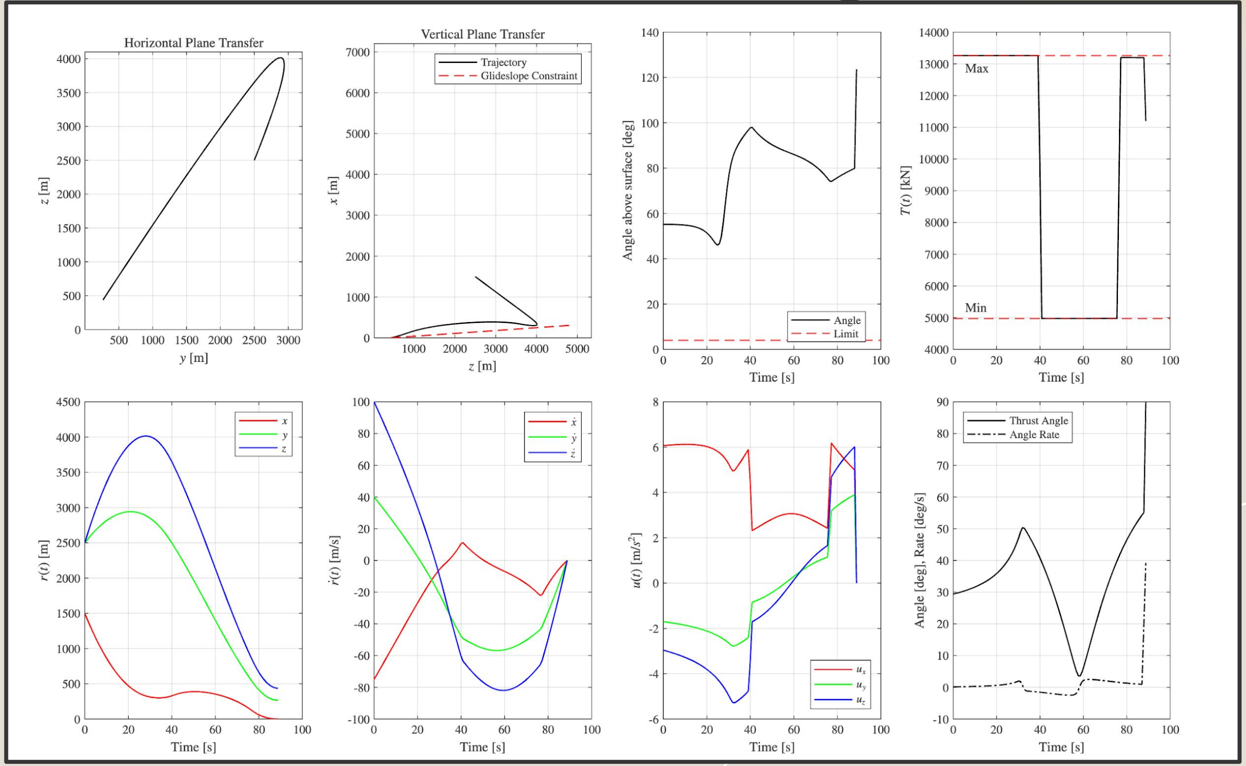
Minimum-Fuel Overview

Simulation Results - Landing-Error



Minimum-Landing-Error - 3D Trajectory

Simulation Results - Landing-Error



Minimum-Landing-Error Overview

Thank you