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Reducing Landing Site Contamination Using 3-D Trajectory Optimization for Surface Hoppers

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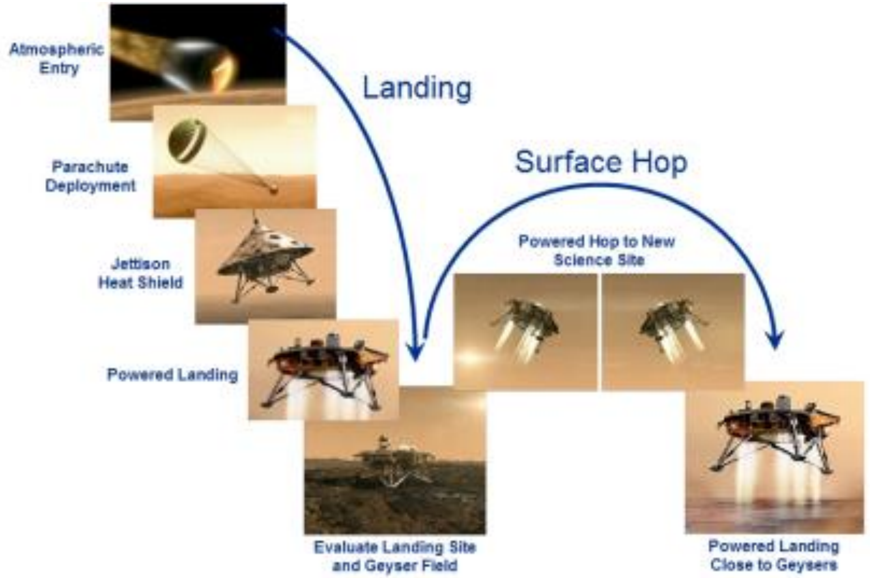
Motivation

This study investigates minimization of surface contamination from vehicle propulsive events during landing (e.g., during a **Surface hop for Mars Geyser Hopper**) .

- Surface alterations from propulsion events could be counterproductive or hazardous to the mission, depending on the science objectives.

This is of interest for human or robotic missions, that may rely on minimizing contaminants in the vicinity of landing sites for:

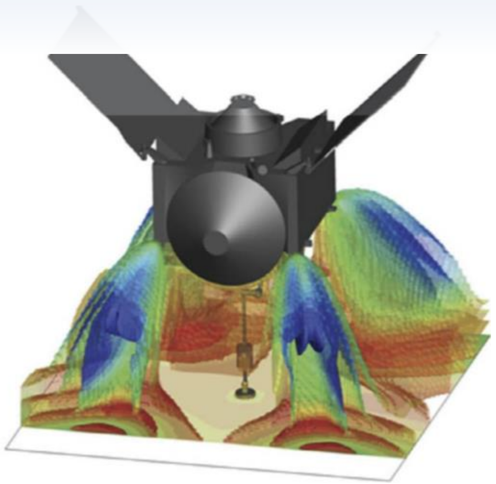
- Sampling pristine soils for science
- Mining or In Situ Resource Utilization (ISRU)
- Proximity landing to other surface assets



Mission Concept: Mars Geyser Hopper

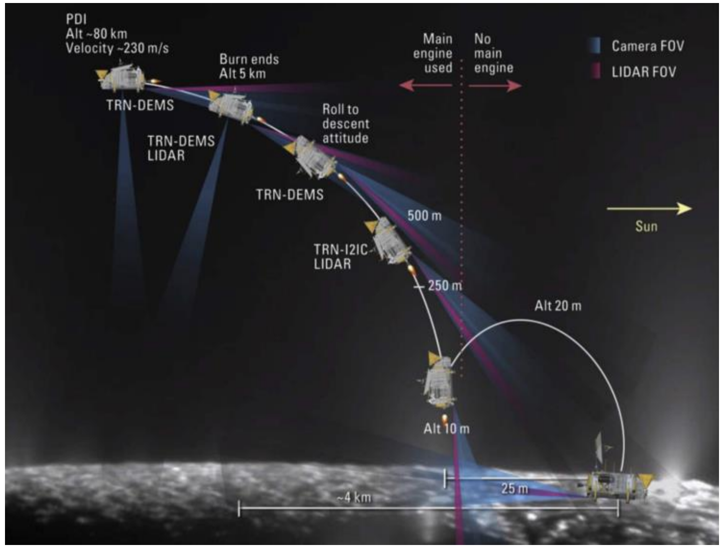
Ref: Landis, G., Oleson, S., & McGuire, M. (2012). Design study for a Mars geyser hopper. In *50th AIAA aerospace sciences meeting including the new horizons forum and aerospace exposition*

Prior work



Dworkin, J. P., et al. (2018). OSIRIS-REx contamination control strategy and implementation. Space science reviews, 214(1), 1-53.

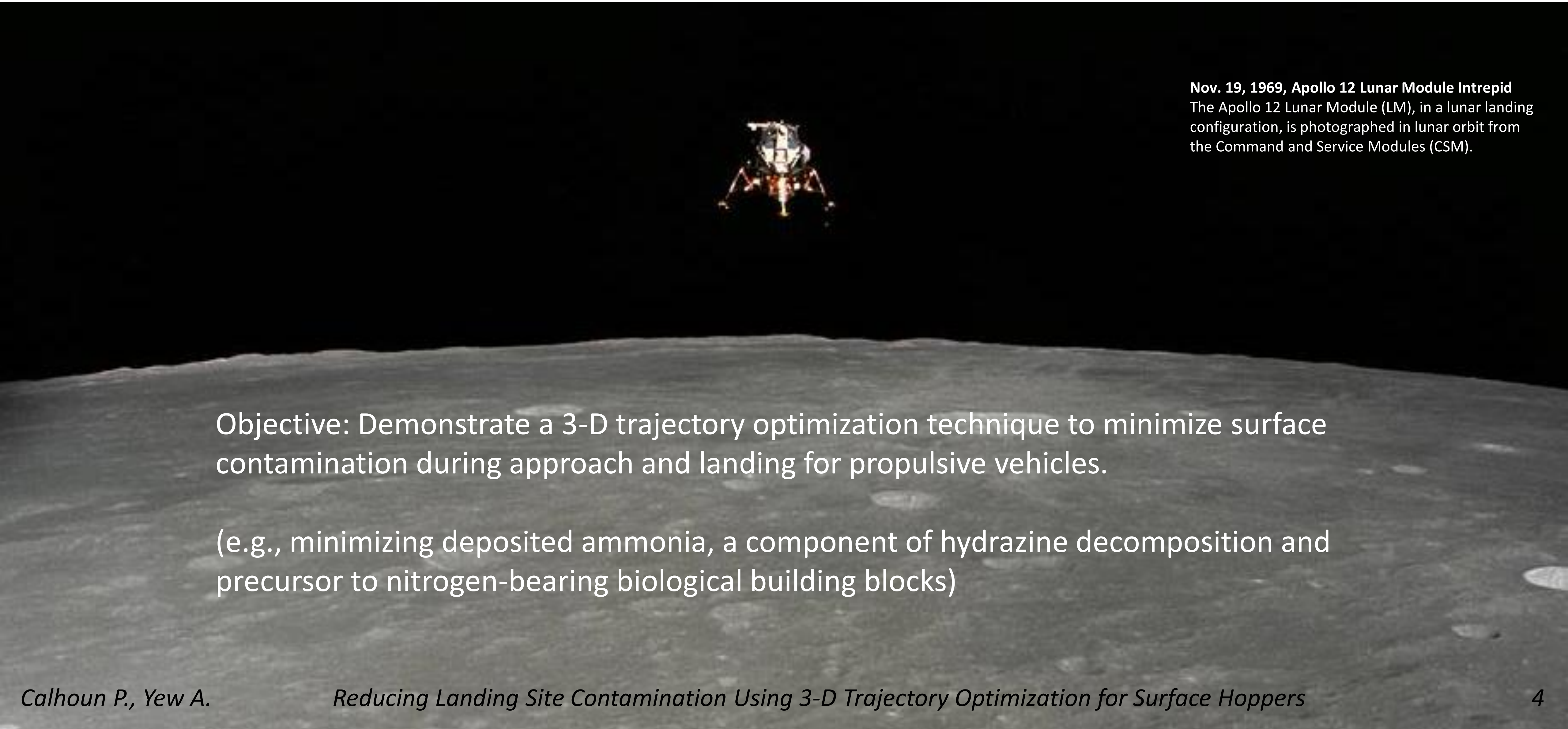
OSIRIS-REx was the first surface mission to impose hydrazine contamination thresholds as a science requirement. It was initially written in terms of the fraction of hydrazine to sample collected, but later revised to exclude any reference to the sample collected or sampling site.



MacKenzie, et al. (2021). The Enceladus Orbilander mission concept: Balancing return and resources in the search for life. The Planetary Science Journal, 2(2), 77.

Orbilander is a life assessment mission to detect life signatures and understand the potential habitability of Enceladus. As such, contamination considerations for a landing was analyzed by utilizing estimates based on blast zones of Mars and Lunar landers. However, the analysis is incomplete.

Objective



Nov. 19, 1969, Apollo 12 Lunar Module Intrepid
The Apollo 12 Lunar Module (LM), in a lunar landing configuration, is photographed in lunar orbit from the Command and Service Modules (CSM).

Objective: Demonstrate a 3-D trajectory optimization technique to minimize surface contamination during approach and landing for propulsive vehicles.

(e.g., minimizing deposited ammonia, a component of hydrazine decomposition and precursor to nitrogen-bearing biological building blocks)

Model Overview

Optimal flight trajectories determined by simulation and nonlinear programming using Direct Collocation (DC) with implicit Simpson-Hermite integration to ensure the feasibility of optimized trajectory state solutions, as described in Pollicelli's Thesis [1]. Framework uses a representative model of the 3-D motion for a vehicle subject to local gravity.

States: downrange, vertical, and cross range positions (P_d , P_v , P_c) , respective velocities (V_d , V_v , V_c), thrust vector direction angles (θ, ϕ), vehicle wet mass (m), and plume contamination deposition at landing location (C).

$$\dot{P_d} = V_d$$

$$\dot{V_d} = -T\frac{\sin(\theta)}{m}$$

$$\dot{P_v} = V_v$$

$$\dot{V_v} = -T\frac{\cos(\theta)\cos(\phi)}{m} - g_L$$

$$\dot{P_c} = V_c$$

$$\dot{V_c} = -T\frac{\cos(\theta)\sin(\phi)}{m}$$

$$\dot{\theta} = \omega_\theta$$

$$\dot{\phi} = \omega_\phi$$

$$\dot{m} = -\frac{T}{g_0 I_{sp}}$$

$$\dot{C} = T_{dc}\, C_{max}(d_p)\,\cos^4(\alpha_p)$$

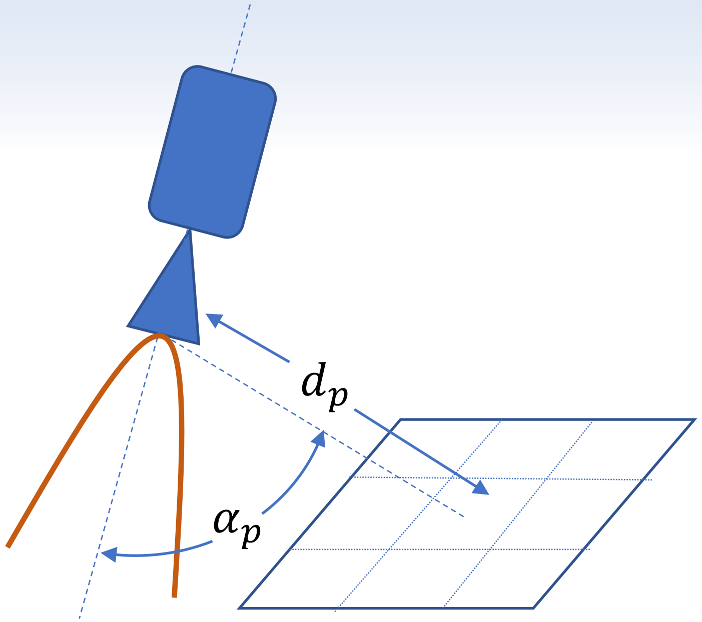
T = thrust magnitude
θ = thrust pitch angle from zenith
ϕ = thrust roll angle from zenith
ω_θ= thrust pitch rate
ω_ϕ= thrust roll rate
g_L = local gravity
g_0 = Earth gravity constant
I_{sp} = thruster specific impulse
T_{dc} = thruster duty cycle
$\dot{C}_{max}$ = max contamination rate
α_p= plume axis angle to landing target
d_p= distance plume exit plane to landing target

[1] Policelli, M. J. (2014). Vertical takeoff vertical landing spacecraft trajectory optimization via direct collocation and nonlinear programming. [Master's Thesis, The Pennsylvania State University]. The University Libraries.

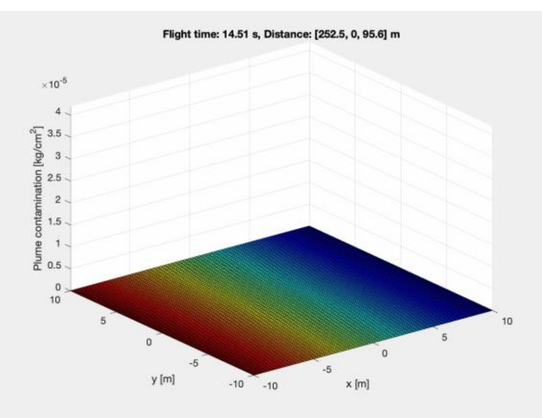
Contamination model

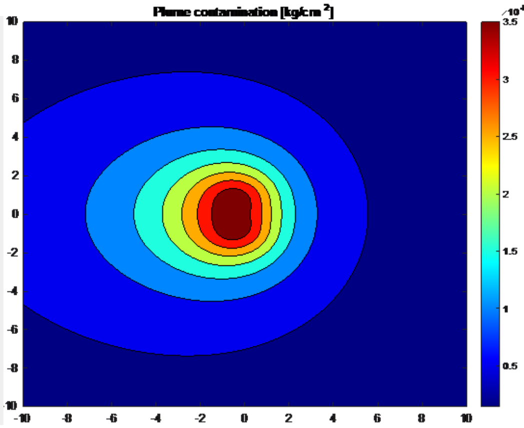
The contamination rate is defined as the exhaust mass projected onto the landing coordinates. Rocket plume geometry and density field used for assessing the surface contamination is modeled approximately, based on analytical models developed in the literature[1,2].

$$\dot{C} \;=\; T_{dc}\, C_{max}(d_p)\, \cos^4(\alpha_p)$$



- Plume envelope takes the form of a $\cos^4$ function of the angle from the thrust plume centerline to the landing site (α_p)
- Maximum contamination rate (C_{max}) prescribed along the exit plume centerline, is a function of distance from exit plane to landing site (d_p)
  - Decreases linearly to zero at a specified distance.
  - Contamination rate ($\dot{C}$) is modulated by thruster duty cycle (T_{dc}).





[1] Roberts, L. (1966). The interface of a rocket exhaust with the lunar surface. The Fluid Dynamic Aspects of Space Flight, 269-290.

[2] Boyd, I. D., & Stark, J. P. W. (1990). Modeling of a small hydrazine thruster plume in the transition flow regime. *Journal of Propulsion and Power*, *6*(2), 121-126.

Optimization and constraints

To enforce a dual minimization for both fuel consumption (fuel) and surface contamination (C), the cost function (f) is a weighted quadratic sum of fuel and contamination.

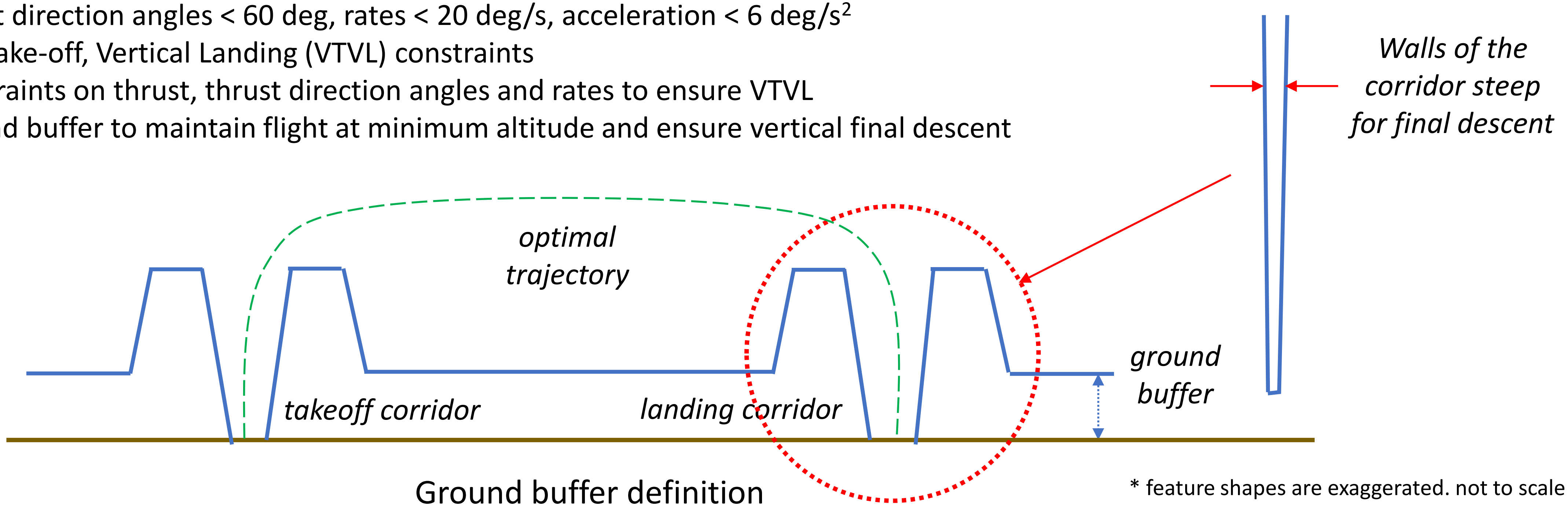
$$f \; = \; (1 - W_C)\, \mathrm{fuel}^2 + W_C\, \mathrm{C}^2$$

Typical constraints for flight implementation.

- Thrust direction angles < 60 deg, rates < 20 deg/s, acceleration < 6 deg/s^2

Vertical Take-off, Vertical Landing (VTVL) constraints

- Constraints on thrust, thrust direction angles and rates to ensure VTVL
- Ground buffer to maintain flight at minimum altitude and ensure vertical final descent



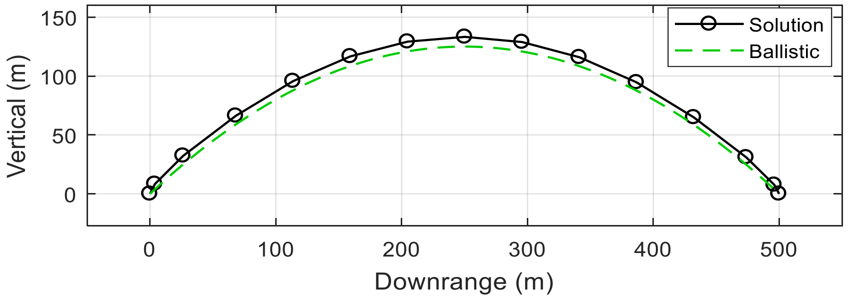
Ground buffer definition

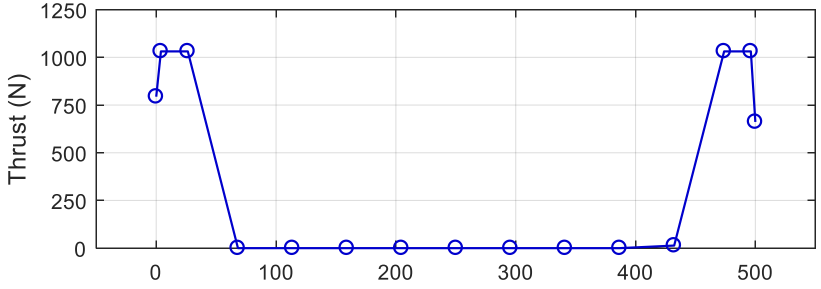
* feature shapes are exaggerated. not to scale

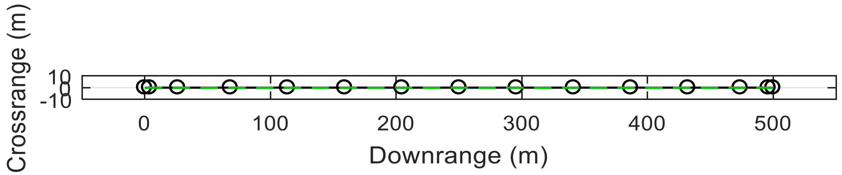
Ballistic Ref. Trajectory: No weight on Contamination (Wc = 0)

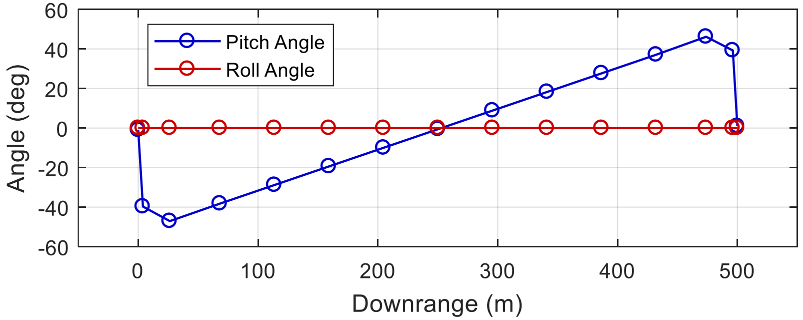
Near-ballistic trajectory was found when contamination weight is set to zero. The optimal solution found approximated a simple two-dimensional ballistic trajectory, even though the state variables included the out-of-plane states (crossrange and roll angle). A slight lofting of the trajectory resulted from the imposed VTVL constraints.

For this near ballistic trajectory, the <u>fuel usage was found to be 7.6 kg, and the contamination was 36 mg</u>









Parameters are representative of a lunar application.

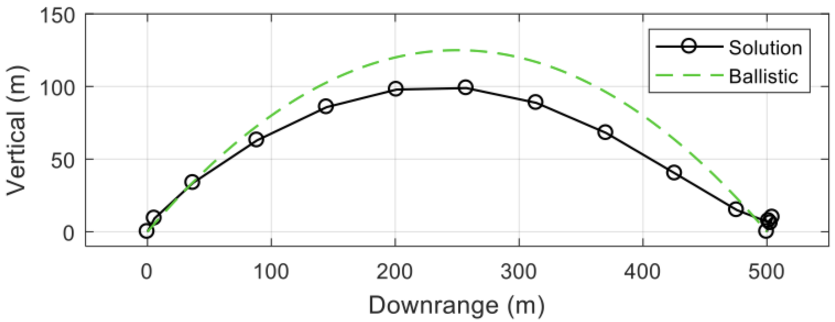
- 500 m downrange hop, initial wet mass = 170 kg, max thrust = 1070 N, Isp = 150 sec., Additional constraints include VTVL, min. altitude = 3 m

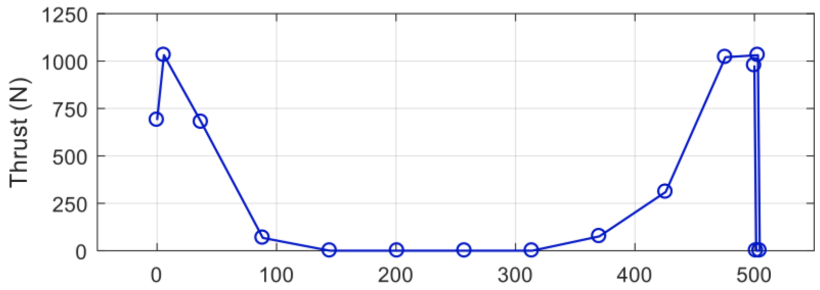
Significant Out-of-Plane Motion when Minimizing Fuel and Contamination (Wc = 0.4)

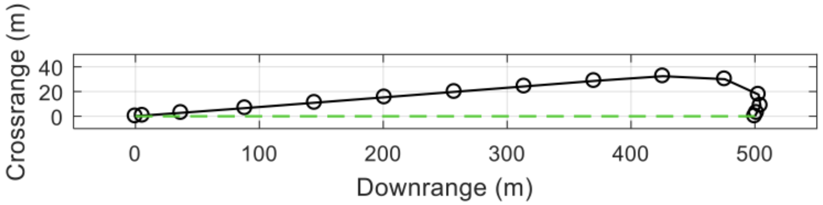
Optimal trajectories with significant out-of-plane motion for increases in contamination weight.

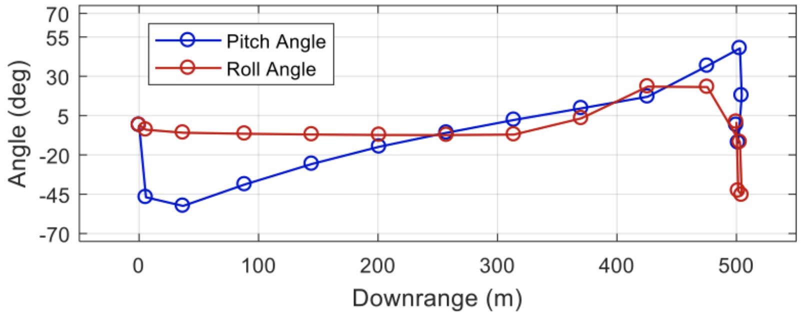
- Trajectories are slightly depressed from the ballistic flight reference in these cases.
- An agile maneuver is performed on final descent to vector the thrust both in-plane and out-of-plane to minimize contamination while simultaneously avoiding excessive fuel usage.

Out-of-Plane trajectory (Wc = 0.4), the fuel usage = 9 kg (18.4% increase)_, and the contamination = 8 mg (78% reduction)









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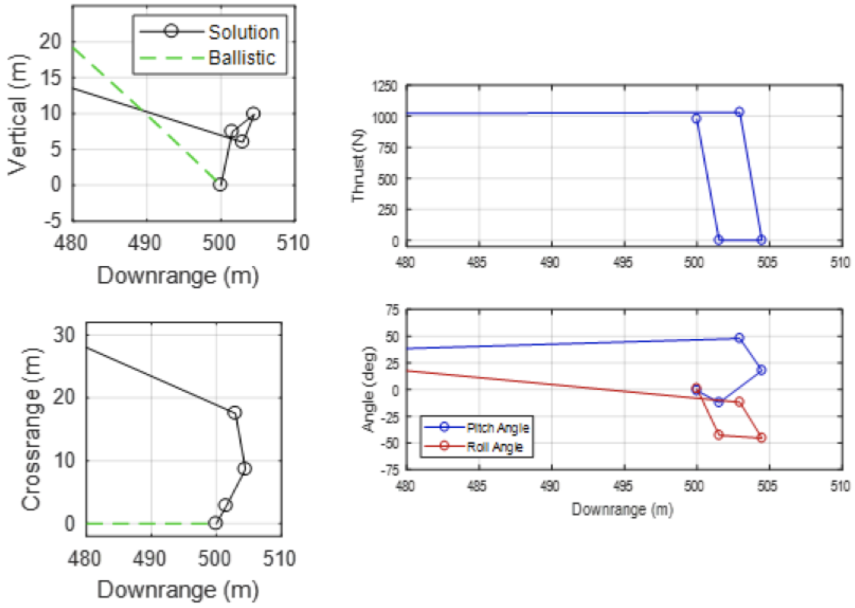
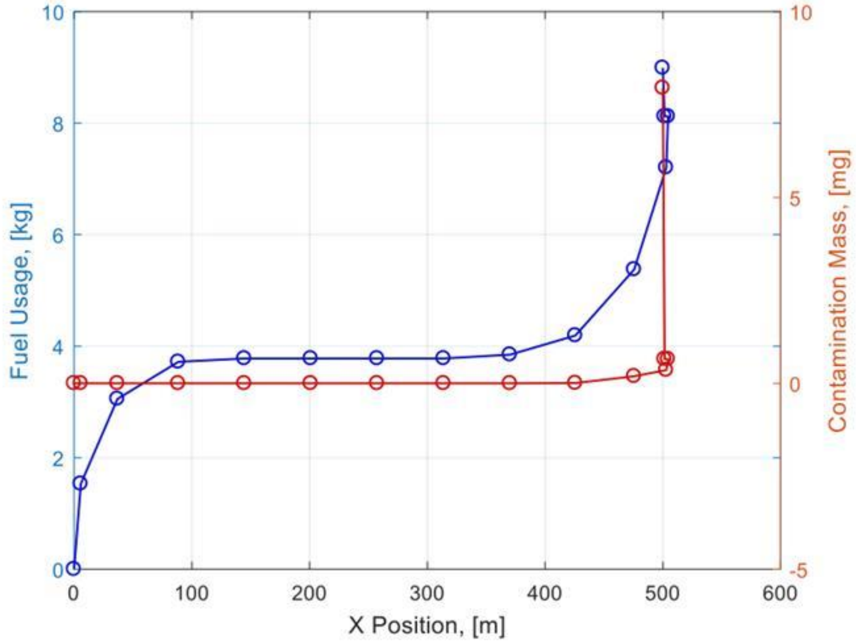
Significant Out-of-Plane Motion when Minimizing Fuel and Contamination (Wc = 0.4)

Trajectory inflections observed in the final descent phase, manifested as hovering and crossrange approach

- A significant reduction of contamination during final descent results from exploiting the relatively narrow plume as compared to cosine loss of vertical component of thrust
- A small roll maneuver at the beginning sets up conditions for exploiting the out-of-plane maneuvers.
- Vectoring along crossrange during final descent points away from the landing site to minimize plume contamination.





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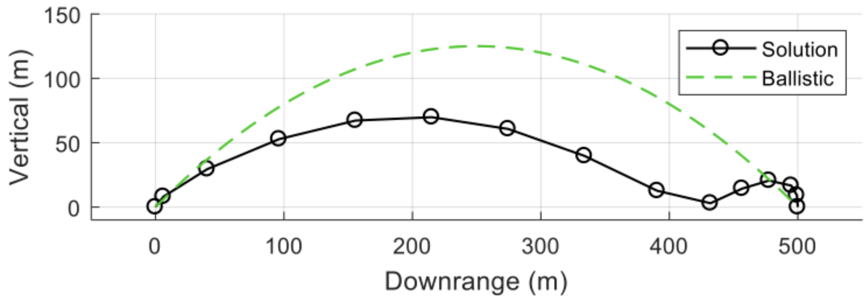
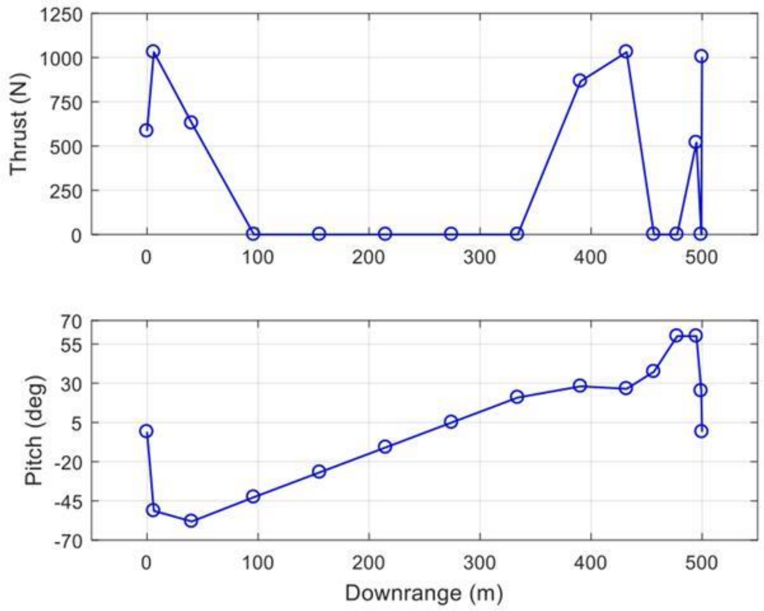
"Second Hop" Maneuver to Minimize Contamination for In-plane Restricted Trajectory

Optimization for in-plane only maneuvers investigate the impact of restricting the trajectory to in-plane only motion.

- Case was selected to provide a good comparison with the previous 3-D case having same fuel usage (Wc = 0.2)
- The second hop is a typical solution for in-plane restricted trajectory. This hop is less fuel efficient than 3-D cases
- 3-D maneuvers can vector thrust out-of-plane, away from landing site, while closely approximating the fuel optimal ballistic trajectory.
- <u>Contamination is 13.5 mg (37.5% of the fuel-optimal ballistic trajectories), but a 68% increase over 3-D case with same fuel usage</u>





Parameters representative of a lunar application.

- 500 m downrange hop, initial wet mass = 170 kg, max thrust = 1070 N, Isp = 150 sec., Additional constraints include VTVL, min. altitude = 3 m

Conclusions and Future Work

Conclusions:

- Demonstrated a 3-D trajectory optimization method to simultaneously minimize fuel consumption and landing site contamination.
    - Compromise between contamination reduction and additional fuel usage can be adjusted by changing the respective weighting coefficients in the cost function.
- Out-of-plane maneuvers are more effective in reducing landing site contamination for the same additional fuel usage.
    - This is accomplished by vectoring the thrust out-of-plane while more closely maintaining the fuel optimal ballistic trajectory in the pitch plane.
- Feasible trajectories with realistic constraints on vehicle parameters obtained with some additional fuel.
    - Higher contamination weights produce more complex descent trajectories including hovering maneuvers, trajectory inflections, and target flyovers.

Future work:

- Incorporate and study real surface terrain models.
- Improve contamination model to provide more accurate estimates of expected surface deposition.
- Apply method to optimize a variety of other surface interactions that might be of interest for a mission.

Acknowledgements

Thank you!

- Michael Policelli [1] – provided basic optimization framework and code base, and consultation
- Mehdi Benna – discussions on mission applications and relevance of the research

[1] Policelli, M. J. (2014). Vertical takeoff vertical landing spacecraft trajectory optimization via direct collocation and nonlinear programming. [Master's Thesis, The Pennsylvania State University]. The University Libraries.