

TOWARD AUTONOMOUS PRECISION LUNAR LANDING

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OUTLINE

1. Background

2. Navigation

3. Guidance

4. Dynamics

5. Control

6. Conclusion

OUTLINE

1. Background

2. Navigation

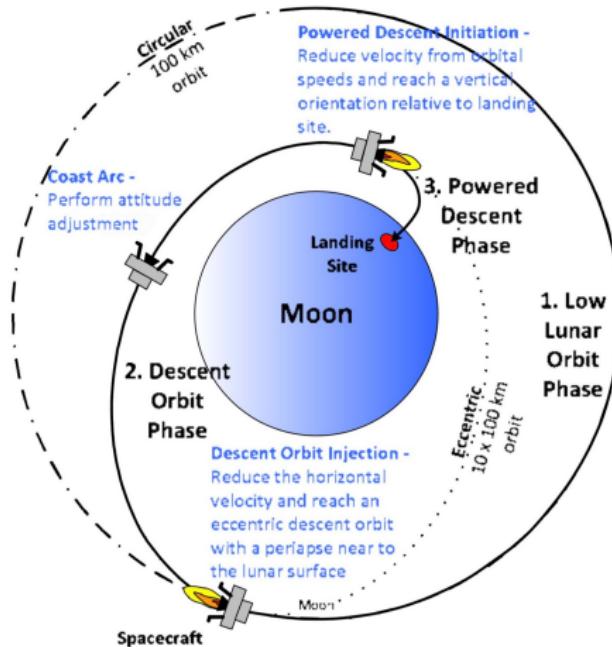
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BACKGROUND: LUNAR DESCENT

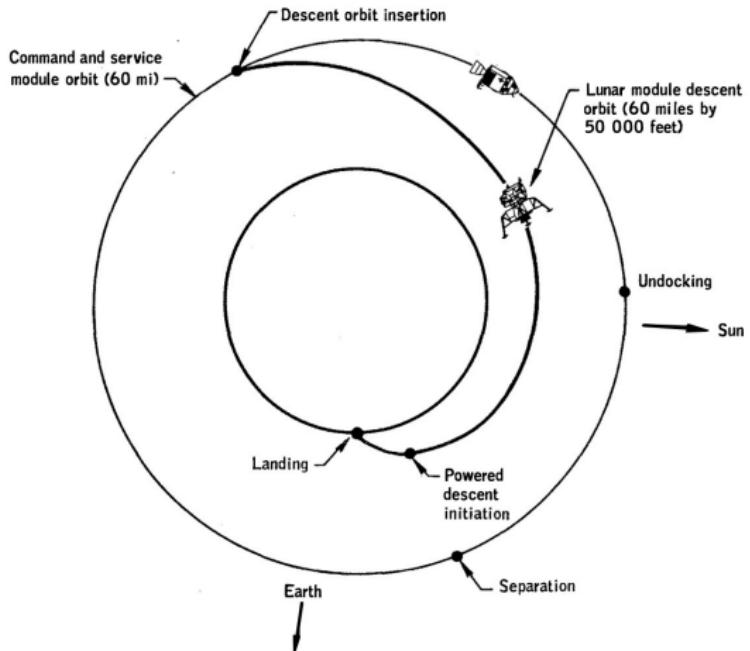


Phases of Lunar Descent

[Bilodeau et al., 2014]

BACKGROUND: LUNAR DESCENT

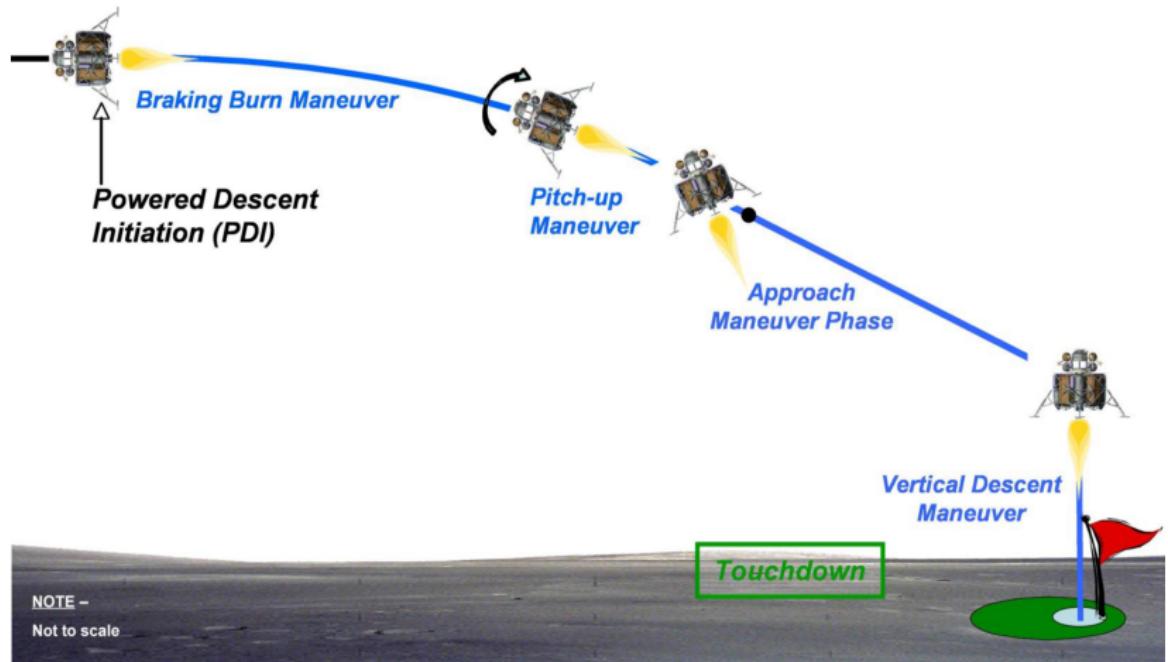
NASA-S-69-3709



Phases of Lunar Descent: Apollo 11

[Low, 1969]

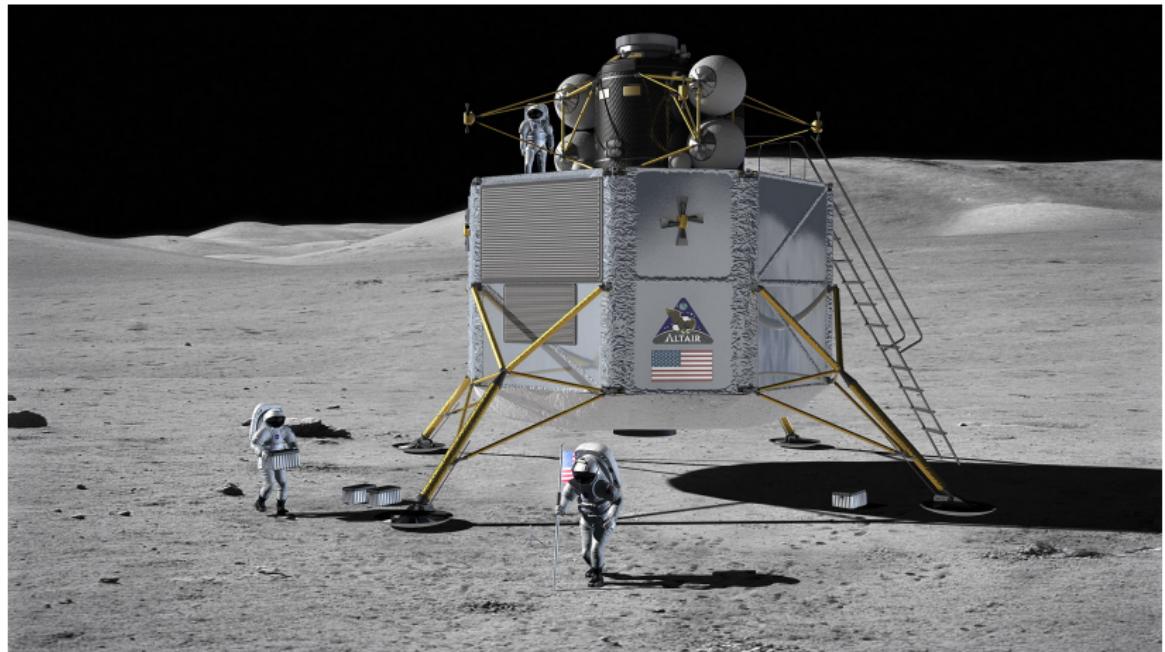
BACKGROUND: POWERED DESCENT



The Powered Descent Phase of Lunar Landing

[Kos et al., 2010]

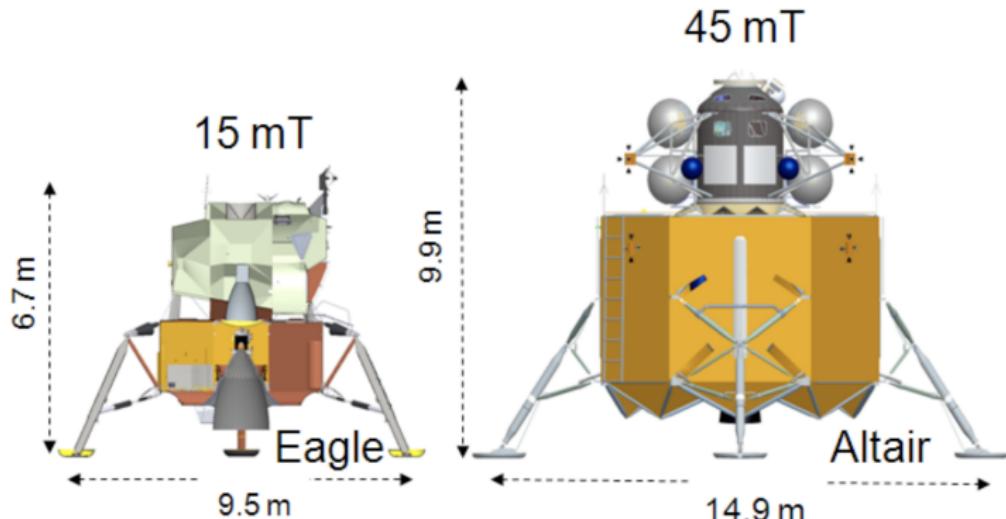
BACKGROUND: THE VEHICLE



A Render of the Altair Lunar Lander

[Source: www.nasaspacesflight.com]

BACKGROUND: THE VEHICLE



Eagle v. Altair

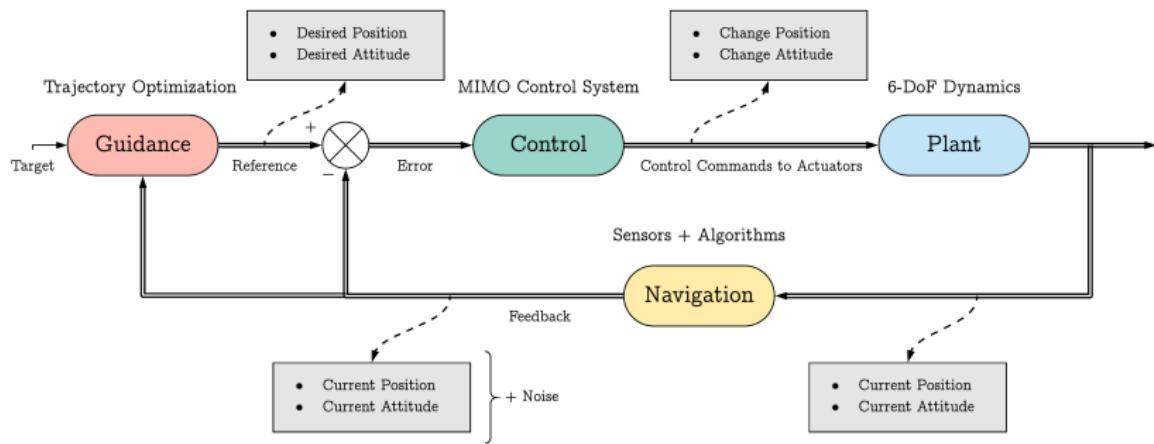
[Lee et al., 2010]

BACKGROUND: GNC

At each time-step:

- Current position and attitude $\Rightarrow ?$
 - ▶ Navigation
- Desired position and attitude at the next time-step $\Rightarrow ?$
 - ▶ Guidance
- *Error-correction* $\Rightarrow ?$
 - ▶ Control

BACKGROUND: GNC FLOW



OUTLINE

1. Background

2. Navigation

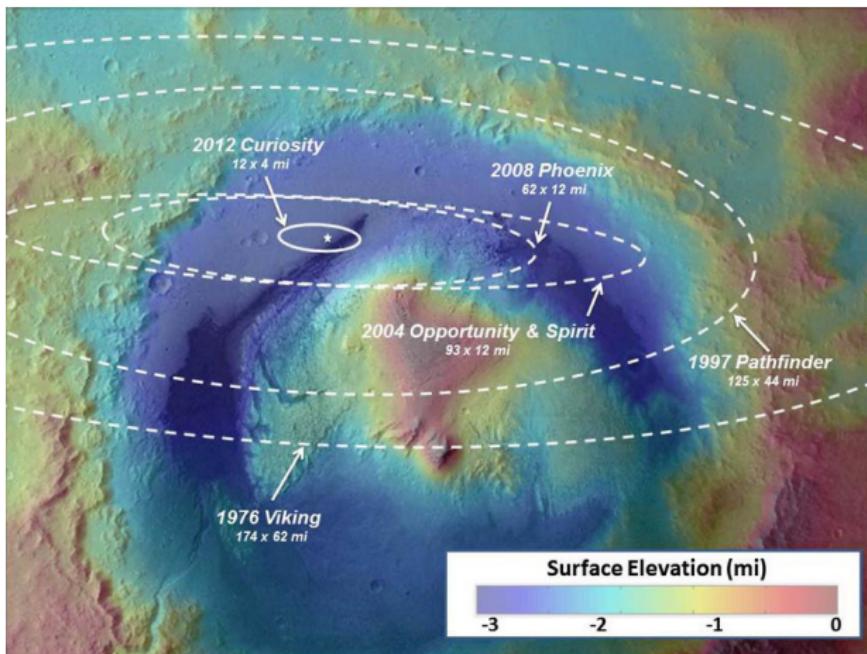
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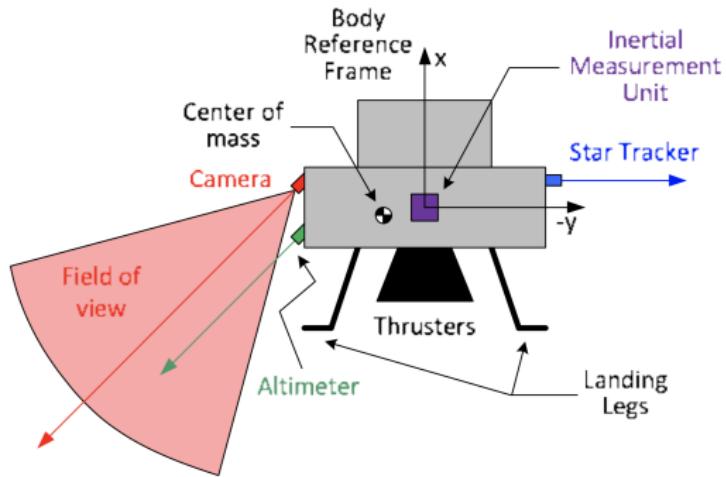
NAVIGATION: BACKGROUND



Landing Ellipses (Mars)

[Credit: NASA/JPL-Caltech/ESA]

NAVIGATION: BACKGROUND



Sensors

[Bilodeau et al., 2014]

NAVIGATION: BACKGROUND

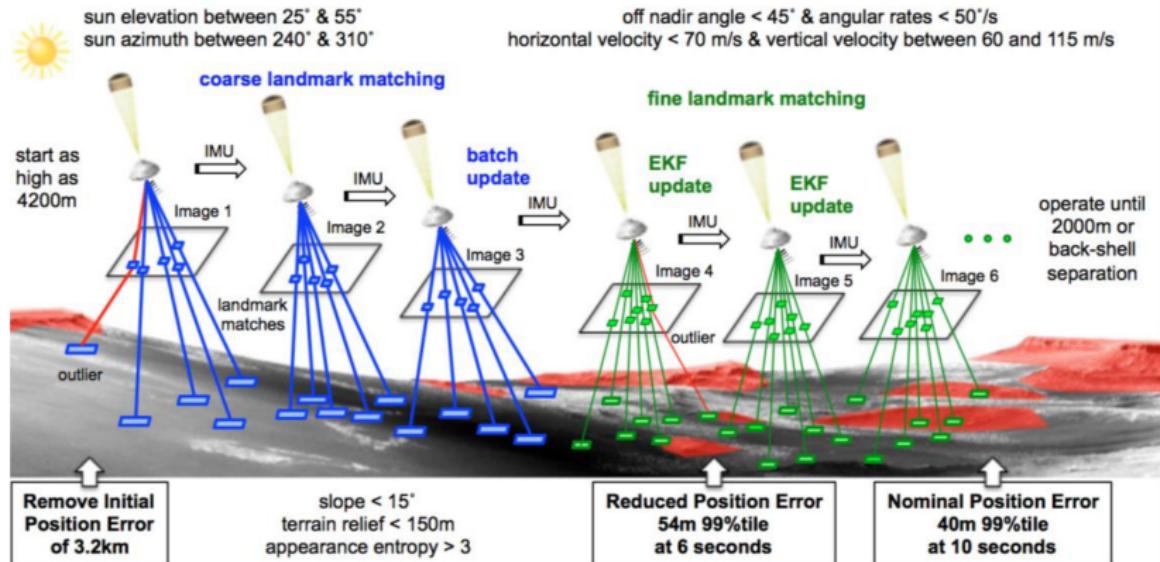
IMU

- Acceleration $\xrightarrow{\int}$ Velocity $\xrightarrow{\int}$ Position
- Drift \rightarrow error in position grows quadratically
- Good for tracking sudden movements

Vision

- Dual-purpose \longrightarrow Navigation + HDA
- If images are blurry \rightarrow hard to detect features
- Distinct disadvantage \rightarrow won't work in the dark

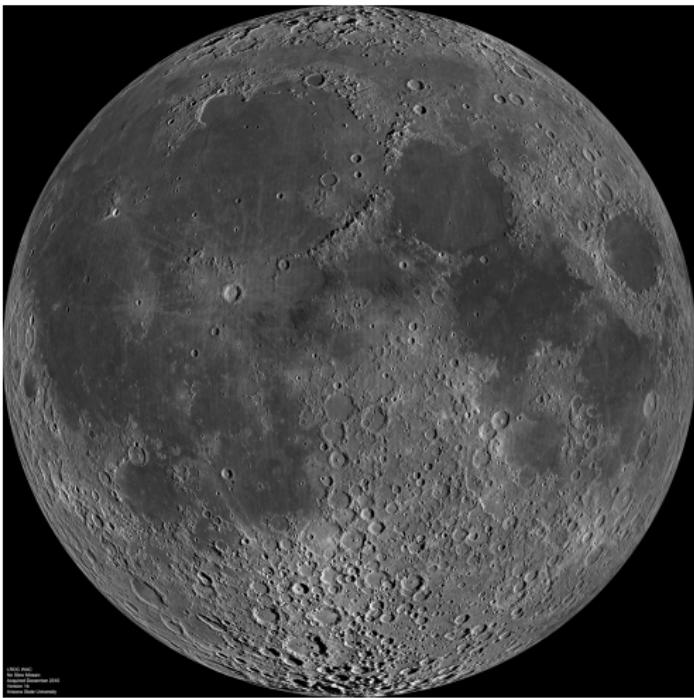
NAVIGATION: BACKGROUND



Terrain Relative Navigation (Mars 2020)

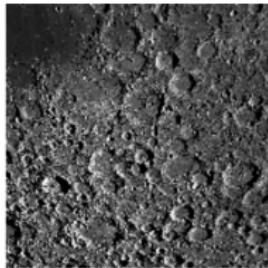
[Johnson et al., 2017]

NAVIGATION: THE MAP



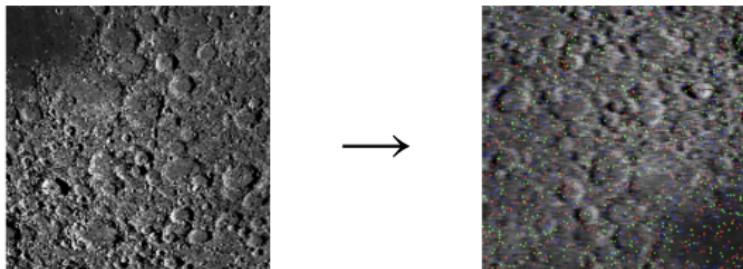
Onboard Map (1400×1400 pixels): 1 pixel \Rightarrow 1.241 km
[Credit: NASA/GSFC/Arizona State University]

NAVIGATION: DESCENT IMAGERY



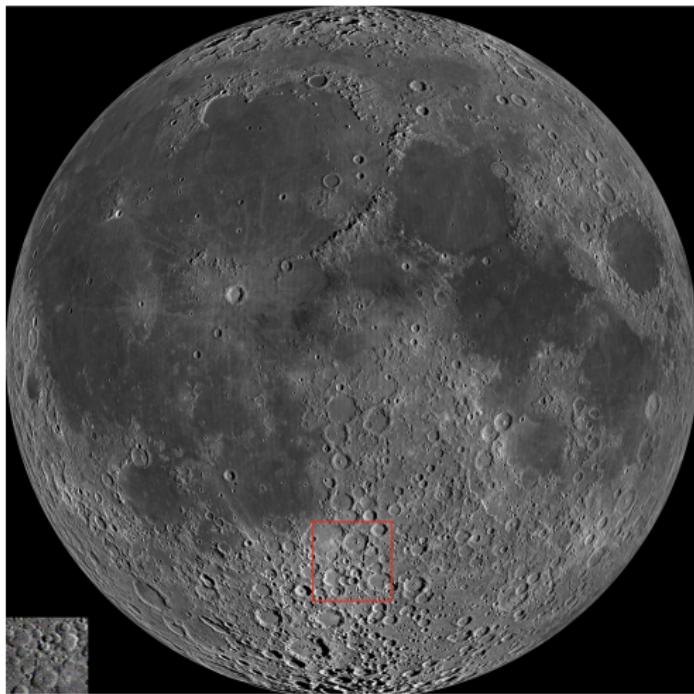
Expectation

NAVIGATION: DESCENT IMAGERY



Expectation → Reality

NAVIGATION: MAP RELATIVE LOCALIZATION



MRL → Localization Error: 1 pixel (1.241 km)

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GUIDANCE: BACKGROUND

Optimization:

$$\begin{aligned} & \text{minimize} && f_0(x) \\ & \text{subject to} && f_i(x) \leq 0, \quad i = 1, \dots, m \\ & && h_i(x) = 0, \quad i = 1, \dots, p \end{aligned}$$

[Boyd and Vandenberghe, 2004]

GUIDANCE: BACKGROUND

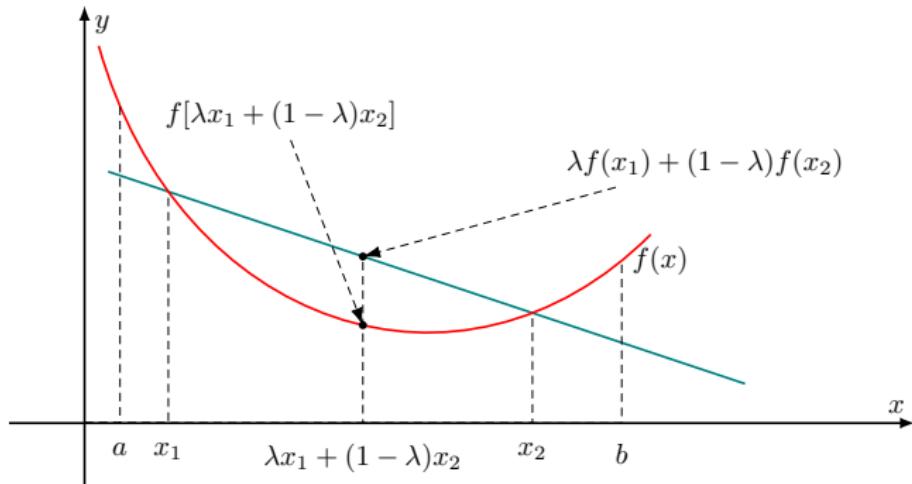
Convex Optimization:

$$\begin{aligned} & \text{minimize} && f_0(x) \\ & \text{subject to} && f_i(x) \leq 0, \quad i = 1, \dots, m \\ & && h_i(x) = 0, \quad i = 1, \dots, p \end{aligned}$$

f_0, f_1, \dots, f_m are convex; equality constraints are affine

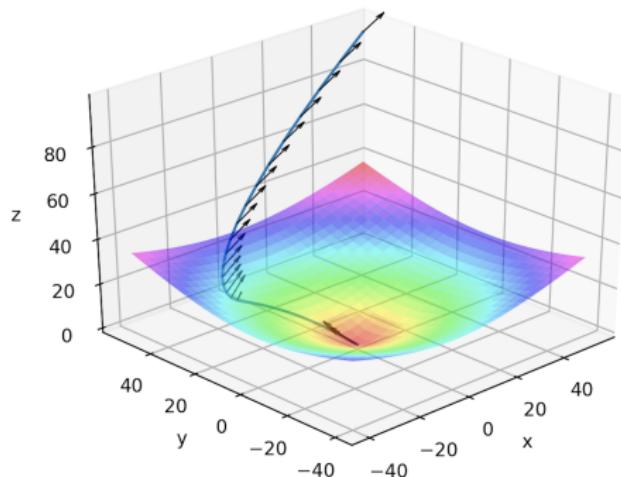
[Boyd and Vandenberghe, 2004]

GUIDANCE: BACKGROUND



Convex Function

GUIDANCE: TRAJECTORY OPTIMIZATION



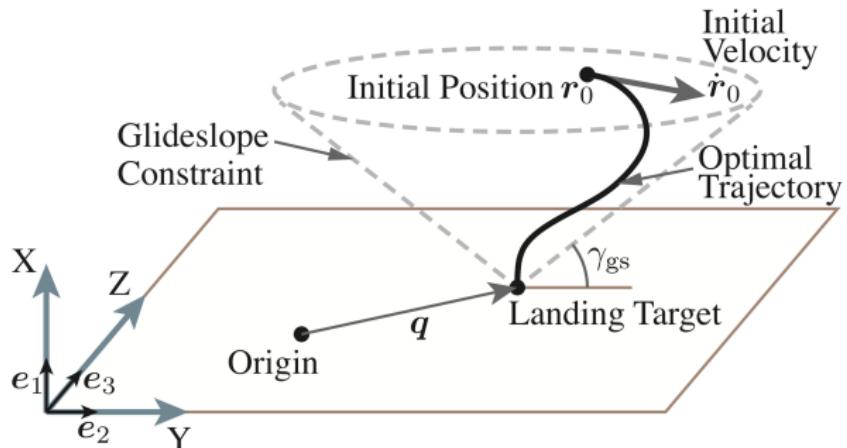
00 00 03 44

CC

11, Houston. Your guidance has converged; you're looking good.

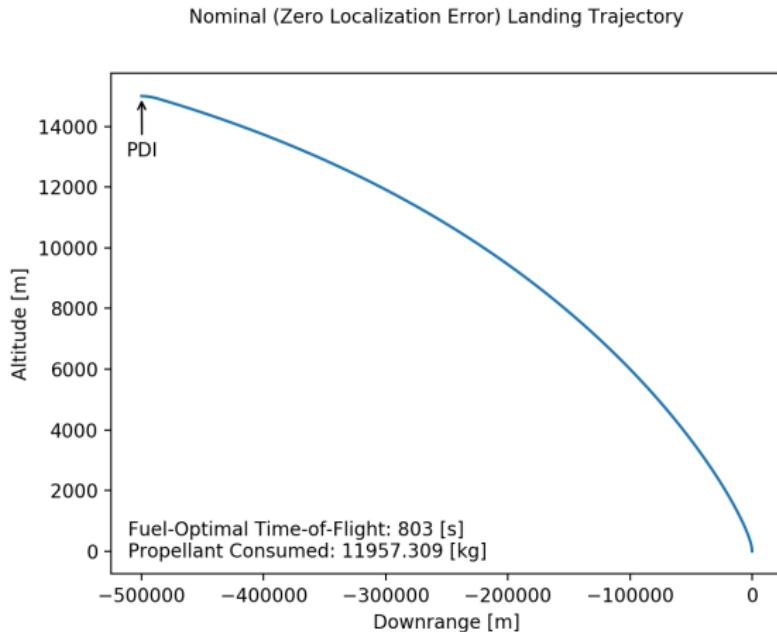
[Source: Apollo 11 Technical Air-to-Ground Voice Transcription]

GUIDANCE: FUEL-OPTIMAL ROCKET LANDING



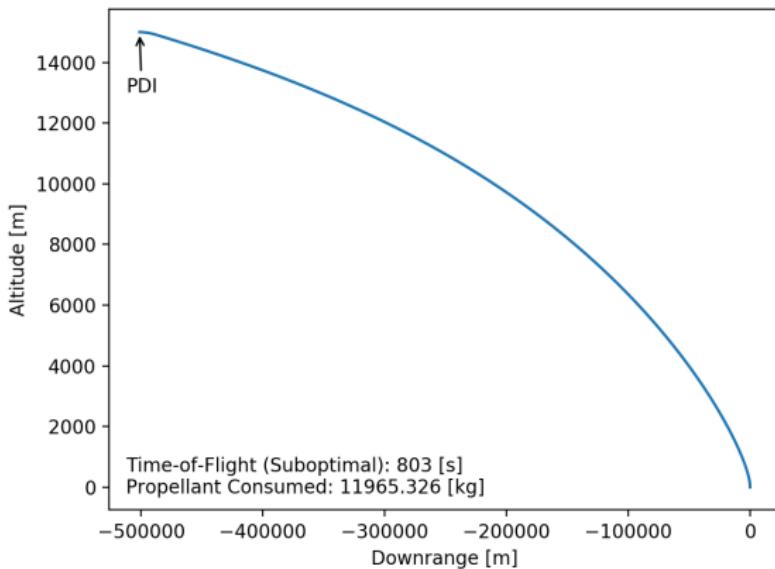
The Fuel-Optimal Rocket Landing Guidance Problem
[Açikmese et al., 2012]

GUIDANCE: NOMINAL TRAJECTORY



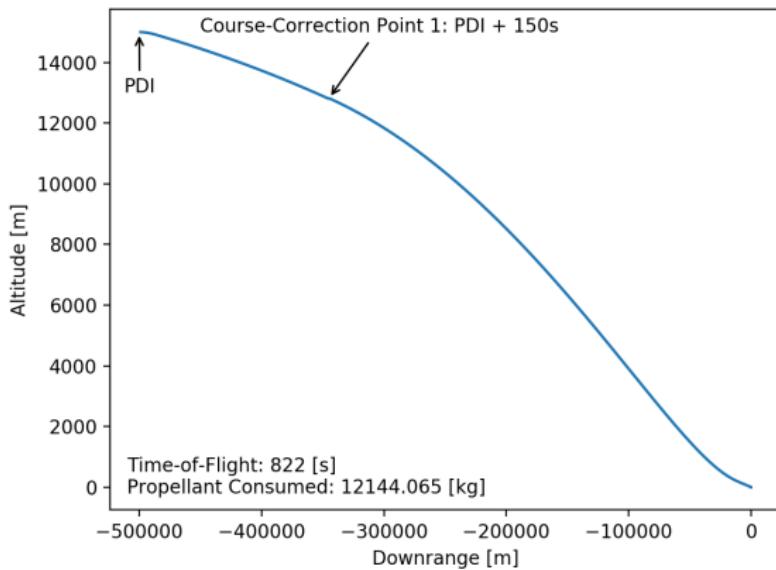
GUIDANCE: ACTUAL TRAJECTORY

Landing Trajectory with a Map-Relative Localization Error of 1 [px] (1.241 [km])



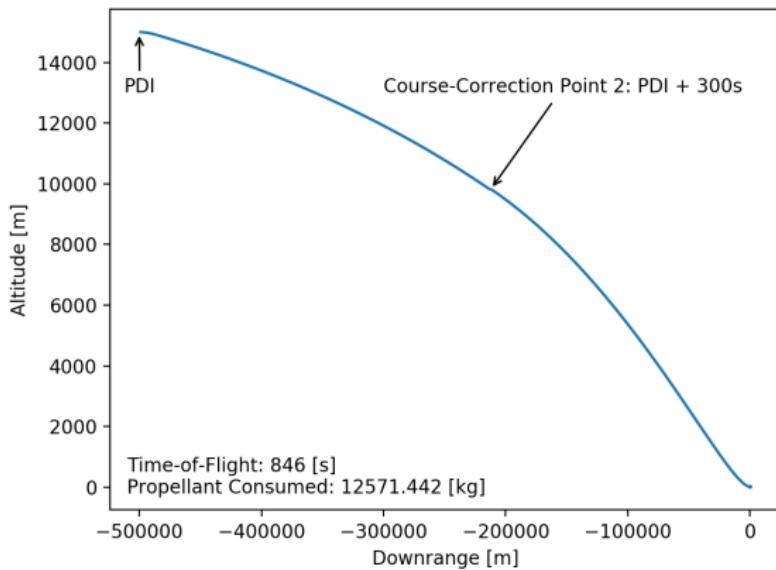
GUIDANCE: THE COURSE-CORRECTION MANEUVER

Landing Trajectory with Course-Correction Maneuver Performed at Point 1



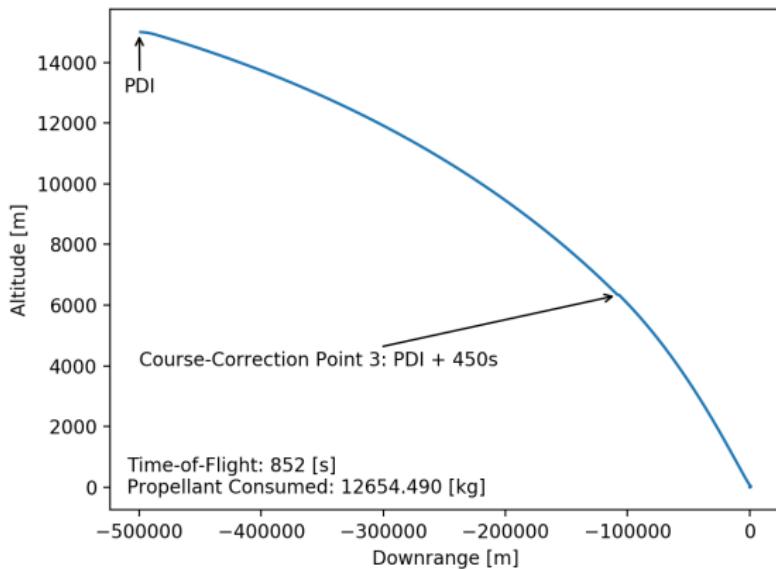
GUIDANCE: THE COURSE-CORRECTION MANEUVER

Landing Trajectory with Course-Correction Maneuver Performed at Point 2



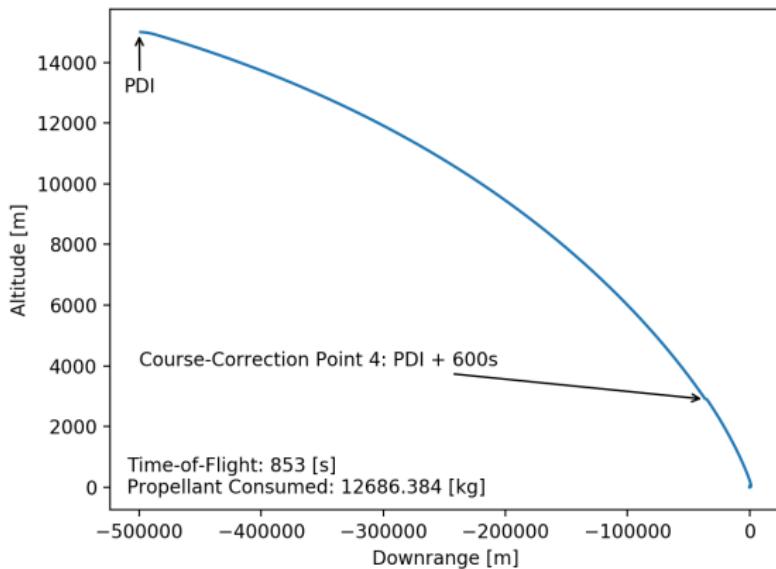
GUIDANCE: THE COURSE-CORRECTION MANEUVER

Landing Trajectory with Course-Correction Maneuver Performed at Point 3



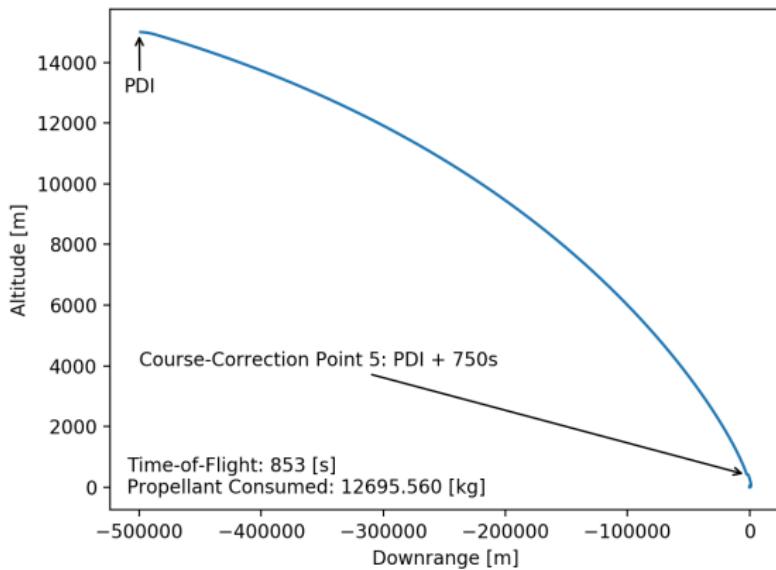
GUIDANCE: THE COURSE-CORRECTION MANEUVER

Landing Trajectory with Course-Correction Maneuver Performed at Point 4

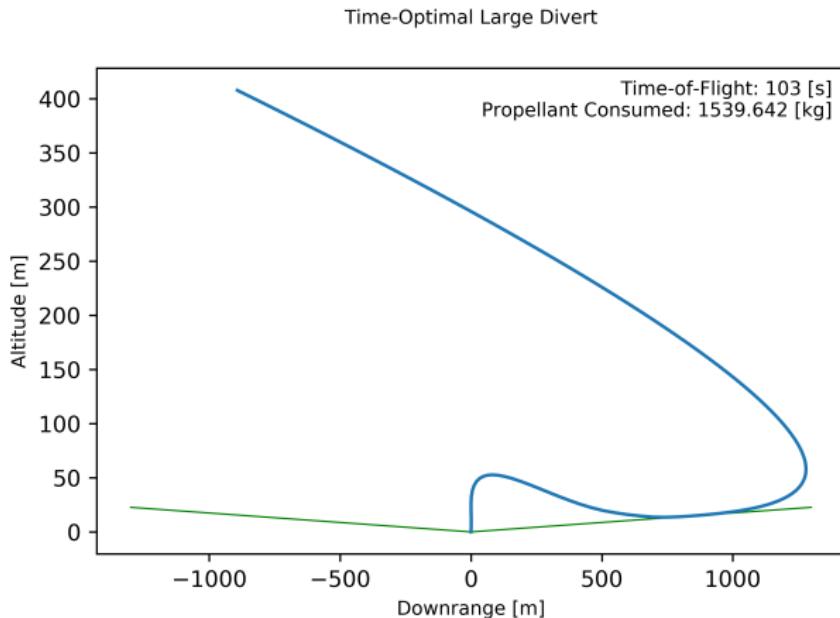


GUIDANCE: THE COURSE-CORRECTION MANEUVER

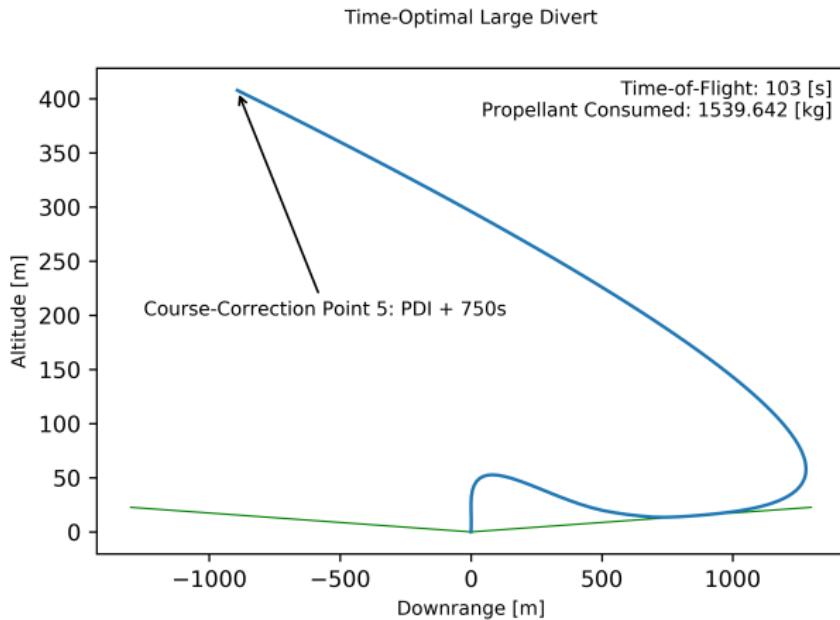
Landing Trajectory with Course-Correction Maneuver Performed at Point 5



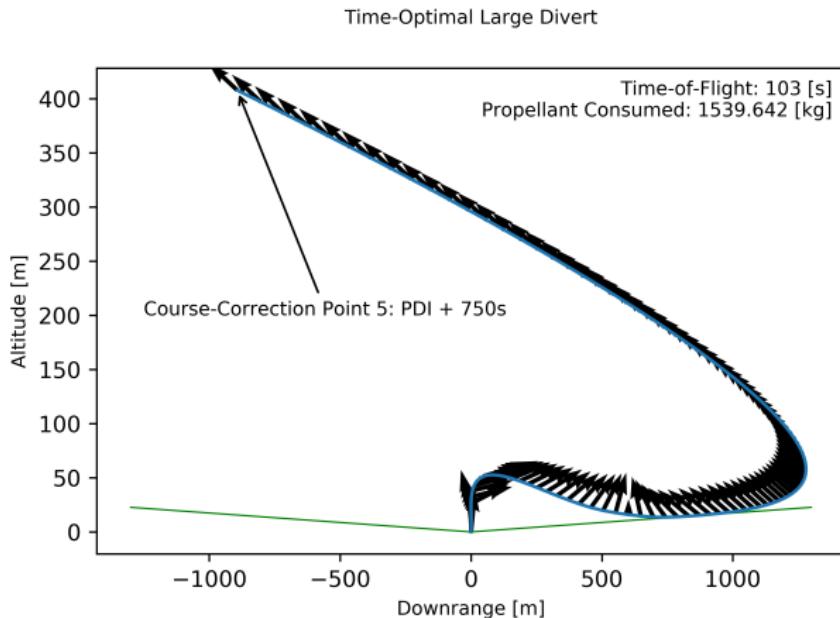
GUIDANCE: THE COURSE-CORRECTION MANEUVER



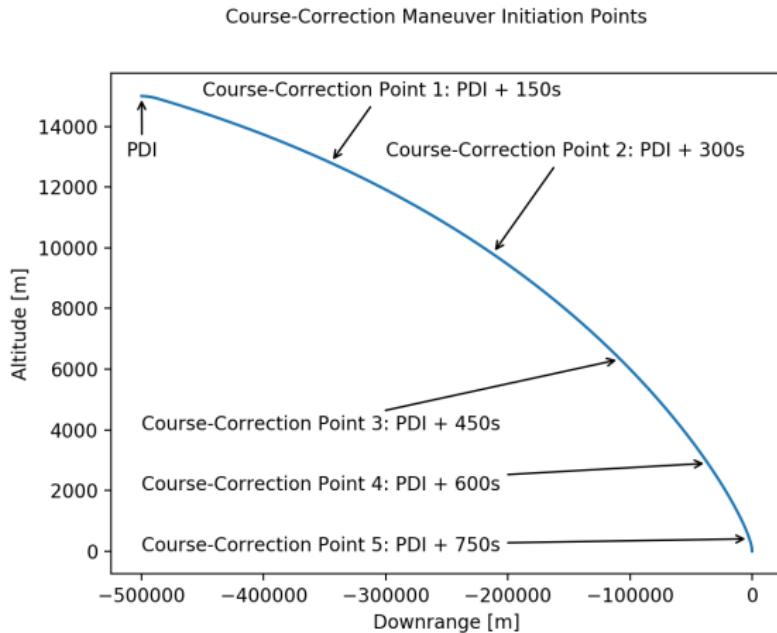
GUIDANCE: THE COURSE-CORRECTION MANEUVER



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GUIDANCE: THE COURSE-CORRECTION MANEUVER



GUIDANCE: THE COURSE-CORRECTION MANEUVER

```
Wet mass at correction point 1: 34914.595468356114 kg
Propellant consumed at correction point 1: 2130.404531643908 kg
Initial conditions at correction point 1: position, velocity
[-345127.31668656  12799.94957184]
[967.7163352 -17.76153298]

Wet mass at correction point 2: 32658.28643080762 kg
Propellant consumed at correction point 2: 4386.713569192401 kg
Initial conditions at correction point 2: position, velocity
[-212468.3977577  9800.3366802]
[795.88842796 -21.97925771]

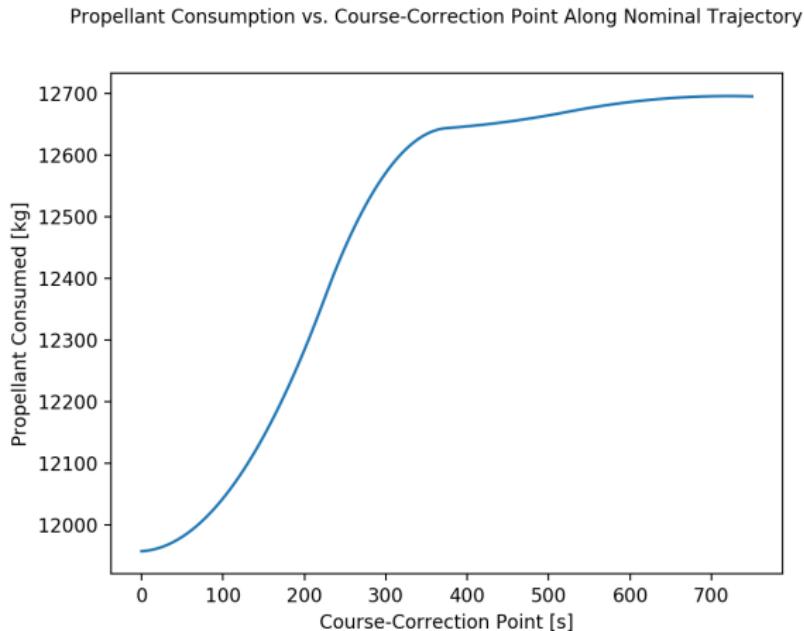
Wet mass at correction point 3: 30401.904243792083 kg
Propellant consumed at correction point 3: 6643.095756207938 kg
Initial conditions at correction point 3: position, velocity
[-107925.92645045  6326.11552129]
[592.71617699 -23.77378757]

Wet mass at correction point 4: 28145.498270589553 kg
Propellant consumed at correction point 4: 8899.50172941047 kg
Initial conditions at correction point 4: position, velocity
[-36214.35519724  2898.71862314]
[358.12210351 -20.94233618]

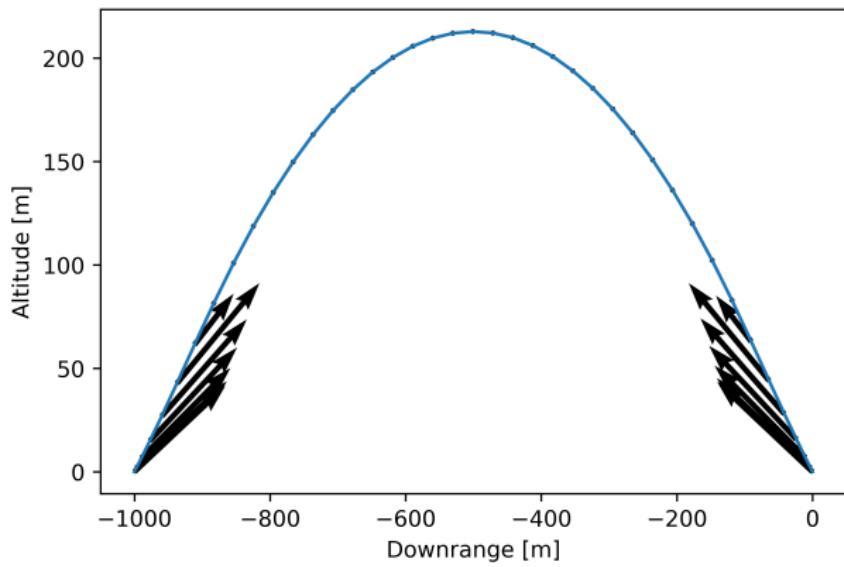
Wet mass at correction point 5: 25889.082041647805 kg
Propellant consumed at correction point 5: 11155.917958352216 kg
Initial conditions at correction point 5: position, velocity
[-2133.69172449  407.78011924]
[ 90.59795127 -10.80132465]
```

Guidance Program Output

GUIDANCE: THE COURSE-CORRECTION MANEUVER



GUIDANCE: LUNAR HOPPER



Optimal 1 km Hop Trajectory for the Lunar Hopper
(NASA Big Idea Challenge 2020)

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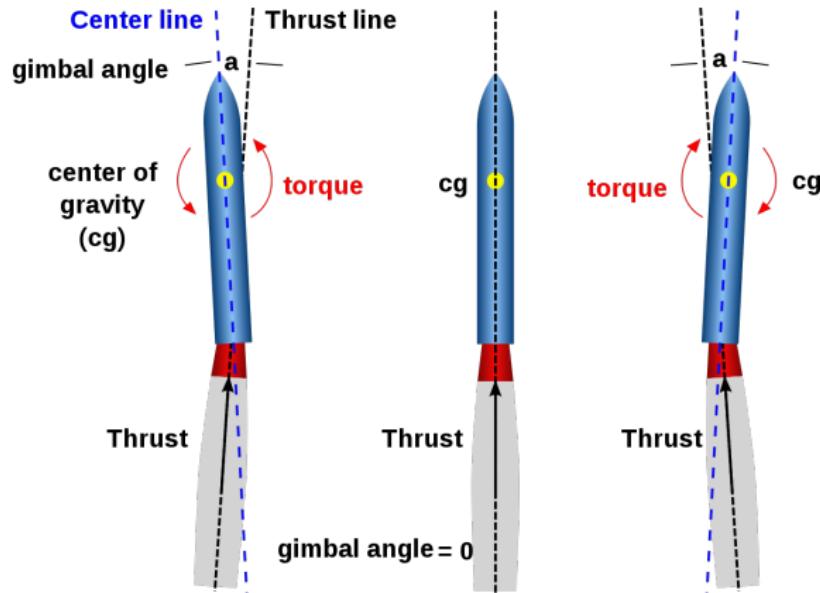
3. Guidance

4. Dynamics

5. Control

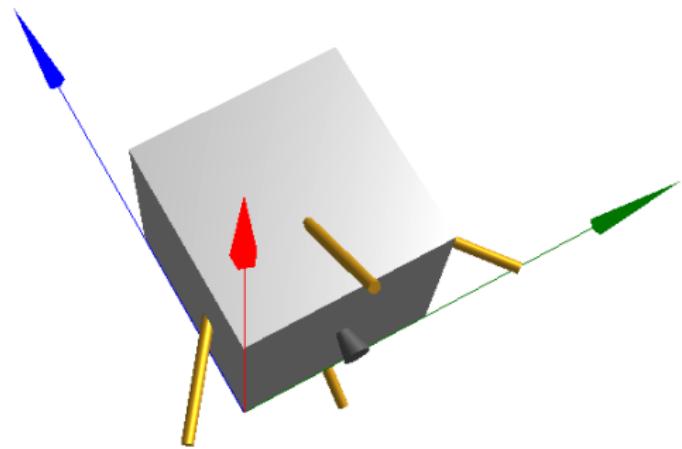
6. Conclusion

DYNAMICS: BACKGROUND



[Source: www.grc.nasa.gov]

DYNAMICS: MODELING (KANE'S METHOD)



The Lunar Lander Model

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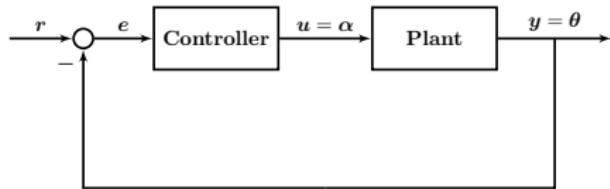
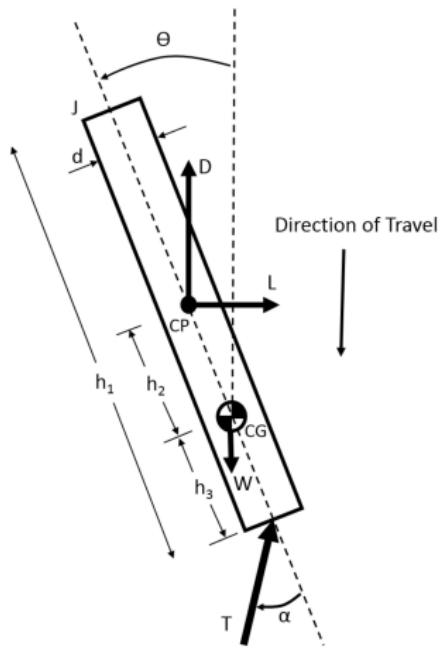
CONTROL: BACKGROUND



Hypersonic Reentry of a Falcon 9 FT First-Stage Booster

[Credit: www.deviantart.com/brickmack]

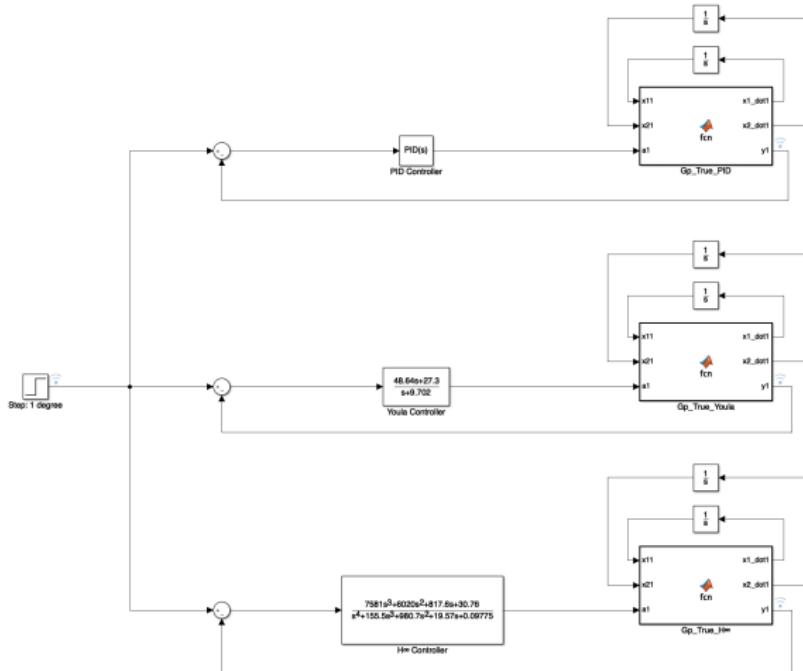
CONTROL: DESIGN



The Plant

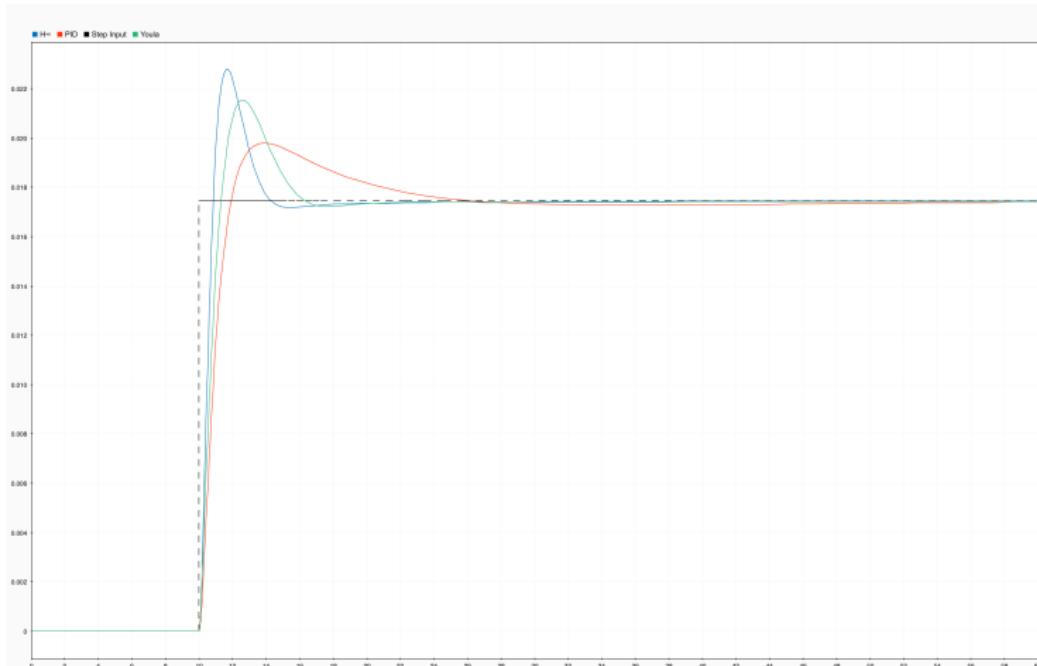
[Cox and Clausing, 2016]

CONTROL: DESIGN



Block Diagram

CONTROL: RESPONSE



Step Responses

OUTLINE

1. Background

2. Navigation

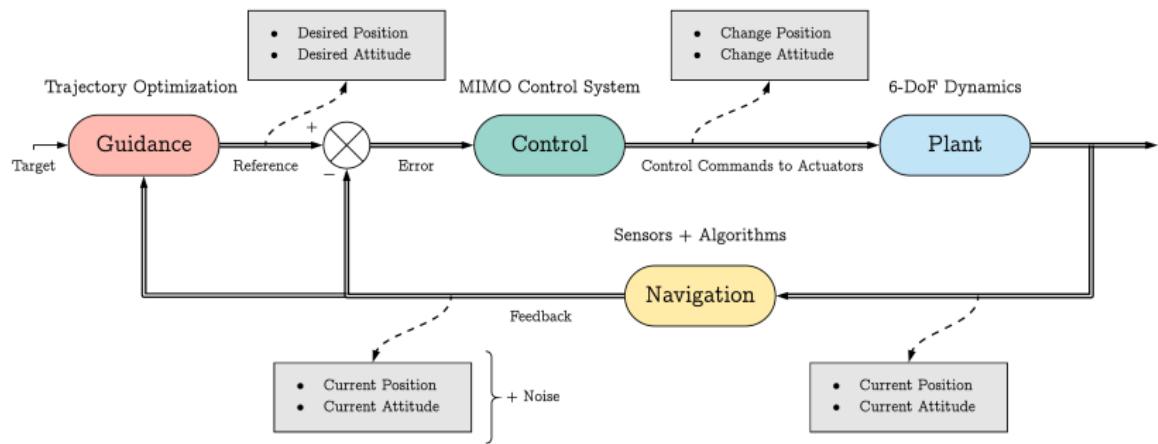
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GNC FLOW REVISITED



THANK YOU

Questions?

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REFERENCES

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