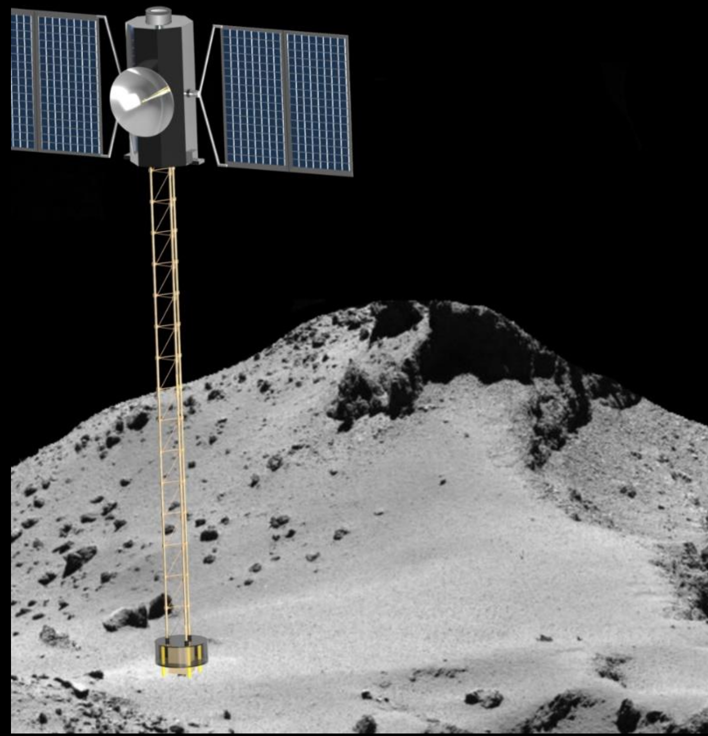

GUIDANCE, NAVIGATION AND CONTROL OF SPIKE FOR DESCENT, LANDING AND HOPPING ON AN ASTEROID

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Outline

- Introduction
- SPIKE Spacecraft
- Mission Concept
- Asteroid Dynamical Environment Modeling
- Spacecraft Dynamics Model
- Descent Phase Simulations
- Landing Phase Simulations
- Hopping dynamics
- Conclusion

Asteroid Surface Exploration

Geohistory

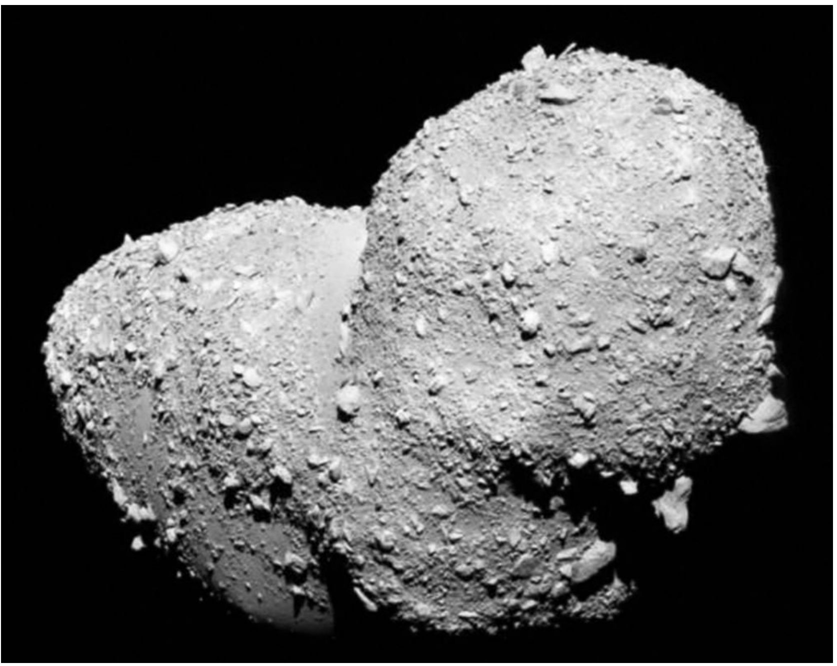
Security/Deflection

ISRU

Short, focused, high-risk, high-return…

Complements flyby and orbital observation science.

Science Focused



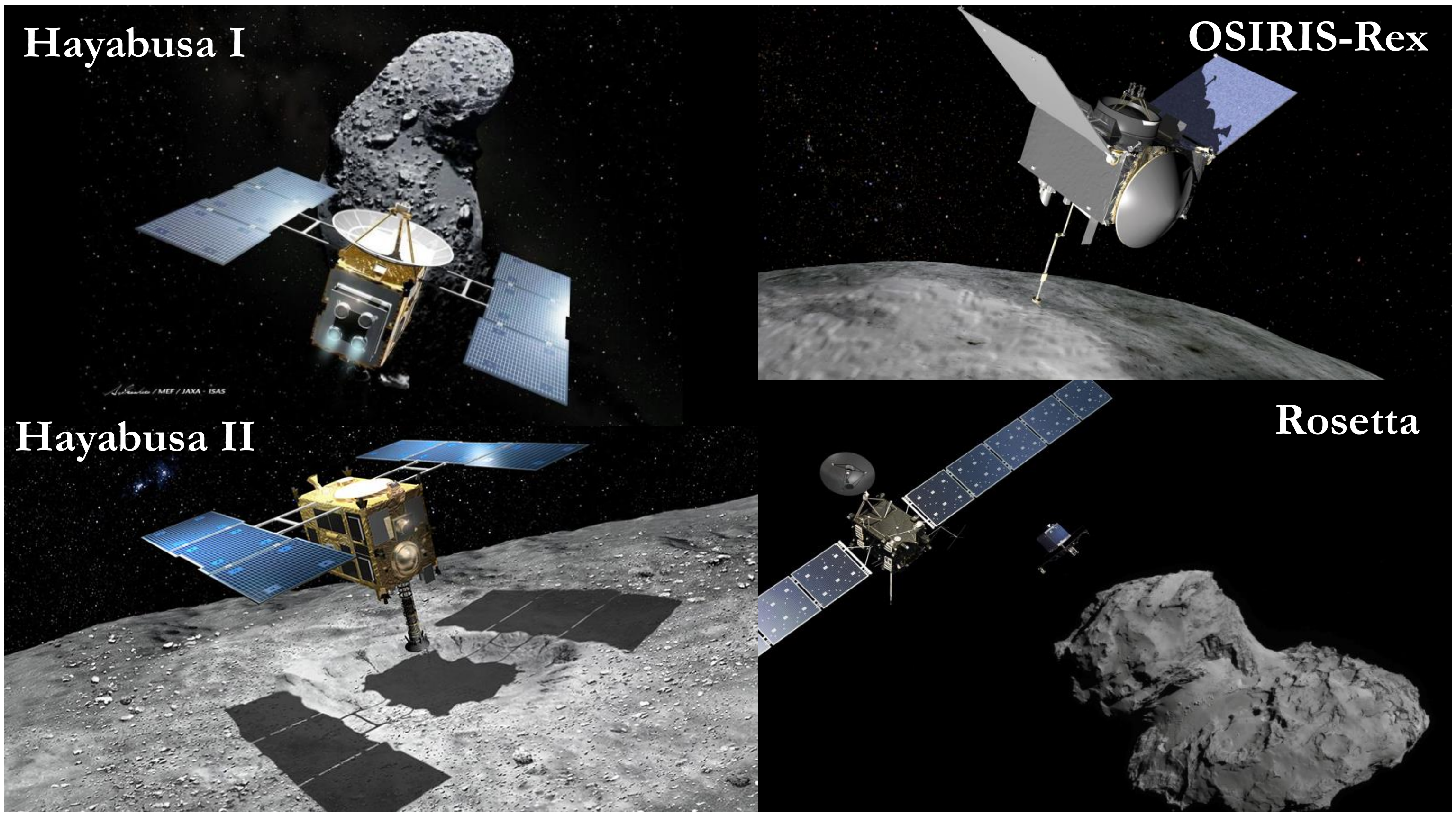
- Determine early geo-history, composition
- Seismic analysis from multiple locations
- Analyze pristine, unearthed regolith

Take a step back in time to the primordial solar system…

Challenges

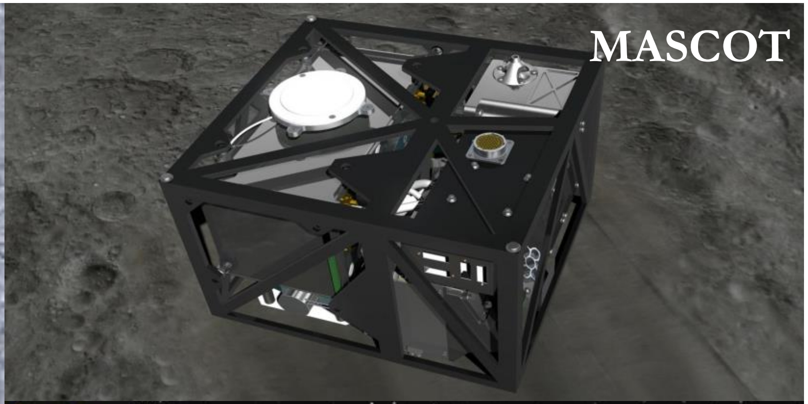
- Asteroid mobility
  - Low-gravity, low-escape velocity
- Surface contact risks
  - Dust
  - Static charge
  - Tracking and communication
- Varying high and low temperature

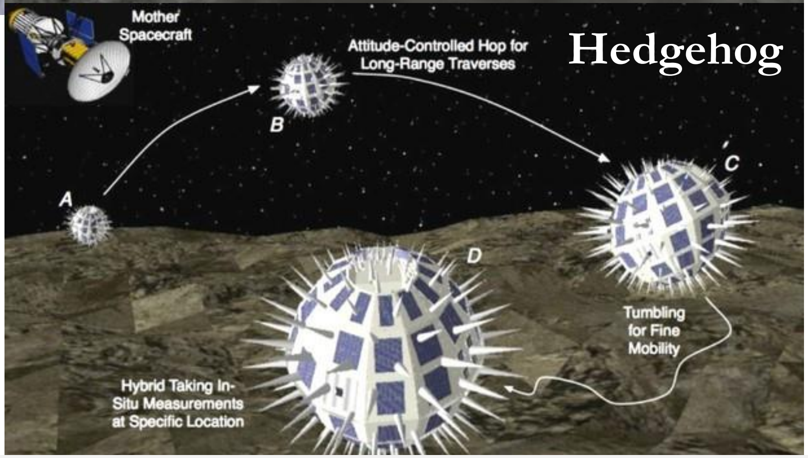
Related Work



Current missions envisions performing touch-and-go operations over an asteroid surfaces

Related Work



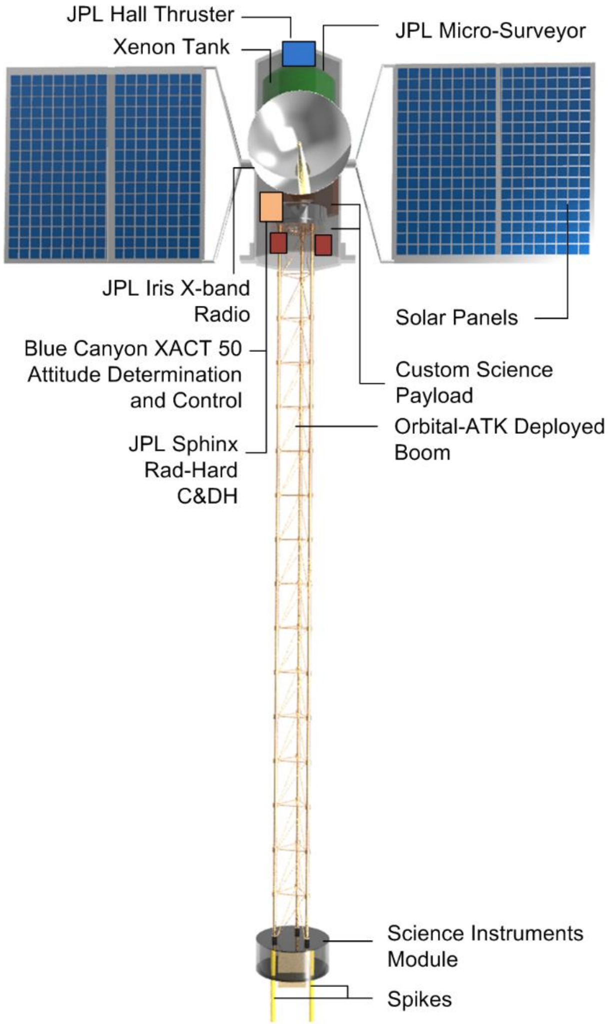


Augmented with small landers….

SPIKE Spacecraft

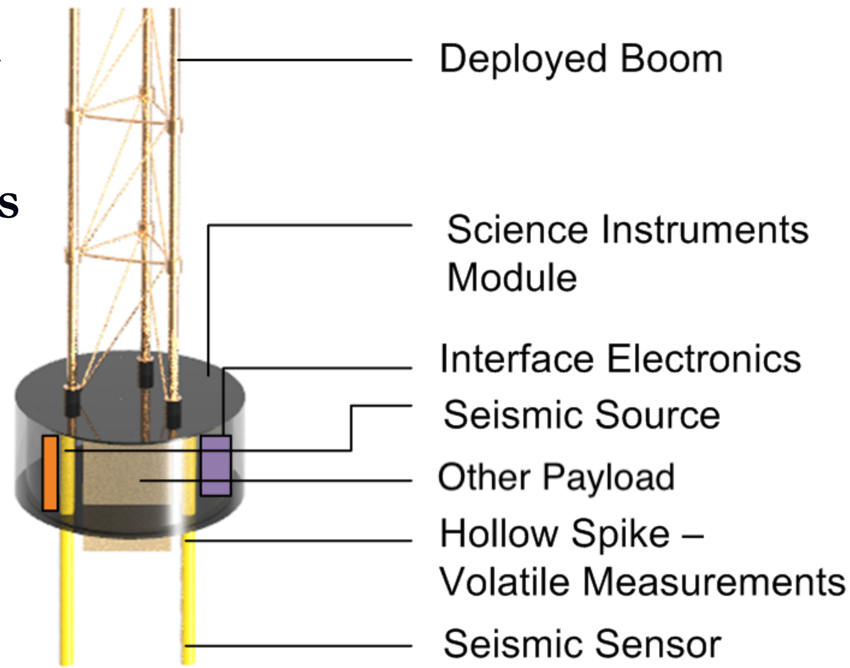
Keep the spacecraft at a safe distance

- Amphibious lander/flyby spacecraft
- Based on JPL Micro Surveyor
- Propelled by xenon fueled solar-electric Hall thrusters (5km/s delta v)
- Solar panels can generate 750W
- Blue Canyon's XACT 50 (star-tracker, IMU, 3-axis reaction wheels)
- JPL's DSN compatible IRIS X-band Radio V2.1 (256 KBps)

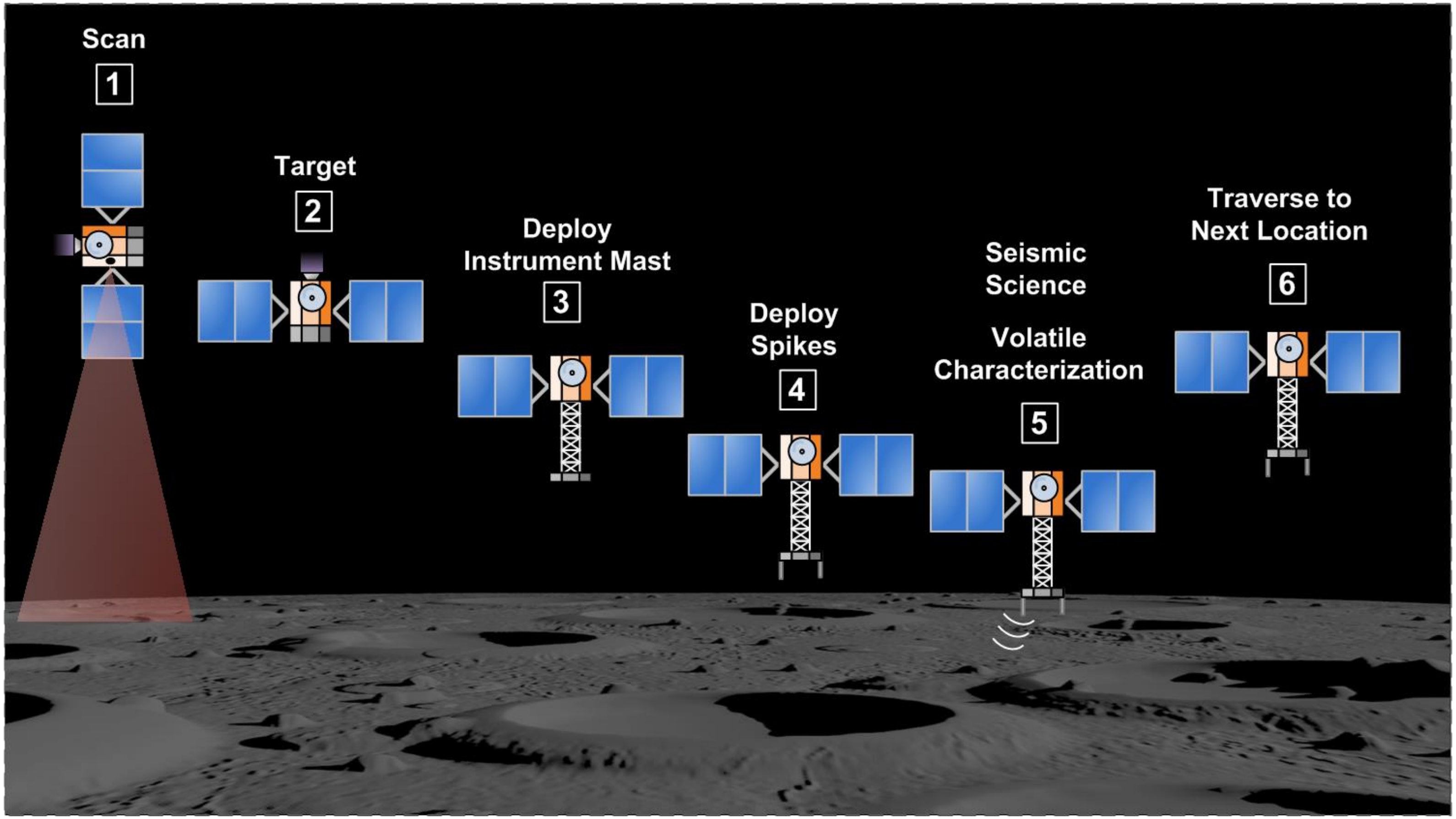


SPIKE Spacecraft

- Onboard instruments would be used to
  - Analyze subsurface volatiles and organics
  - Conduct seismology on asteroids
- Science Payload includes
  - Seismometers
  - Cameras
  - Other instrument will be designed to access >10 cm beneath the surface of the asteroid

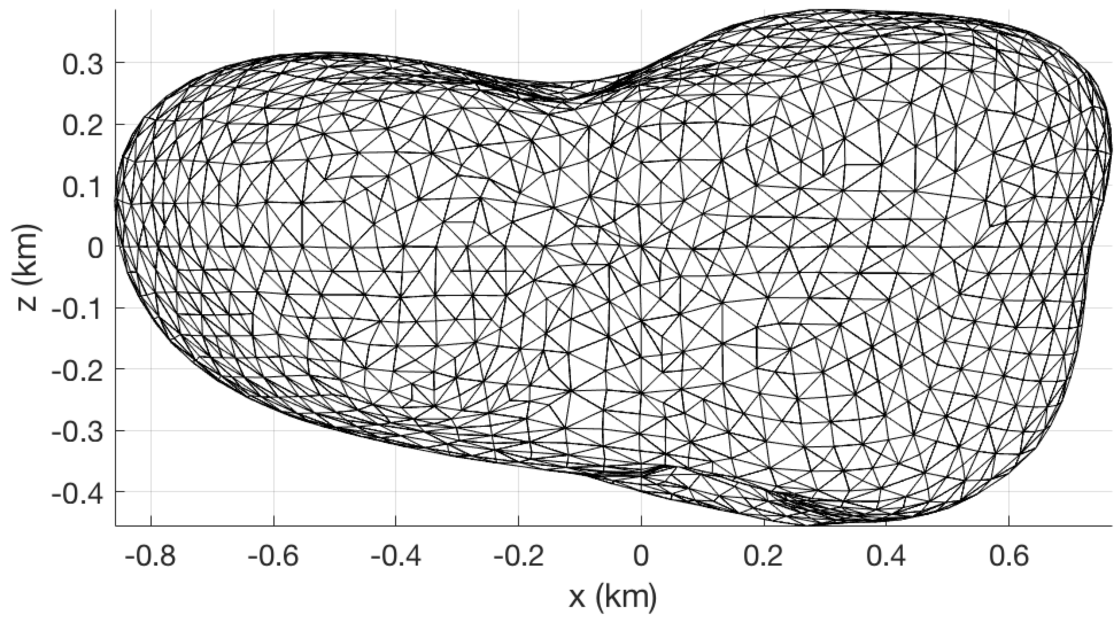


Mission Concept



Asteroid Dynamical Environment Modeling

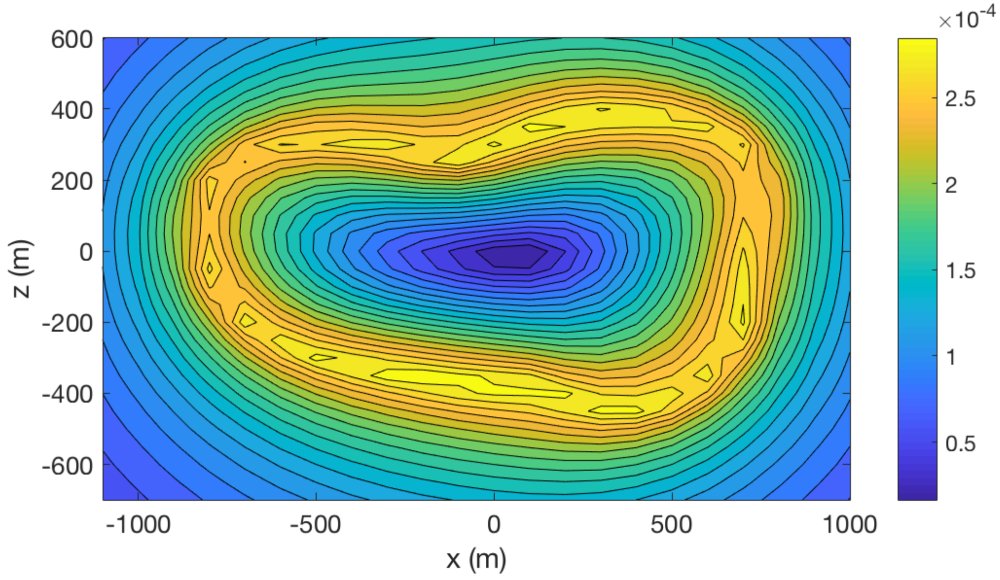
- Asteroid's shape described as a polyhedron



- Polyhedron Model of Asteroid Castalia

Gravitational Model

- Gravitational potential of a constant density polyhedron can be determined by
  - $V(r) = -\frac{1}{2} G\rho \sum_{e \,\epsilon\, edge} r_e^T E_e r_e \cdot L_e + \frac{1}{2} G\rho \sum_{f \,\epsilon\, face} r_f^T F_f r_f \cdot \omega_f$



- Gravitational field of asteroid Castalia

Disturbance Forces

- **We modeled solar-radiation pressure and third-body gravitational perturbation**
  - $D = \frac{\eta d.R}{|d|^3} - \frac{\mu}{|R-d|^3}(R-d)$

η: **solar radiation pressure coefficient**

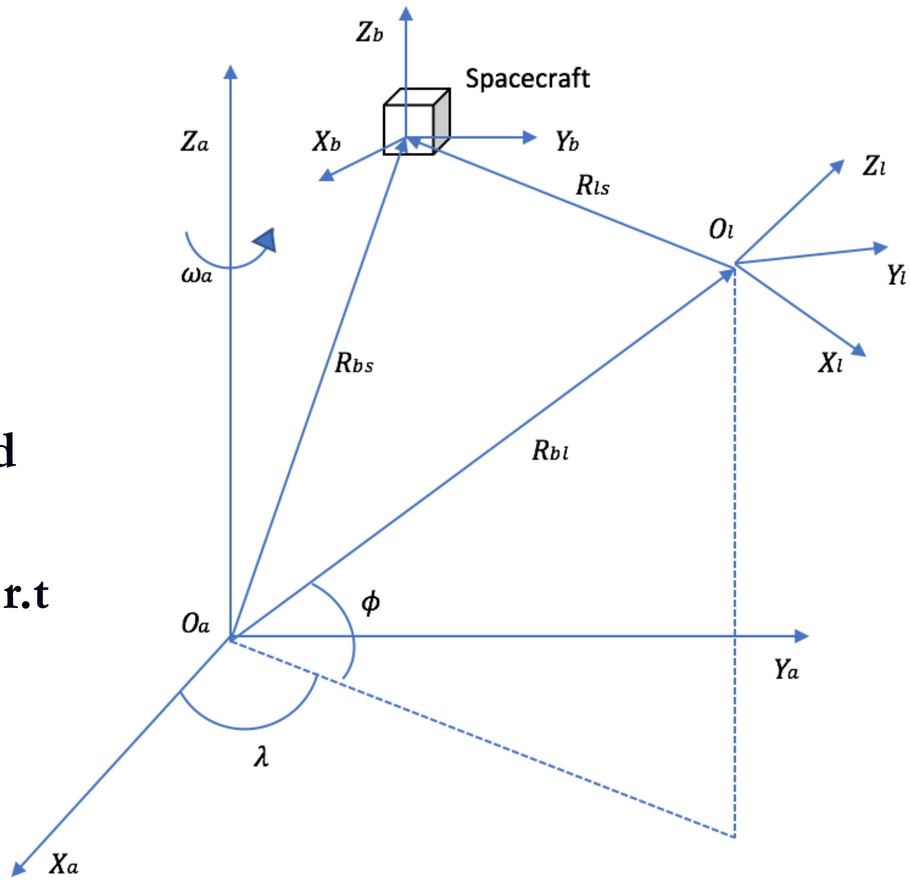
d : **position vector of the sun from the asteroid**

R : **position vector of the spacecraft w.r.t to asteroid's body fixed coordinate system**

μ : **product of gravitational constant and mass of sun**

Spacecraft Dynamics Model

- O_a-$X_aY_aZ_a$: asteroid's body fixed coordinate system
- O_l-$X_lY_lZ_l$: landing site coordinate system
- O_b-$X_bY_bZ_b$: spacecraft's body fixed coordinate system
- $\boldsymbol{\omega_a}$: angular velocity of asteroid w.r.t it's spin axis Z_a



Spacecraft Dynamics Model

- **Equation of motion of the spacecraft in the asteroid's body fixed coordinate system is:**

$$\ddot{R}_{bs} + 2\omega \times \dot{R}_{bs} + \omega \times (\omega \times R_{bs}) + \dot{\omega} \times R_{bs} = U + G + D$$

$$\omega = [0\ 0\ \omega_a]^T \qquad \dot{\omega} = [0\ 0\ 0]^T$$

U: control acceleration

G: gravitational acceleration

D: disturbance acceleration

Spacecraft Dynamics Model

- The relationship between R_{bs}, R_{ls} and R_{bl} is

$$R_{bs} = T_l^b R_{ls} + R_{bl}$$

$$\text{where, } T_l^b = \begin{bmatrix} \cos\lambda\sin\phi & -\sin\lambda & \cos\lambda\cos\phi \\ \sin\lambda\sin\phi & \cos\phi & \sin\lambda\cos\phi \\ -\cos\phi & 0 & \sin\phi \end{bmatrix}$$

- The equation of motion of the spacecraft in the landing site coordinate system is

$$\ddot{R}_{ls} + 2\left(T_l^b\right)^{-1}\omega \times \left(T_l^b \dot{R}_{ls}\right) + \left(T_l^b\right)^{-1}\omega \times \left(\omega \times \left(T_l^b R_{ls} + R_{bl}\right)\right) = u + g + d$$

$$u = \left(T_l^b\right)^{-1} U,\ g = \left(T_l^b\right)^{-1} G,\ d = \left(T_l^b\right)^{-1} D$$

Descent Phase

- The spacecraft is made to follow a general trajectory
- The spacecraft flies to a point directly above the intended landing site in time $\boldsymbol{\tau}$
- The desired acceleration profile passes through the initial and final state

$$a_d(t) = C_0 + C_1 t + C_2 t^2$$

$$v_d(t) = C_0 t + \frac{1}{2} C_1 t^2 + \frac{1}{3} C_2 t^3 + v_0$$

$$r_d(t) = \frac{1}{2} C_0 t^2 + \frac{1}{6} C_1 t^3 + \frac{1}{12} C_2 t^4 + v_0 t + r_0$$

Descent Phase Controller

- **Define position tracking error and velocity tracking error as:**

$$e = R_{ls} - r_d$$
$$e_d = \dot{R}_{ls} - v_d$$

- **We design a PD control law to track the reference position and velocity profiles.**

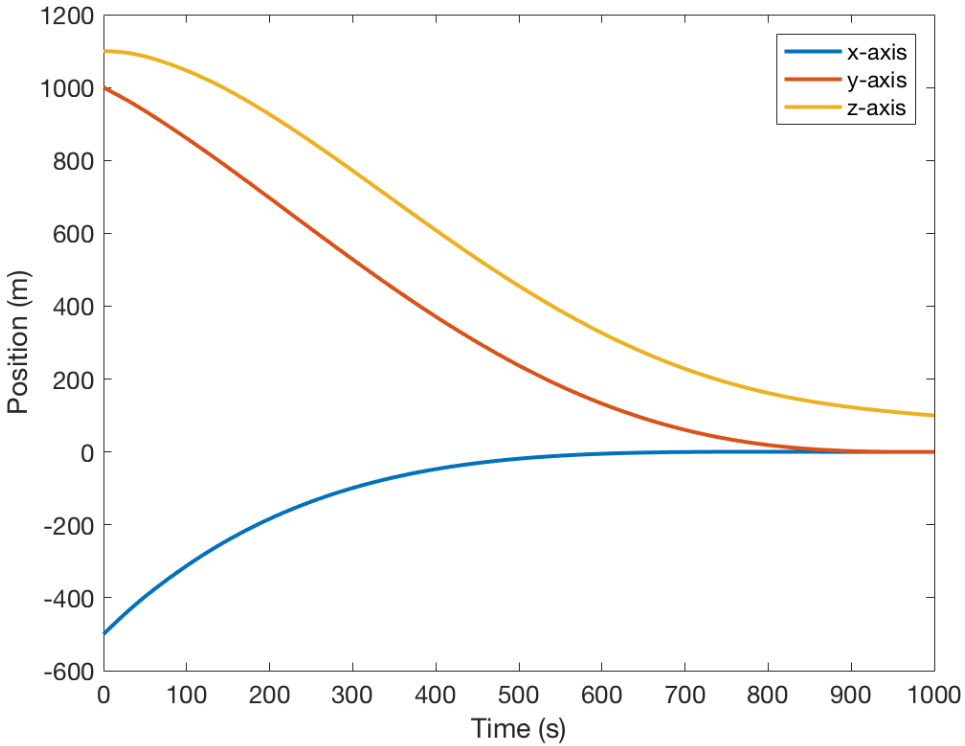
$$u = -k_p e - k_d e_d$$

k_p and k_d are proportional and derivative controller gains

Descent Phase Simulation

Final position	[0, 0, 100] m

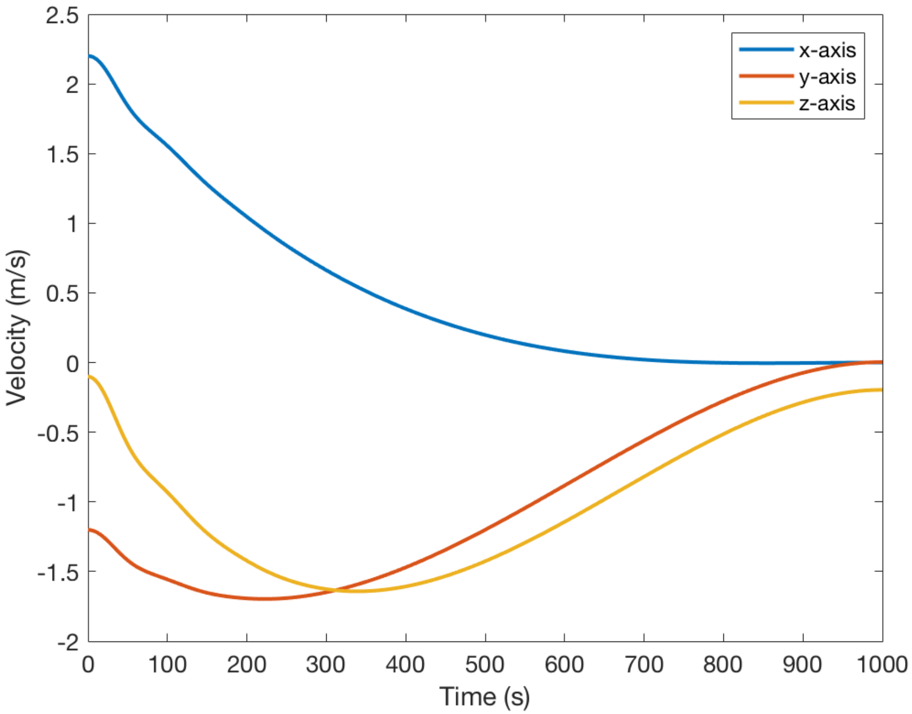
Parameters	Value
Mass of Spacecraft	50 kg
Dimensions	60 × 36 × 36 cm
Landing site	[726, 0, 286] m
Initial position	[-500, 1000, 1100] m
Initial velocity	[2.2, -1.2, -0.1] m/s
Final position	[0, 0, 100] m
Final velocity	[0, 0, -0.2] m/s



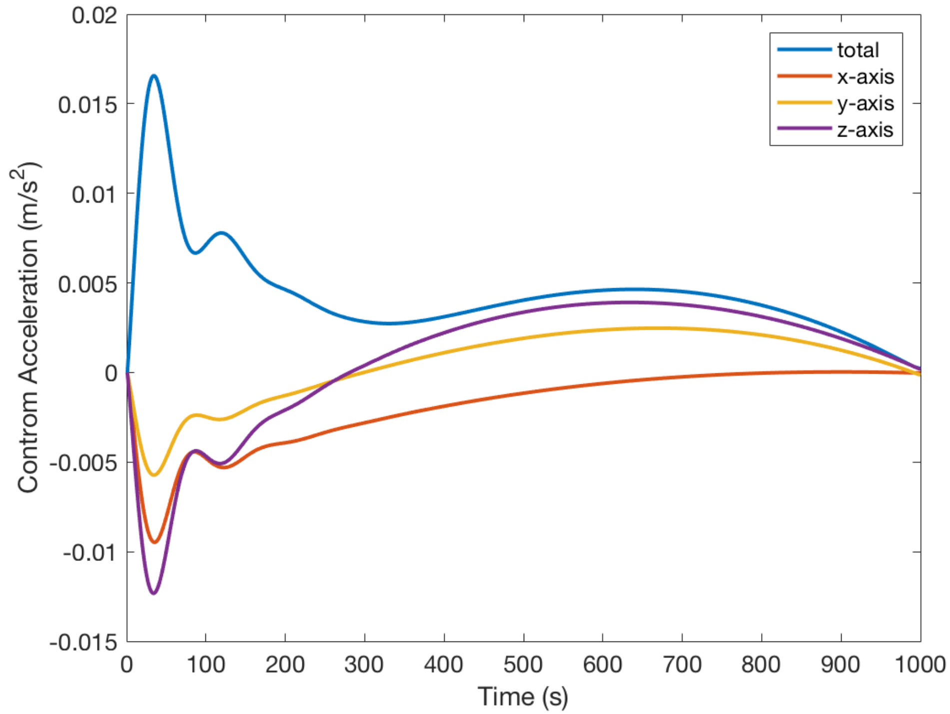
Initial and final position and velocity defined w.r.t the landing site coordinate system

Descent Phase Simulation

Final velocity [0, 0, -0.2] m/s



Control acceleration less than 0.02 m/s^2



Landing Phase

- Spacecraft modeled as inverted pendulum
- Spacecraft descends with an initial velocity under the action of gravity
- Reaction wheels controls the attitude of the spacecraft so that it lands vertically on its extended boom
- The attitude dynamics is represented as:

$$\dot{\omega} = -J^{-1}(\omega \times J\omega) + \tau_c + \tau_d$$

J: moment of inertia of the spacecraft

τ_c: control torque, τ_d: disturbance torque

Landing Phase Controller

- **Control torque is modelled by a PD control law**

$$\tau_c = -C_p(q - q_d) - C_d(\omega - \omega_d)$$

$q\,, q_d$: actual and desired Euler angles

$\omega\,, \omega_d$: actual and desired angular velocities

$C_p\,, C_d$: proportional and derivative controller gains

Landing Phase Simulations

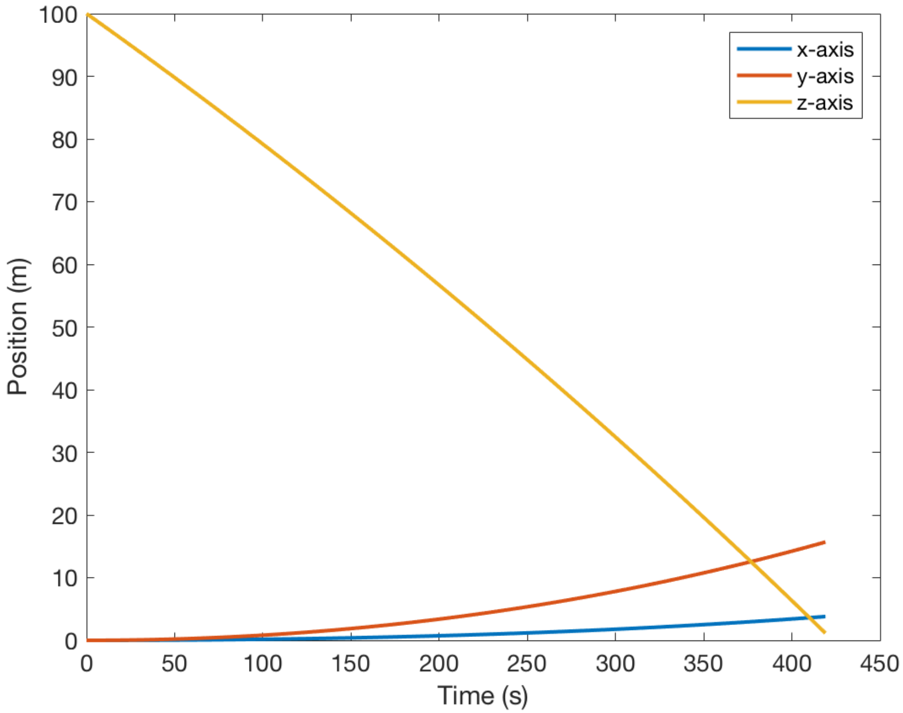
Parameters	Value
Reaction wheel mass	0.75 kg
Reaction wheel dia.	11 cm
Reaction wheel height	3.8 cm
Maximum torque	0.025 Nm
Initial position	[0, 0, 100] m
Initial velocity	[0, 0, -0.2] m/s
Initial Euler angles	[0.1745, -0.3491, 0.3491] rad
Initial angular velocity	[0.1, 0.2, -0.1] rad/s

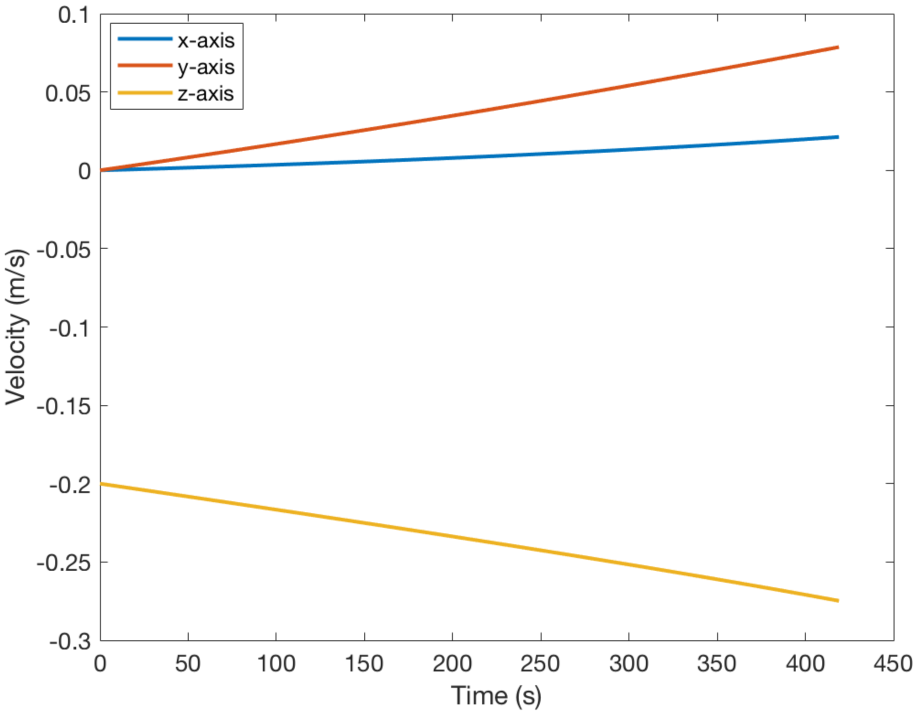
Initial position, velocity, Euler angles and angular velocities defined w.r.t the landing site coordinate system

Landing Phase Simulations

Final position	[3.7, 15.6, 0] m

Final velocity	[0.02, 0.07, -0.27] m/s

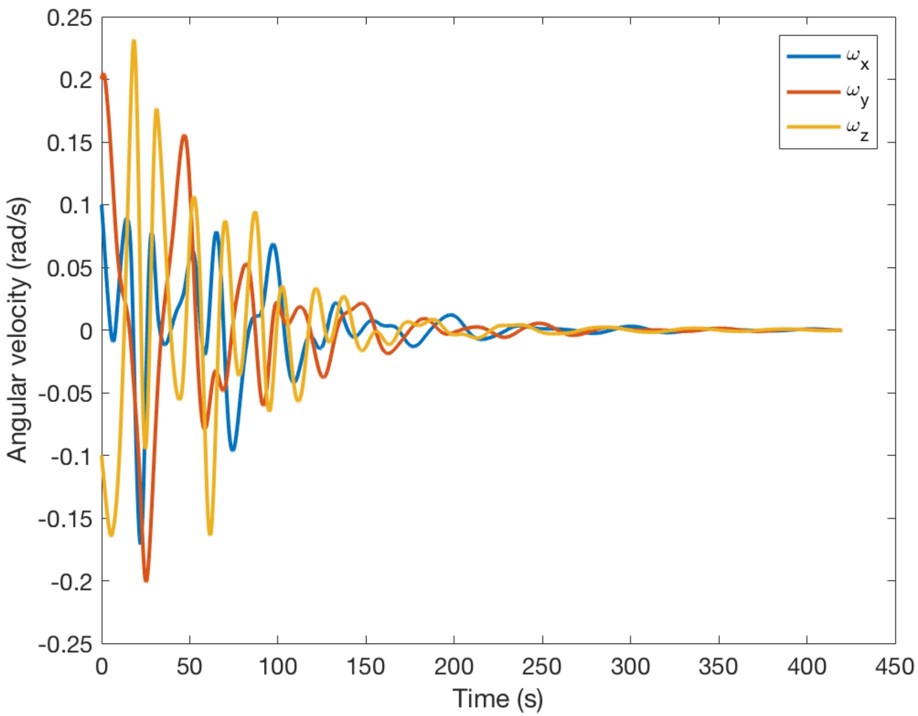


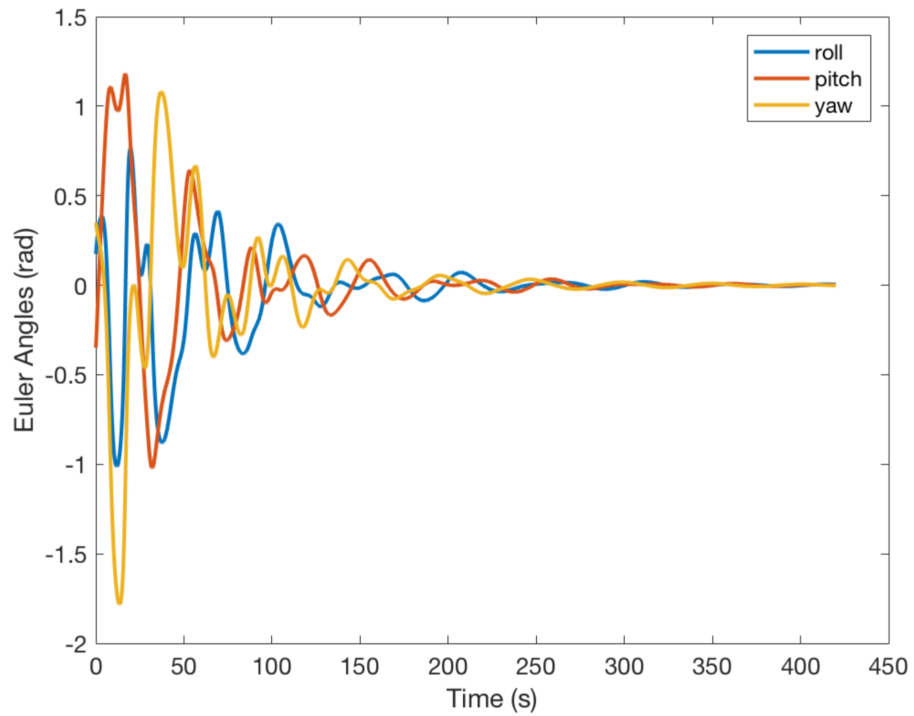


Landing Phase Simulations

Final angular velocities	[0, 0, 0] rad/s

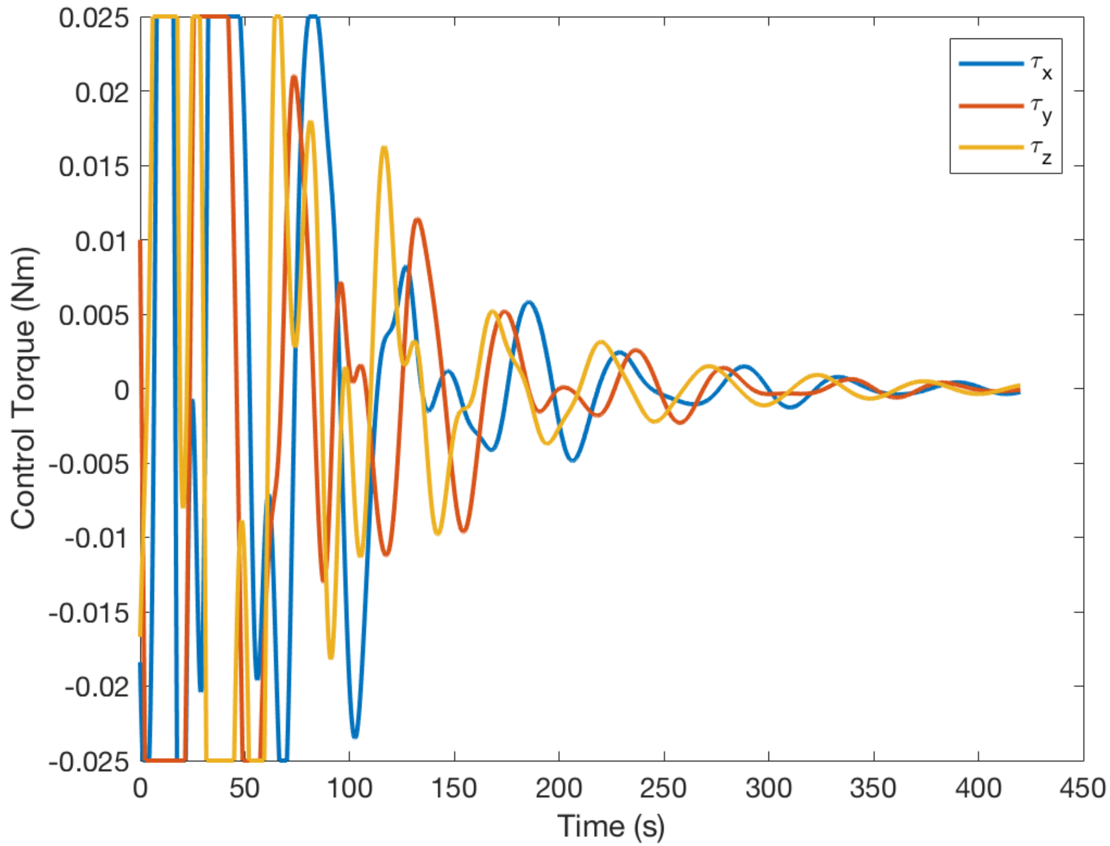
Final Euler angles	[0, 0, 0] rad



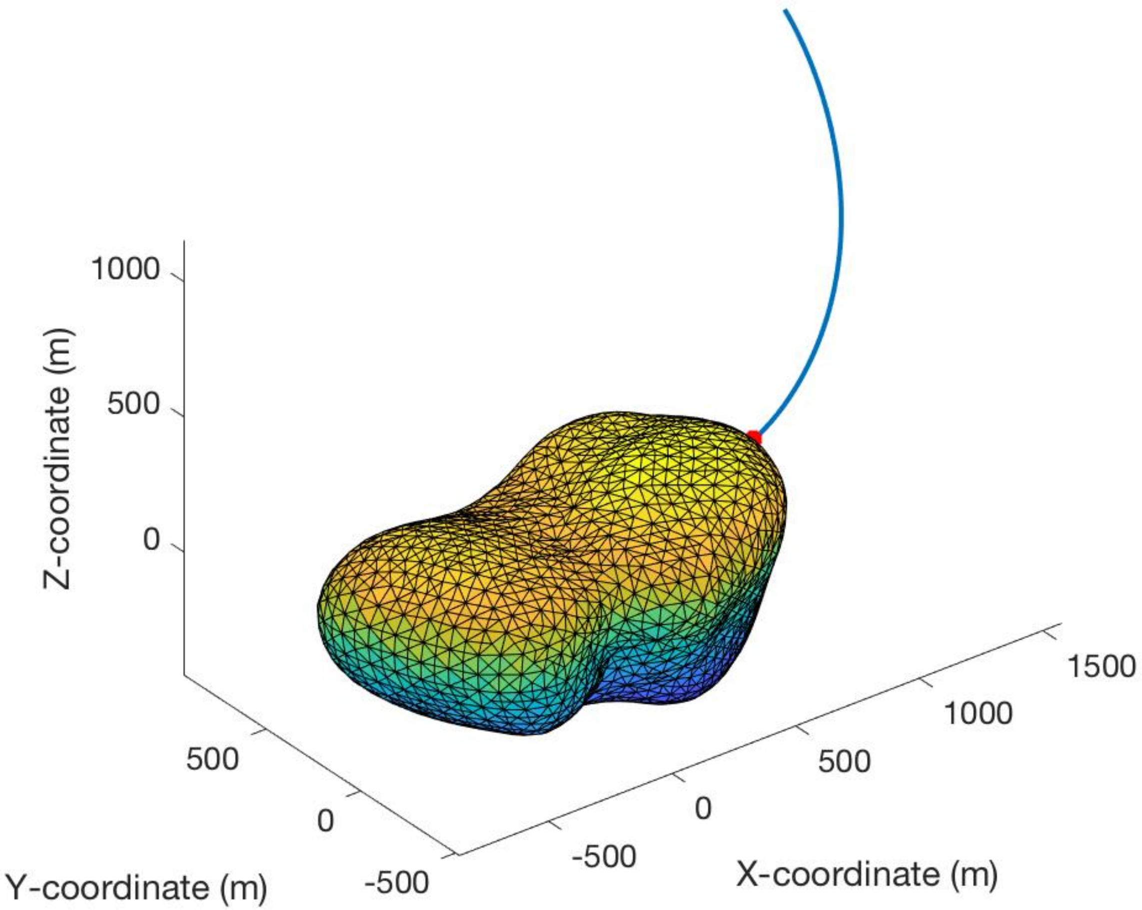


Landing Phase Simulations

Control torque less than 0.025 Nm

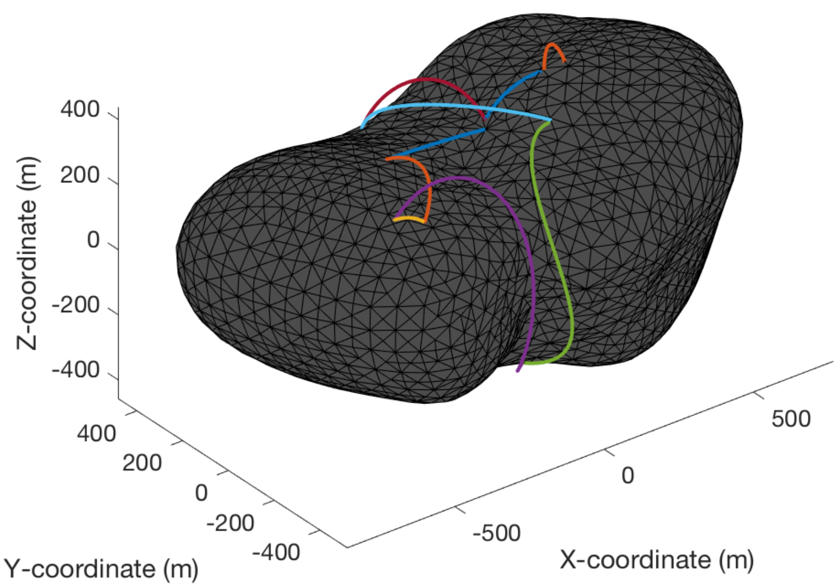


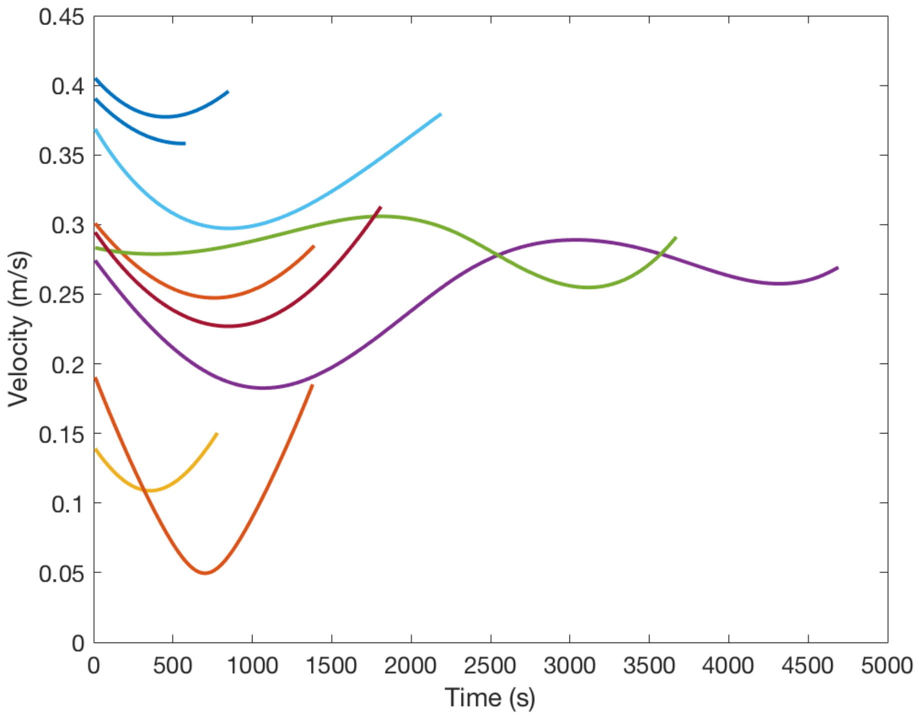
Descent and Landing Trajectory



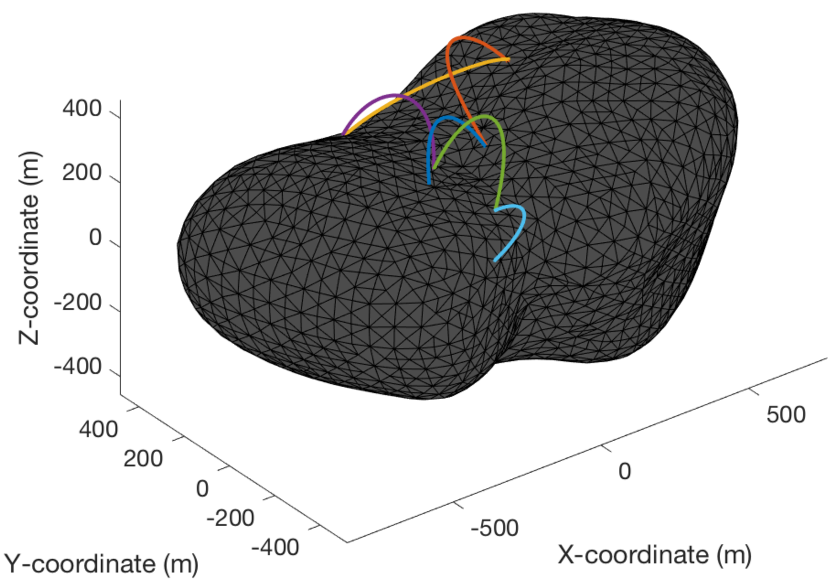
Hopping Dynamics

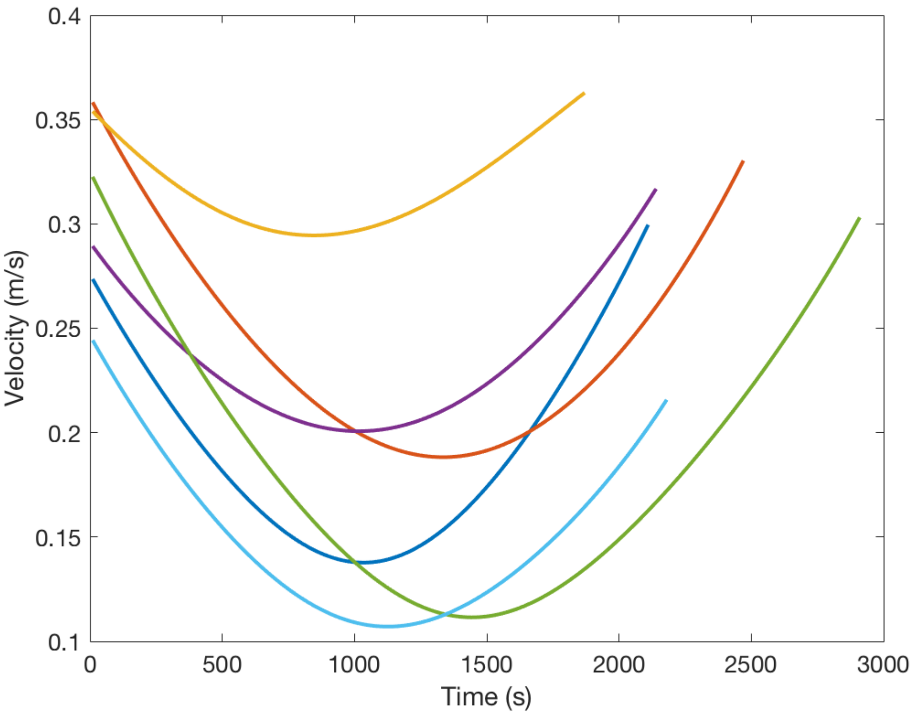
- Simulated hopping trajectories with initial velocities between 0.1 to0.45 m/s





Hopping Dynamics





- Large portion of the trajectories are irregular
- Demonstrates extreme non-Keplerian behavior around irregularly shaped minor celestial bodies (Scheeres, 2012)

SPIKE Concept Videos

Conclusions

- Presented GNC capabilities of SPIKE.
- Presented detailed dynamics of the spacecraft w.r.t a small asteroid's frame of references.
- PD control law developed for a finite time descent trajectory.
- Presented attitude control of the spacecraft with the onboard reaction wheels during its landing phase.
- Also, presented the feasibility of SPIKE performing multiple long-range hops to explore the asteroid.

Thank You

Questions ?