Geometric Control for Autonomous Landing on Asteroid Itokawa using Visual Imagery

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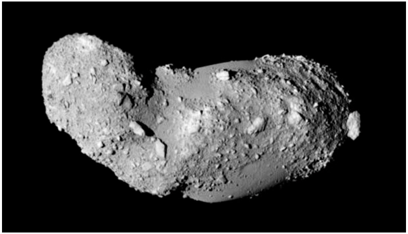
Asteroid Missions

- Science - insight into the early formation of the solar system
- Mining - vast quantities of useful materials
- Impact - high risk from hazardous near-Earth asteroids



Asteroid Mining

- Useful materials can be extracted from asteroids to support:
  - Propulsion, construction, life support, agriculture, and precious/strategic metals
- Commercialization of near-Earth asteroids is feasible

Element	Price ($\$\,\mathrm{kg}^{-1}$)	Sales ($\$\,$M/yr)
Phosphorous (P)	0.08	2167
Gallium (Ga)	300.00	1544
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Platinum (Pt)	12 394.00	1705
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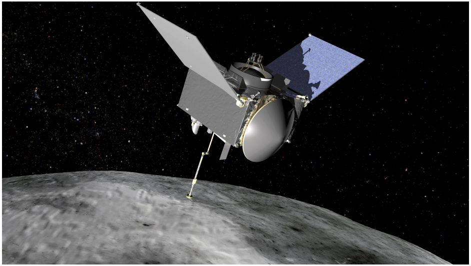
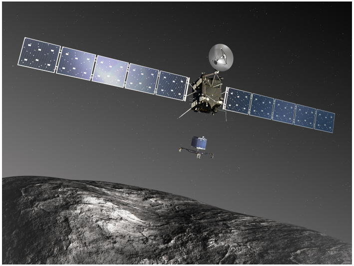
- Long history of asteroid/planetary missions
  - NEAR, Hayabusa, OSIRIS-REX, Rosetta
- Asteroid landing is particularly challenging:
  - Challenging dynamics - low gravity and spinning
  - Poor model - ground based observation of dim bodies
  - Attitude coupling - pertubations are large





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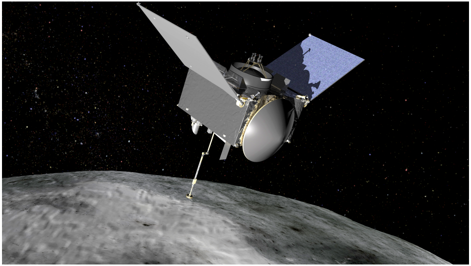

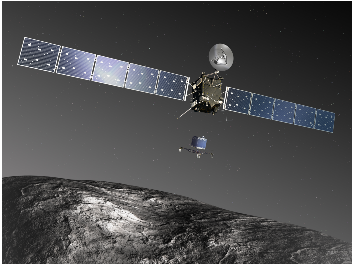

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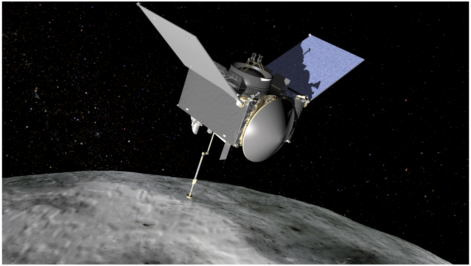

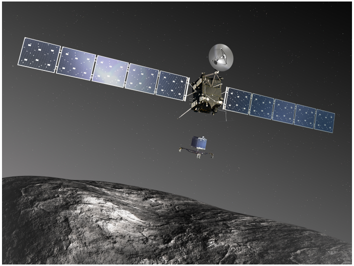

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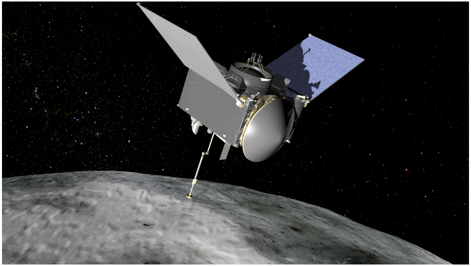

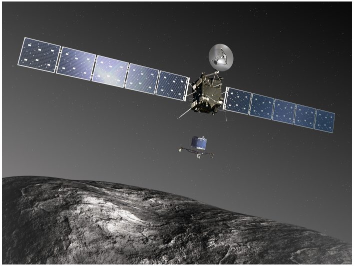

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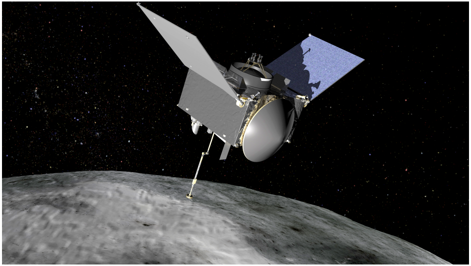

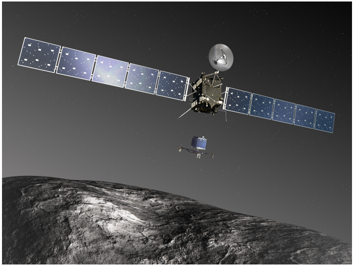

Problem Statement

1. Develop copuled equations of motion for a spacecraft
2. Use EOMs on $\mathsf{SE}(3)$to derive landing control law
3. Implement monocular localization to provide state estimates
4. Alleviates many of the issues of past approaches:
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Gravitational Modeling

- Asteroids are extended bodies not point masses
- Spherical Harmonic - only valid outside of circumscribing sphere

$$U(\boldsymbol{r}) = \frac{\mu}{r} \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} \left(\frac{R}{r}\right)^{n} P_{n,m}(\sin\phi)\left\{C_{nm}\cos(m\lambda) + S_{nm}\sin(m\lambda)\right\}$$

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- Potential is a function of only the shape model
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$$U(\boldsymbol{r}) = \frac{1}{2} G\sigma \sum_{e \in \text{edges}} \boldsymbol{r}_e \cdot \boldsymbol{E}_e \cdot \boldsymbol{r}_e \cdot L_e - \frac{1}{2} G\sigma \sum_{f \in \text{faces}} \boldsymbol{r}_f \cdot \boldsymbol{F}_f \cdot \boldsymbol{r}_f \cdot \omega_f$$

Kinematics of Dumbbell

- Dynamics derived on $\mathsf{SE}(3)$, Special Euclidean group
- Rigid dumbbell model - captures attitude coupling
  - $x \in \mathbb{R}^3$ - inertial position of COM
  - $R \in \mathsf{SO}(3)$ - transforms from body to inertial frame
  - $\Omega \in \mathbb{R}^3$ - the angular velocity of the spacecraft
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Equations of Motion

- Polyhedron potential in translational and rotational dynamics

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{v}, \\ (m_1 + m_2)\,\dot{\boldsymbol{v}} &= m_1 R_A \frac{\partial U}{\partial \boldsymbol{z}_1} + m_2 R_A \frac{\partial U}{\partial \boldsymbol{z}_2} + \boldsymbol{u}_f, \\ \dot{R} &= R S(\boldsymbol{\Omega}), \\ J\dot{\boldsymbol{\Omega}} + \boldsymbol{\Omega} \times J\boldsymbol{\Omega} &= \boldsymbol{M}_1 + \boldsymbol{M}_2 + \boldsymbol{u}_m. \end{aligned}$$

- Moment on dumbbell

$$\boldsymbol{M}_i = m_i \left(S(R_A^T \boldsymbol{\rho}_i) R^T \frac{\partial U}{\partial \boldsymbol{z}_i} \right).$$

Nonlinear Control

- Geometric control used to track a desired trajectory
- Developed directly on the nonlinear manifold
  - Avoids chattering issues of sliding mode control
  - Incorporates attitude dynamics
  - Stability guarantee

$$\begin{aligned}\boldsymbol{u}_m &= -k_R e_R - k_\Omega e_\Omega + \Omega \times J\Omega - J\left(\hat{\Omega} R^T R_d \Omega_d - R^T R_d \dot{\Omega}_d\right) \\ &\quad - \boldsymbol{M}_1 - \boldsymbol{M}_{\mathbf{2}}, \\ \boldsymbol{u}_f &= -k_x e_x - k_v e_v + (m_1 + m_2)\ddot{x}_d - \boldsymbol{F}_1 - \boldsymbol{F}_2\end{aligned}$$

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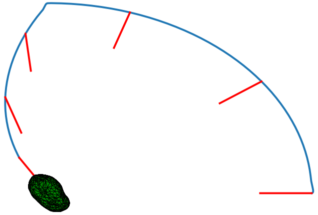
Landing trajectory

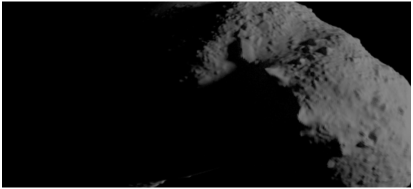
- Goal: transition from orbit about Itokawa to vertical descent
- Attitude controlled to point camera at surface
  - $\boldsymbol{b}_1$ - body axis points at surface
  - $\boldsymbol{b}_3$ - orthogonal projection in $\boldsymbol{e}_3, \boldsymbol{b}_1$ plane

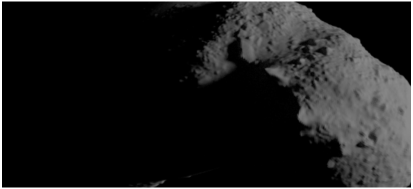
$$\begin{aligned}
\boldsymbol{b}_{1d} &= -\frac{\boldsymbol{x}}{\|\boldsymbol{x}\|}, \\
\boldsymbol{b}_{3d} &= \frac{\boldsymbol{f}_3 - (\boldsymbol{f}_3 \cdot \boldsymbol{b}_{1d})\, \boldsymbol{b}_{1d}}{\|\boldsymbol{f}_3 - (\boldsymbol{f}_3 \cdot \boldsymbol{b}_{1d})\, \boldsymbol{b}_{1d}\|}, \\
\boldsymbol{b}_{2d} &= \boldsymbol{b}_{3d} \times \boldsymbol{b}_{1d}, \\
R_d &= \begin{bmatrix} \boldsymbol{b}_{1d} & \boldsymbol{b}_{2d} & \boldsymbol{b}_{3d} \end{bmatrix}.
\end{aligned}$$



Simulated imagery using Blender

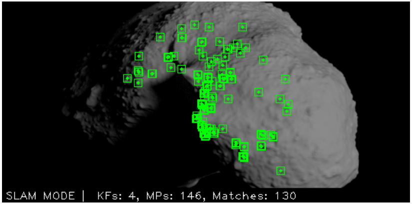
- Free & open-source 3D computer graphics program
- Offer programmatic interface through Python
- Images of Itokawa emulated to match NEAR MSI camera

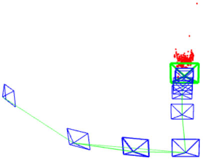




Monocular Localization

- ORB-SLAM2 - Open-source mapping and localization framework
- Allows for real-time monocular based SLAM
- Utilized here to demonstrate localization from imagery





Conclusions

- Nonlinear controller for landing on an asteroid
- Coupled dynamics derived and considered on $\mathsf{SE}(3)$
- Localization performed using simulated monocular imagery
- Future Research Goals:
    - Utilize state estimates directly in controller
    - Update shape and gravity model in real-time

Thank you

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School of Engineering & Applied Science

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