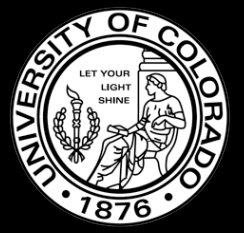

Automated Design of Observation and Landing Trajectories at Small Bodies

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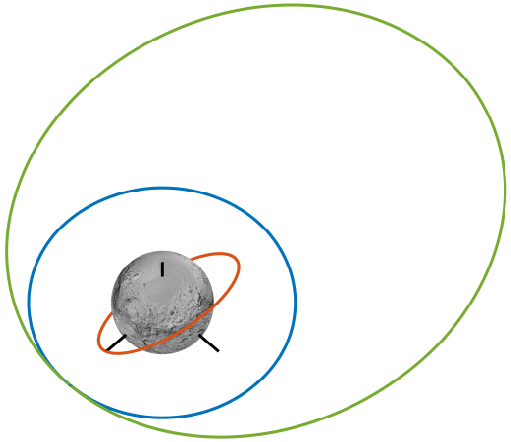
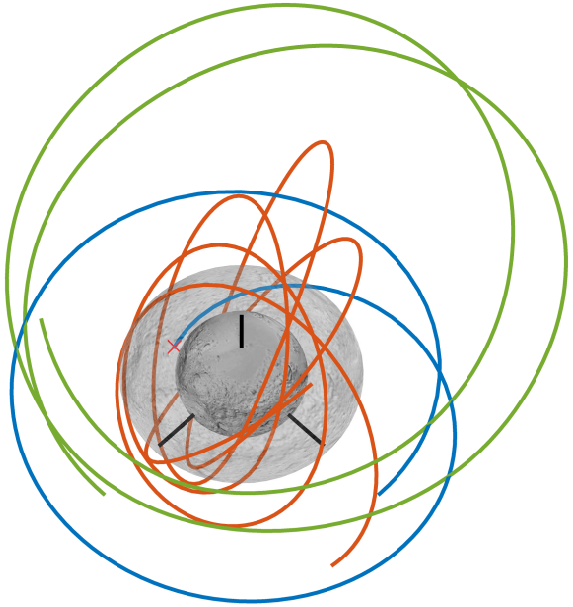
Small Body Orbit Dynamics

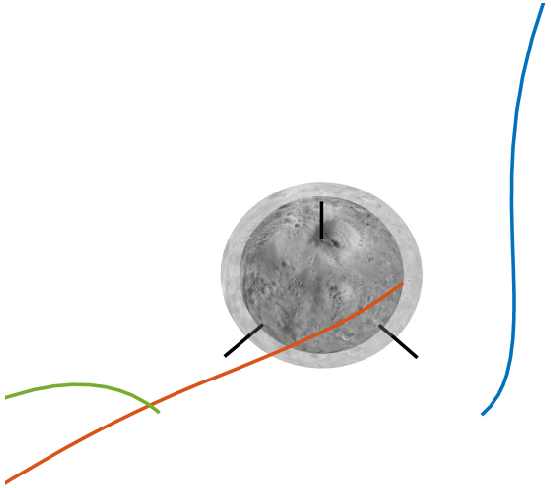
Irregular shapes and proportionally large external forces complicate mission design by producing highly sensitive, non-periodic motion.



Spherical Body



Asteroid Itokawa
(Highly elongated)



Martian moon Phobos
(Strong tidal forces)

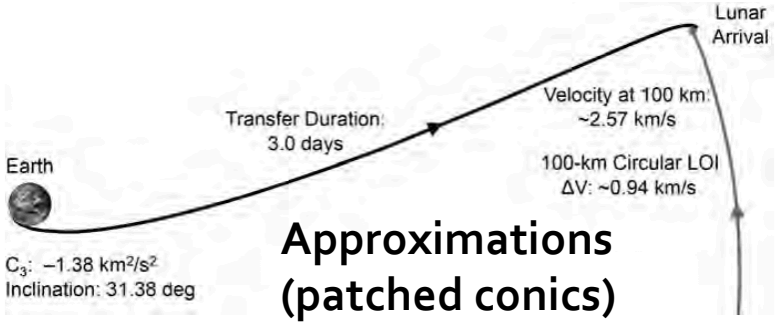
NASA GNC Tech Report, 2013

- High-level goals:
  - 1) enable new science missions
  - 2) increase science and investment return
  - 3) reduce cost, velocity change (ΔV), mass, and risk
  - 4) ensure safety of trajectories within unstable, highly dynamic environments
- *"Central to mission design capabilities is the ability to **rapidly design efficient and innovative trajectories**."*
- *"Increasingly **more complex dynamical models** must be used to perform preliminary designs."*
- *"Much of the current mission design capability is based on techniques developed decades ago to meet more simplistic mission goals and often cannot **support new concepts**."*
- *The **techniques** and analyses for designing small-body missions are **still in their infancy**."*

Component 1: Abstraction

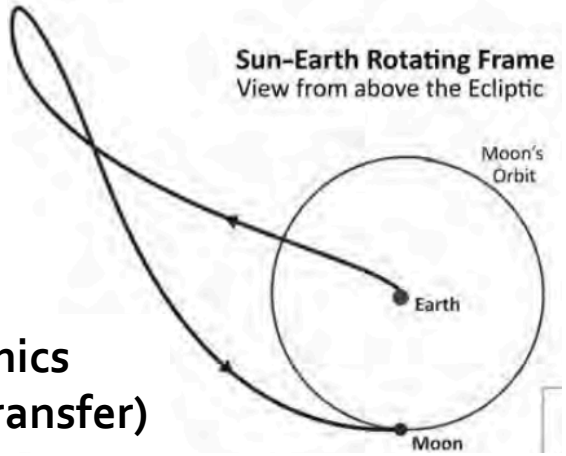
Trajectories are incidental.
Objectives and safety constraints are fundamental.

Separate treatment of the two sequential problems can cause nuanced solutions to be overlooked.



Approximations (patched conics)

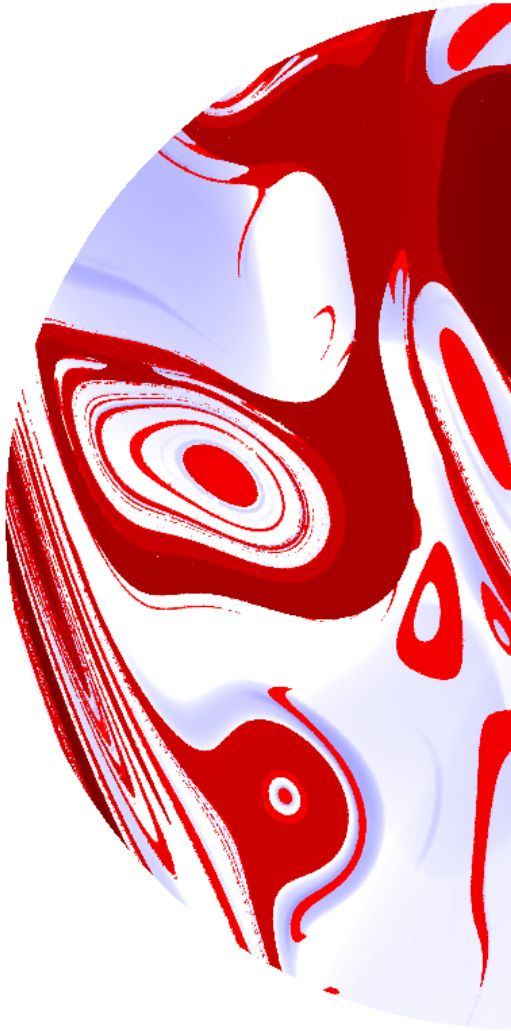
Analogy: transfers in three-body problem
(Anderson and Parker 2014)



Full dynamics (low-energy transfer)

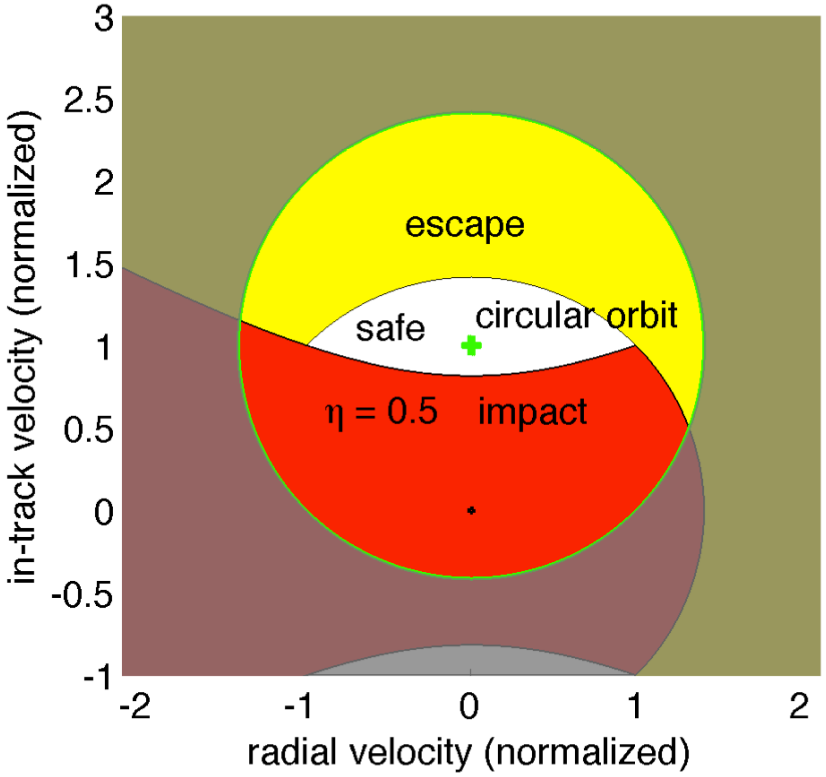
Component 2: Reachability

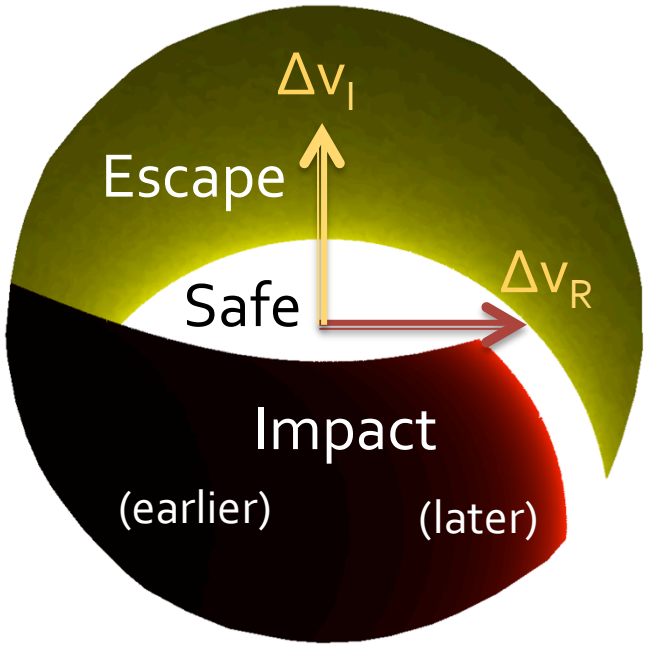
- Design space is too large and complex for complete exploration, and analytical a-priori reductions do not exist
- Reduction based on initial state and control authority reveals the most directly relevant trade-space information for maneuver design
- Naturally facilitates continuous re-planning, opportunism, and robustness
- Technical enabler: efficient heuristic search of the set of reachable mission outcomes



Reachable Sets

Kepler problem results (spherical body).
Position on map: selection of initial velocity
Color: safety outcome of resulting trajectory.



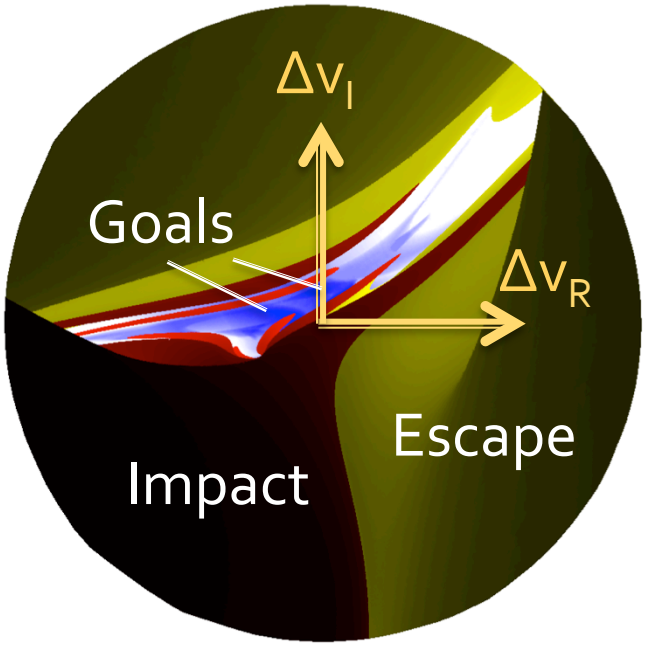


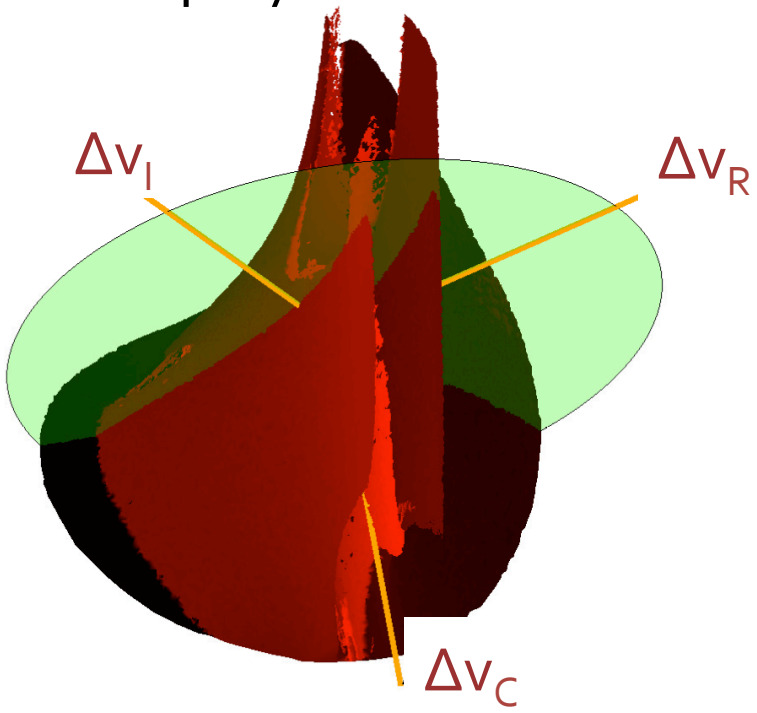
Close-Range Passes

Non-Keplerian system: Martian moon Phobos

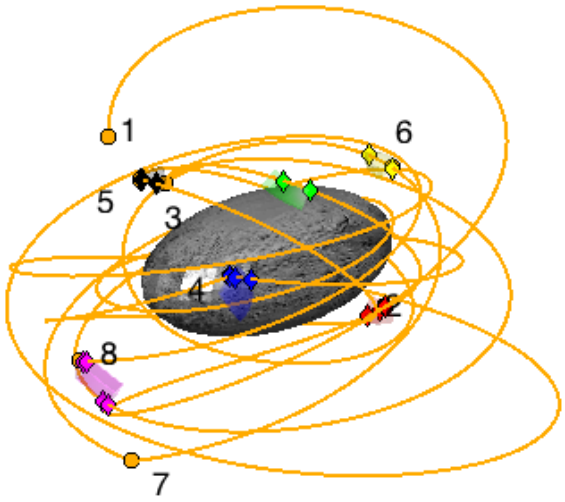
Desired operation: close-range fly-over of specific target sites

- High-resolution science results
- Characterize hazards and opportunities for lander
- Access vantage points for lander deployment



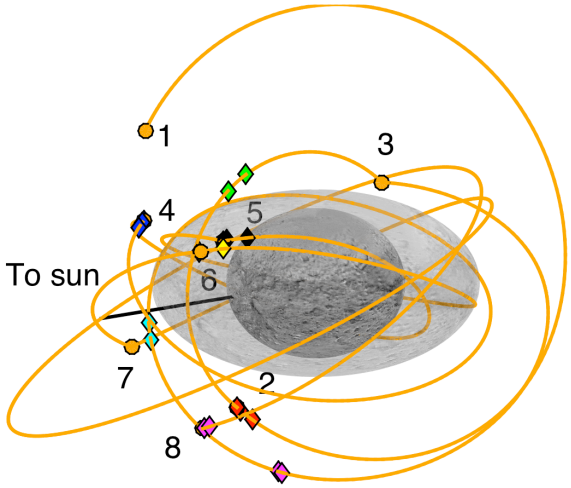


Close-Range Passes



Rotating Frame

Asteroid Itokawa
(Highly elongated)

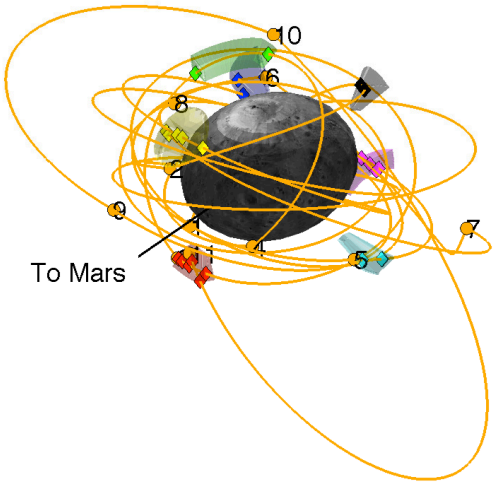


Inertial Frame

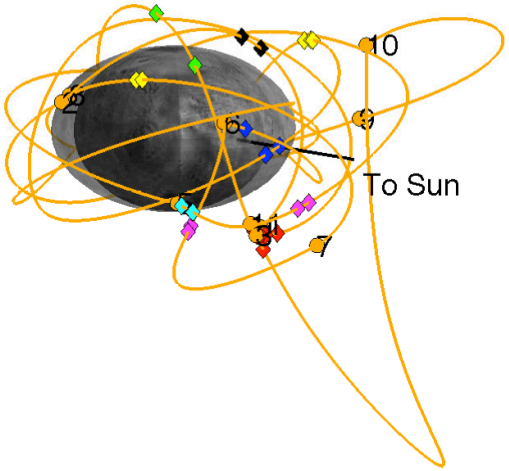
Maneuver location

Goal region

Goal arc start/end



Martian moon Phobos
(Strong tidal forces)

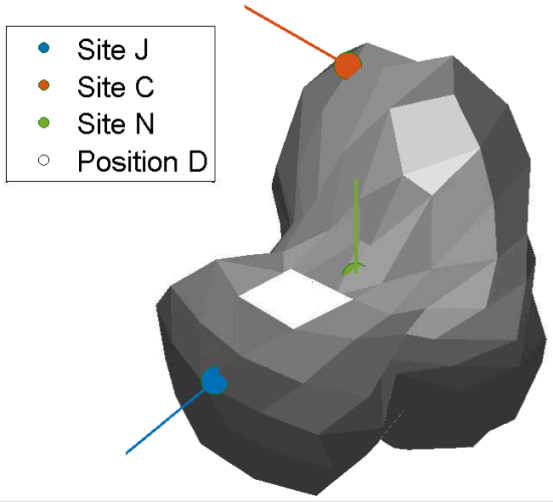


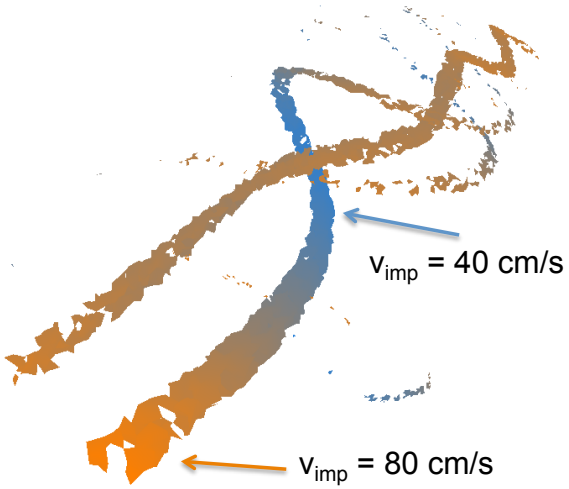
Ballistic Lander Deployment

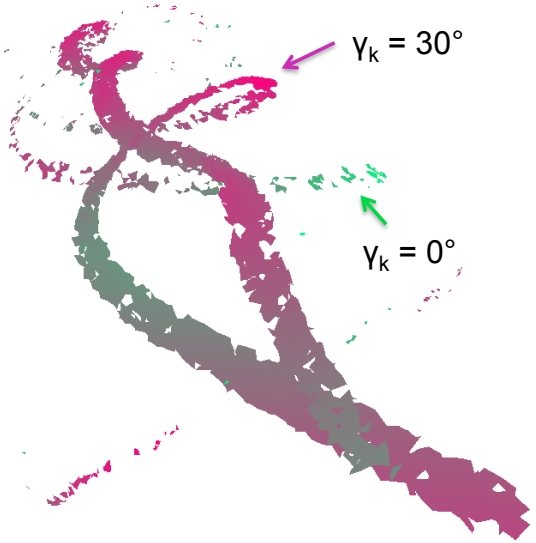
Non-Keplerian system: Comet 67P Churyumov-Gerasimenko

Desired operation: Identify low-energy ballistic trajectories to specified landing sites on the body surface

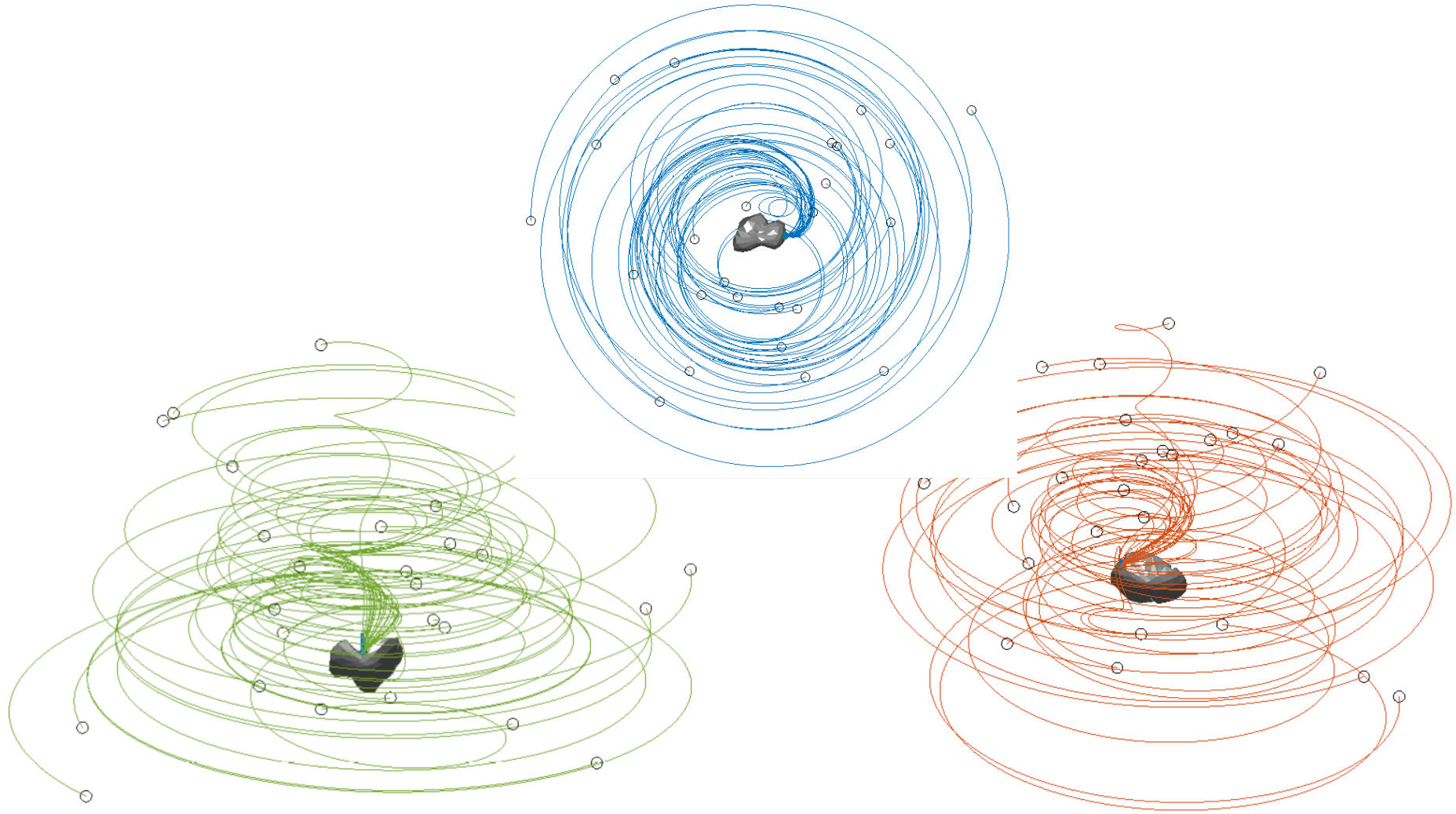
- Leverage non-Keplerian forces to decrease impact speed
- Control impact geometry relative to irregular shape
- Reduce complexity of landing systems on payloads







Ballistic Lander Deployment

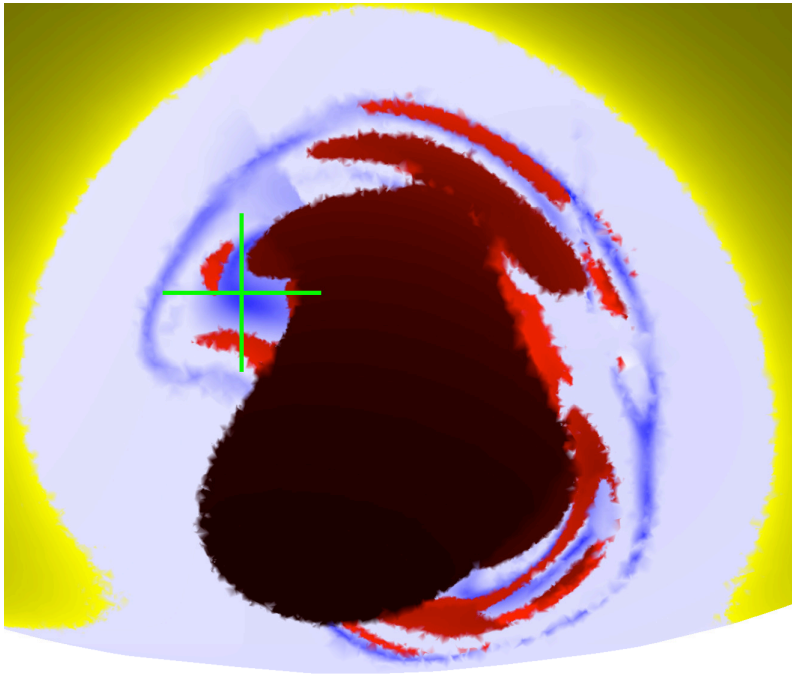


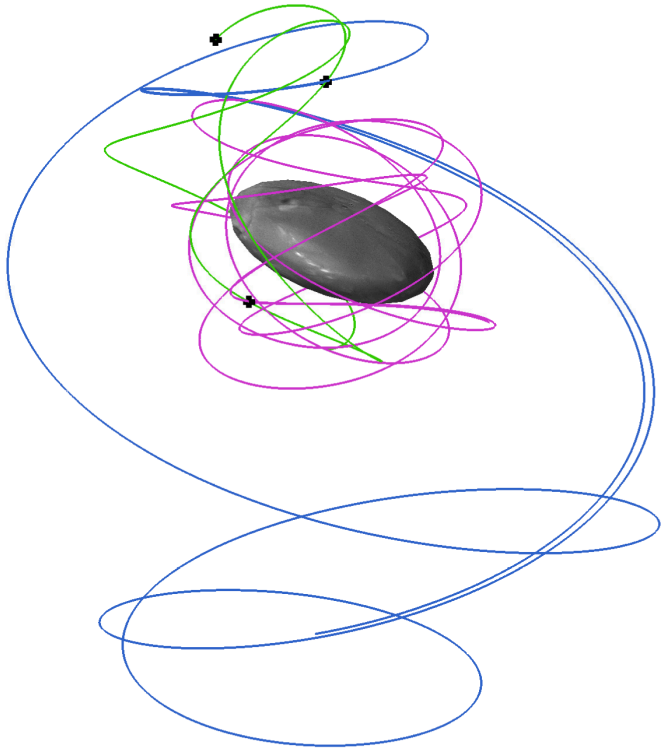
Orbit Periodicity

Non-Keplerian system: highly elongated ellipsoid

Desired operation: return to initial state (repeat motion)

- Observe evolution of active body (comet)
- Routine communication with lander
- Safe holding pattern





Summary / Future Work

- New mission design paradigms are required for enabling ambitious mission concepts at small bodies
- Abstraction and reachability analysis effectively capture the relevant maneuver design trade space, easing the planning of numerous types of high-level operations
- Future work will center upon robustness to uncertainty and increased complexity of goals and constraints

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1. Komendera, E., Garland, J., Bradley, E., and Scheeres, D. 2015. "Efficiently evaluating reachable sets in the circular restricted 3-body problem". *Aerospace and Electronic Systems*, IEEE Transactions on, 51(1), 454–467.

2. Surovik, D.A. and Scheeres, D. J. 2014. "Autonomous maneuver planning at small bodies via mission objective reachability analysis". *AIAA/AAS Astrodynamics Specialist Conference*.

3. Surovik, D.A. and Scheeres, D.J. 2015. "Adaptive reachability analysis to achieve mission objectives in strongly non-Keplerian systems". *Journal of Guidance, Control, and Dynamics*, 38(3), 468–477.

4. Surovik, D.A., and Scheeres, D.J. 2015 "Heuristic Search and Receding-Horizon Planning in Complex Spacecraft Orbit Domains." *Twenty-Fifth International Conference on Automated Planning and Scheduling*.