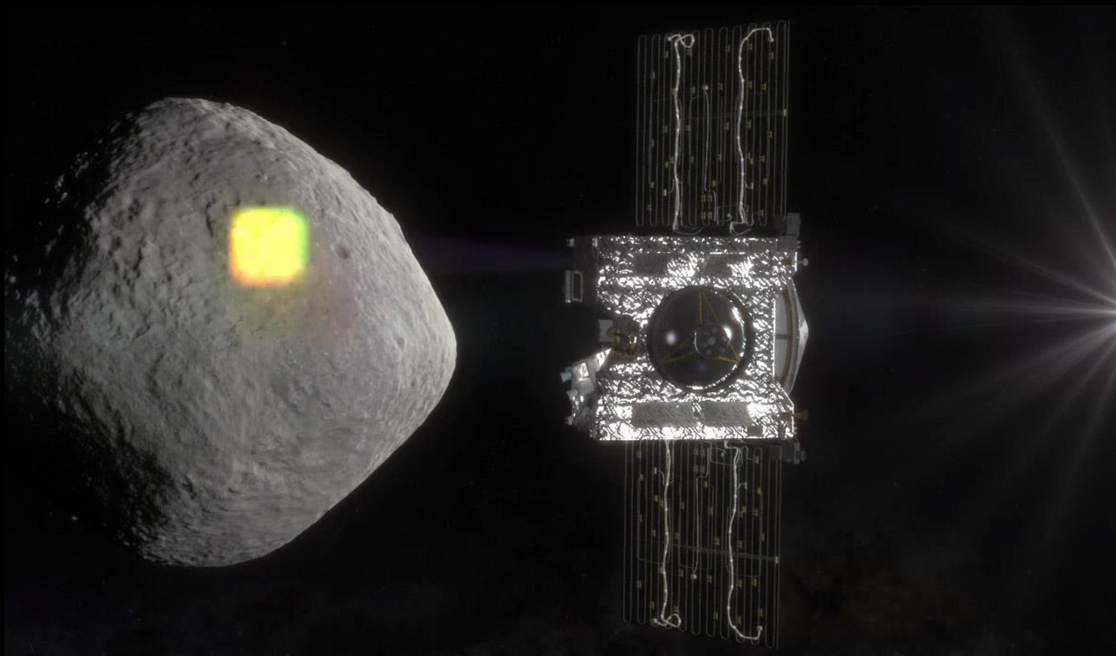
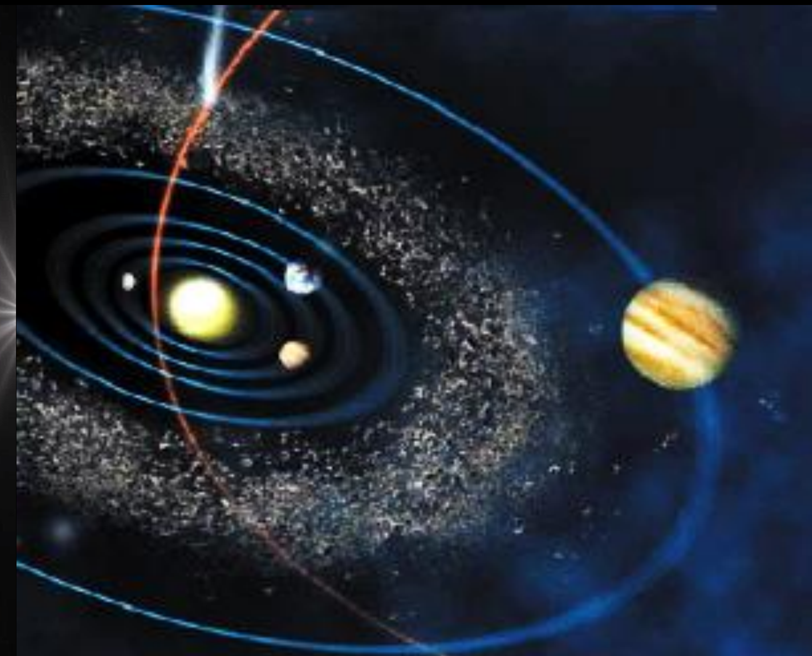




Trajectory design for asteroid surface mapping missions with flybys of spacecraft swarms

Ravi teja Nallapu,
Ph.D. Student,
Aerospace Engineering,
University of Arizona

Outline

- Motivation
- Objective
- Challenges
- Approach
- Simulation
- Results
- Discussion
- Future work

Motivation

Geo-history

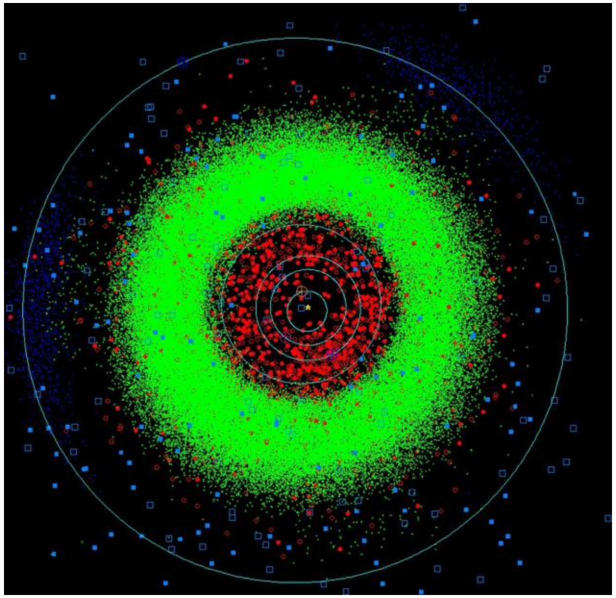
Security/Deflection

ISRU

Asteroid exploration is tied to planetary science, security, space economy.

Motivation

- 2 million asteroids estimated in the main asteroid belt.
- 17,000 asteroids found near earth.
- They hold valuable resources such as water, carbon and rare metals that may one day support a spacefaring civilization.



Main belt and near-Earth Asteroids

Asteroids can be pitstops for interplanetary travel

Motivation

- Surface maps yield crucial geological information of the asteroid:
  - Orbit
  - Composition
  - Density
  - Shape
  - Gravity field

Asteroid Bennu

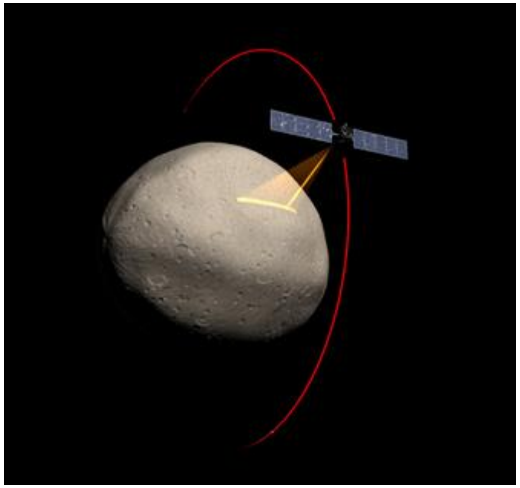
Surface mapping missions pave the way for surface exploration missions

The Swarm approach

- *"Whole greater than the sum of the parts"*
- **Solve a complex task using many individuals.**
- **Individuals are simple, low-cost, disposable.**

Mapping trajectories

- **The mapping trajectories of the spacecraft, can be broadly classified into 2 types, when surface interactions are not considered:**
  - **Orbits**
  - **Flybys**



DAWN's orbit around Vesta

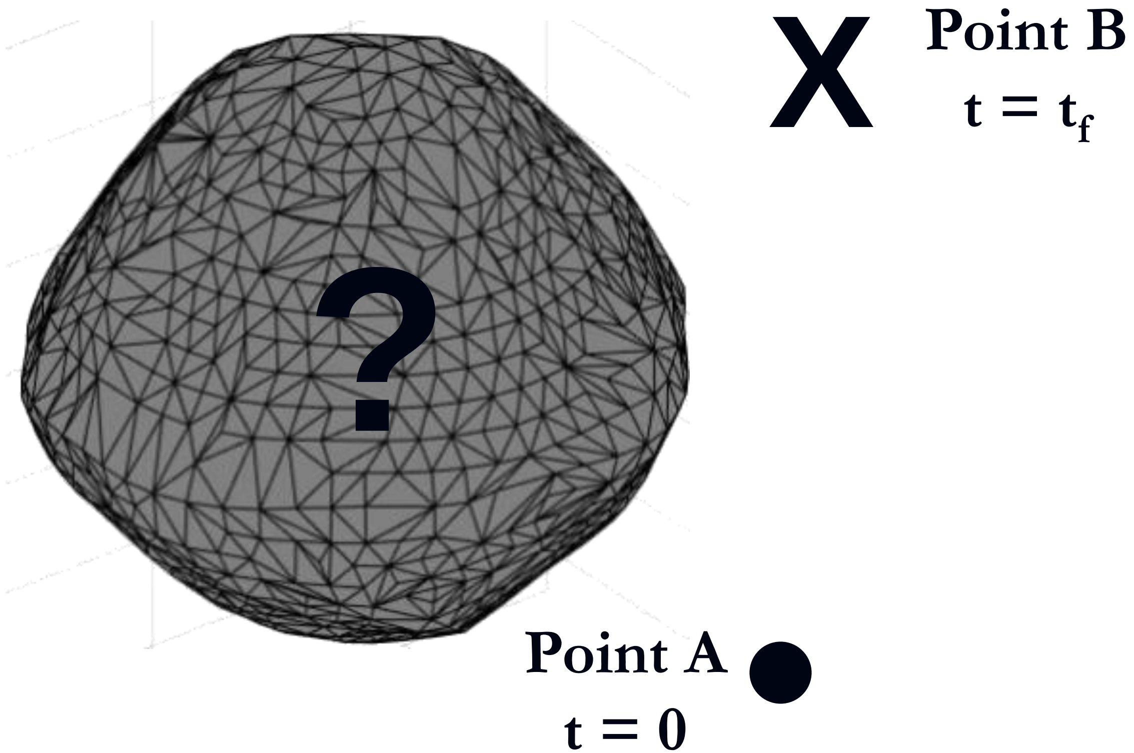
Rosetta's flyby of Steins

Trajectory comparison

Flyby	Orbits
Pros: • Ideal for short period observations • Relatively fuel efficient • Single spacecraft design can be used for multiple targets • Can be extended to observe multiple targets • Swarm deployment is easier compared to orbital operations **Cons:** • Sun vector is a crucial factor for visual observations • Shorter inspection times • Multiple flybys may be required to completely observe the target	**Pros:** • Dedicated to single target body observations • Suitable for long term observations • Sun vector is not a crucial factor **Cons:** • Orbit insertion burns are fuel expensive • Susceptible to gravitational instabilities • Spacecrafts need to be separately designed for different target bodies • Difficult to deploy an orbiting constellation

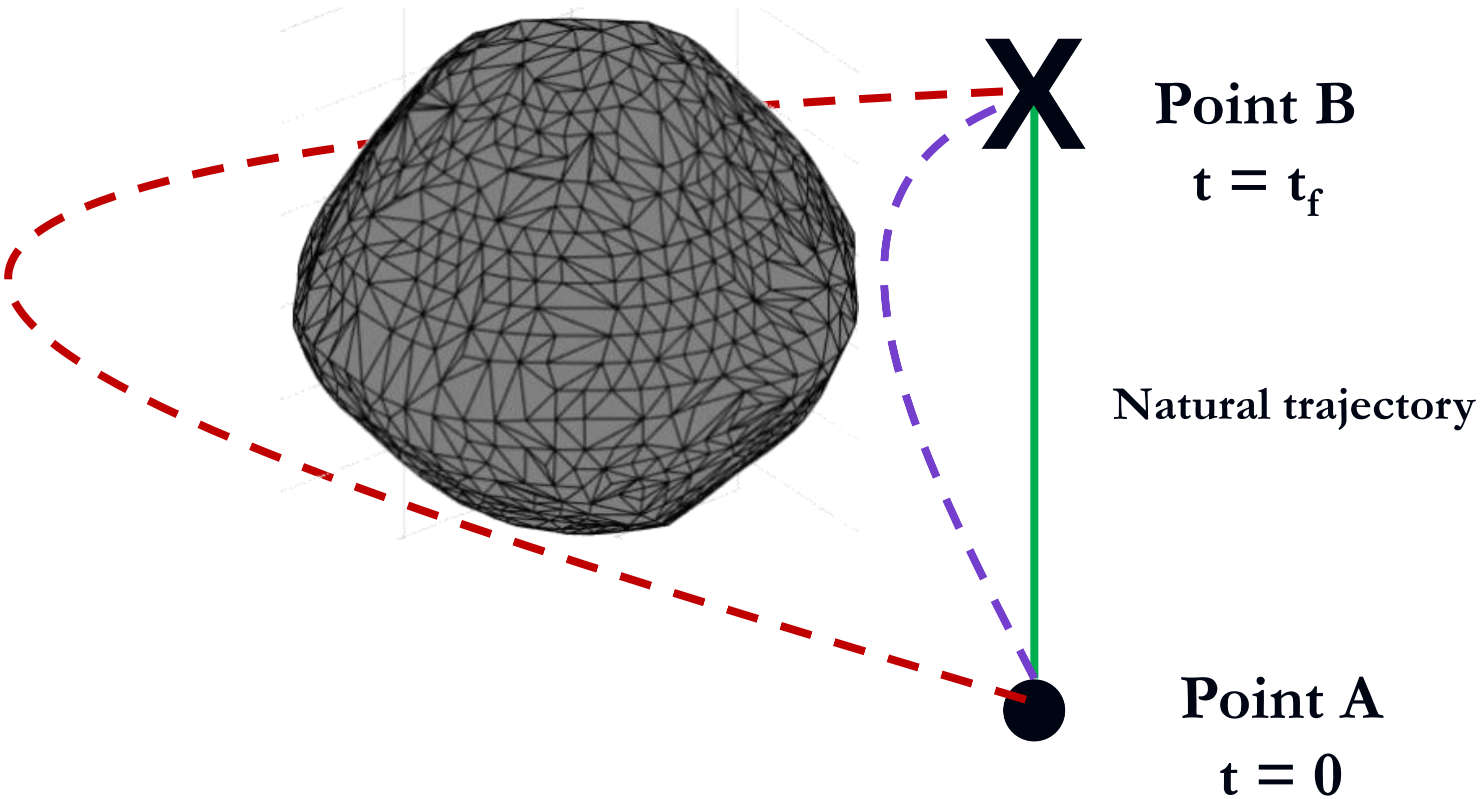
Flybys are suitable for low cost, low thrust missions; can be deployed on a spacecraft swarm

Trajectory design



Objective is to find a trajectory that connects the current position to its destination in desired time

Trajectory design



Trajectories allowed by the dynamics minimize fuel

Objective

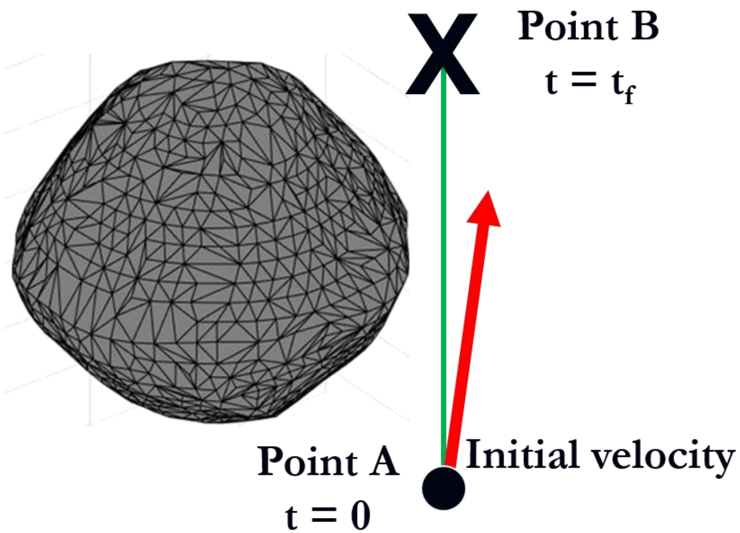
- To find the trajectories allowed by local gravity field, which takes a spacecraft from its current location to a desired location with in a given time.
- Extend this to find trajectories for spacecraft swarm, so that all spacecrafts reach their destinations within specified times.

Challenges

- Complex dynamics around around the asteroid.
- Each asteroid exhibits different dynamics.
- Solar radiation is a significant perturbation
- Keplerian tools cannot be used to design trajectories.

Problem reduction

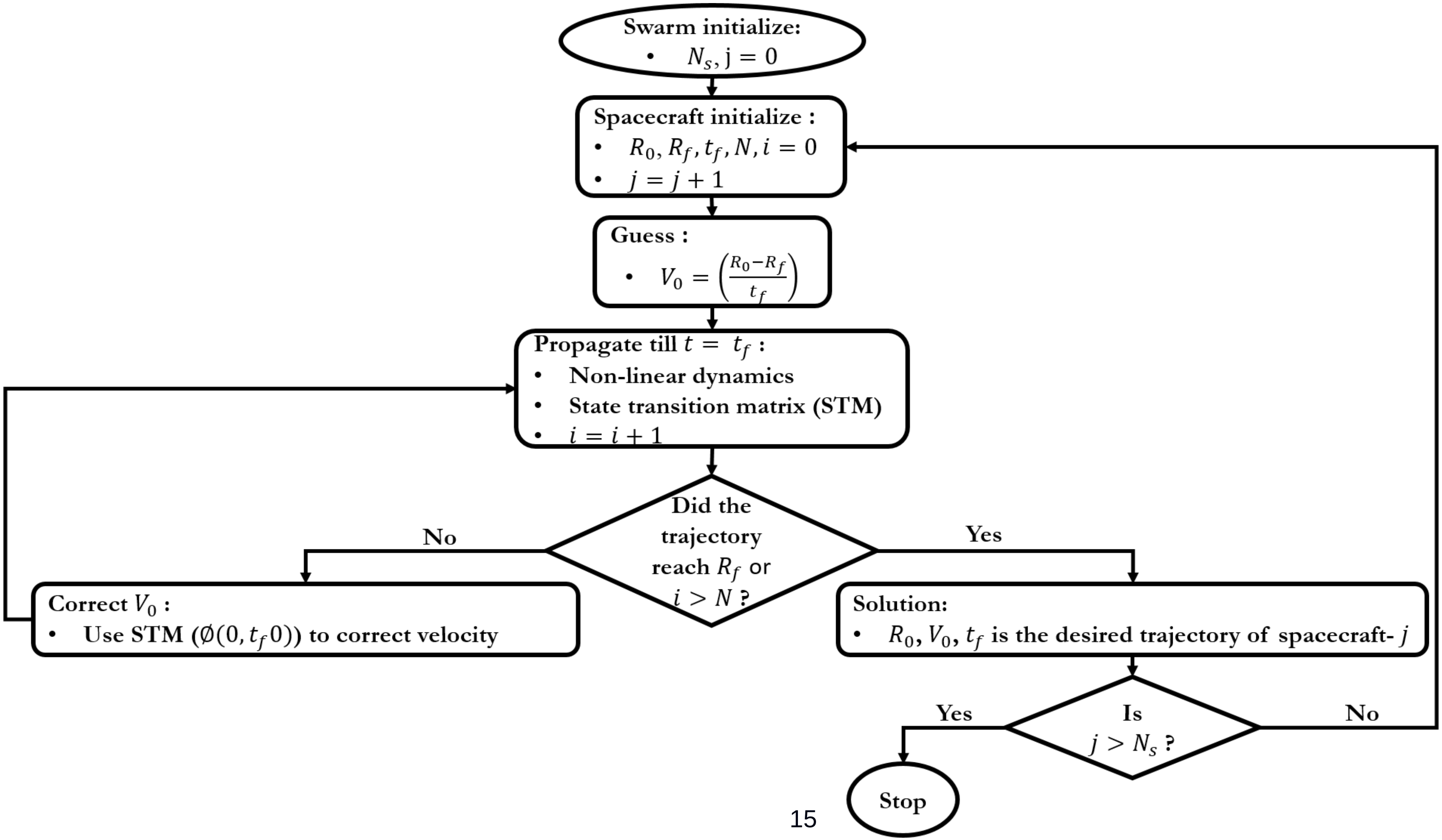
- For a given initial and final positions, and a flyby time, the trajectory is specified by finding the required initial velocity.



Approach

- Iterative schemes to search for the desired initial condition are developed.
- The schemes are performed over the entire swarm population to obtain required initial conditions
- The initial conditions are then propagated forward in time to obtain the trajectories
- Gravity, solar tide, and SRP are used to model the dynamics

Trajectory design algorithm



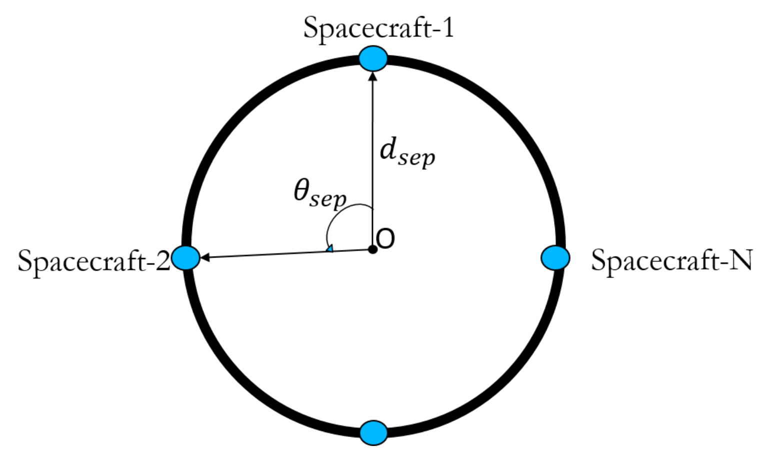
Spacecraft swarm

- **A ring shaped spacecraft swarm of N uniformly separated spacecraft as follows**
- **The location of the j[th] spacecraft is given by:**

$$R_j = \begin{bmatrix} d_{sep}\cos(j-1)\theta_{sep} \\ d_{sep}\sin(j-1)\theta_{sep} \\ z \end{bmatrix}$$

- **Where:**

$$\theta_{sep} = \frac{2\pi}{N}$$



Swarm layout

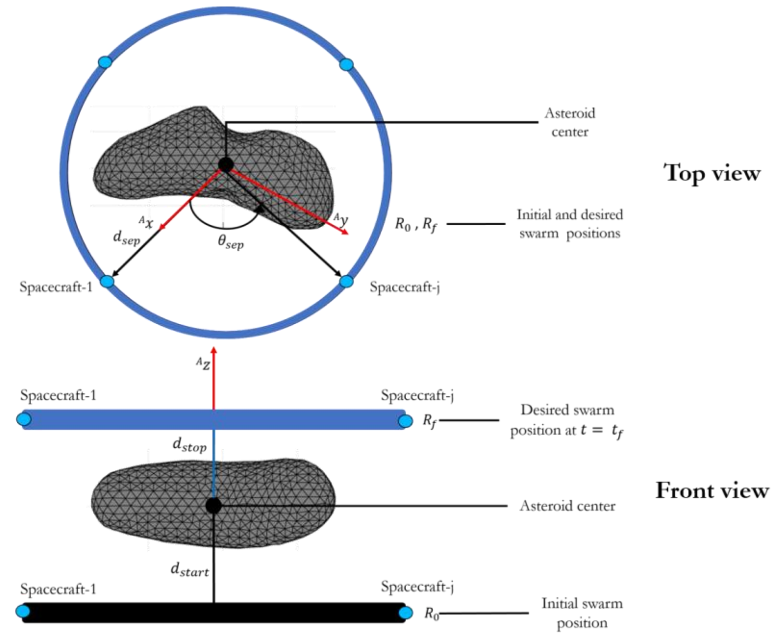
Simulations

- The trajectory design algorithm is demonstrated for the ring shaped swarm.
- The Swarm is desired to fly by the asteroid 433 Eros
- The spacecrafts need to maintain a radial separation of 50 Km from the center of the asteroid
- The spacecrafts are desired to travel a distance of 60 km along the spin axis of the asteroid in 10 minutes
- Nominal 12U CubeSat parameters are used for the spacecraft model

Swarm simulations

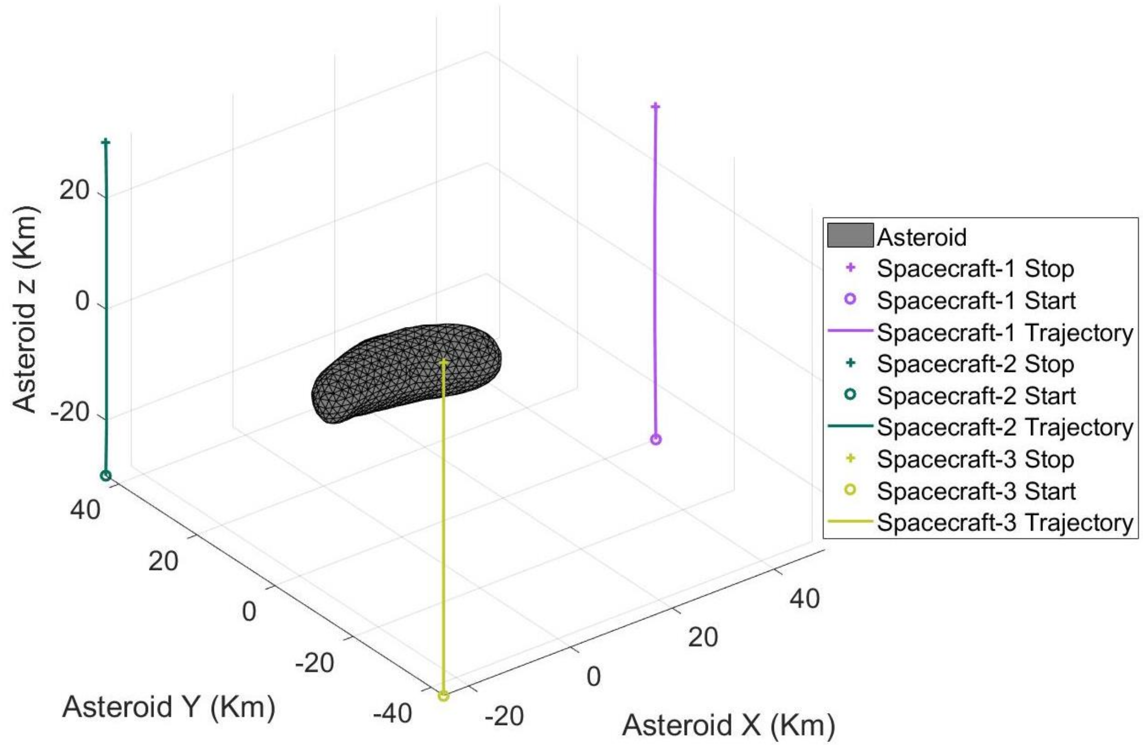
- **The following parameters were used for simulating the flyby with the spacecraft swarm**

Parameter	Value
Asteroid	433 Eros
Number of spacecraft	3, 4, 5
Radial separation (Km)	50
Starting distance (Km)	-30
Stopping distance (Km)	30
Flyby duration (mins)	10



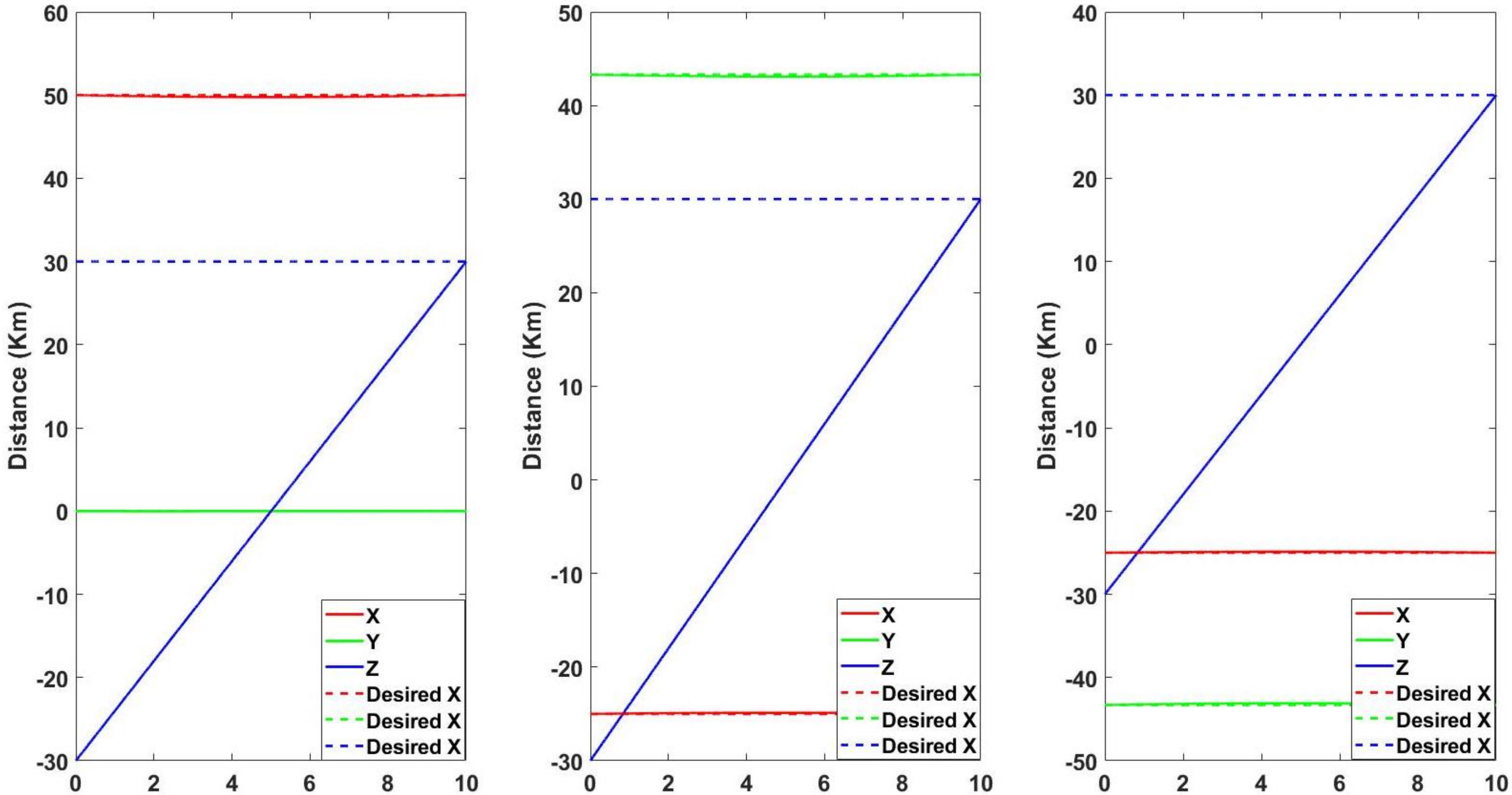
Targeting geometry with the spacecraft swarm

3 spacecraft trajectories



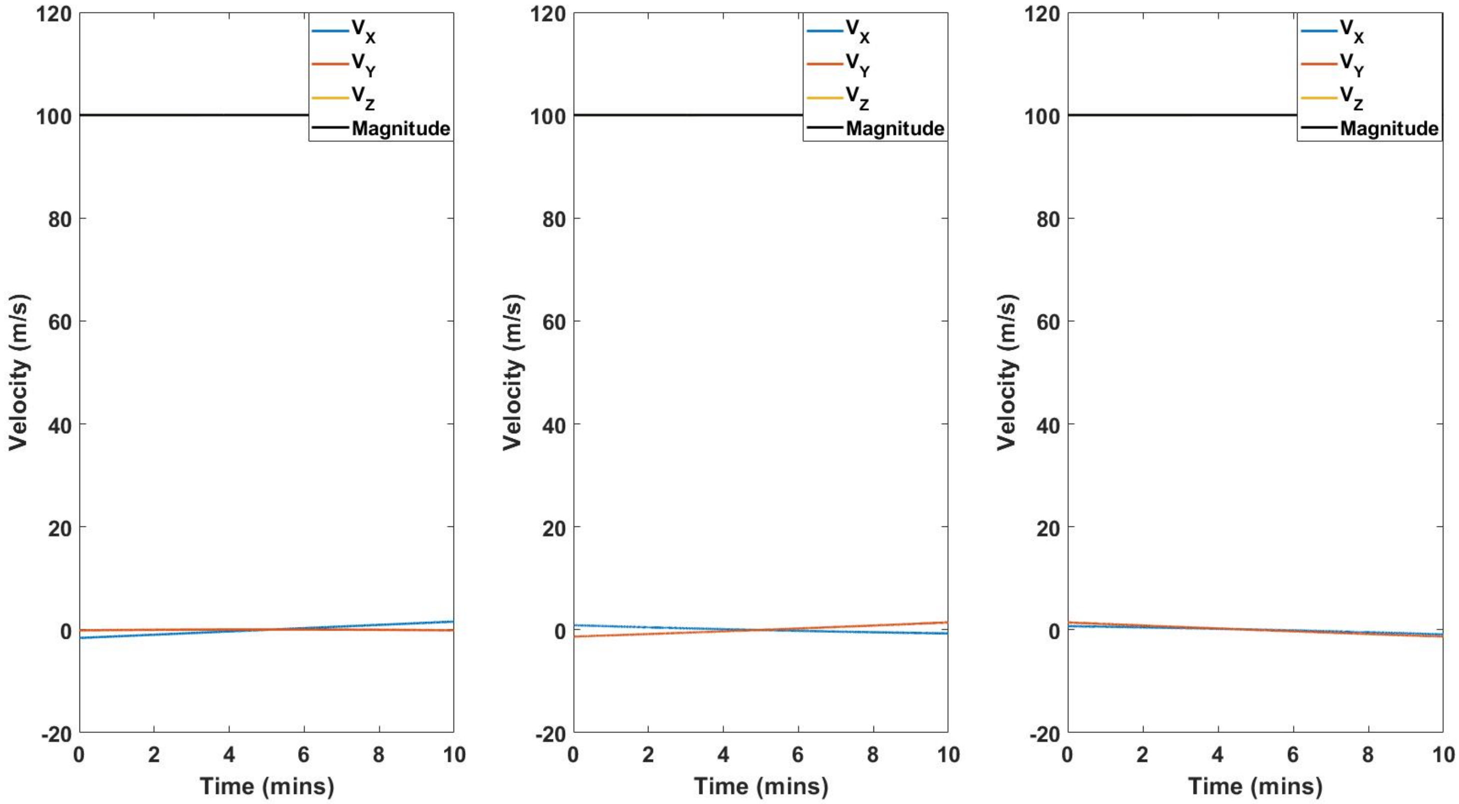
The trajectories generated for 3 spacecrafts

Spacecraft positions



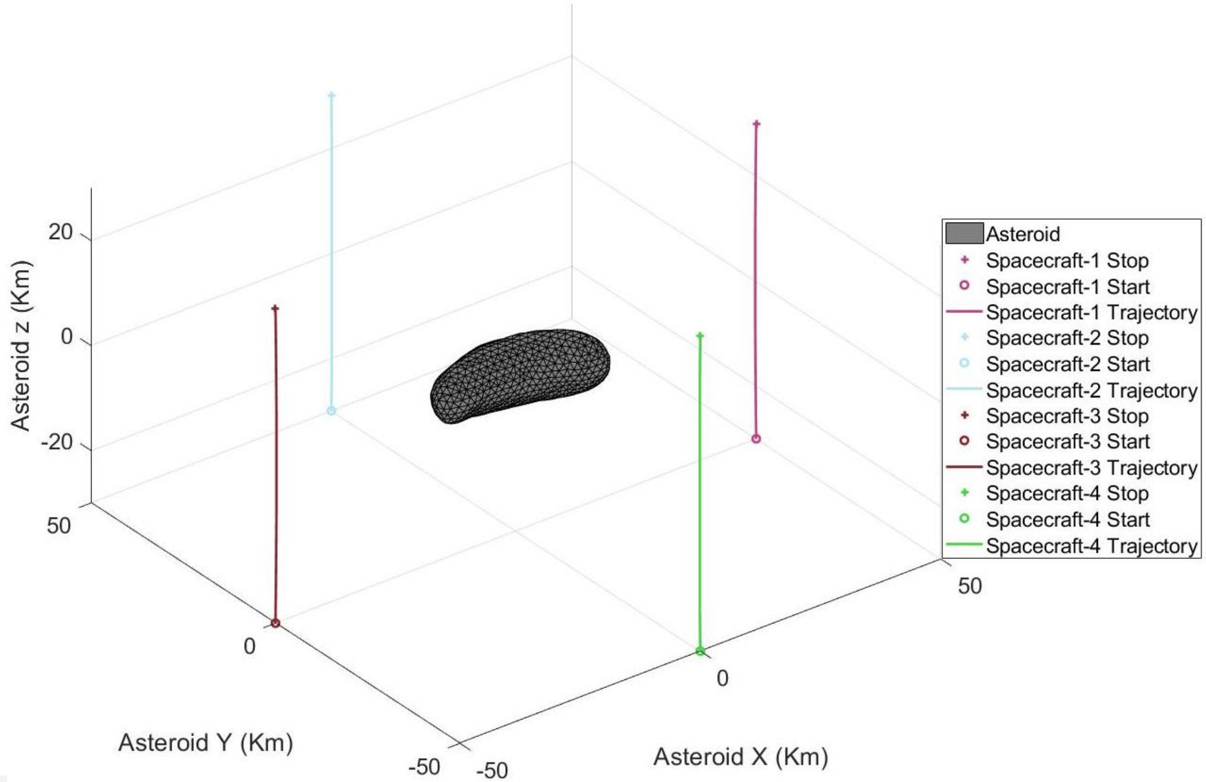
The algorithm yields desired flyby trajectories, with in the desired 10 minutes time

3 spacecraft flyby



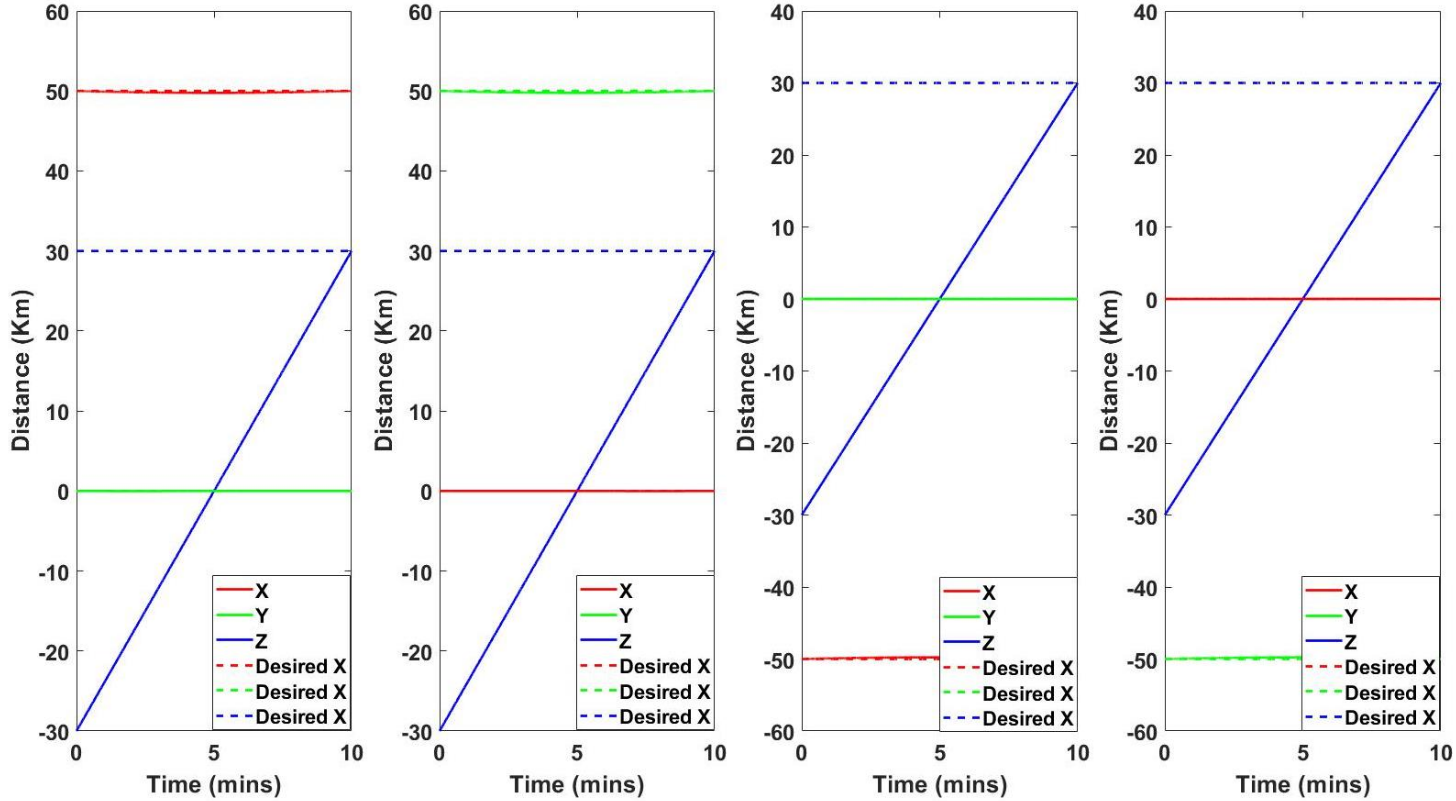
All the spacecrafts fly with a 100 m/s velocity during the flyby

4 Spacecraft trajectories



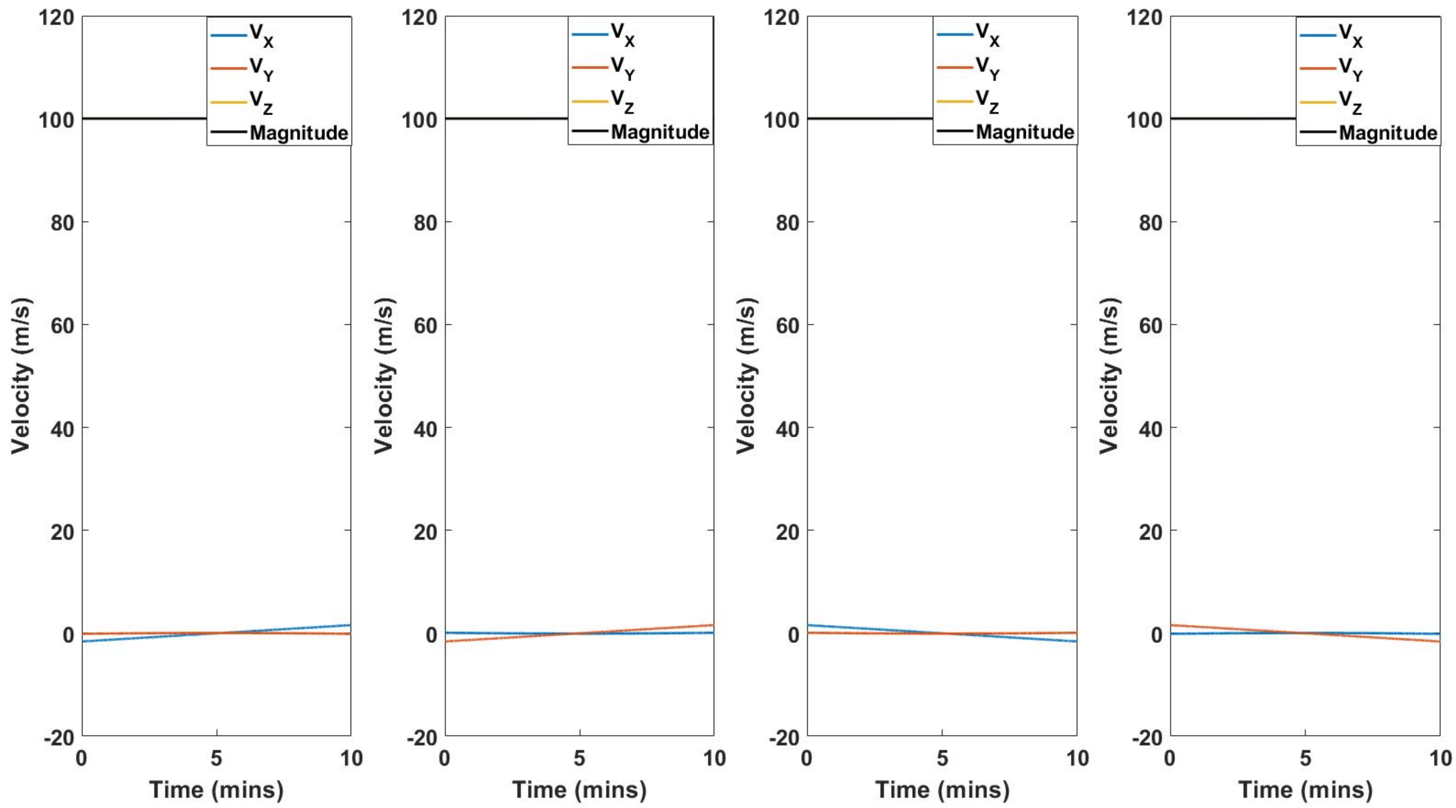
The trajectories generated for 4 spacecrafts

Spacecraft positions



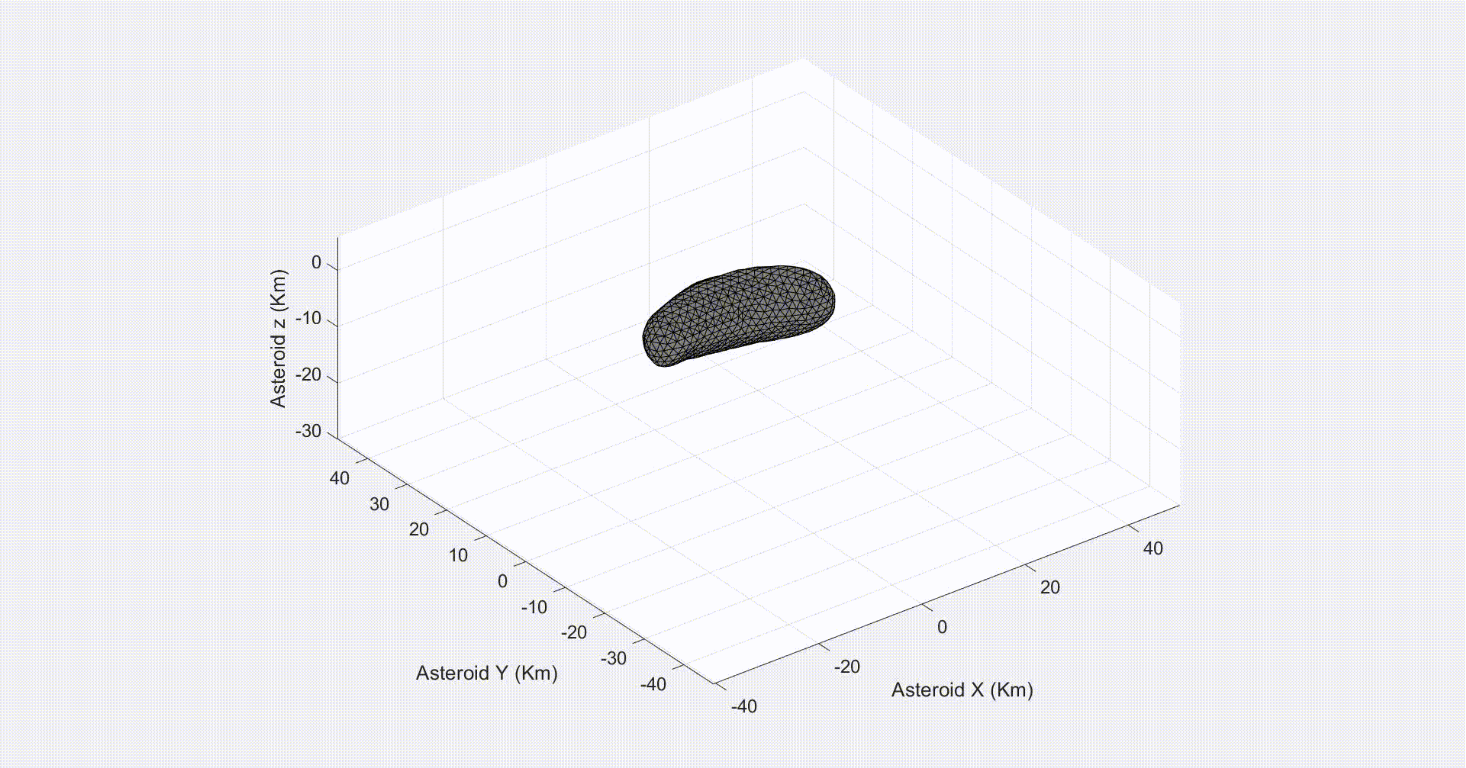
The algorithm yields desired flyby trajectories, with in the desired 10 minutes time

Flyby velocities



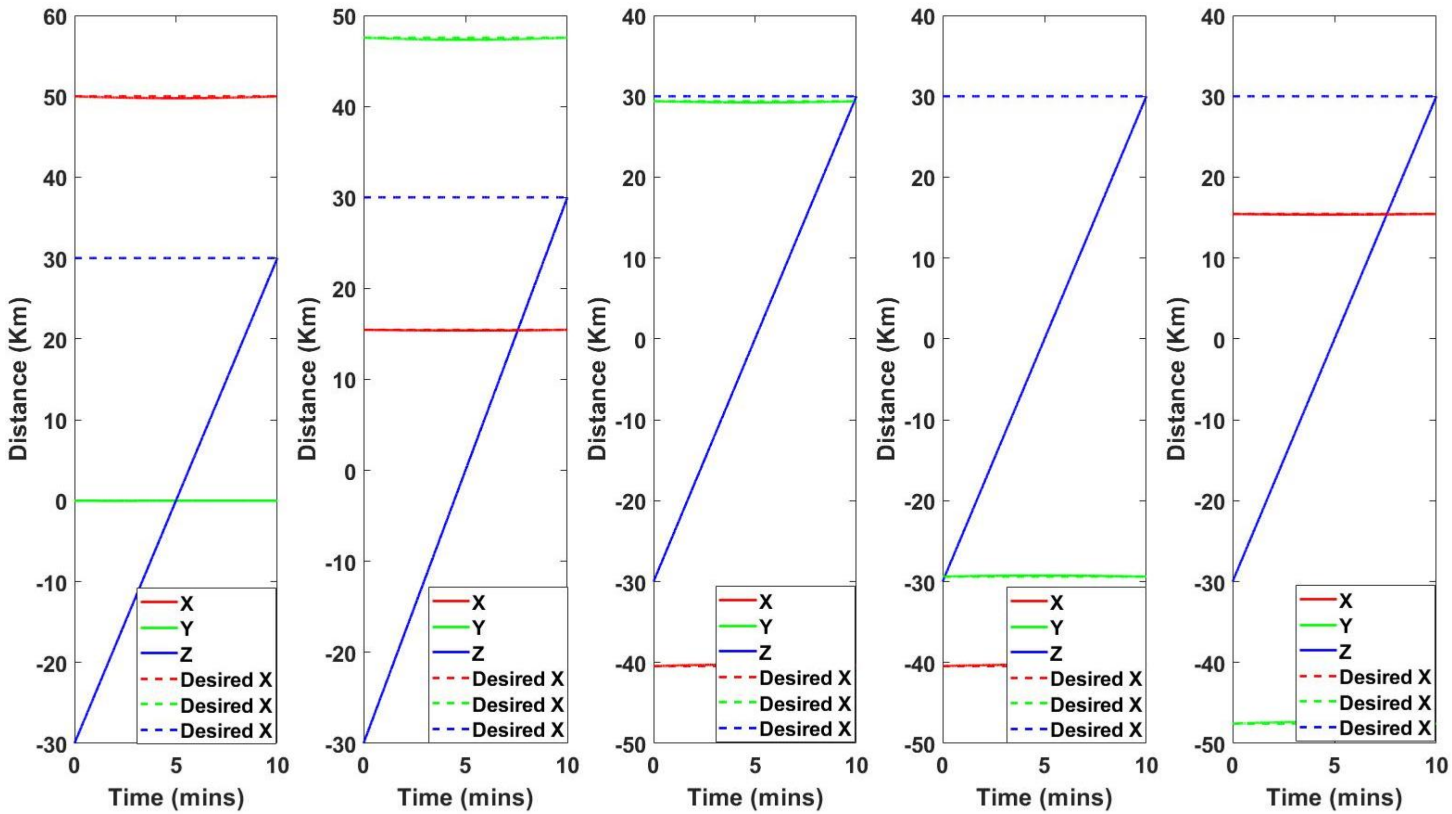
All the spacecrafts fly with a 100 m/s velocity during the flyby

Results



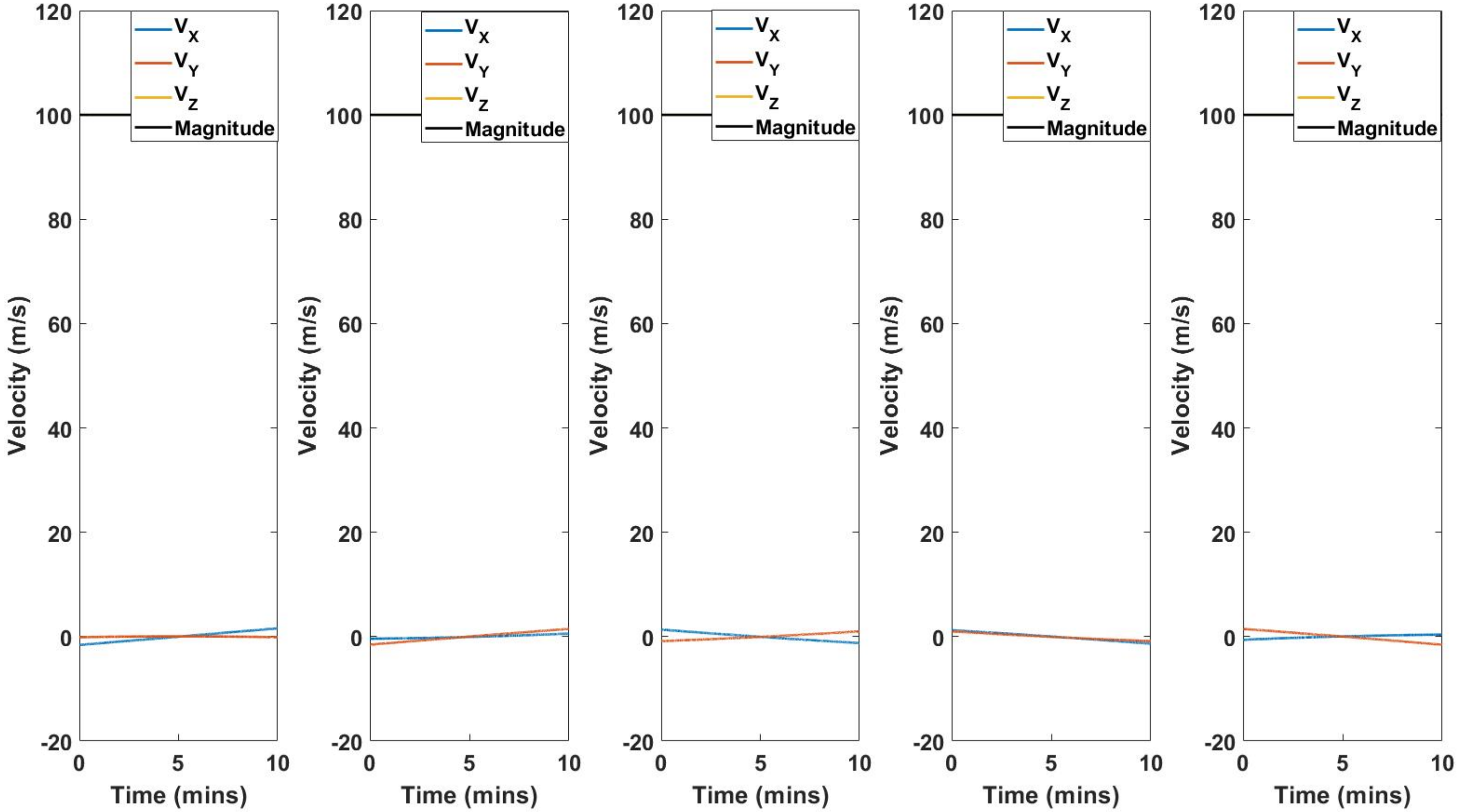
The trajectories generated for 5 spacecrafts

Spacecraft positions



The algorithm yields desired flyby trajectories, with in the desired 10 minutes time

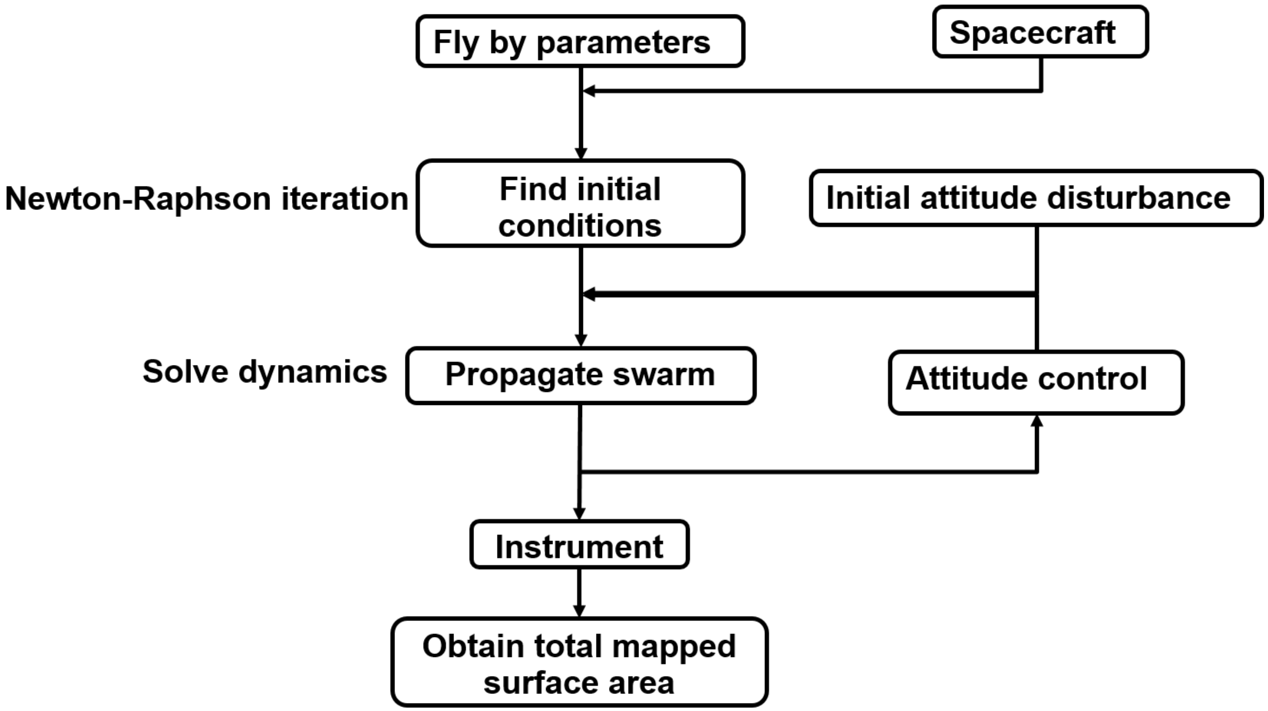
Flyby velocities



All the spacecrafts fly with a 100 m/s velocity during the flyby

Mapping demonstration

- A mapping simulator which couples the trajectory and attitude control with the following architecture



Results

- **The simulator is demonstrated with 2 sets of attitude control strategies:**
  1. **Nadir pointing**
  2. **Field of view Sweeping**

In both the cases, the area mapped by the instrument is noted

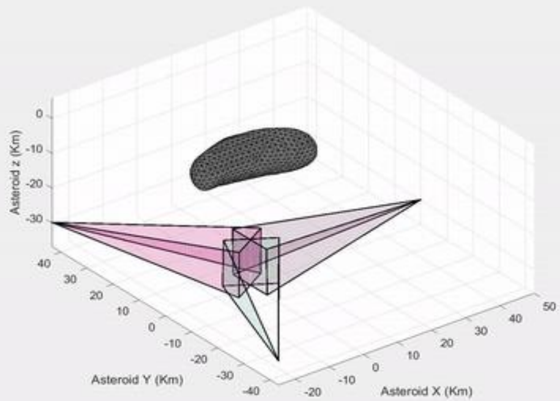
Instrument parameters

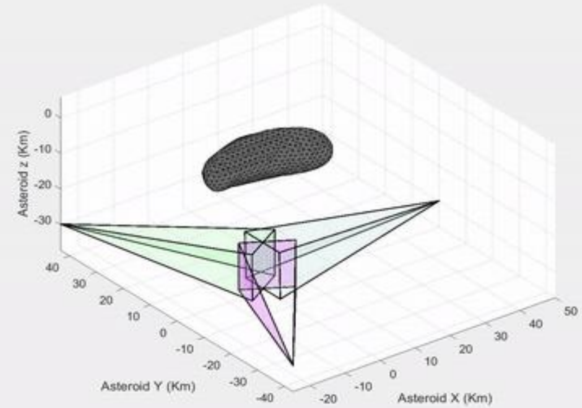
- **The following are the parameters of the onboard instrument on the**

Parameter	Value
FOV	15
Near distance (m)	0.1
Far distance (Km)	500,000
Frame rate (fps)	5

A pinhole camera model is used to simulate the instrument

3 Spacecraft mapping

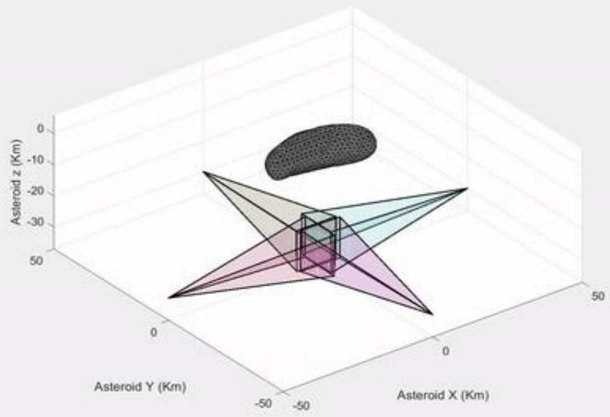


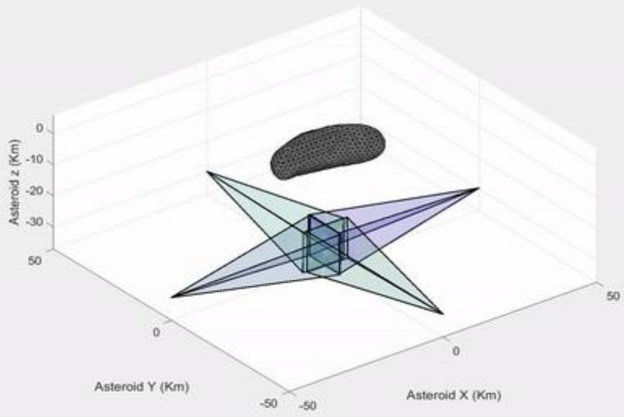


Nadir pointing	
Observed Area (Km^2)	698.01
% Observed Area	63.26

FOV Sweeping	
Observed Area (Km^2)	1103.34
% Observed Area	100

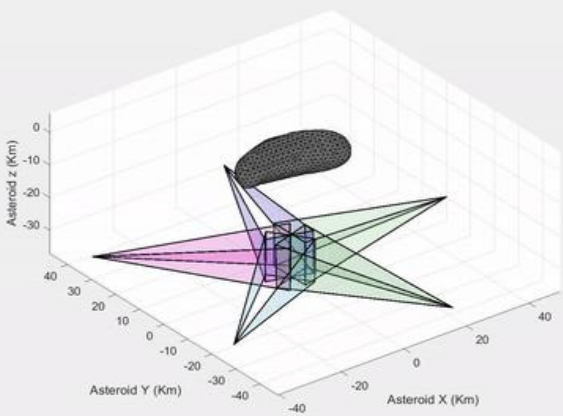
4 Spacecraft mapping

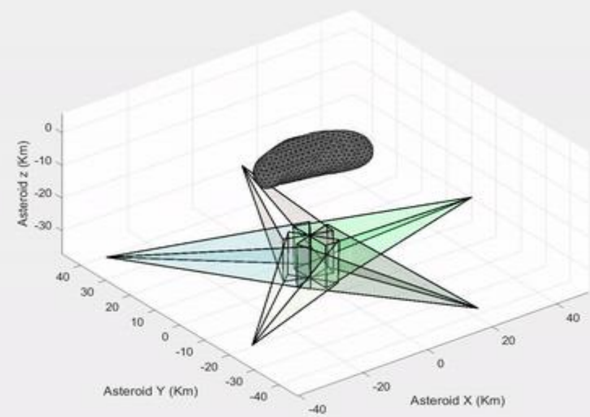




Nadir pointing		FOV Sweeping	
Observed Area (Km^2)	965.89	Observed Area (Km^2)	1103.34
% Observed Area	87.54	% Observed Area	100

5 Spacecraft mapping





Nadir pointing		FOV Sweeping	
Observed Area (Km^2)	852.30	Observed Area (Km^2)	1103.34
% Observed Area	76.24	% Observed Area	100

Discussion

- Surface mapping missions of asteroids yield rich geological information.
- Flyby trajectories performed by spacecraft swarm are better suited for surface mapping than orbits
- This work presented a trajectory design algorithm for a swarm of spacecrafts around asteroids
- The algorithm uses an iterative numerical scheme using the state transition matrix, to find the desired natural trajectories

Discussion

- The algorithm is demonstrated for a circularly symmetric swarm consisting of 3, 4,& 5 spacecrafts.
- The demonstrations showed a flyby around the asteroid 433 Eros, where the spacecrafts are required to travel at a speed of 100 m/s.
- These trajectories are then coupled with attitude control strategies to 100% surface mapping coverage.

Future work

- Integrate with strategies to search for optimal mapping locations.
- Integrate with optimal attitude tracking strategies to improve coverage with minimal energy.
- Design flyby sequences to map multiple asteroids.

Thank You

Questions ?

References

1. Scheeres, Daniel J. Orbital Motion in Strongly Perturbed Environments : Applications to Asteroid, Comet and Planetary Satellite Orbiters. Springer, Berlin, Heidelberg, 2011;2012;, doi:10.1007/978-3-642-03256-1.
2. Hamilton, Douglas P., and Joseph A. Burns. "Orbital Stability Zones about Asteroids." Icarus, vol. 92, no. 1, 1991, pp. 118-131.
3. Scheeres, D. J. "Dynamics about Uniformly Rotating Triaxial Ellipsoids: Applications to Asteroids." Icarus, vol. 110, no. 2, 1994, pp. 225-238.
4. Scheeres, D. J. "Satellite Dynamics about Small Bodies: Averaged Solar Radiation Pressure Effects." Journal of the Astronautical Sciences, vol. 47, no. 1-2, 1999, pp. 25-46.
5. D.J, Scheeres. "Orbit Mechanics about Asteroids and Comets." Journal of Guidance, Control, and Dynamics, vol. 35, no. 3, 2012, pp. 987-997.
6. Melman, J. C. P., E. Mooij, and R. Noomen. "State Propagation in an Uncertain Asteroid Gravity Field." Acta Astronautica, vol. 91, 2013, pp. 8-19.
7. Chanut, T. G. G., O. C. Winter, and M. Tsuchida. "3D Stability Orbits Close to 433 Eros using an Effective Polyhedral Model Method." Monthly Notices of the Royal Astronomical Society, vol. 438, no. 3, 2014, pp. 2672-2682.
8. Xian-Yu Wang Sheng-Ping Gong Jun-Feng Li. "A Method for Classifying Orbits Near Asteroids." 力学学报：英文版, vol. 30, no. 3, 2014;2017;, pp. 316-325.
9. Niedling, Julian, et al. Development of a Tool for Analyzing Orbits Around Asteroids, vol. 158, 2016.
10. Werner, Robert A., and Daniel J. Scheeres. "Exterior Gravitation of a Polyhedron Derived and Compared with Harmonic and Mascon Gravitation Representations of Asteroid 4769 Castalia." Celestial Mechanics and Dynamical Astronomy, vol. 65, no. 3, 1996, pp. 313-344.
11. García Pardo, Diego. *Analysis and implementation of gravity field models for planets and asteroids*. BS thesis. 2014.
12. Cangahuala, L. A. Augmentations to the Polyhedral Gravity Model to Facilitate Small Body Navigation, vol. 120, 2005
13. Hu, W., and D. J. Scheeres. "Numerical Determination of Stability Regions for Orbital Motion in Uniformly Rotating Second Degree and Order Gravity Fields." Planetary and Space Science, vol. 52, no. 8, 2004, pp. 685-692.