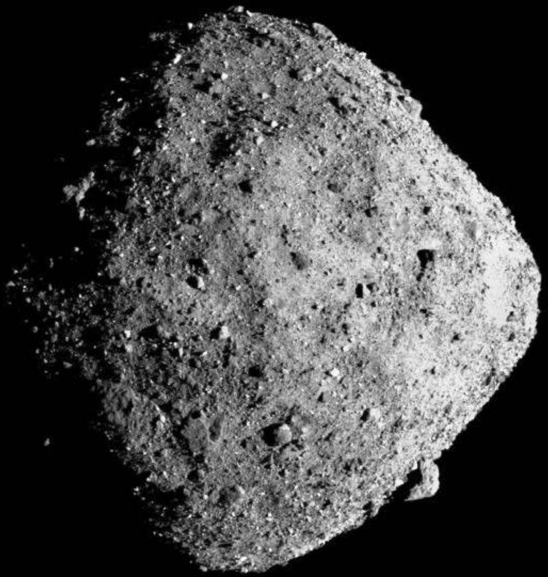

Towards Development and Testing of an Engineering Model for an Asteroid Hopping Robot

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Introduction

- Why asteroid exploration is important
- Surface mobility and AMIGO Overview
- Engineering Model Testing
- Sublimate Propulsion
- Nozzle geometry design
- MEMS Fabrication Methods

Motivation: Asteroid Exploration

Asteroid Exploration

- Planetary Science Decadal Survey highlights key questions asteroids can answer
- In-situ analysis required for in-depth analysis on internal structure, surface regolith, thermal effects, etc.

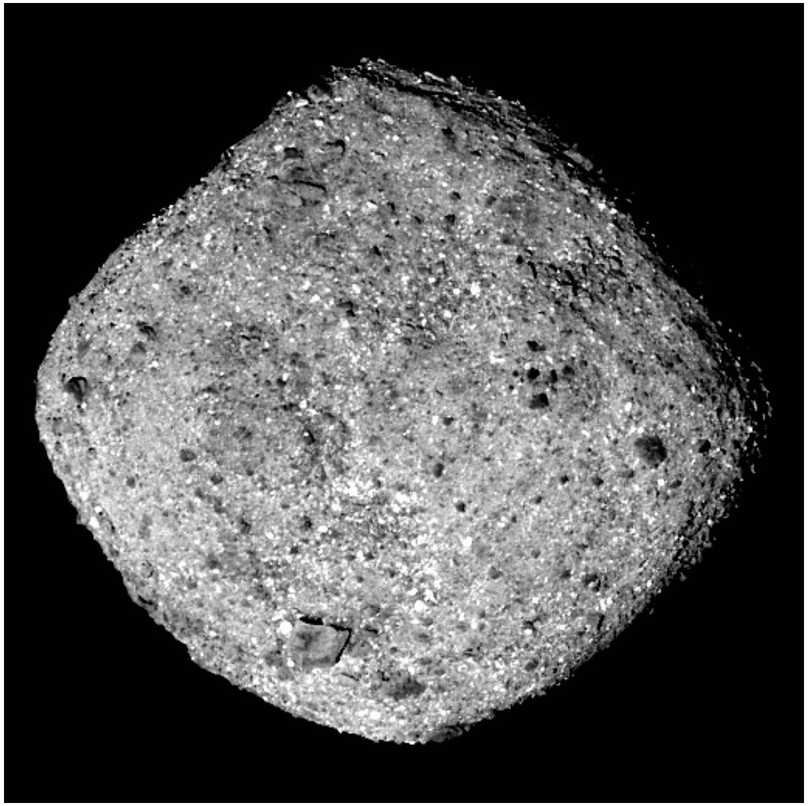


Figure: Bennu Arrival from OSIRIS-Rex (Credit: NASA, Goddard, University of Arizona)

Asteroid Surface Exploration

Geohistory

Security/Deflection

ISRU

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

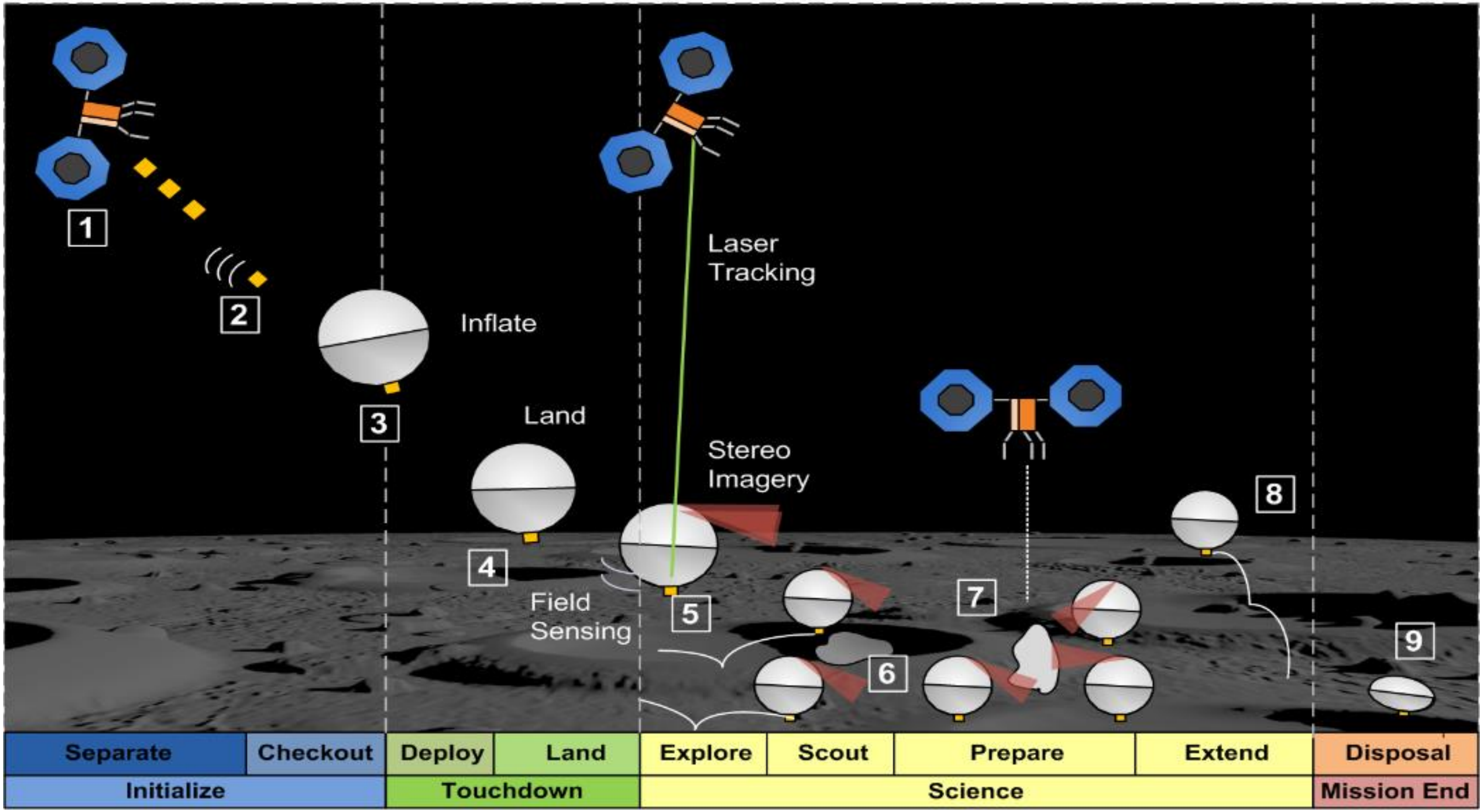
Complements flyby and orbital observation science.

Asteroid Surface Hopping

- Collect science data at multiple locations
- Mobility through:
  - Roving
  - Internal actuation
  - Mechanical systems
  - Thrusting

Figure: Surface of Ryugu from MINERVA-II 1B (Credit: JAXA, University of Tokyo et al.)

AMIGO ConOps



AMIGO Mission Concept

- Stereo imaging
- Geologic imaging
- Thermal fatigue
- Seismic sensing
- Electric field measurements
- Complements orbital science and flyby missions

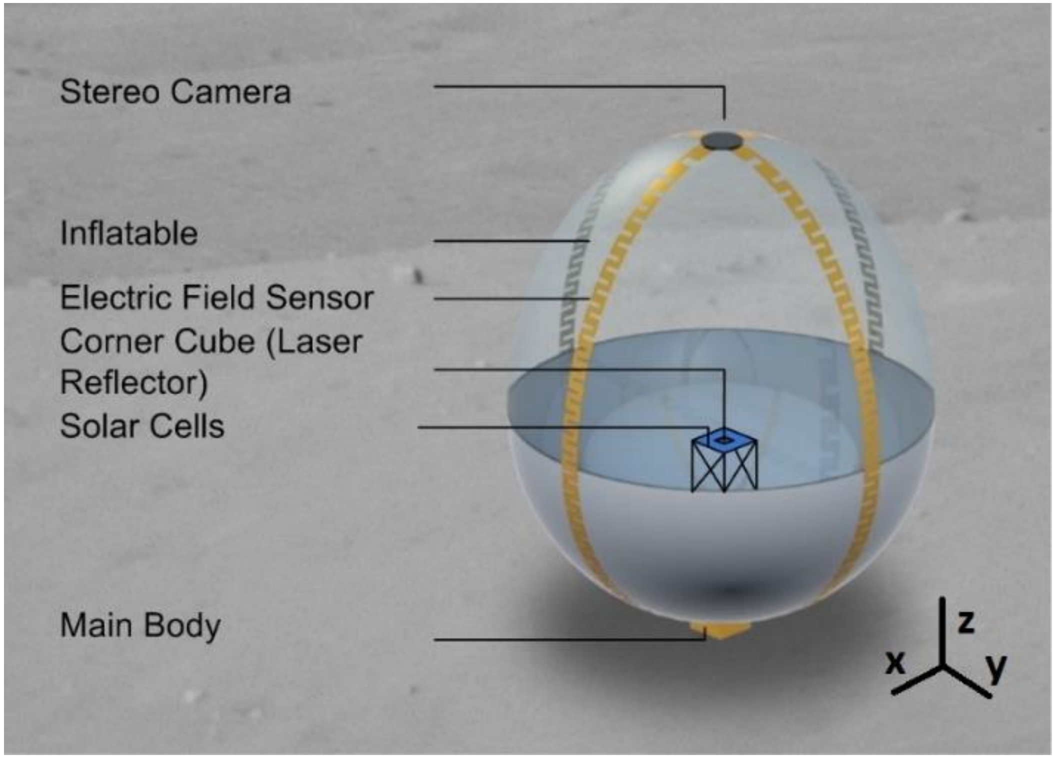


Figure: AMIGO Overview

AMIGO Internals

- Housing for:
  - Computer/ power system
  - Inflatable deployment
  - Science instruments
  - Propulsion components

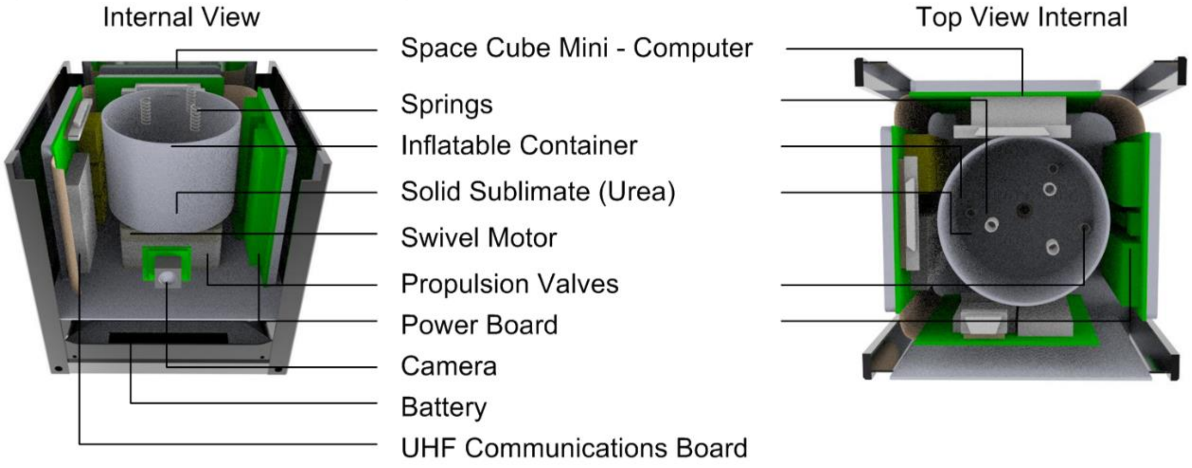


Figure: AMIGO Internals

Engineering Model

Components

- Parallel effort to develop low cost 1U cubesat for general use
- Avionics: ¼ U
  - Computer: Teensy Board
  - Batteries: Li-Ion 18650 (~17 WHr)
- Propulsion: ¼ U
- Inflatable structure: ¼ U
- Mock science instruments: ¼ U

Figure: AMIGO Internals

Testing

- Microgravity simulation: helium filled pseudo-inflatable
- Simulant regolith to understand surface interaction
- Test path planning algorithm from top mounted camera
- Use micro-thrusters for hopping

Sublimate Micro-Propulsion

Sublimate Propulsion

- Extension of cold gas systems
- Usable with low-cost, readily-available chemicals
- Store propellant as solid – higher storage density
- Control chamber pressure by heating elements
- Lower pressure than conventional cold gas

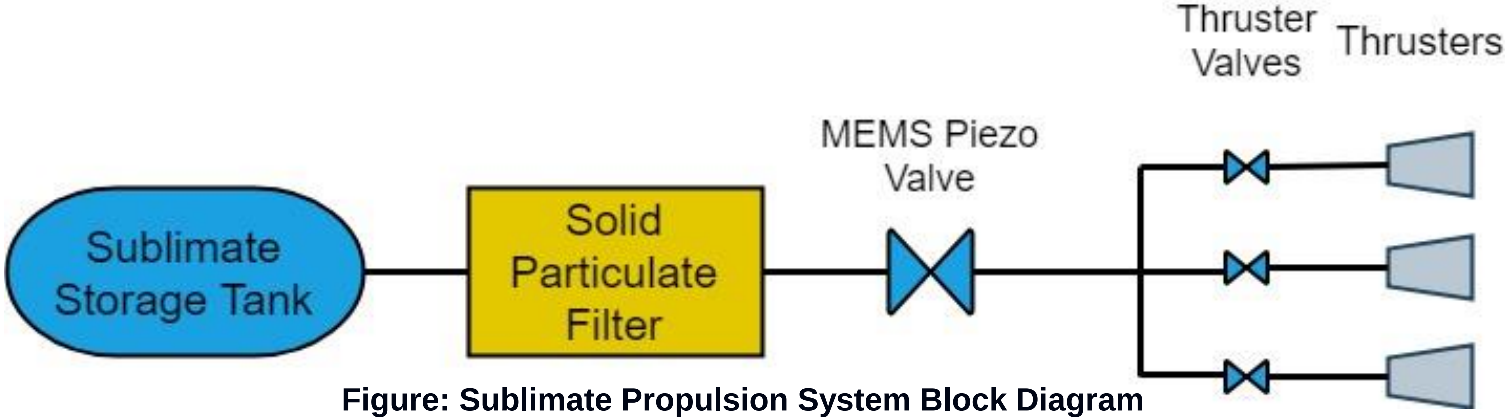


Figure: Sublimate Propulsion System Block Diagram

Thruster Chip

- Bottom mounted MEMS thruster chip for hopping
- x-y control authority
- Discretized micro-nozzles allow three saturation modes by individual actuation

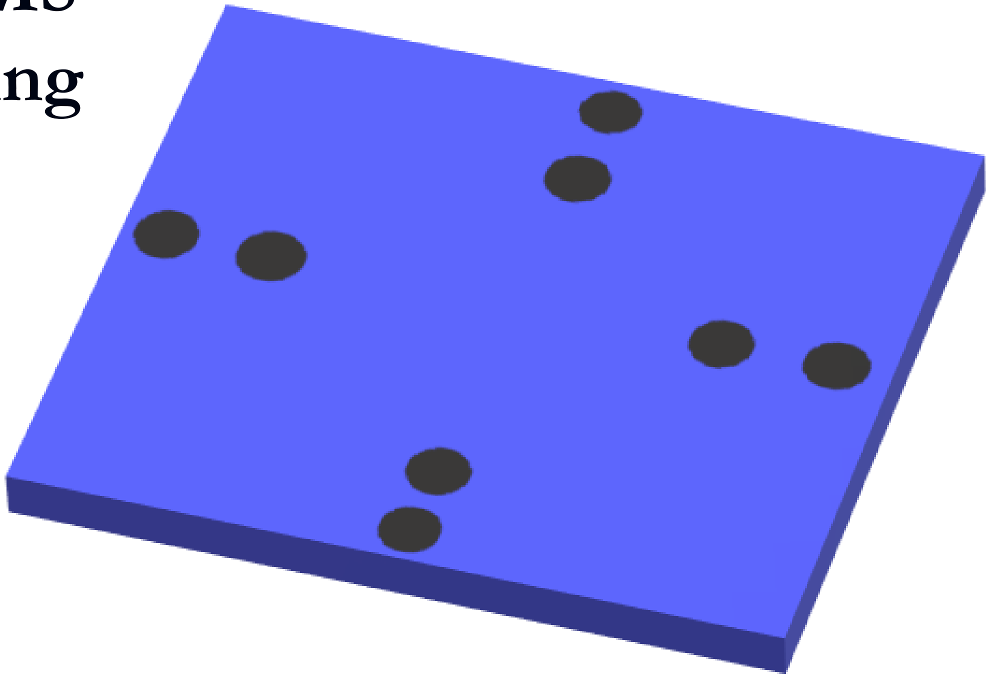
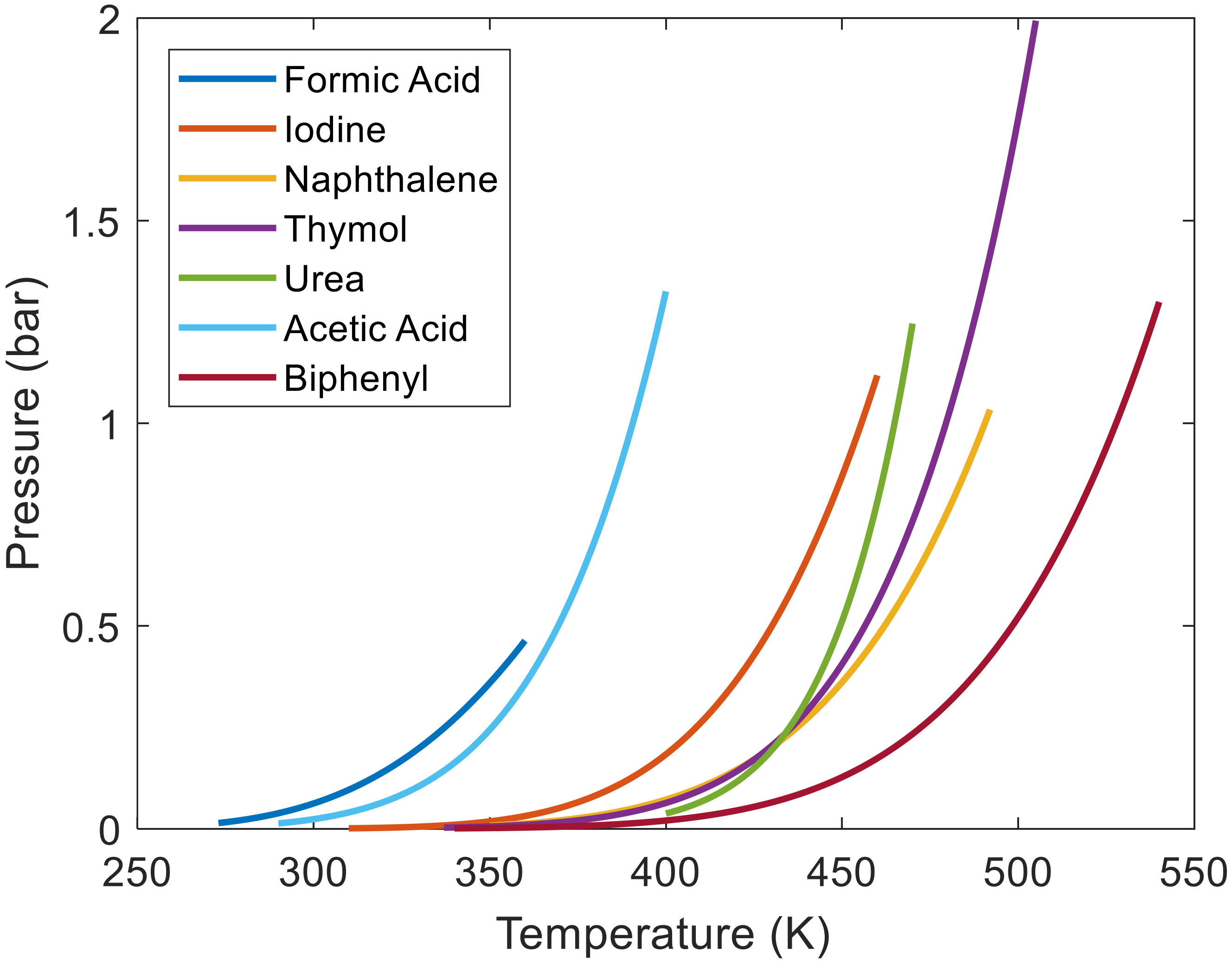


Figure: Thruster Chip

Sublimate Propellant Candidates



Nozzle Geometry Design

Algorithm Flow

- **Determine required thrust coefficient from required thrust:** $C_F = \frac{F}{p_c A_t}$
- **Determine viscous loss thrust coefficient through derived throat and wall Reynold's number**

$$C_{F_v} = \frac{17.6e^{0.0032\varepsilon}}{\sqrt{Re_{t,w}}}$$

- **Determine discharge coefficient**

$$C_D = 0.8825 + 0.0079 ln(Re_t)$$

Algorithm Flow

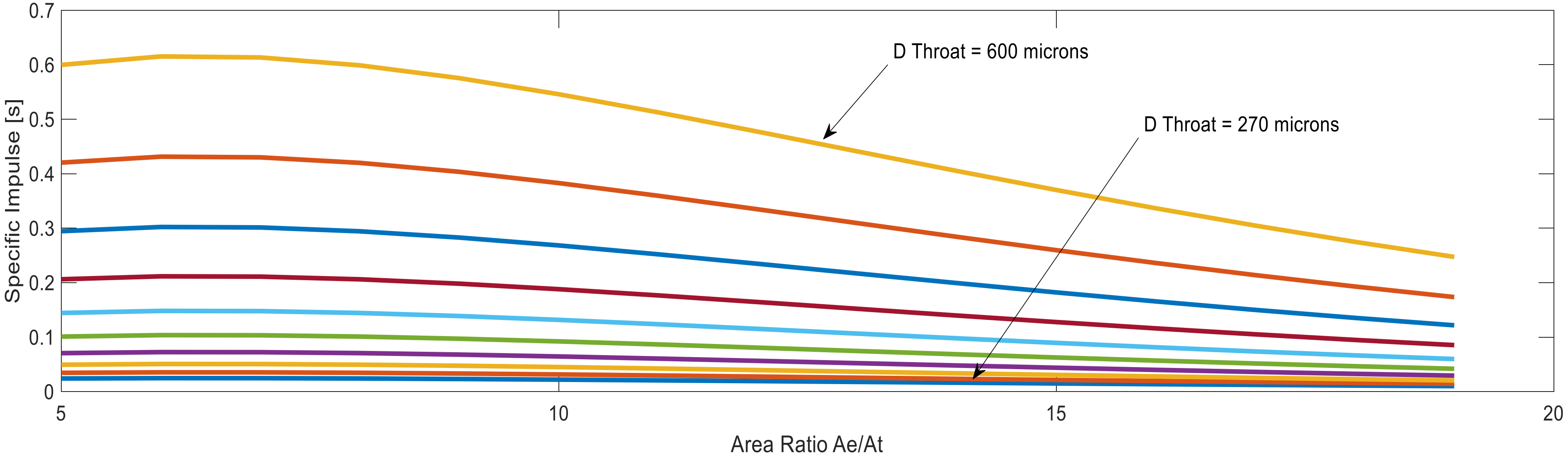
- Determine required isentropic thrust coefficient and thrust: $C_{F_i} = C_F + C_{F_v}$
- Find nozzle geometry to produce such thrust from corrected mass flow rate and exhaust velocity

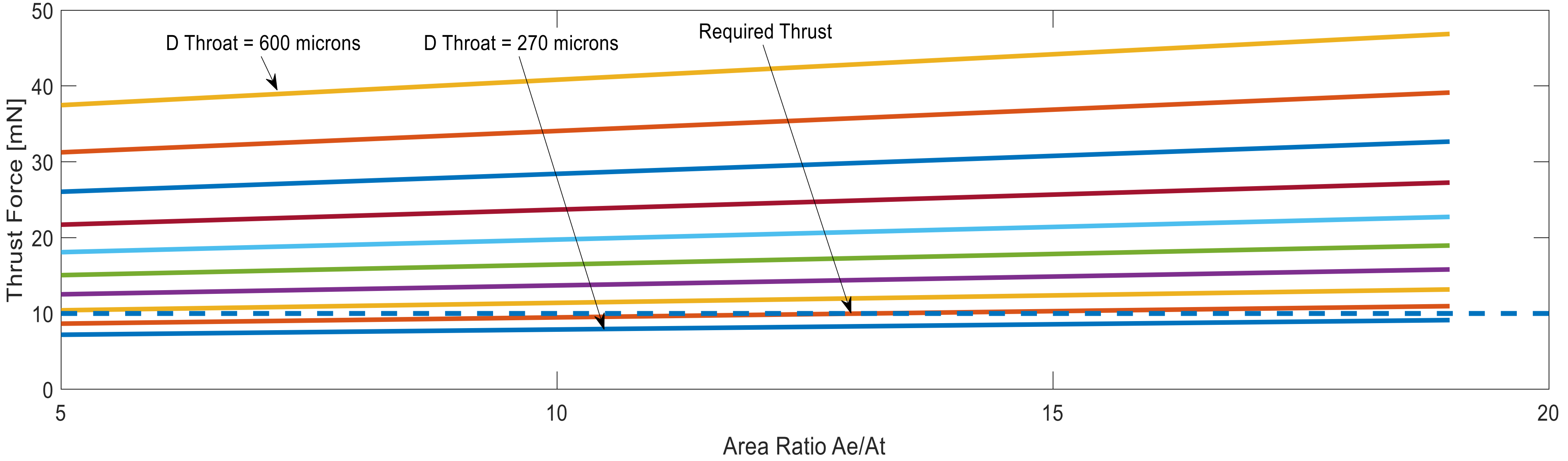
$$F_i = \lambda \dot{m} v_{e_i}$$

$$\dot{m} = C_D \rho_e A_e v_{e_i}$$

$$v_{e_i} = \frac{\dot{m} R T_e}{p_e A_e}$$

- Iterate through combinations of throat diameter and expansion ratio


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Specific Impulse [s]
5
10
15
20
Area Ratio Ae/At
D Throat = 600 microns
D Throat = 270 microns


50
40
30
20
10
0
Thrust Force [mN]
5
10
15
20
Area Ratio Ae/At
D Throat = 600 microns
D Throat = 270 microns
Required Thrust

MEMS Fabrication

Etching Techniques

- Dry etching: deep reactive ion etching
- Wet etching:
  - Anisotropic: Si reaction with KOH
  - Isotropic: Si reaction with HF and HNO_3

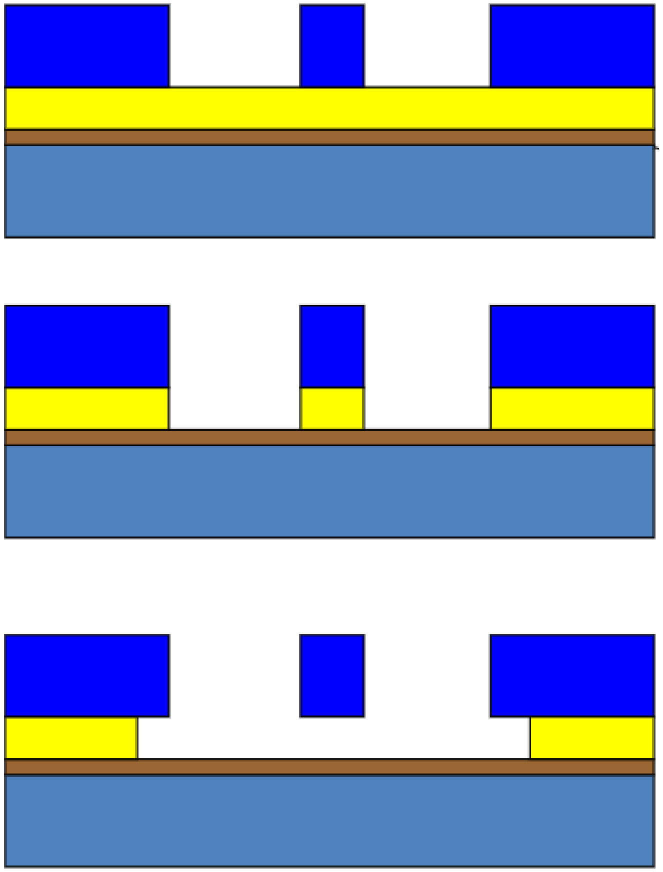


Figure: Anisotropic vs Isotropic Etch

DRIE

- Step 1: polymer deposition
- Step 2: ion bombardment to expose bottom face
- Step 3: isotropic etch
- Decrease etch time each step to make conical geometry
- Very expensive

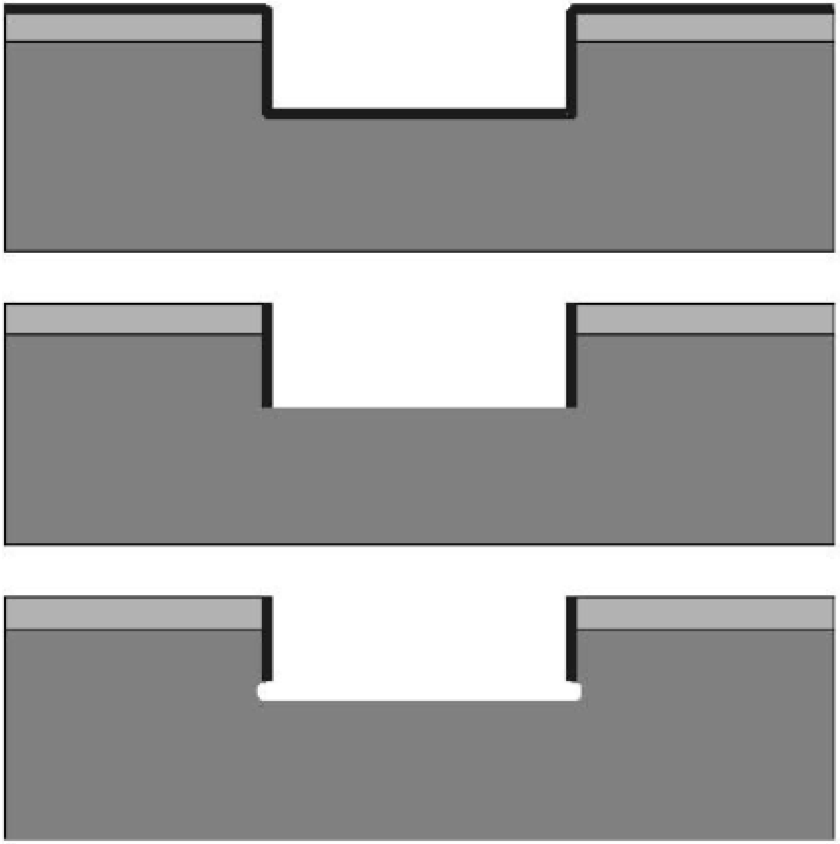


Figure: DRIE Etching Process

Anisotropic Etching

- Exploit crystal structure to etch along certain lattices
- Easily creates quasi-conical nozzles
- Semi-vertex angle fixed by crystal plane etched

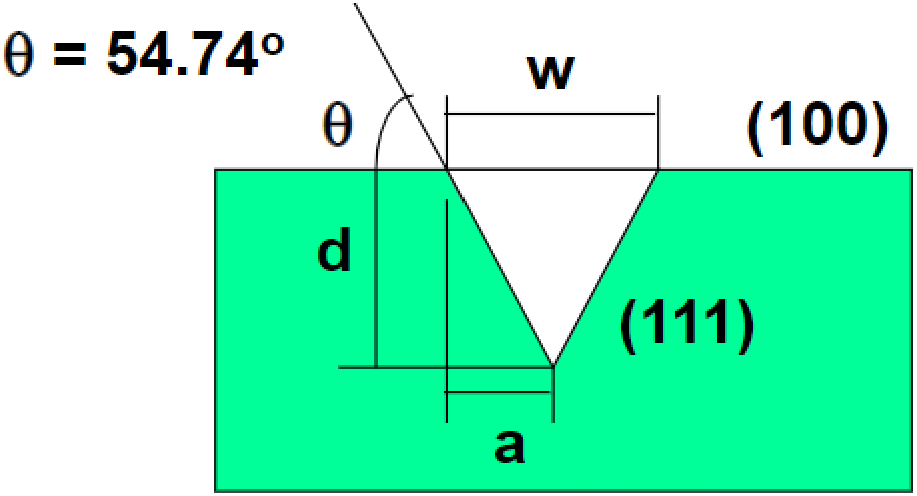


Figure: Anisotropic Etch of Silicon <100> Face

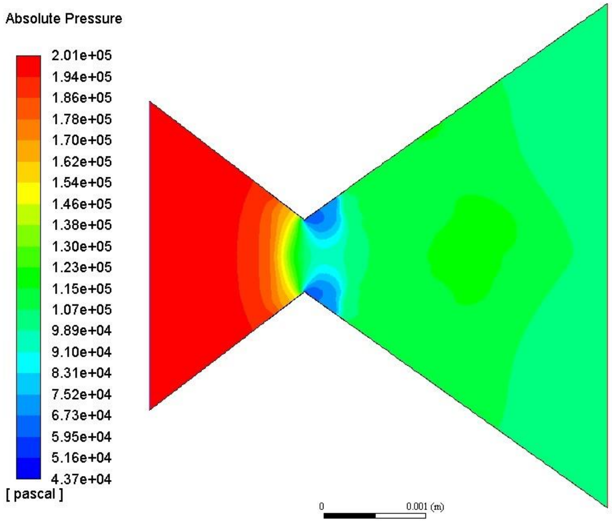


Figure: CFD of 35° Nozzle

Isotropic Etching

- Etch along each crystal face at equal rates
- Better for larger, simple geometries
- Not limited to quasi-3D shapes
- Downside: requires nitride deposition, not readily available at UA facilities

Micro-Milling

- Micron-level precision
- Able to produce rounded nozzle throats to mitigate separation
- Most feasible machining option for the simple conical nozzles

Conclusion

- Showed reasoning behind an asteroid surface hopping robot
- Benefits of sublimate-stored, cold gas thrusting system shown
- Method for designing micro-nozzles has been developed
- Fabrication methods explored based on traditional MEMS manufacturing

Thank You

- **Acknowledgement: Dr. Eniko Enikov**