Precision Hopping/Rolling Robotic Surface Probe Based on Tensegrity Structures

BEST Lab Seminar
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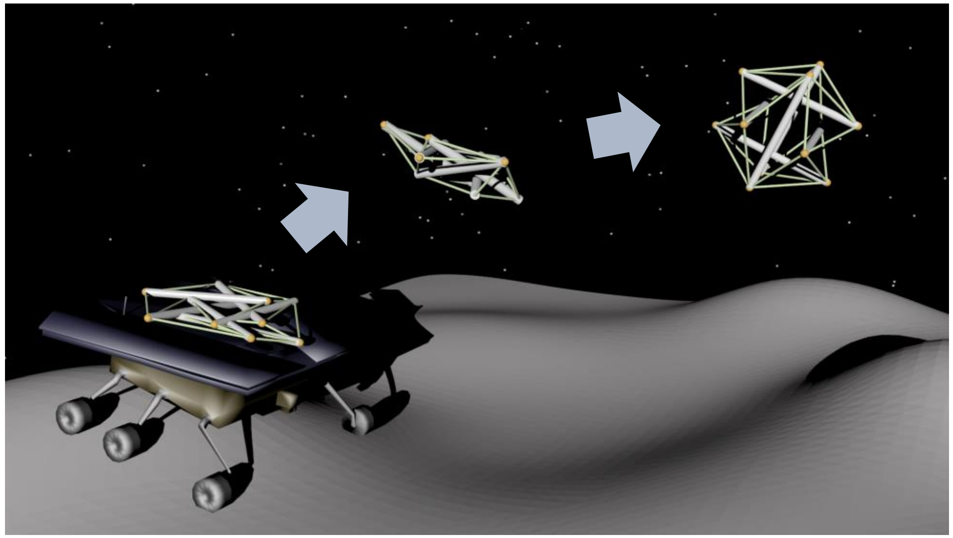
Research Objectives & Mission Requirements

- Secondary payload to larger base rover
- 10 kg probe deliver 1 kg payload 1 km away
- Only lasts for hour or two (must be quick)
- Deliver payload accurately
- Handles difficult terrain (e.g., 30% slopes)

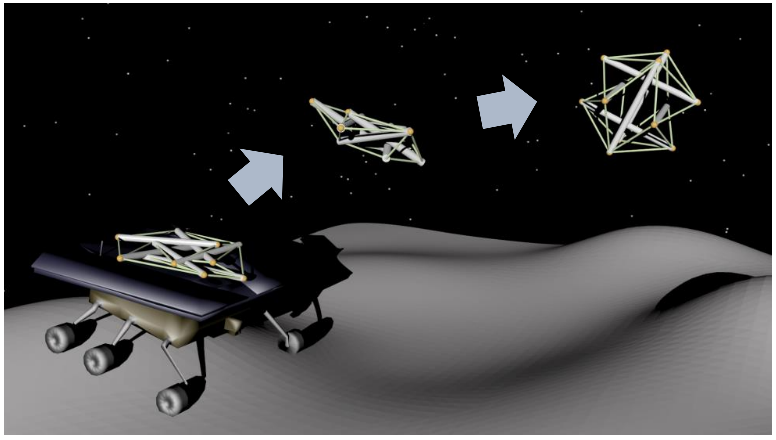
Our Tensegrity-Based Solution



- Can be packed as secondary payload
- Easy “spring” out deployment
- Can roll in difficult terrains
- Adding rocket control adds tremendous speed and ability to handle extreme terrains

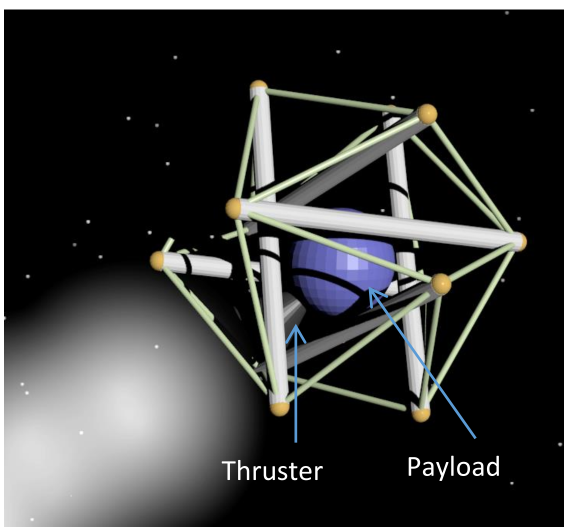
Deployment

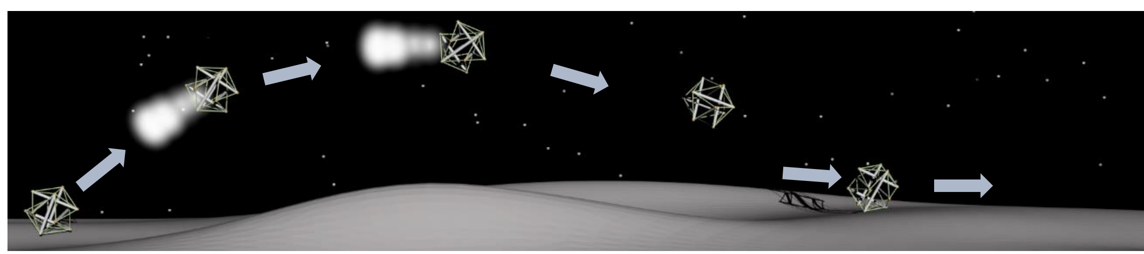
- Tensegrity structures are naturally elastic and can be packed and unpacked.
  - Takes up minimal packed volume
  - Expands naturally for deployment
    - Avoids deployment ramps
    - Avoids complex unpacking



Thruster Mobility

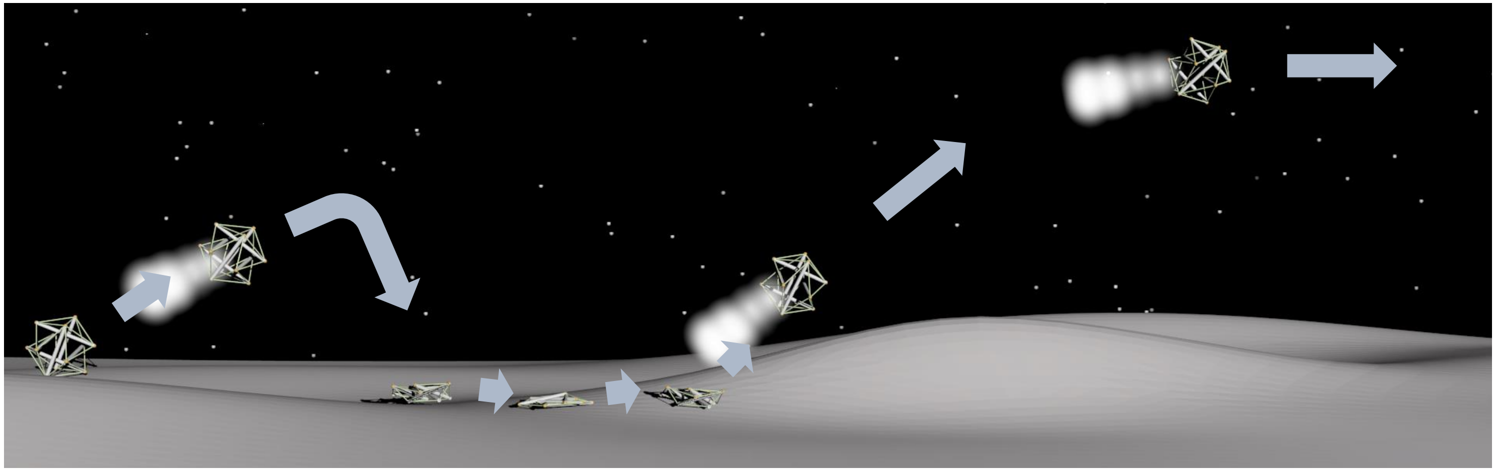
- We propose adding a thruster to a tensegrity robot
  - Enables fast travel time
  - Can go over extreme terrain
  - Can escape from inconvenient spots





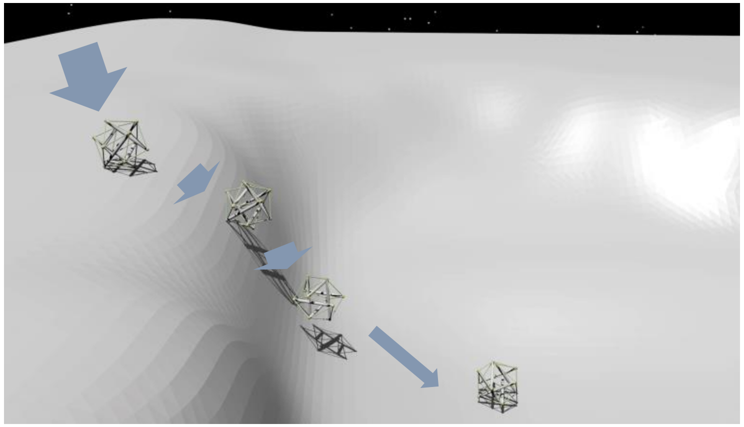
Multiple Hops

- Tensegrity structures can withstand significant impact while protecting payloads
  - Enables probe that can make multiple hops
    - Can explore surface *en route*
    - Allows for imprecise thruster navigation
    - Reduces impact forces on landing



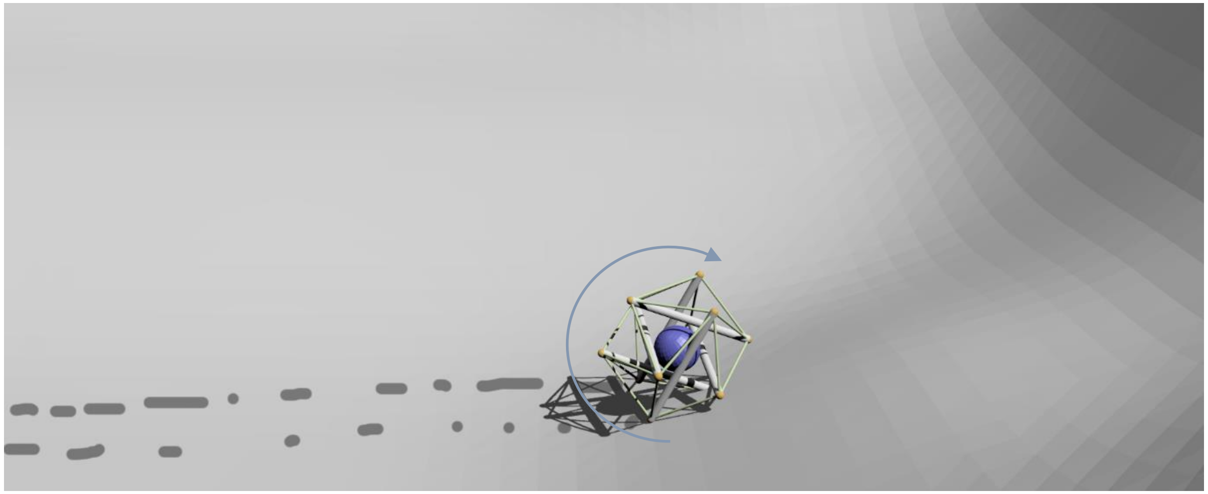
Navigating Extreme Terrains

- Tensegrity ball can safely navigate difficult terrains: roll down steep cliffs, roll off of large rocks
  - Allows for safe landing in almost any spot
  - Allows for entry to interesting points of interest
  - Allows for reliable navigation



Mobility

- Actuated tensegrity can roll
  - Allows fine-tuned delivery of payload
  - Can explore interesting local area once landed
  - Can explore interesting features such as lava tubes



Speed

Technical Approach to Enable the Mission

1. Develop thruster and hopping profile to safely deliver payload
2. Determine sensor feedback & controls needed to orient thruster and navigate effectively
3. Characterize and improve performance using simulation and hardware prototype

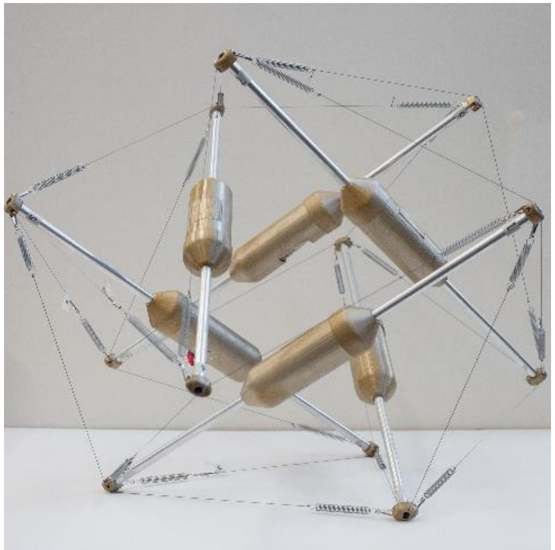
Thrusters

- Cold gas thrusters are cheap, simple and exhaust will not melt objects
- Liquid or solid rockets have far more thrust to weight ratio (lighter tank and higher Specific Impulse, I_{SP})

Developed New Physical Prototype

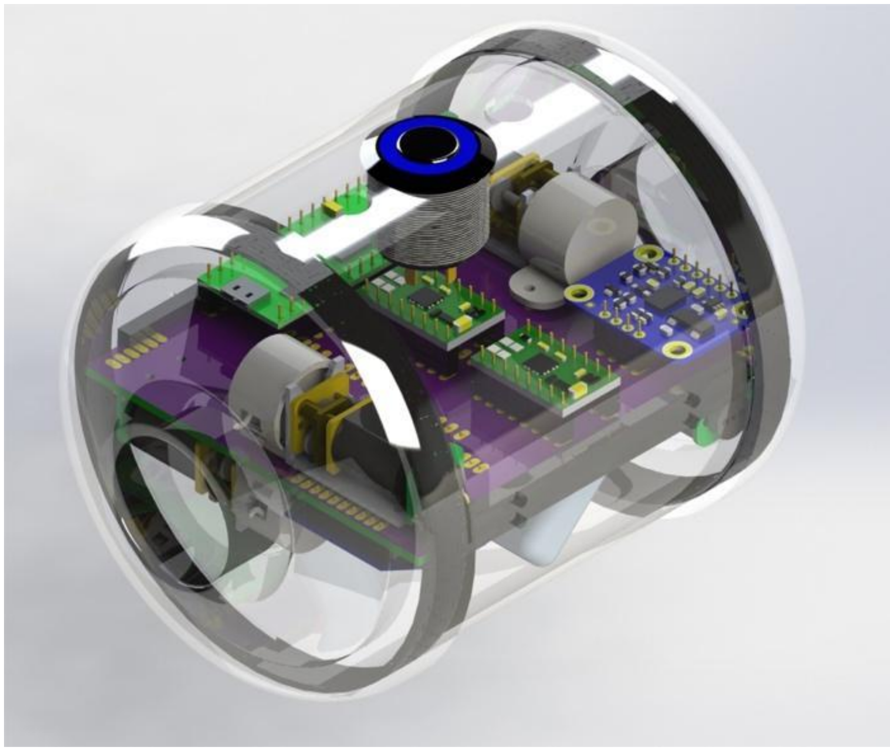
- Distributed controllers/sensors at the centers of the rods, clearing the center space of the structure for additional payloads.

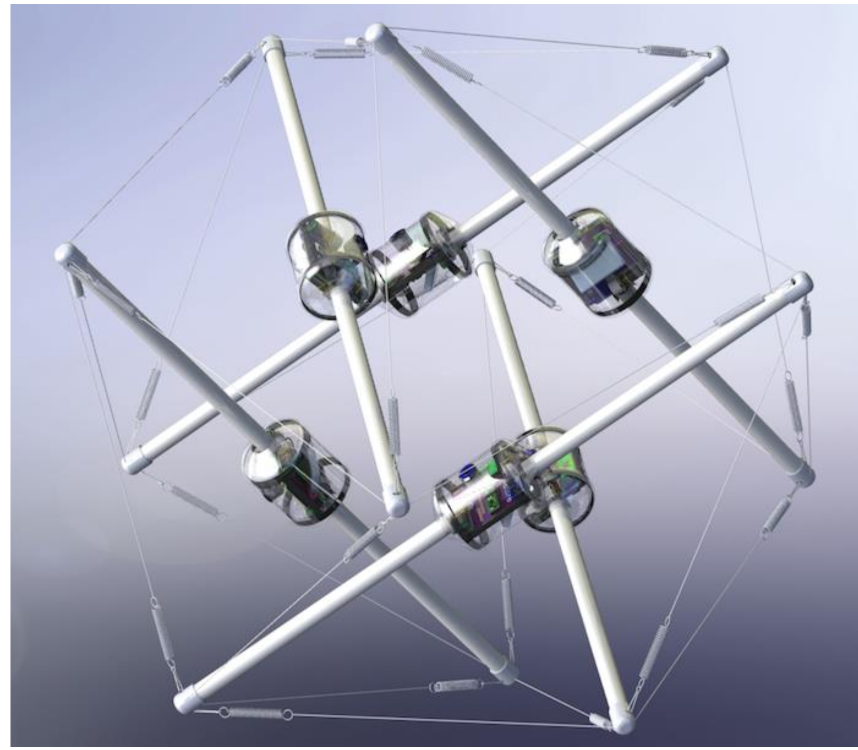
Previous Prototype



ESI Prototype TT-3

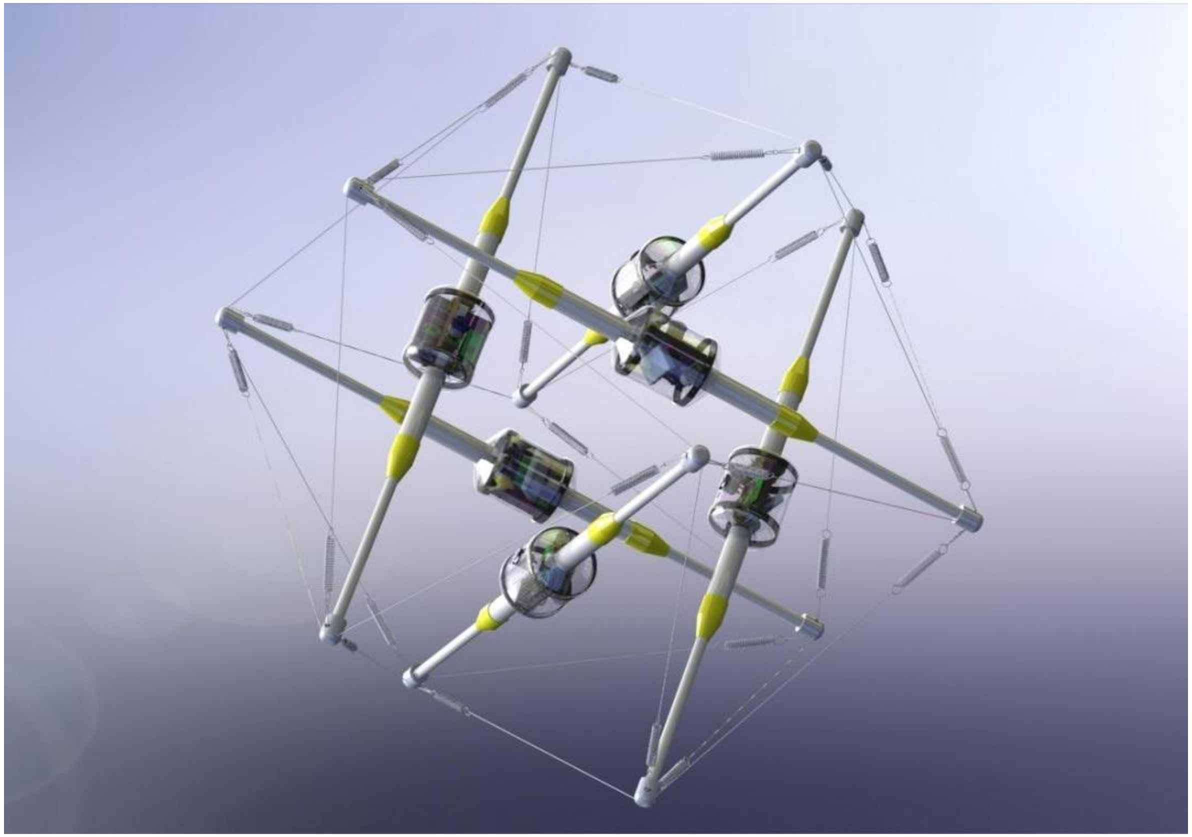
TT-4 Hardware Prototype





- Improved hardware design for better performance and reliability.
- Integrated IMUs for contact surface detection.

TT-4$_{impact}$ Hardware



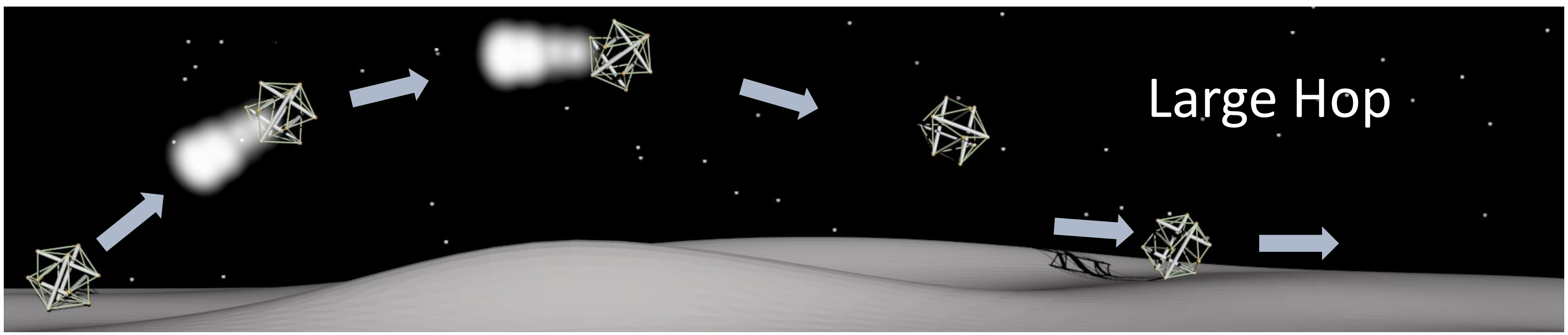
- Passive structure (1 meter rods).
- Robust modules to sustain high impact.
- IMUs for impact measurement.

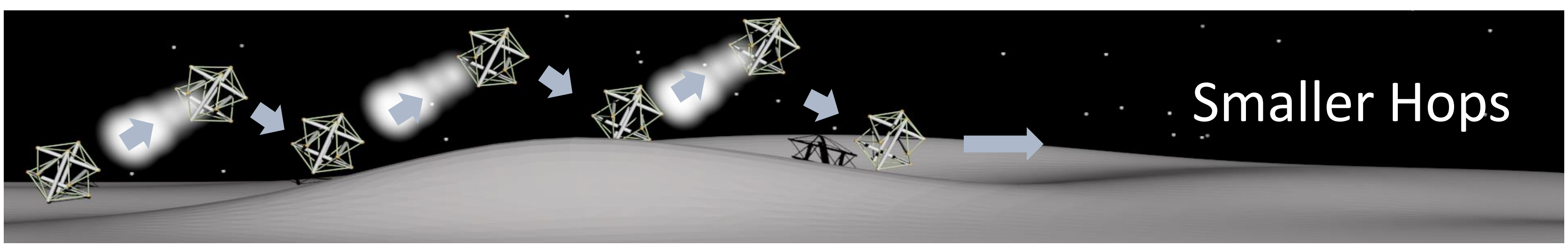
Need for Gimbaled Thruster

- In the presence of noise, an initial error in thrust direction could cause off-track lateral motion of the robot, wasting part of its propellant in moving towards an undesirable lateral direction.
- Thus the need for thrust orientation control for energy-efficient operation of the robot.

Hopping Profile Objective

- Larger hops are more efficient (less propellant)
- Smaller hops have less impact stress

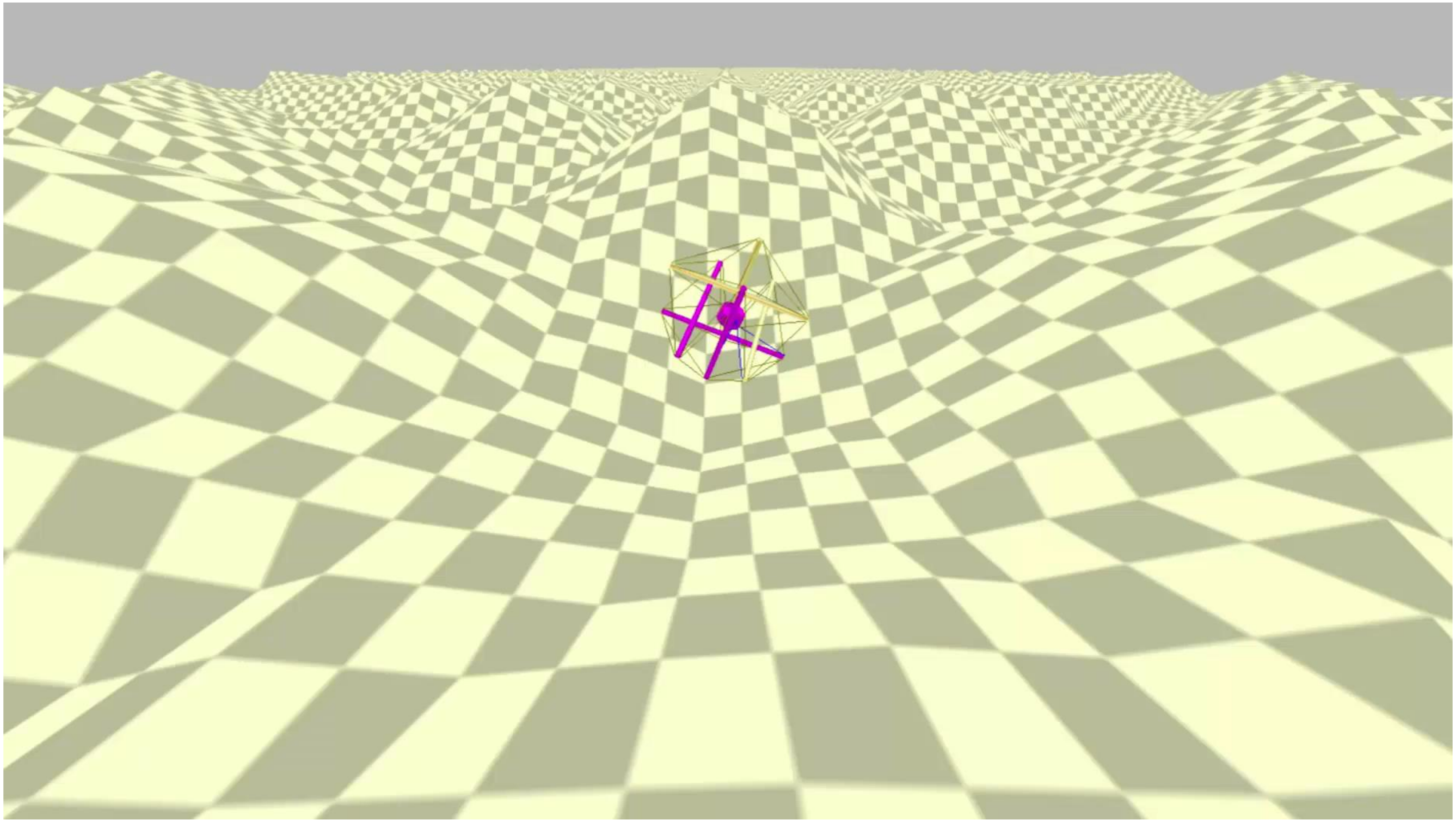




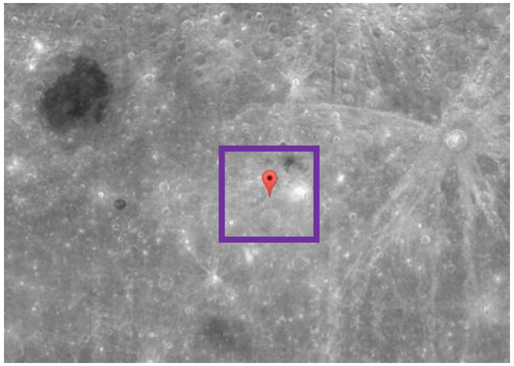
Hopping Profile Objective

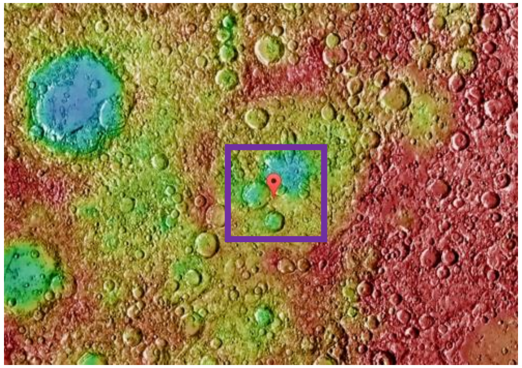
- Find energy-efficient combination of thruster and hopping profile that satisfies mission requirements:
  - Travels 1 km
  - Maximum drop of 60 m on the moon

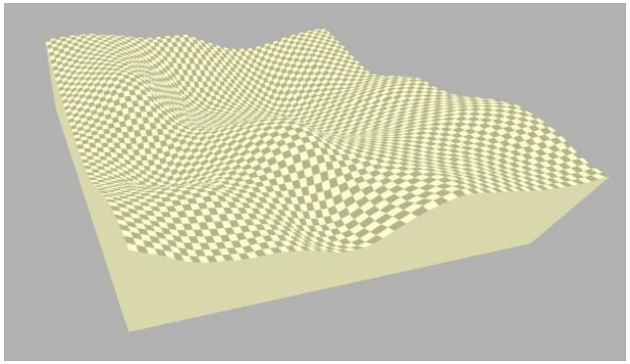
Initial Simulations in NTRT



Realistic Lunar Terrain in NTRT

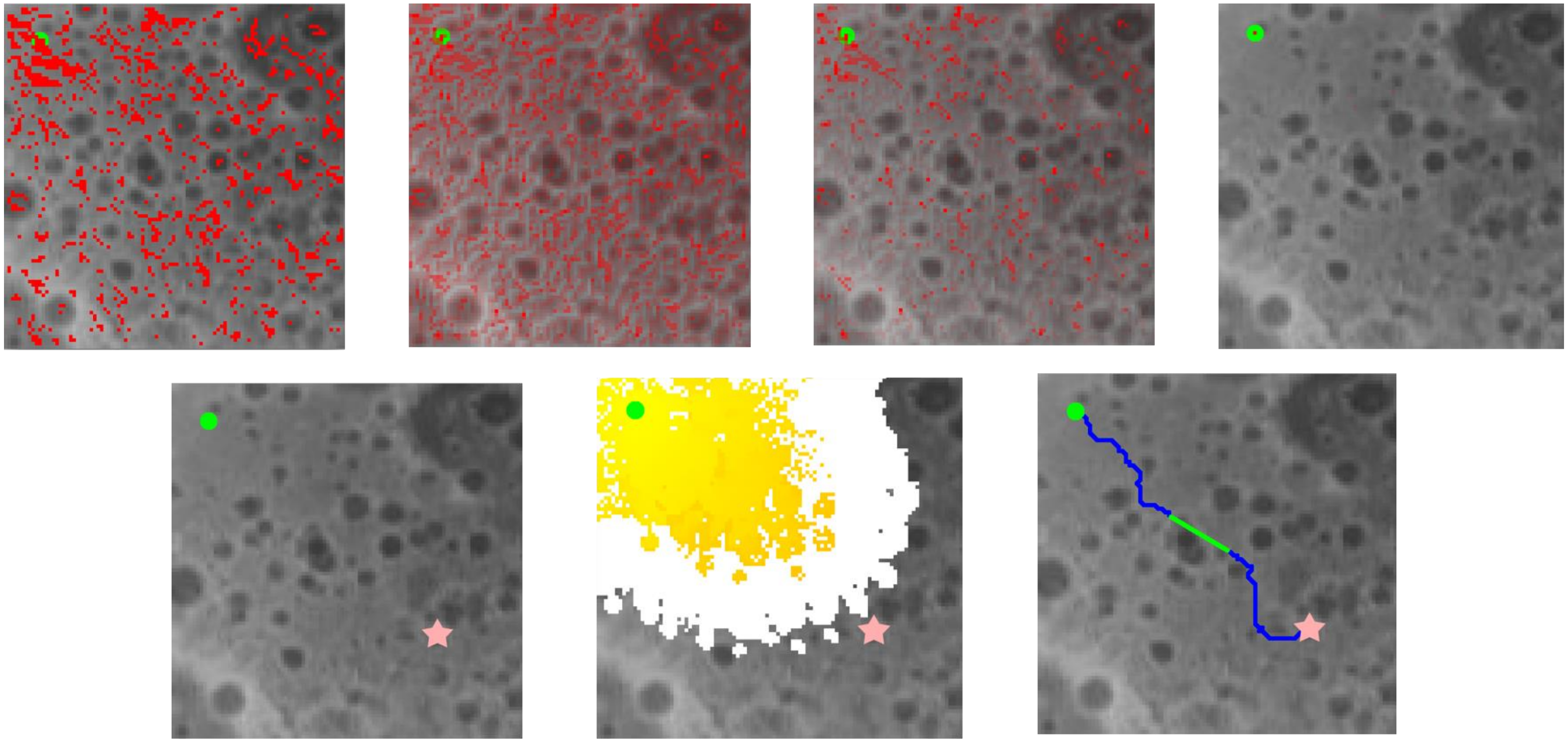






- Import realistic terrain using STL files as the ground in NTRT
- Terrain above sourced from the USGS Unified Lunar Control Network digital elevation model from 2005.
- Missions can be simulated in a more realistic setting

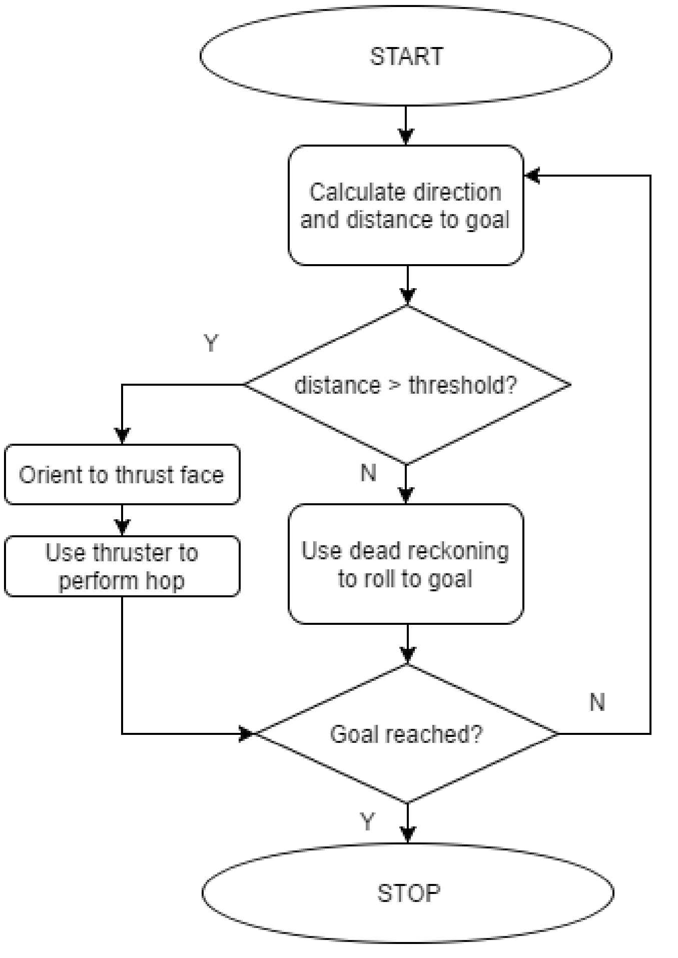
Localization and Path Planning



- Topographic map of a region of the moon was used for localization.
- A* path finding algorithm is used to plan the lowest cost path for the robot to travel

Mission Profile Overview

- Goal: Enable the robot to travel from an arbitrary starting point to an end point using a combination of rolling and hopping motions



Controls Objective

- Three sets of control events for optimizing navigation:
  - Positioning tensegrity robot for launch
  - Controlling thrust vector during launch and flight
  - Controlling robot on ground

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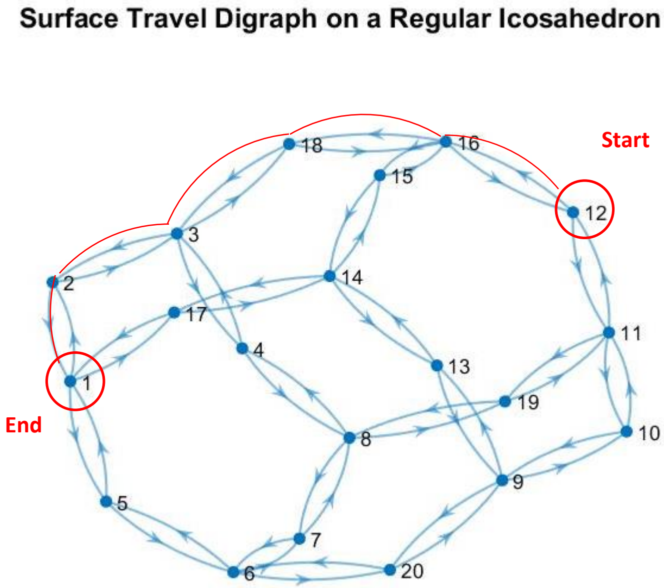
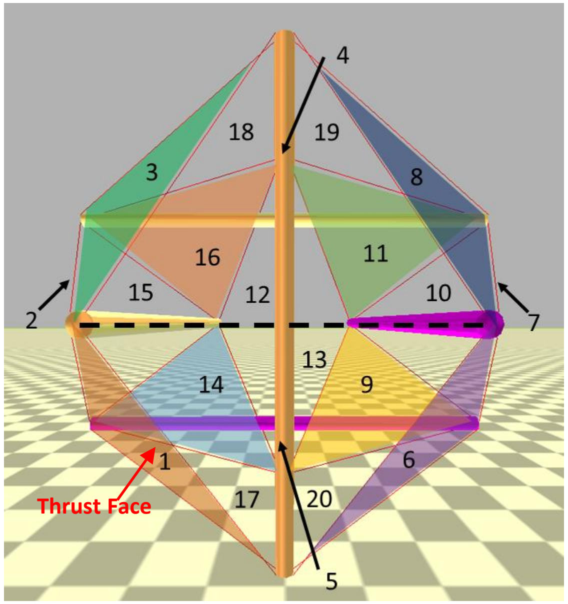
Trajectory Generation for Rolling





- Trajectory generation using Dijkstra's algorithm to search for shortest path from any start surface to the thrust surface
- Contact surface detection performed using a simulated IMU located on the payload

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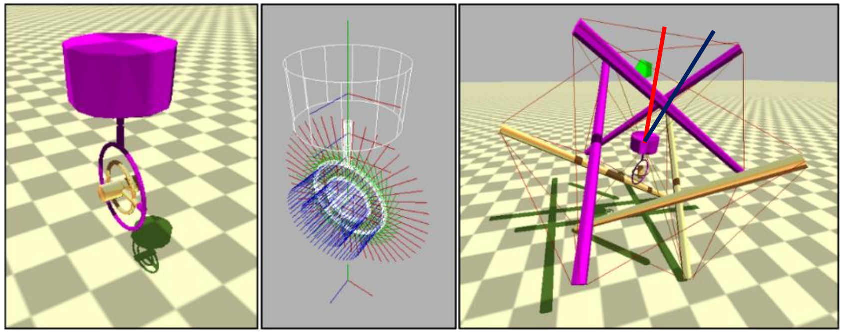
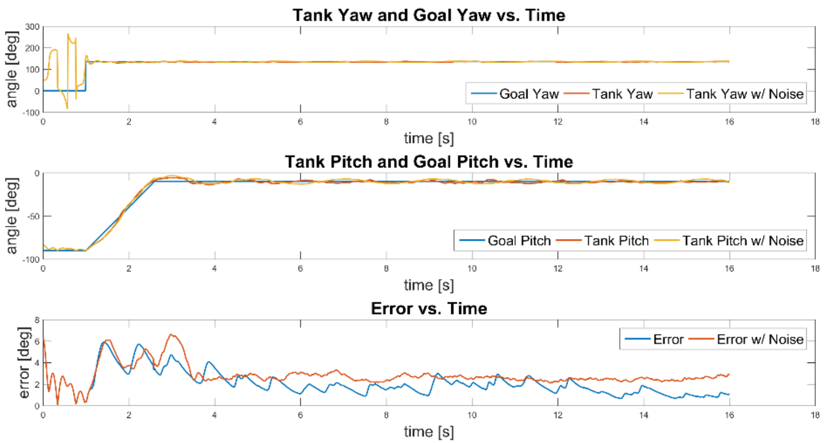
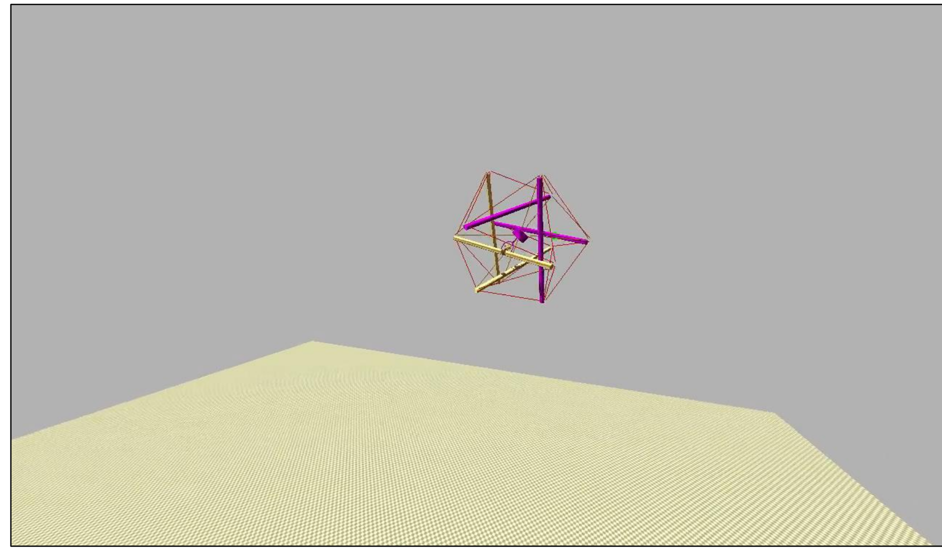
Gimbaled Nozzle System

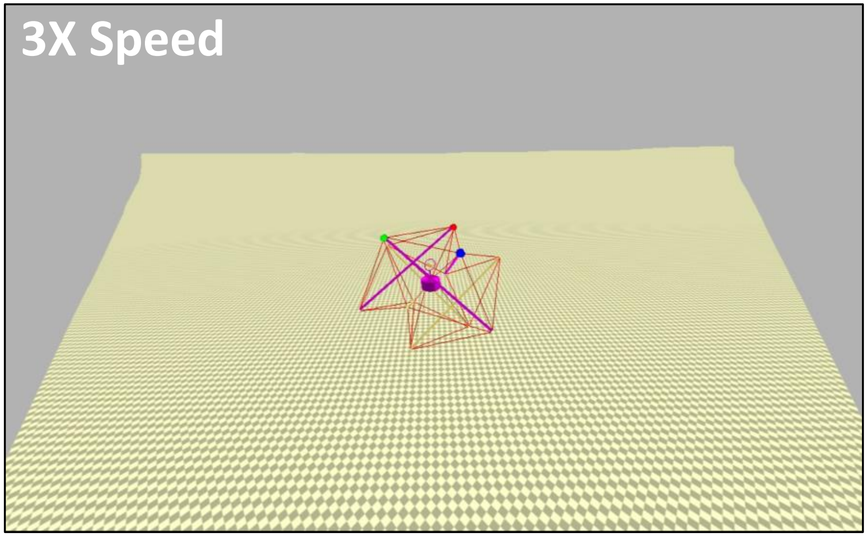


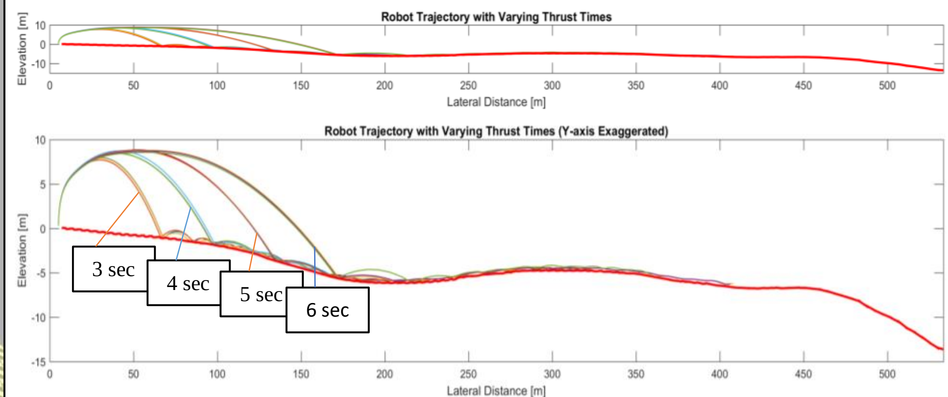




- Gimbaled nozzle thrusters allow for a moment to be generated about the center of mass
- LQR controller created using simplified lumped mass dynamic model is simulated in NTRT

Controlled Hopping Simulation





- Realistic hopping profiles on lunar terrain are simulated in NTRT
- Thruster feedback control allows for greater propellant fuel efficiency and lower maximum drop height

Controls Objective

- Three sets of control events for optimizing navigation:
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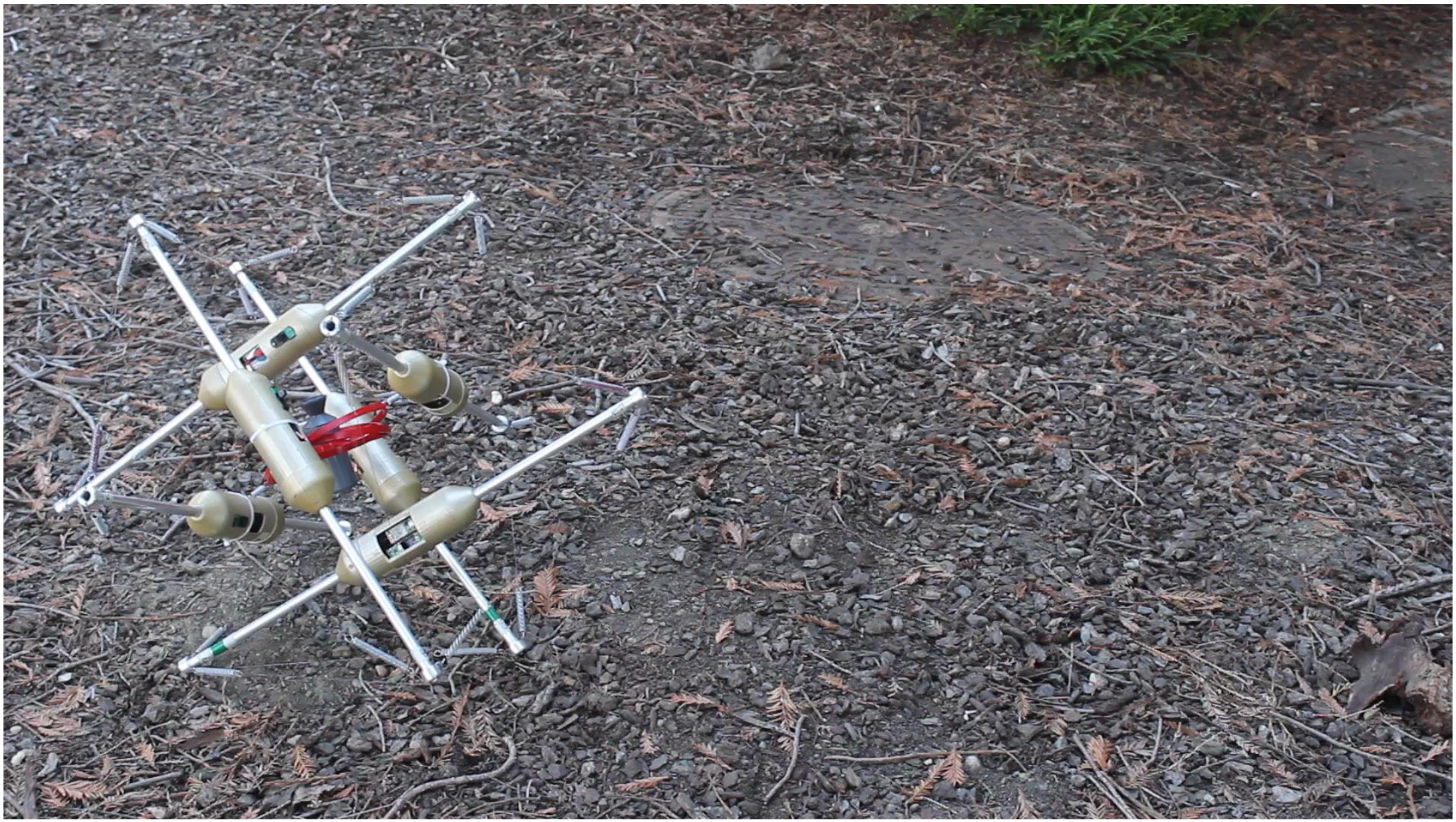
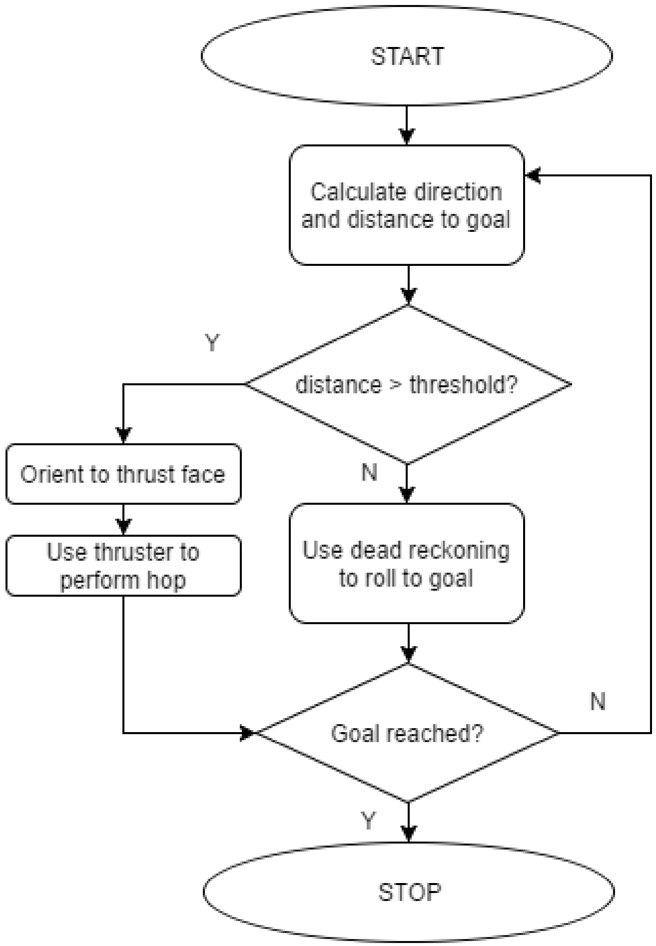
  - ➢**Controlling robot on ground**

Precision Punctuated Rolling



Full Mission Profile Simulation



Future Work

- Implement trajectory generation and closed-loop walking on TT3 hardware
- Characterize system dynamics with gimbaled-nozzle testbed
- Impact testing and payload protection