INTERNALLY ACTUATED ROVERS FOR ALL-ACCESS, LOW-GRAVITY SURFACE MOBILITY

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Outline

• Motivation
• Preliminary Design
• Prototype and Experimentation
• Computational Dynamics Model
• Motion Planning and Control
• Conclusions
• Future Work
Motivation

- Small Solar System bodies, e.g. asteroids or Martian moons, represent critical venues for space exploration
  - “Stepping stones” for human exploration
  - Potential wealth of natural resources
  - Insight into early Solar System history and planetary processes [2]
  - Comets as potential seeds for life on planets [20]
- Proper investigation of these environments requires extended surface contact at multiple locations [2]
  - E.g. characterization of regolith mechanics

*Need for precise mobility in milli- to microgravity environments*
Challenges

- Current mobility techniques are poorly suited for low gravity environments [4]-[7]
  - Wheeled rovers bound to very low speeds due to lack of traction
  - Legged systems are mechanically complex and depend on soil mechanics
  - Thrusters increase complexity and may contaminate surface
- Furthermore, any external, moving component is susceptible to dust contamination

*These challenges motivate the use of internally actuated mobility platforms*
Mobility Concept

- Rotational kinetic energy is converted to translational kinetic energy
- Torque between hub and flywheel can induce ground forces that can generate hopping or tumbling motion
Mission Structure

- Deploy one/several rovers
- Supported by orbiting mothership
- Applicable to a range of celestial small bodies
- Due hazardous environment, rovers should be quasi-expendable

**Goal:** Simple, low-cost, scalable mobility platform
Hedgehog: Spacecraft/Rover Hybrid

- Instrument port could be used for optics, sampling, etc.
- Power subsystem undefined. Solar is one option.
- Orthogonal faces simplify motion planning and control.
- Vertices provide traction in hard terrain.
- Edges distribute force to provide traction and avoid sinkage in soft terrain.
- Subsystems and payload.
- Various foot/spike designs depending on mission.
- 3 Orthogonal flywheels and DC motors.
Prototype and Test Stand

First Generation:

Second Generation:
Prototype and Test Stand

Third Generation:
Computational Dynamics Model

- Microgravity environment very difficult to physically simulate
  - XYZ-gantry crane: limited degrees of freedom
  - Drop towers/parabolic flights: limited range/time
  - Buoyancy tanks: exogenous fluid dynamics

*Need for computational modeling to aid in design and testing*

Computer model of prototype showing the hub (cube), spike tips (blue grid), and principal axes (black lines)
Demonstrations
Motion Control

- Even with perfect knowledge of state in a disturbance-free environment, motion planning and control is difficult
  - Gyroscopic effects of spinning flywheels strongly couple rotational degrees of freedom
  - Impulsive ground contact of non-spherical craft can generate unpredictable hopping vectors

*Need for simple, robust control algorithm that can be executed semi-autonomously*
Hybrid Control Algorithm

**Spin-up:**
- Apply torque to flywheels to reach desired angular velocities
- Closed-loop control to prevent undesired craft tumbling

**Coast (default):**
- No torque applied until switching conditions met
- Used while craft is settling from hop

**Flywheel Braking:**
- Apply constant braking torque until flywheels come to rest w.r.t. craft
- High torque minimizes ‘gravity loss’ torque

- ✓ On Ground
  - ✓ $\omega_{\text{flywheel}} = \omega_{\text{objective}}$
  - ✓ $\omega_{\text{flywheel}} < \omega_{\text{objective}}$
  - ✓ $\omega_{\text{flywheel}} = 0$

- ✓ $\omega_{\text{flywheel}} = \omega_{\text{objective}}$
- ✓ $\omega_{\text{craft}} = 0$
Motion Control Results

- 4 arbitrarily placed waypoints
- 500 seconds of real time
- Avg. speed of ~1.6 cm/s
- Order of magnitude faster than wheeled systems [5]
Motion Control Results

3D Trajectory of Center of Mass

- Hopping
- Tumbling
Conclusions

- Conceptual design of simple, low-cost, fault-tolerant mobility platform for low gravity environments
- Developed computational dynamics model to design and test internally-actuated, microgravity mobility platforms
- Prototype and experimentation of mobility platform in 5DoF, milli-gravity test stand
- Preliminary validation of computer model using experimental results
- Control algorithm that demonstrates precision waypoint tracking
Future Work

- Integrate prototype and test stand to test motion control algorithm
- Non-uniform terrain and gravity in simulation and experimentation
- Design of spikes/feet
- Parabolic flights
- Ground contact model that accounts for granular media
- Power subsystem
- Sensing/localization subsystem
- Optimize control algorithm for time-of-travel or power usage
Questions?
References


