Assistive Free-Flyers with Gecko-Inspired Grippers for Automated Logistics in Space

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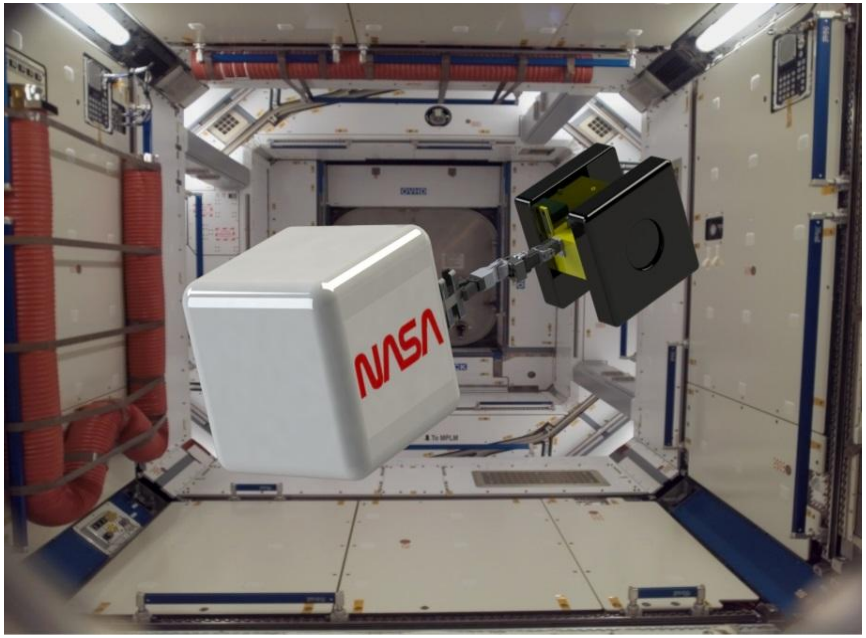
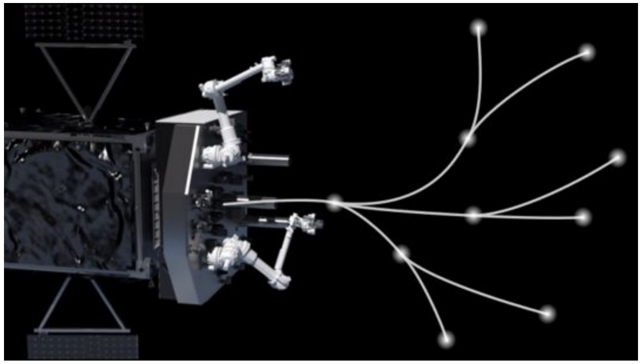


Goal

Assistive free-flyers on the ISS

- Perching for inspection/monitoring
- Tool retrieval, return
- Unpacking cargo



Restore-L Servicer

Complex in-space manipulation and proximity operations tasks

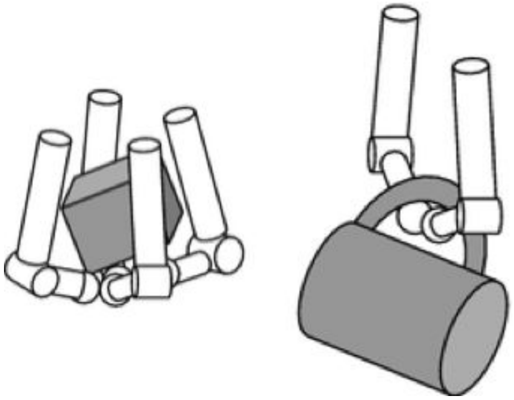
- On-orbit servicing, assembly
- Debris removal
- EVA assistance

AERCam Sprint

Current State of the Art

Traditional spacecraft docking and robotic manipulators

- Require complex time-consuming procedures for maneuvering, alignment, docking
- Often need specialized docking or grasping features
- Difficult to capture moving, spinning objects



ISS Canadarm during resupply

Capturing the Wester 6 satellite

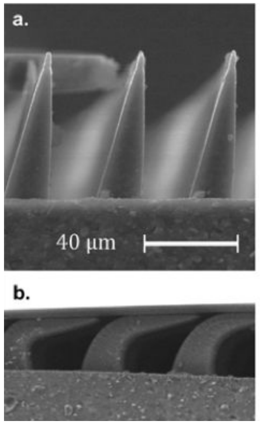
Adhesive Grippers

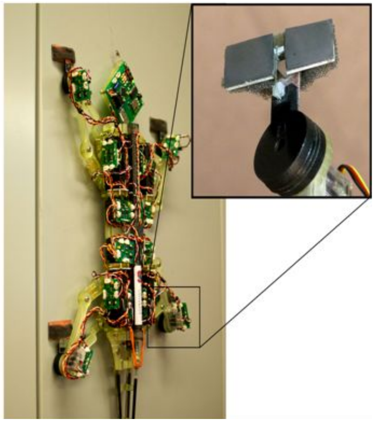
Key idea:

- Directionally-aligned fibers create van der Waals adhesion under shear stress
- Two opposing pads form a surface gripper

Advantages:

- **Versatile:** Able to grasp without enclosing
- **Gentle:** Very low attach/detach forces
- **Dynamic:** Able to capture moving, spinning objects
- **Ease of use:** Motion planning is greatly simplified



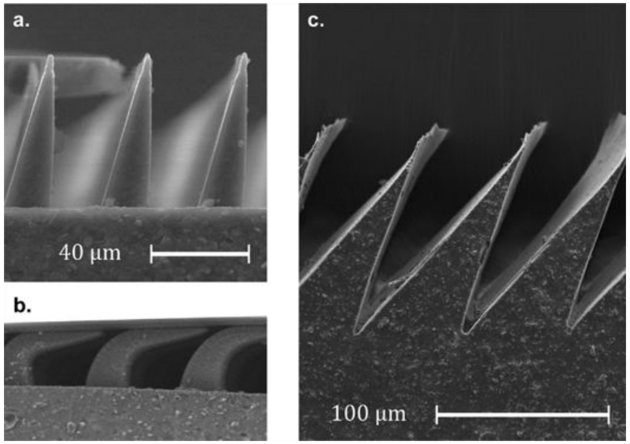


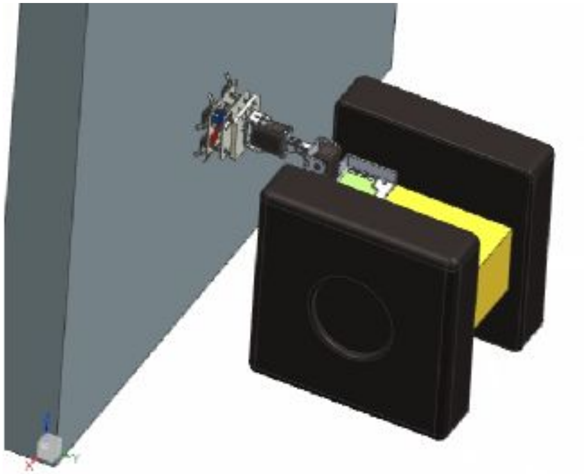
Research Goal:

- Integrate dry adhesion-based grasping for free-flying robots to enable them to manipulate payloads and perch on walls in a microgravity space environment

Key Investigation Objectives:

- Integrate a flat-surface gecko-inspired adhesive gripper with the Astrobee robot on the ISS
- Test the capabilities of the gripper for manual and autonomous perching of the robot onto ISS walls and other flat surfaces





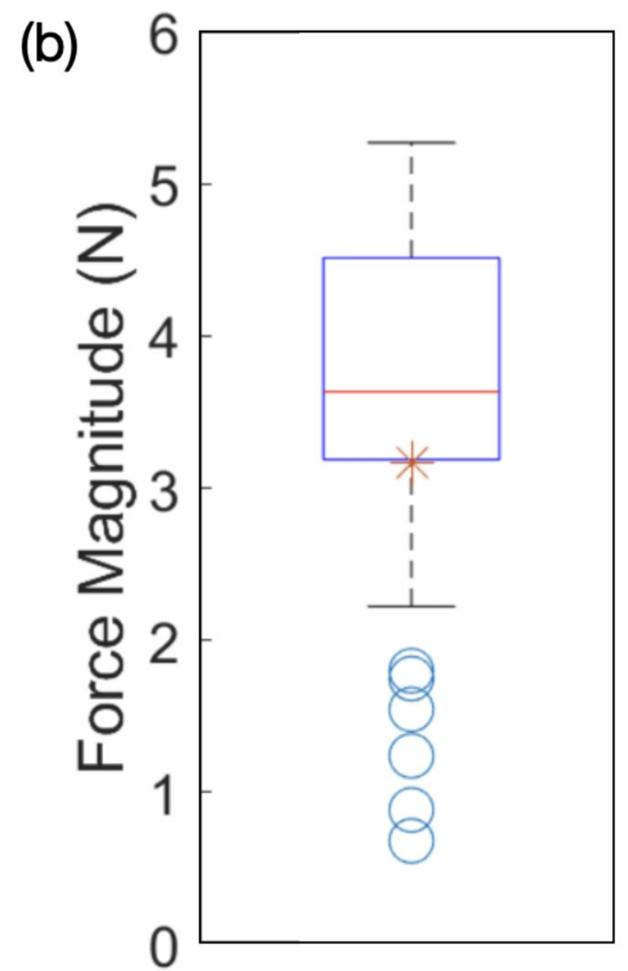
ISS Flight Experiment

Session 1 (03/05/2021):

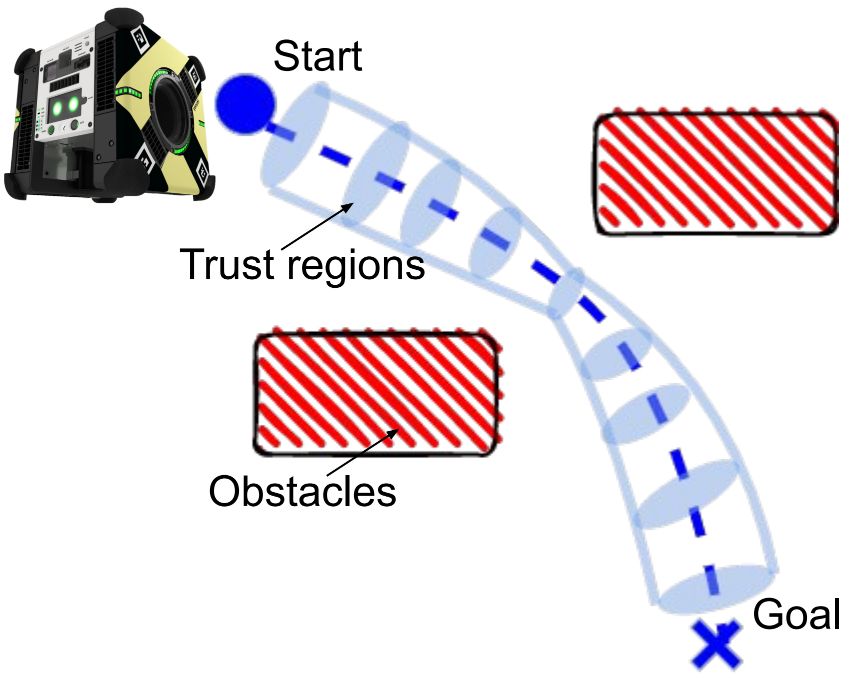
- Unit01 was unpacked and installed.
- Manual adhesive testing and visual inspection showed that there were some damage done to the surface of the adhesive tiles.
- Perching location was selected.

Session 2 (03/11/2021):

- Swapped Unit01 with Unit02 for further testing.
- With astronaut guidance, Astrobee was able to perch on the ISS and pivot around the wrist joint.



ISS Flight Experiment



GuSTO (Guaranteed Sequential Trajectory Optimization) via Sequential Convex Programming

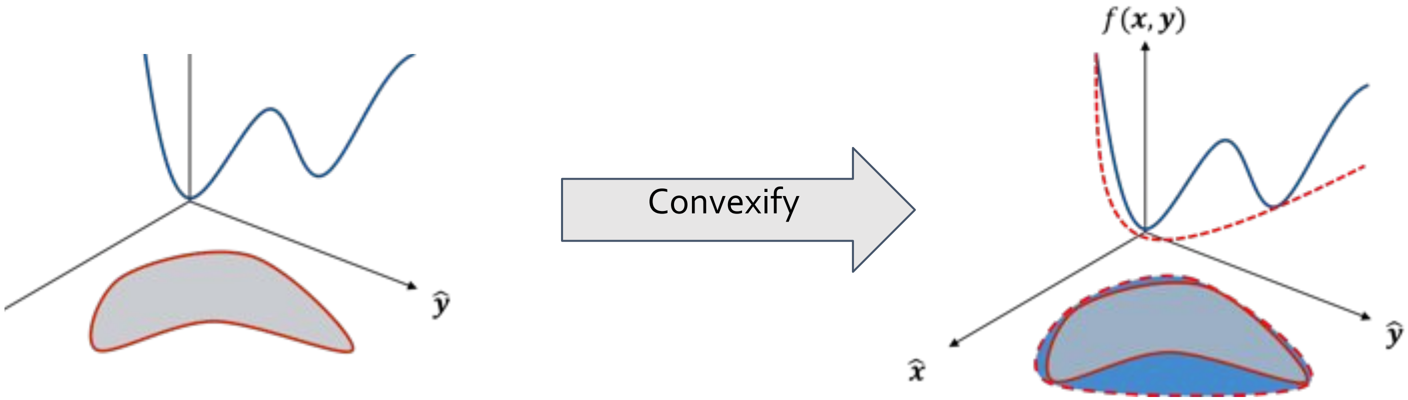
Bonalli et al. ICRA, 2019

GuSTO was designed with Astrobee in mind

- **Real-time optimization** by convexifying problem and using convex solvers
- **Theoretically proven guarantees** on optimality of final trajectory
- **Enforce safety** using trust regions and keep-out zones

Trajectory Optimization

- Sequential convex programming (SCP) has gained traction for trajectory optimization
  - Iterative method for solving non-convex optimization problems



- GuSTO is a new algorithmic framework
  - Provides convergence guarantees for dynamic feasibility, guides user for different initialization strategies
  - Handles a broad class of problems using an optimal control approach: free final-time, goal region constraints on manifolds

[Bonalli, Cauligi, Bylard, and Pavone, ICRA 2019]

Sequential Convex Optimization

- Implementation in Astrobee FSW on-going
  - https://github.com/acauligi/astrobee
- OSQP for solving QP at each iteration
  - State of the art ADMM based QP solver
  - Apache 2.0 license
- osqp-eigen interface for OSQP
  - https://github.com/robotology/osqp-eigen
  - GNU LGPL license

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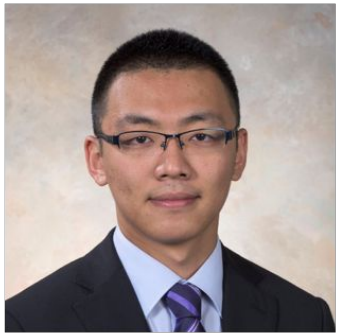

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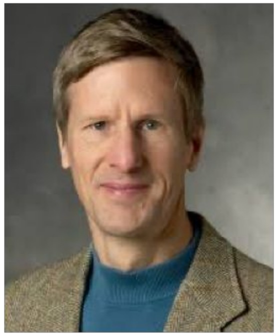

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Publications

- A. Cauligi, T. Chen, S. A. Suresh, M. Dille, R. G. Ruiz, A. M. Vargas, M. Pavone, and M. R. Cutkosky, "Design and Development of a Gecko-Adhesive Gripper for the Astrobee Free-Flying Robot," in *Int. Symp. on Artificial Intelligence, Robotics and Automation in Space*, Pasadena, California, 2020.
- R. Bonalli, A. Bylard, A. Cauligi, T. Lew, and M. Pavone, "Trajectory Optimization on Manifolds: A Theoretically-Guaranteed Embedded Sequential Convex Programming Approach," in *Robotics: Science and Systems*, 2019.
- R. Bonalli, A. Cauligi, A. Bylard, and M. Pavone, "Sequential Convex Programming: Generalized Method and Theoretical Convergence Guarantees for Trajectory Optimization," in *Proc. IEEE Conf. on Robotics and Automation*, 2019.
- P. Glick, S.A. Suresh, D. Ruffatto, M.R. Cutkosky, M.T. Tolley, A. Parness, "A soft robotic gripper with gecko-like adhesives" *IEEE RA-Letters & ICRA 2018*.
- J-P Roberge, W. Ruotolo, V. Duchaine, and M.R. Cutkosky, "Improving Industrial Grippers with Adhesion-Controlled Friction," *IEEE RA-Letters & ICRA 2018*.
- A. Cauligi, A. Bylard, R. Bonalli, and M. Pavone, "A Sequential Convex Programming Approach for Free-Flying Robot Trajectory Generation," in *Int. Symp. On Artificial Intelligence, Robotics and Automation in Space*, 2018.
- A. Bylard, R. MacPherson, B. Hockman, M. R. Cutkosky, and M. Pavone, "Robust capture and deorbit of rocket body debris using controllable dry adhesion." *IEEE Aerospace Conference, March 2017.*
- H. Jiang, E. W. Hawkes, C. Fuller, M. A. Estrada, S. A. Suresh, N. Abcouwer, A. K. Han, S. Wang, C. J. Ploch, A. Parness, and M. R. Cutkosky, "A Robotic Device using Gecko-Inspired Adhesives can Grasp and Manipulate Large Objects in Microgravity," in *Science Robotics* (AAAS), July 2017.
- R. MacPherson, B. Hockman, A. Bylard, M. A. Estrada, M. R. Cutkosky, and M. Pavone, "Trajectory Optimization for Dynamic Grasping in Space using Adhesive Grippers," *Field and Service Robotics*, November 2017.
- M. A. Estrada, H. Jiang, B. Noll, E. W. Hawkes, M. Pavone, and M. R. Cutkosky, "Force and moment constraints of a curved surface gripper and wrist for assistive free flyers," in *Proc. IEEE Conf. on Robotics and Automation*, 2017.
- M. A. Estrada, B. Hockman, A. Bylard, E. W. Hawkes, M. R. Cutkosky, and M. Pavone, "Free-flyer acquisition of spinning objects with gecko-inspired adhesives," in *Proc. IEEE Conf. on Robotics and Automation*, 2016.