Spacecraft Robotics + Control LABORATORY

Ten years of Spacecraft Proximity Operations and Formation Flying at Carleton University

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CASI ASTRO
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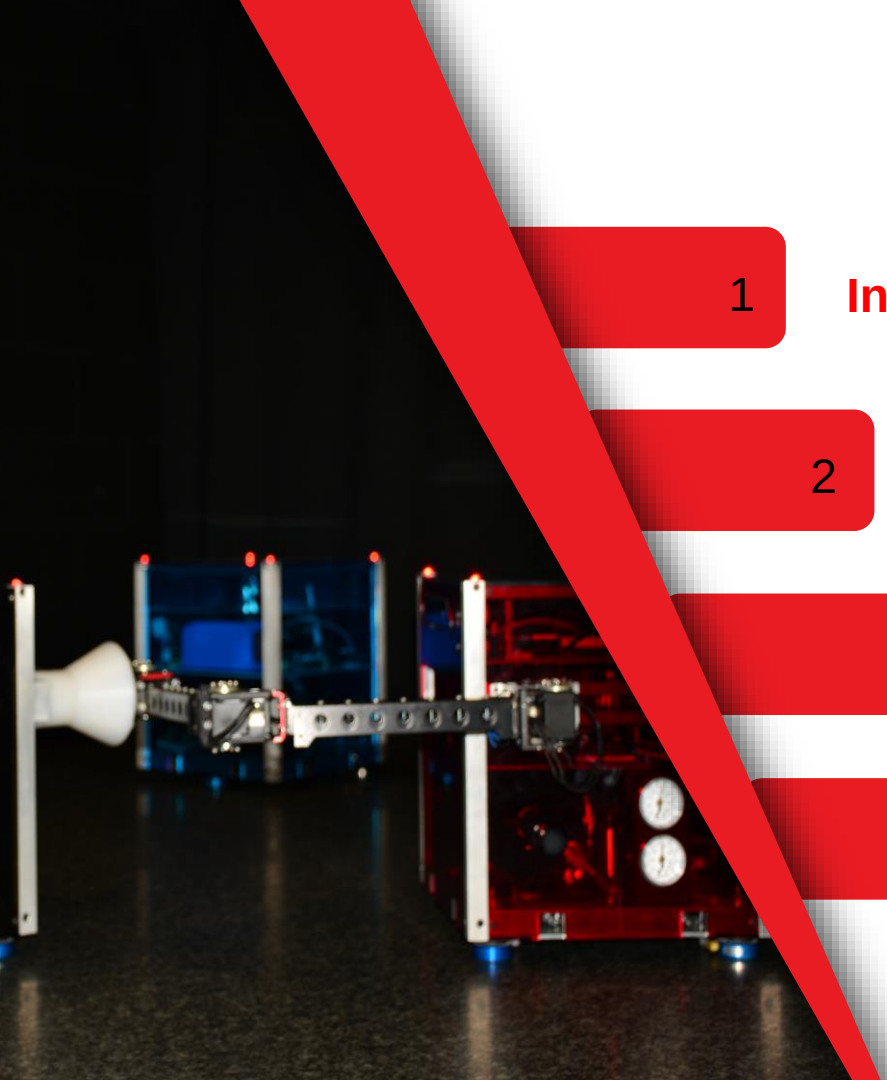
Spacecraft Robotics + Control LABORATORY

Organization of Presentation

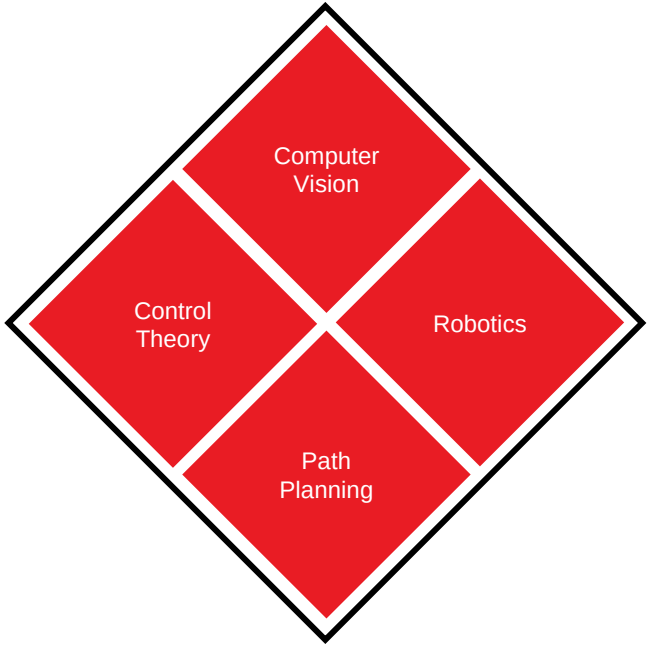
1. Introduction
2. SPOT Overview
3. 10 Years of SPOT
4. Research Highlights



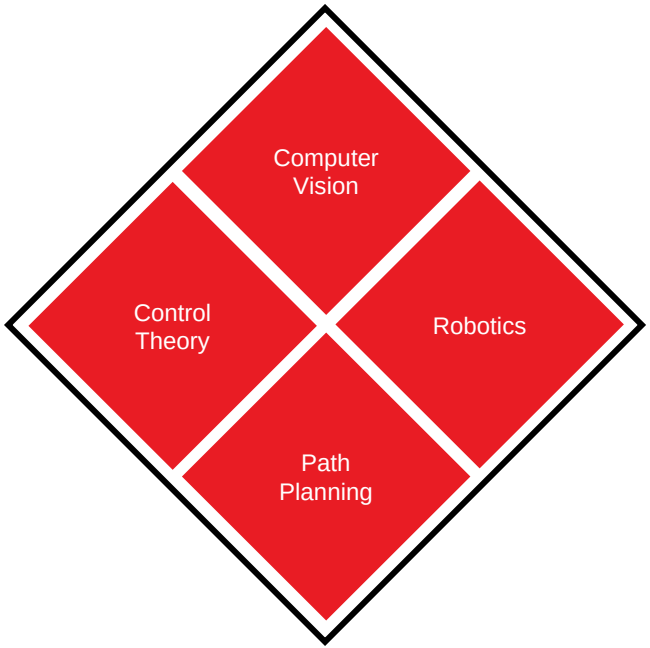
Spacecraft Robotics

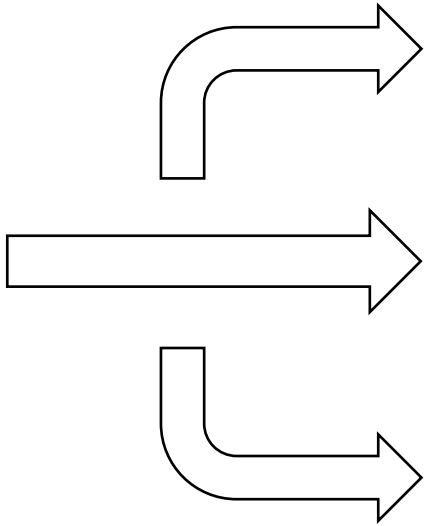
Proximity Operations Enabling Technologies

- Computer Vision
  - Motion Estimation
- Path Planning
  - Collision Avoidance
- Control Theory
  - Motion Matching
- Robotics
  - Capture and Manipulation
  - Docking Mechanism
- Autonomous Onboard Operations



Spacecraft Robotics





ON-ORBIT SERVICING

IN-SPACE ASSEMBLY

SPACE DEBRIS REMOVAL

Spacecraft Robotics

Experimental Validation Technologies

Orbital Demonstrations

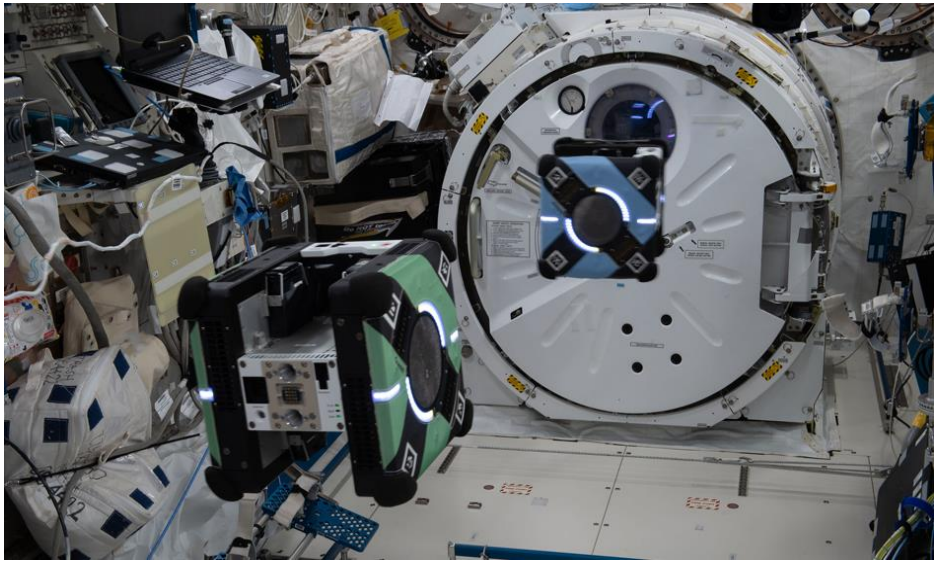
Orbital Express (Image: DARPA)

Spacecraft Robotics

Experimental Validation Technologies

Orbital Demonstrations

Microgravity Testing Facilities



Astrobee (Image: NASA)

Spacecraft Robotics

Experimental Validation Technologies

Orbital Demonstrations

Microgravity Testing Facilities

Spacecraft Kinematics Simulators

OOS-SIM (Image: DLR)

Spacecraft Robotics

Experimental Validation Technologies

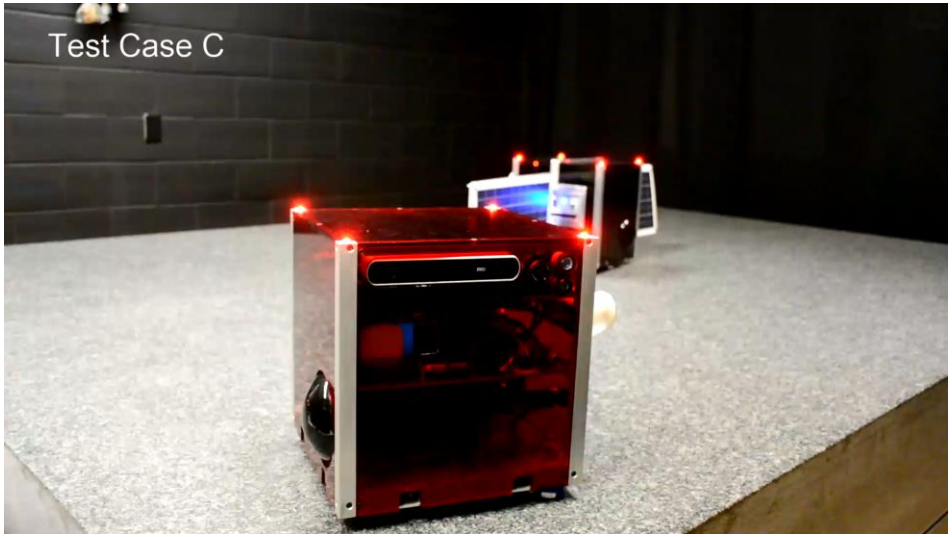
Orbital Demonstrations

Microgravity Testing Facilities

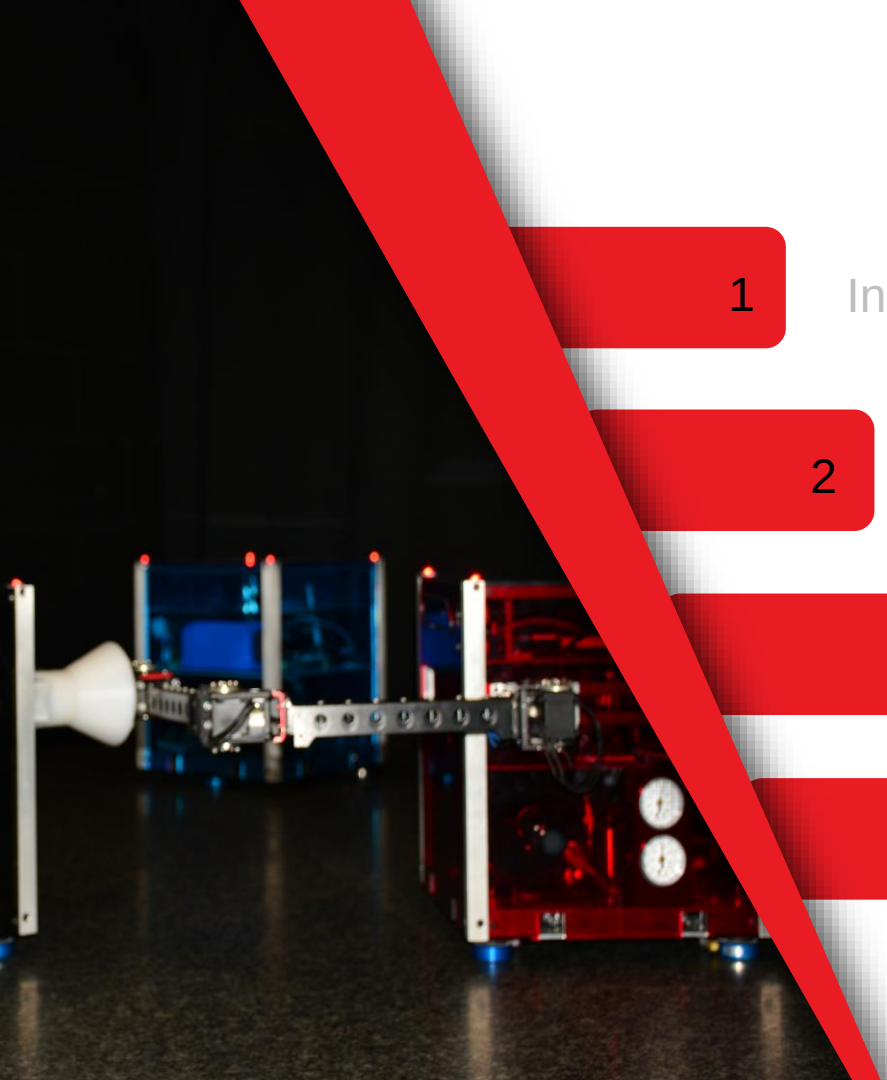
Spacecraft Kinematics Simulators

Spacecraft Dynamics Simulators

- State-of-the-art planar air bearing facility at Carleton University
- Platforms move with three degrees of "frictionless" freedom—simulating a microgravity environment
- Execute real-time, autonomous GNC system

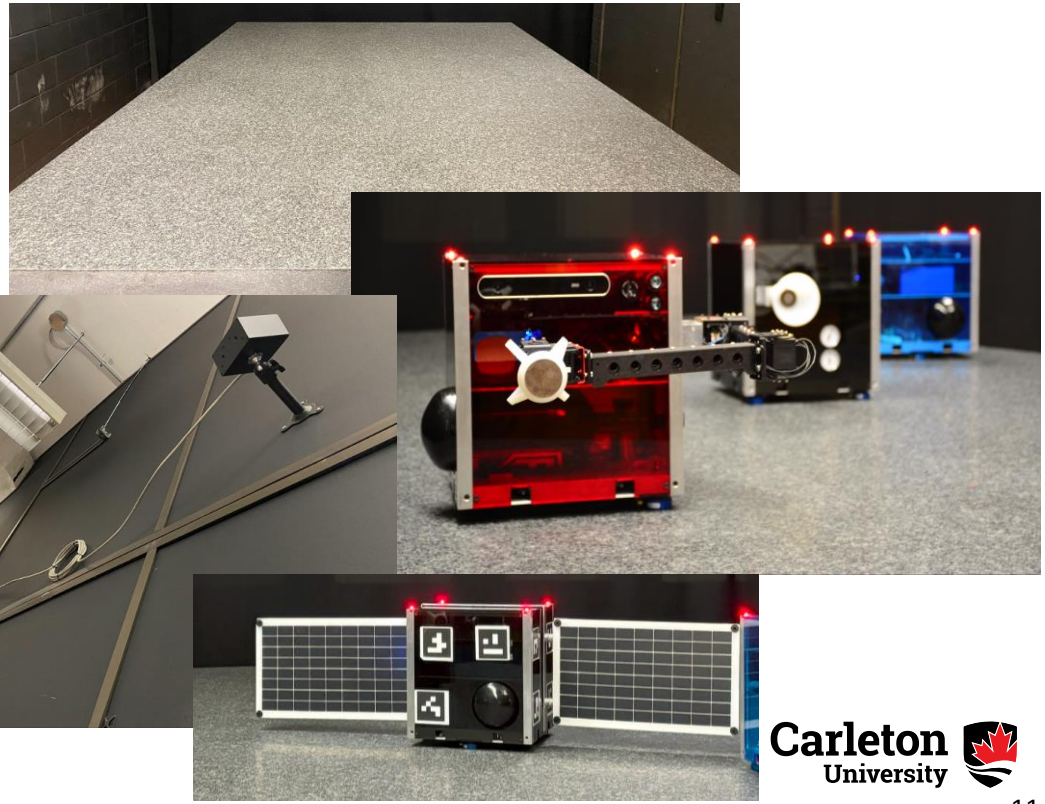


SRCL, "Experimentally Validating Model Predictive Control for Spacecraft Prox Ops with Collision Avoidance", Available: https://www.youtube.com/watch?v=jjdNB43zdak



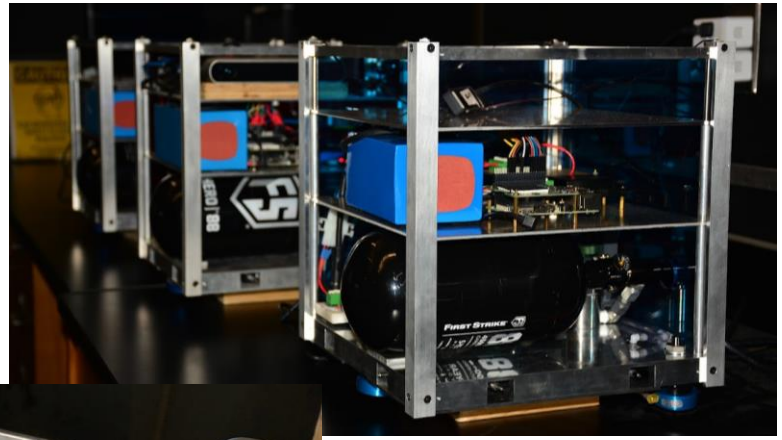
The SPOT Facility

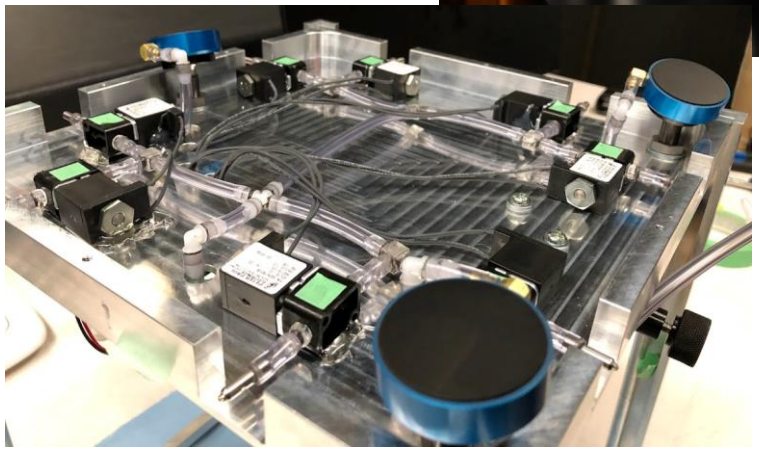
- Spacecraft Proximity Operations Testbed
- Consists of:
  - 3.5 m x 2.4 m granite table
  - 3 spacecraft platforms
  - PhaseSpace motion capture system
- Accessories:
  - Robotic manipulator
  - Docking hardware
  - Vision sensor suite
  - Solar panels



The SPOT Facility

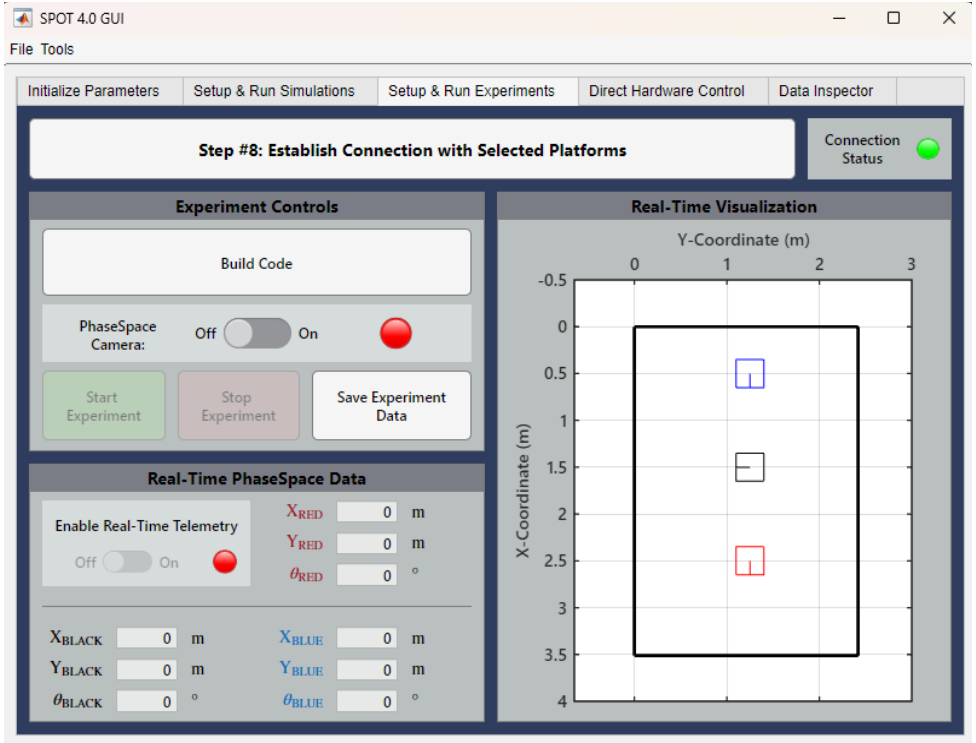
- Spacecraft Proximity Operations Testbed
- Platforms consist of:
  - Onboard computer
    Execution of autonomous GNC system
  - Compressed air tank
  - 3 planar air bearings
    Flotation
  - 8 thrusters
    3DOF control authority

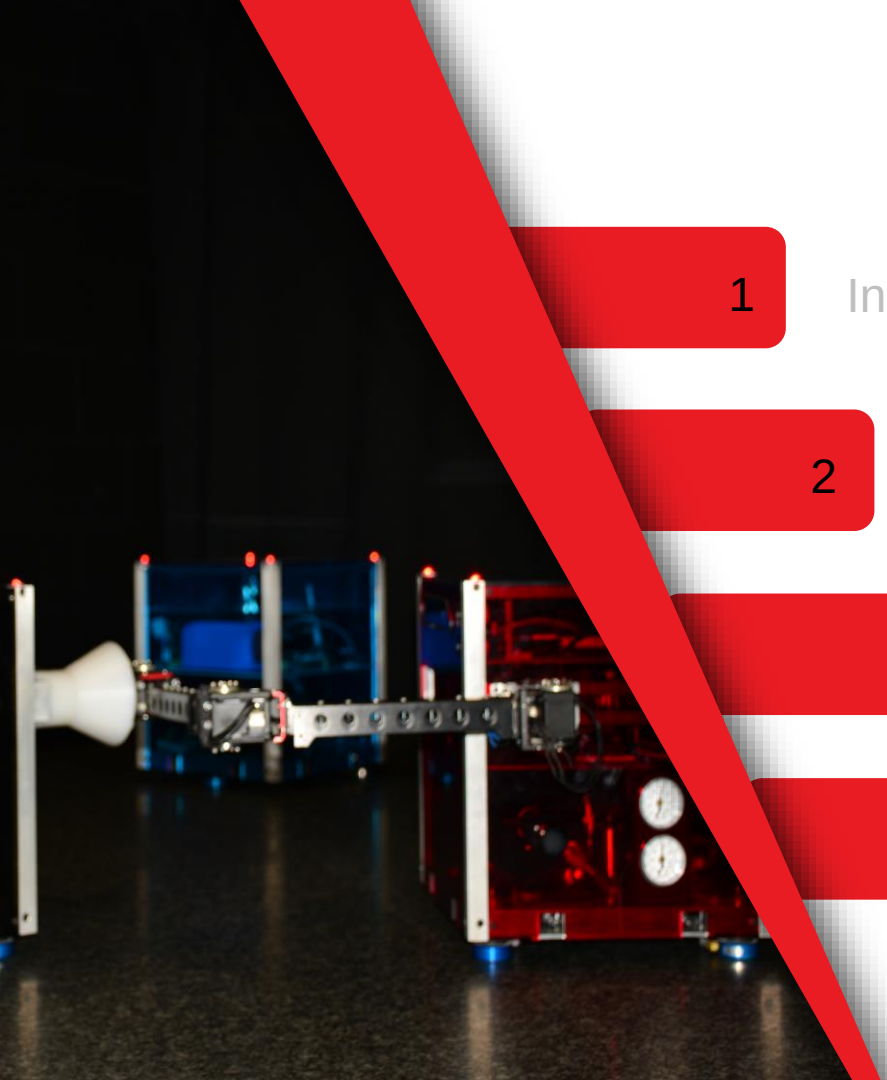




The SPOT Facility

- Spacecraft Proximity Operations Testbed
- Custom SPOT software in MATLAB/Simulink:
  - Run simulations
    - Expected behaviour of experiment
  - Direct hardware control
  - Build code onboard computer
    - Generates executable on onboard computer
  - Run experiments
    - Real-time visualization of platforms
    - Interface with PhaseSpace cameras
    - Save experiment data to ground computer





10 Years of SPOT

10 Years of SPOT

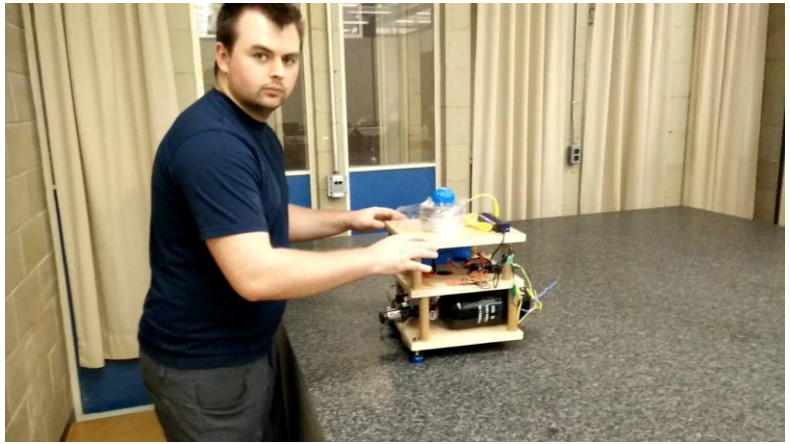
✓ Acquired a large (3.5 m x 2.4 m), flat, and smooth granite table

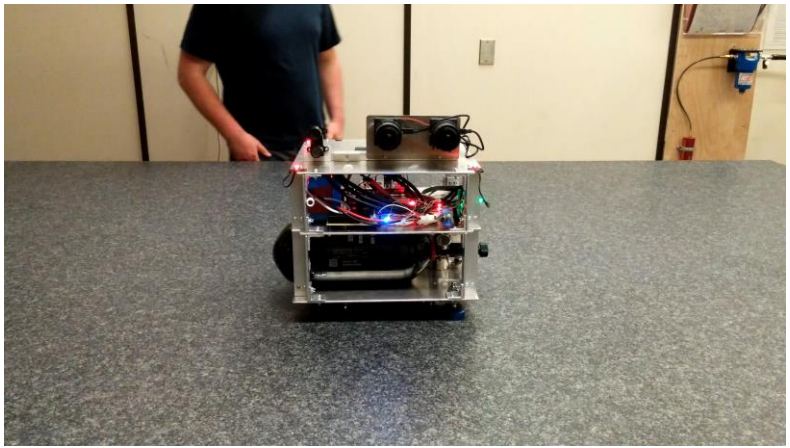
2014

10 Years of SPOT

✓ Built and tested prototypes for the spacecraft platforms

2014 2015





10 Years of SPOT

✓ Final spacecraft platform versions—the chaser (RED) and target (BLACK)

2014 2015 2016

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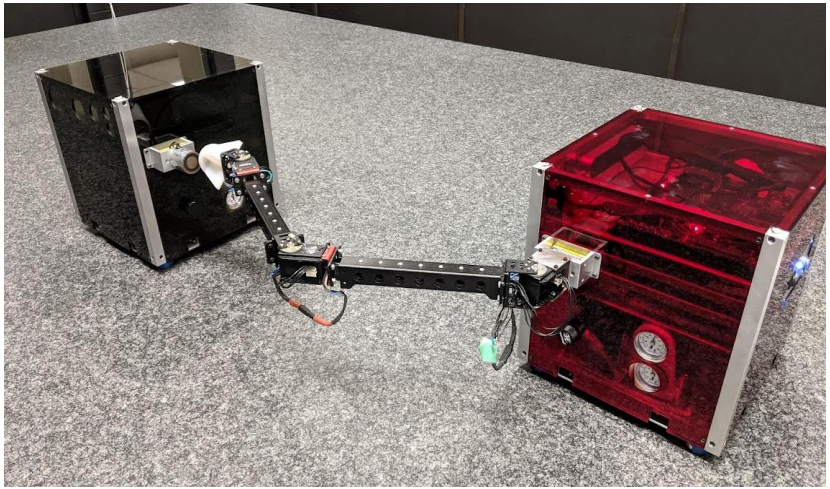
10 Years of SPOT

✓ Integrated a robotic manipulator arm onto the chaser platform

2014 2015 2016 2017

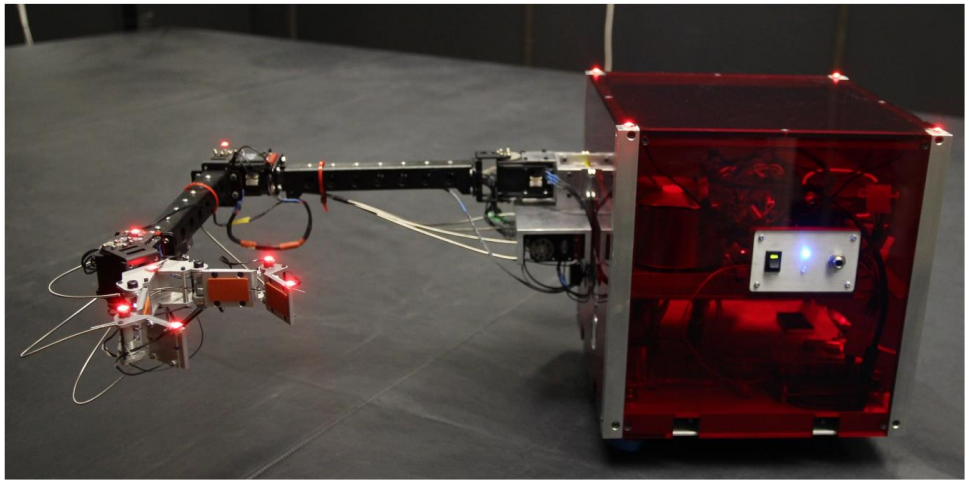


Crain, A., and Ulrich, S., "Experimental Validation of Pseudospectral-based Optimal Trajectory Planning for Free-Floating Robots," *Journal of Guidance, Control, and Dynamics*, Vol. 42, No. 8, 2019, pp. 1726-1742.

10 Years of SPOT

✓ Tested a tendon-driver manipulator

2014 2015 2016 2017 2018

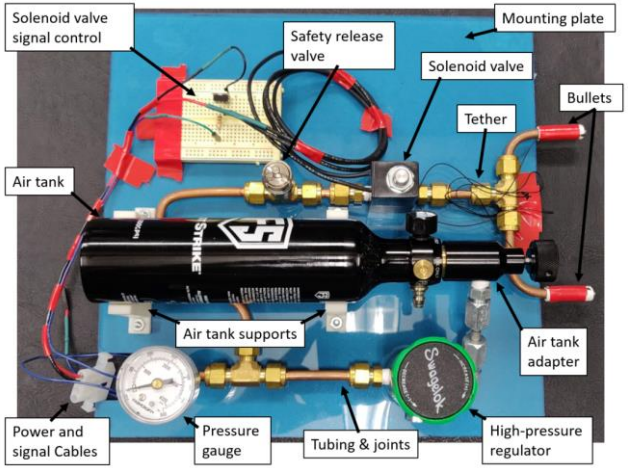


Kernot, J., and Ulrich, S., "Adaptive Control of a Tendon-Driven Manipulator for Capturing Non-Cooperative Space Targets," *Journal of Spacecraft and Rockets*, Vol. 59, No. 1, 2022, pp. 111-128.

10 Years of SPOT

✓ Tested a novel tether deployment design

2014 2015 2016 2017 2018 2019



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Stadnyk, K., and Ulrich, S. "Validating the Deployment of a Novel Tether Design for Orbital Debris Removal," *Journal of Spacecraft and Rockets,* Vol. 57, No. 6, 2020, pp. 1335–1349.

10 Years of SPOT

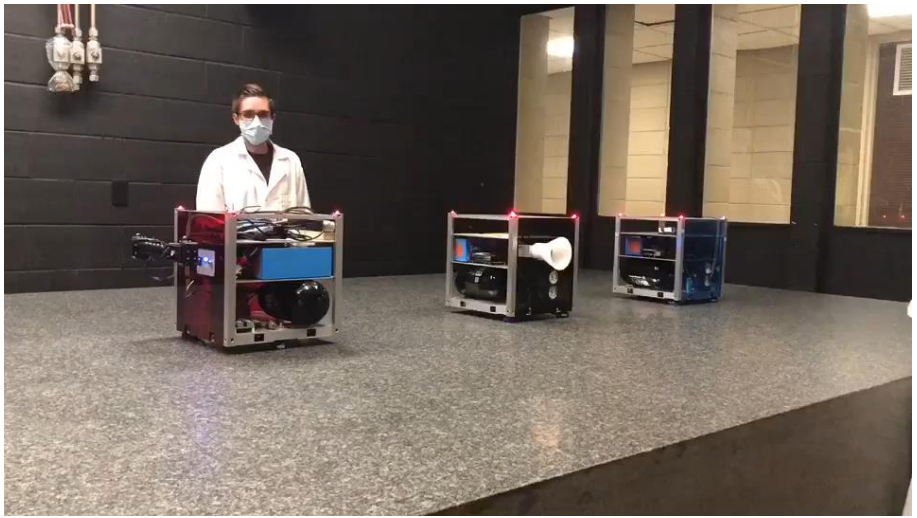
✓ Acquired ZED 2 stereo vision camera

2014 2015 2016 2017 2018 2019 2020

10 Years of SPOT

✓ Built the third platform—obstacle (BLUE)

2014 2015 2016 2017 2018 2019 2020 2022

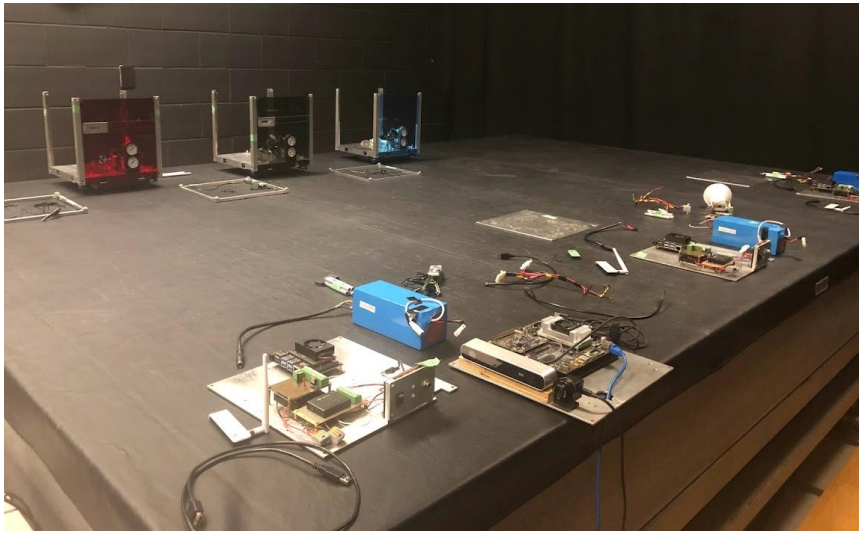


Bashnick, C., and Ulrich, S., "Fast Model Predictive Control for Spacecraft Rendezvous and Docking with Obstacle Avoidance," *Journal of Guidance, Control, and Dynamics,* Vol. 46, No. 5, 2023, pp. 998–1007.

10 Years of SPOT

✓ Upgraded onboard computers (Raspberry Pi 3 → NVIDIA Jetson Xavier NX)

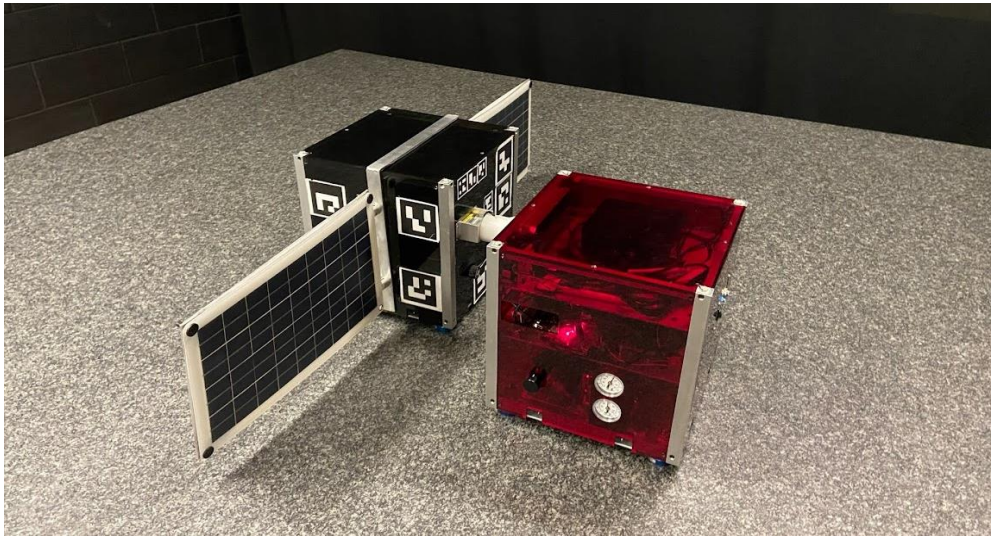
2014 2015 2016 2017 2018 2019 2020 2022 2023



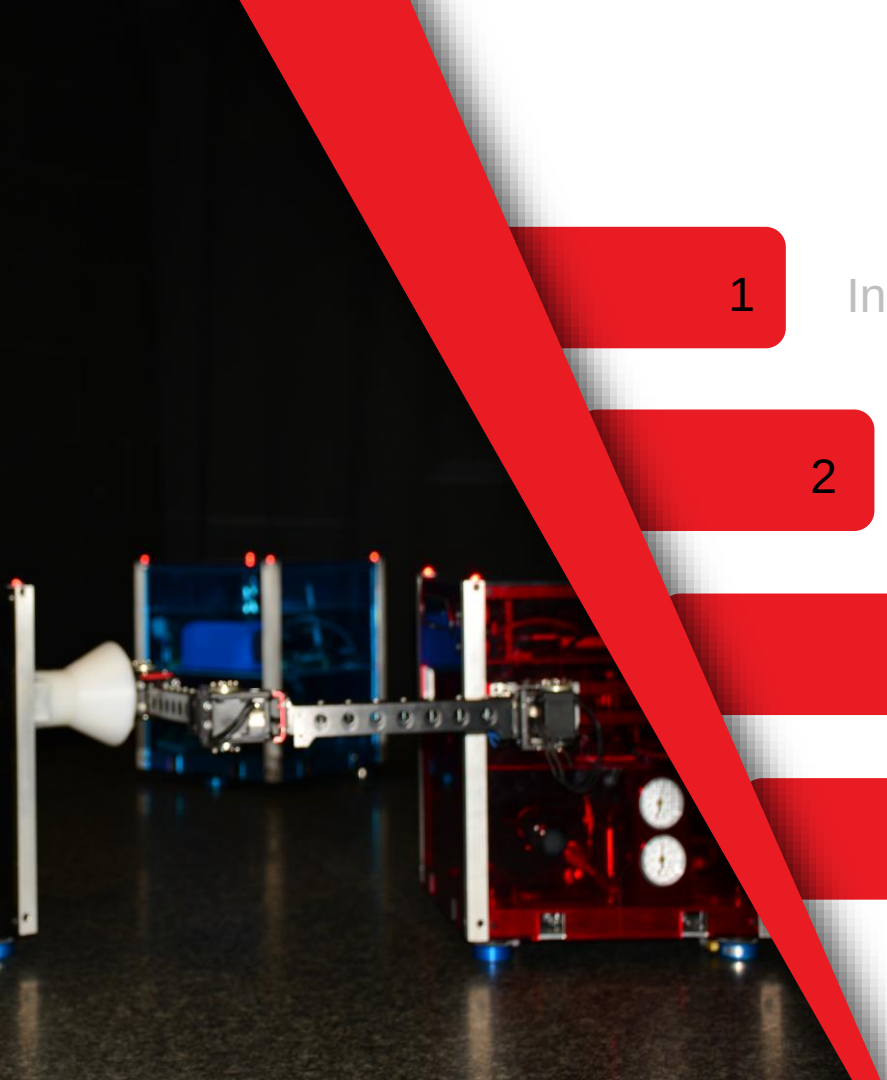
10 Years of SPOT

✓ Designed and manufactured a solar panel bracket to be mounted on any platform

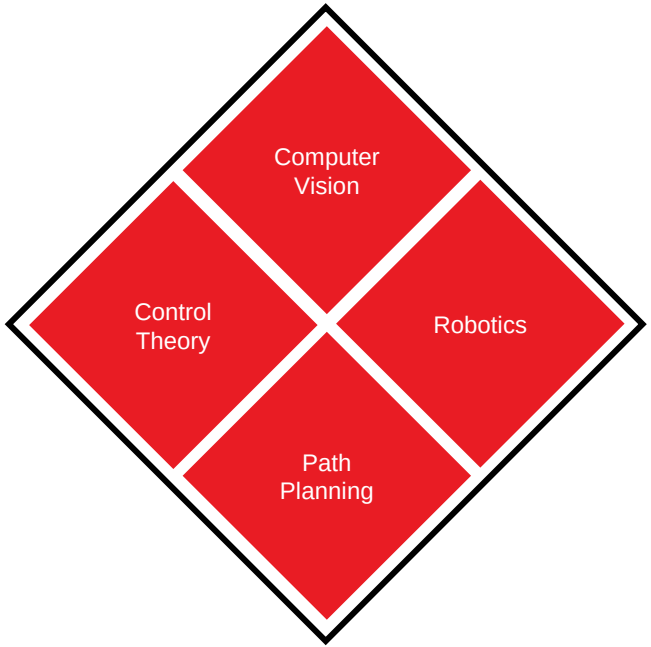
2014 2015 2016 2017 2018 2019 2020 2022 2023 2024



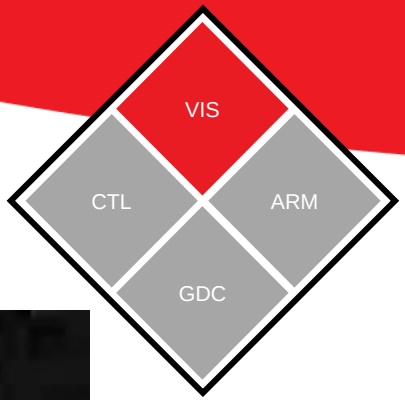
Reid, N., *et al.*, "Cooperative Computer Vision-Driven APF Guidance and Adaptive Control for Spacecraft Proximity Operations," Capstone Final Design Review Report, Carleton University, Ottawa, Canada, 2024.



SPOT Research Highlights



SPOT Research Highlights



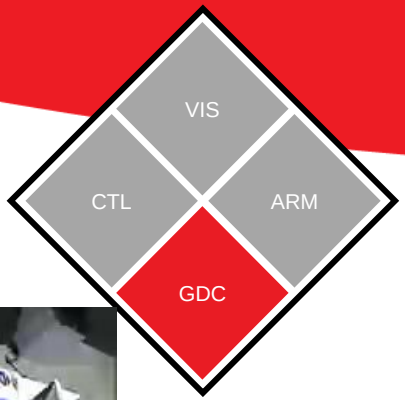
SRCL, "Convolutional Neural Networks for Noncooperative Spacecraft Pose Determination", Available: https://www.youtube.com/watch?v=_wQKHzVfRlE

- ✓ Stereo vision-based convolutional neural network to determine relative pose of an uncooperative target
- ✓ Executed in real-time onboard a Jetson TX2 embedded computer

Carleton University

Despond, F., and Ulrich, S., "Real-time Stereo Vision-based Spacecraft Pose Determination Using Convolutional Neural Networks," *Journal of Spacecraft and Rockets*, accepted.

SPOT Research Highlights



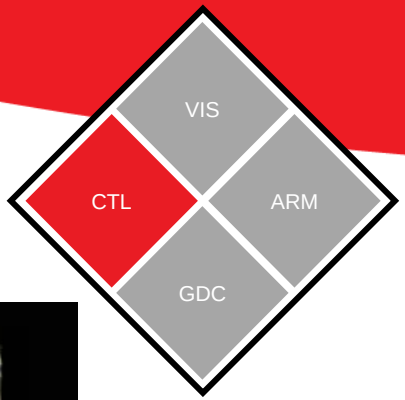
SRCL, "Deep Reinforcement Learning for Spacecraft Proximity Operations Guidance", Available: https://www.youtube.com/watch?v=mosMrTyistw

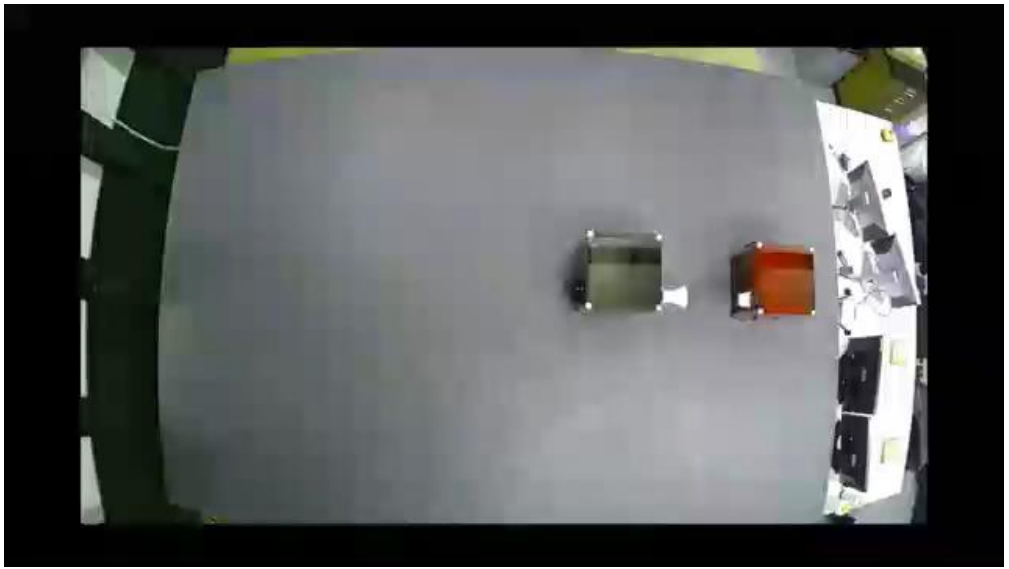
- ✓ "Deep Guidance", which is a Deep Reinforcement Learning-based guidance policy
- ✓ Neural network provides desired velocity signals to be tracked by a conventional controller
- ✓ Executed in real-time onboard a Jetson TX2 embedded computer

Carleton University

Hovell, K., and Ulrich, S., "Deep Reinforcement Learning for Spacecraft Proximity Operations Guidance," *Journal of Spacecraft and Rockets,* Vol. 58, No. 2, 2021, pp. 254–264.

SPOT Research Highlights



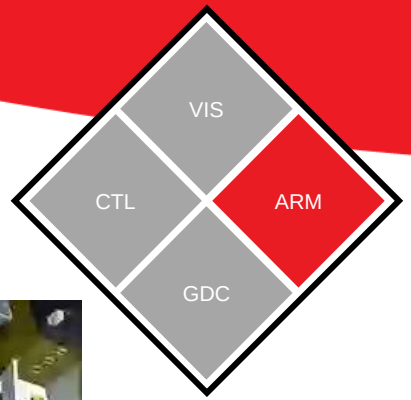


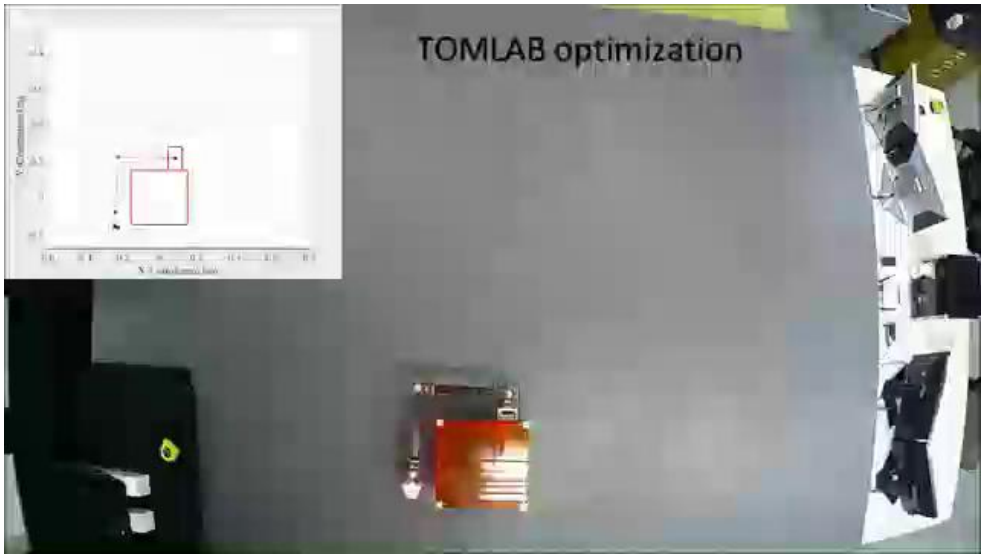
SRCL, "Spacecraft Pose Tracking Control Using the Udwadia-Kalaba Framework", Available: https://www.youtube.com/watch?v=nk0c8XvwCmw

- ✓ Developed a Udwadia-Kalaba-based pose tracking controller
- ✓ Generates exact real-time control forces and torques
- ✓ Also demonstrates docking capabilities

Pothen, A. A., Crain, A., and Ulrich, S., "Pose Tracking Control for Spacecraft Proximity Operations using the Udwadia-Kalaba Framework," *Journal of Guidance, Control, and Dynamics*, Vol. 45, No. 2, 2022, pp. 296-309.

SPOT Research Highlights





SRCL, "Spacecraft Robotic Arm Deployment", Available: https://www.youtube.com/watch?v=8RI49Z7BpIQ

- ✓ Pseudospectral-based optimization of a robotic manipulator deployment that minimizes the base attitude displacement

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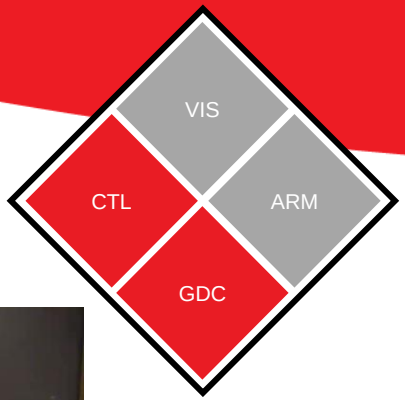
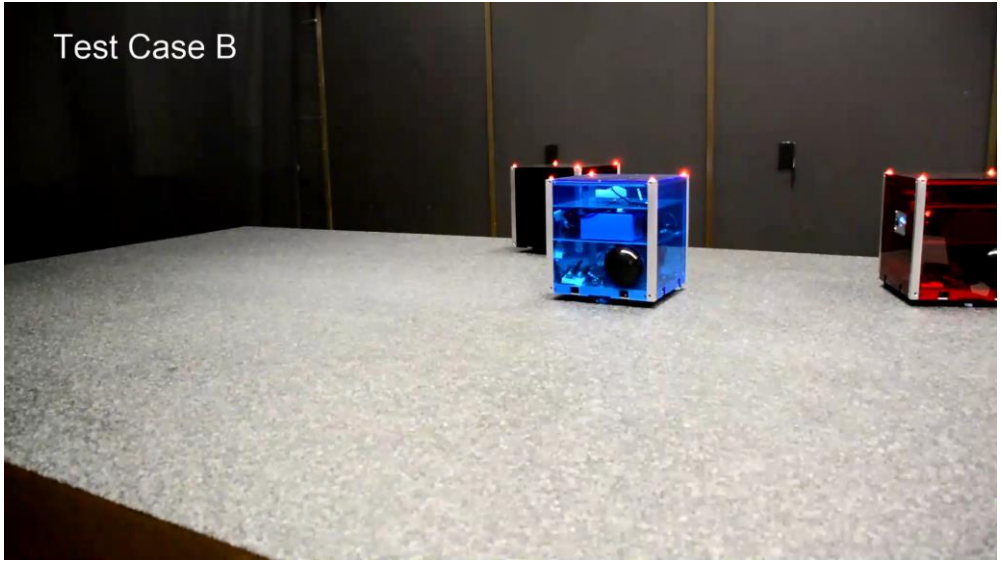
SPOT Research Highlights





SRCL, "Experimentally Validating Model Predictive Control for Spacecraft Prox Ops with Collision Avoidance", Available: https://www.youtube.com/watch?v=jjdNB43zdak

- ✓ Linear-quadratic model predictive control (MPC) generates guidance and control commands for rendezvous and docking
- ✓ Moving obstacle and rotating target
- ✓ Executed in real-time onboard a Raspberry Pi 3 and a Jetson Xavier NX

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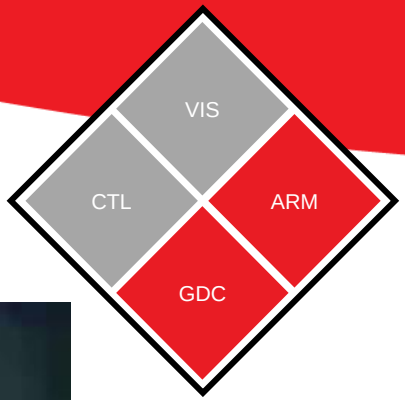
Savytska, C., and Ulrich, S., "Experimentally Validating Model Predictive Control for Spacecraft Proximity Operations with Collision Avoidance," In Preparation.

SPOT Research Highlights



SRCL, "AI-Driven Spacecraft Capture", Available: https://www.youtube.com/watch?v=m7V_EqvJLz0

- ✓ "Deep Guidance" for robotic capture of a spinning target
- ✓ Trained to negate the angular momentum of the combined system
- ✓ Executed in real-time onboard a Jetson TX2 embedded computer

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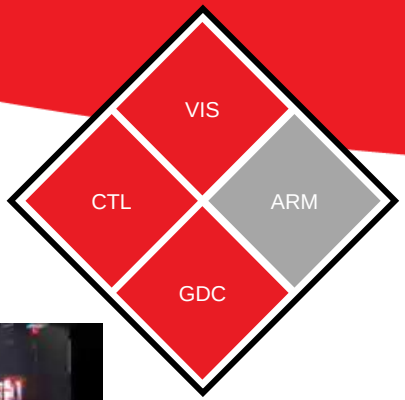
SPOT Research Highlights



SRCL, "Computer Vision-Driven APF Guidance and Adaptive Control for Spacecraft Proximity Operations", Available: https://www.youtube.com/watch?v=31x2ANIjW_I

- ✓ Integrated real-time GNC system for docking to cooperative target
  - Stereo-vision based navigation system
  - APF guidance law
  - Direct adaptive control law

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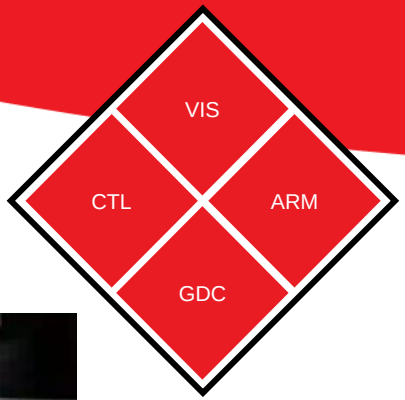
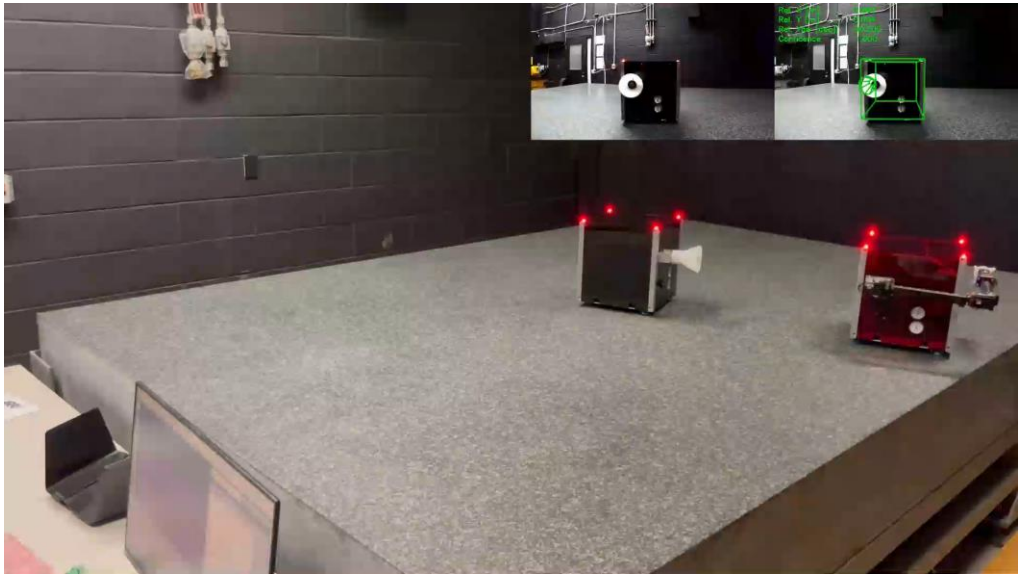
Reid, N., *et al.*, "Cooperative Computer Vision-Driven APF Guidance and Adaptive Control for Spacecraft Proximity Operations," In Preparation.

SPOT Research Highlights





SRCL, "Robotic Capture of an Uncooperative Spinning Spacecraft via Deep Learning Vision and Guidance", Available: https://www.youtube.com/watch?v=egv2pmCyzJM

- ✓ Integrated real-time GNC system for robotic capture of uncooperative target
  - CNN-driven stereo-vision
  - "Deep Guidance" pose tracking
  - Pseudospectral and transpose Jacobian robotic manipulator control law

Carleton University

Crain, A., Hovell, K., Savytska, C., and Ulrich, S., "Optimal Robotic Capture of an Uncooperative Spinning Spacecraft via Deep Learning Vision and Guidance," In Preparation.

Acknowledgements

Funding Partners

Natural Sciences and Engineering Research Council of Canada (NSERC)

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Ontario Centres of Excellence

Defence Research and Development Canada

Canadian Space Agency

Consortium for Aerospace Research and Innovation in Canada (CARIC)

European Space Agency
Open Space Innovation Platform (OSIP)

Industrial Partners

Mission Control Space Services Inc.

Obruta Space Solutions

Bombardier Aerospace
Flight Sciences / Control Laws Group

MDA Robotics and Automation
Guidance, Navigation, and Control
Department

Neptec Design Group Ltd.

EnduroSat AD

Academic and Governmental Collaborators

South Dakota State University
Department of Mechanical Engineering

Massachusetts Institute of Technology
Space Systems Laboratory

New Mexico State University
Department of Mechanical and Aerospace Engineering

U.S. Air Force Research Laboratory
Space Vehicle Directorate

The University of Sydney
School of Aerospace, Mechanical and Mechatronic Engineering

Polish Academy of Sciences' Space Research Center
Space Mechatronics and Robotics Laboratory

Universidad Autonoma de Ciudad Juarez
Department of Mechanical and Industrial Engineering

Deutsches Zentrum für Luft- und Raumfahrt (DLR)
Institut für Robotik und Mechatronik

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