Jun 5th, 7:30 AM

CEU Session #4 - Space Robotics for On-Orbit Servicing and Space Debris Removal

Markus Wilde
Director, FIT ORION Spacecraft Robotics Lab

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Space Robotics for On-Orbit Servicing and Space Debris Removal

Dr. Markus Wilde
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Director, ORION Spacecraft Robotics Lab

Outline

1. Applications of Orbital Robotics
2. History of Crewed and Robotic On-Orbit Servicing
3. The Challenge: Non-cooperative Servicing Clients
    1. Orbital Dynamics
    2. Relative Navigation
    3. Multi-Body Dynamics
    4. Capture Mechanisms
    5. Verification and Validation

This lecture is a summary of the course AEE 5806 – Dynamics and Controls of Spacecraft Rendezvous and Capture

Imagine if…

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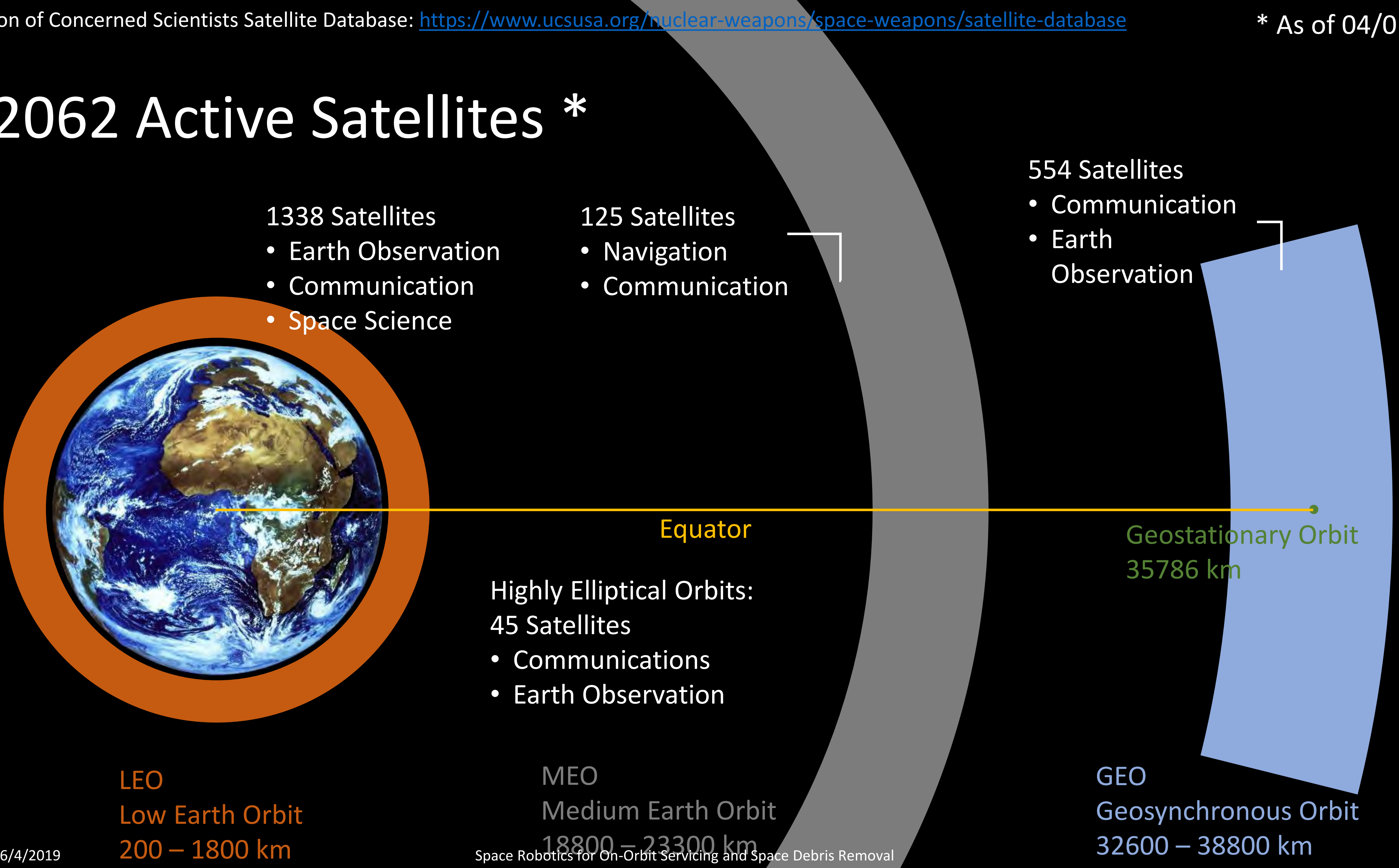
Welcome to Space Flight!

Union of Concerned Scientists Satellite Database: https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database

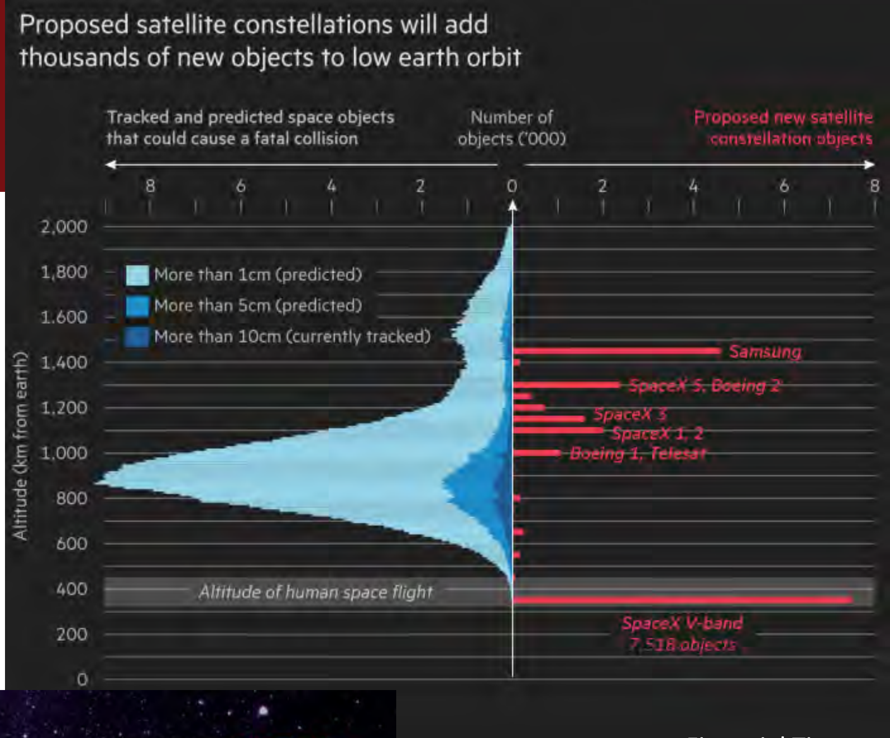
* As of 04/01/2019

2062 Active Satellites *

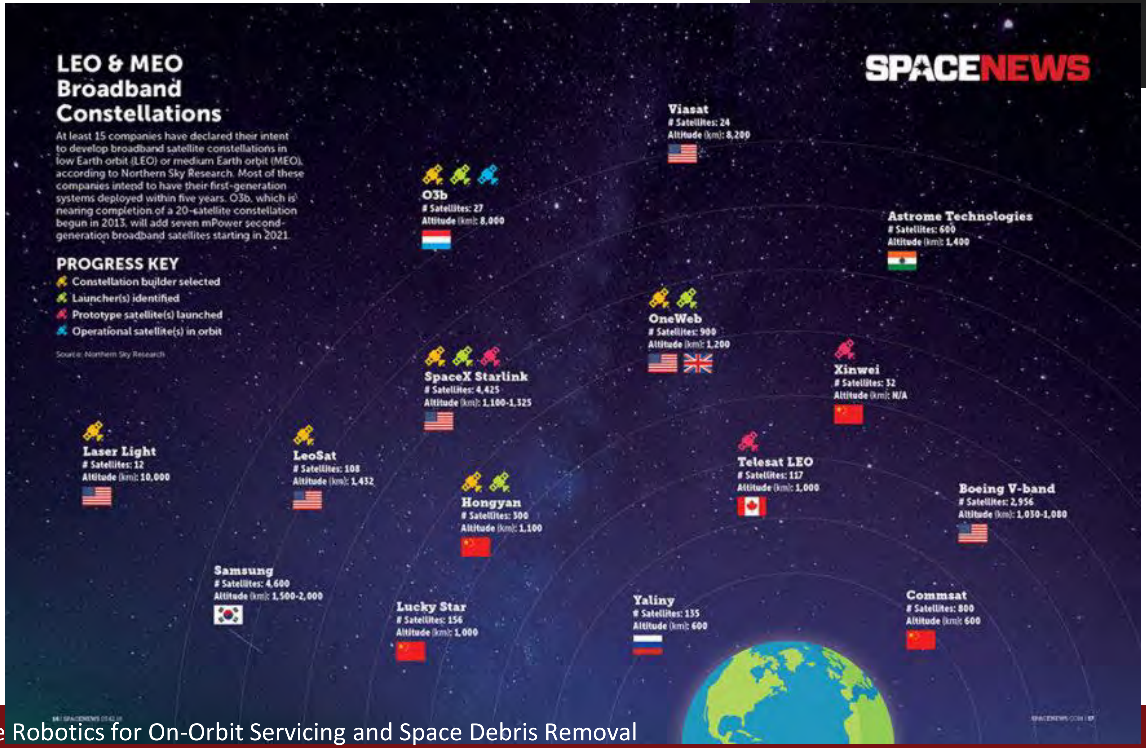


Mega-Constellations

- LEO communications constellations
- Hundreds or thousands of satellites needed for global coverage
- Constellations approved by FCC/ITU:
  - SpaceX Starlink (11,943)
  - Amazon Kuiper (3,236)
  - OneWeb (650)
  - Telesat (292)
  - LeoSat (108)



Financial Times

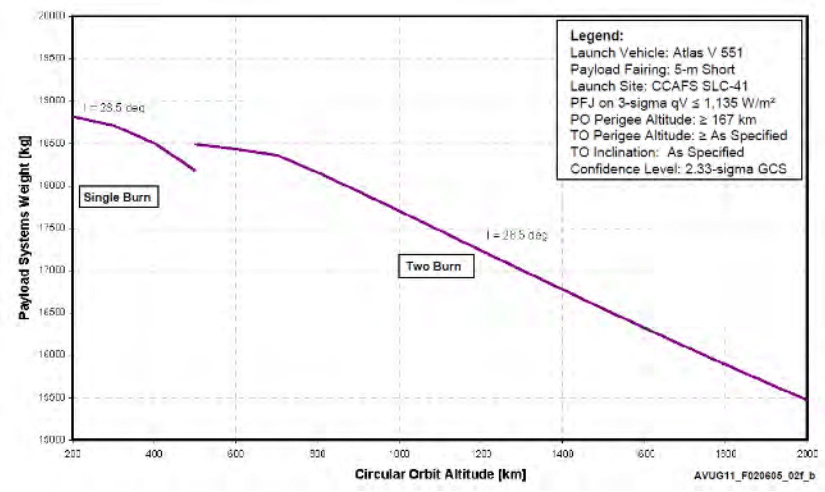


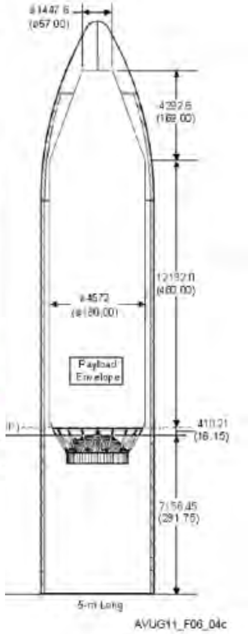
On-Orbit Servicing

- In-orbit maintenance of space systems
- Tasks:
  - Inspection and failure determination
  - Refueling
  - Repair / Upgrade
  - Maneuvering
  - Removal of inactive satellites and debris objects
- Potential:
  - Increased flexibility in design and operations
  - Increased capability over system lifetime
  - Increased return on investment
  - Enduring usability of orbital environment

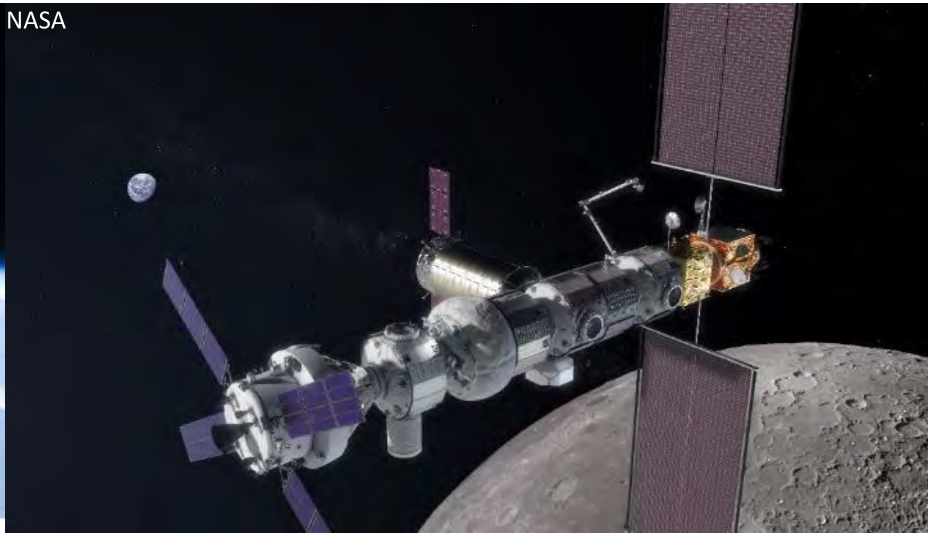
In-Space Assembly

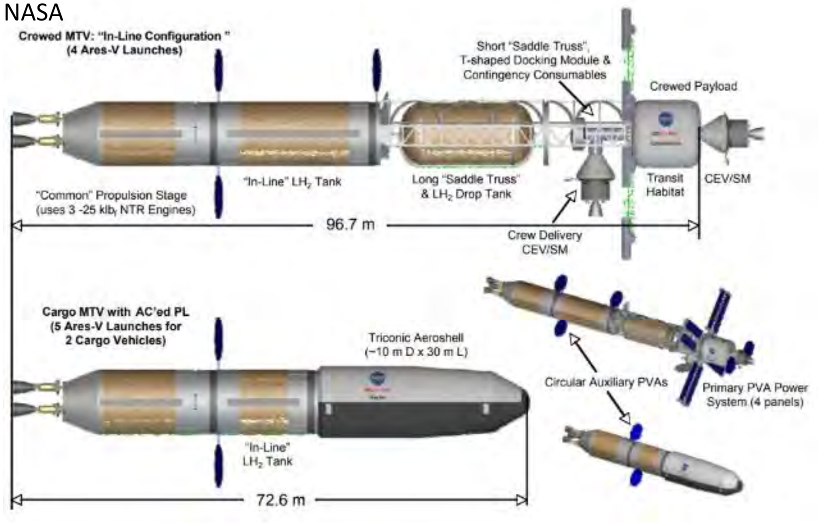
- The direct-launch size and mass is severely limited by the launcher capabilities.
- Larger spacecraft must be launched in modules and then be assembled in orbit.
- Examples:
  - Space Stations
  - Large space structures, e.g. Solar Power Satellites
  - Human Exploration Missions





Example: Atlas V





Asteroid Exploration and Mining

Due to their low gravity fields, touching down on many asteroids is more “docking” than “landing”


JAXA’s Hayabusa 2 mission


NASA’s OSIRIS-Rex mission


Crewed asteroid exploration concept

On-Orbit Servicing: History

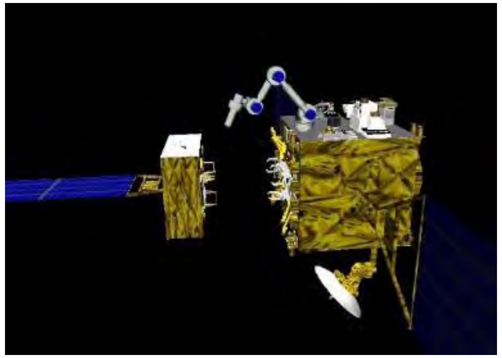
The Space Shuttle

- From onset designed as servicing platform
  - Astronauts
  - Engineers
  - Robotic manipulator
  - Large payload bay
- Many successful servicing missions, including assembly of ISS, repair and upgrade of Hubble

Robotic Servicing Demonstrators

Past

- ETS-VII (JAXA, 1997)
  - LEO
  - Custom target object
  - Telerobotic and automated capture
  - Exchange of Orbital Replacement Unit

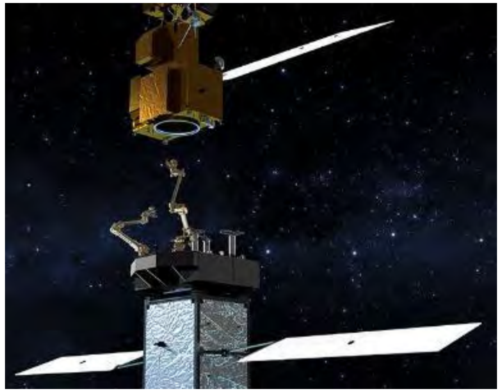


- Orbital Express (DARPA, 2007)
  - LEO
  - Custom target object
  - Autonomous capture
  - Exchange of computer and battery
  - Fuel transfer

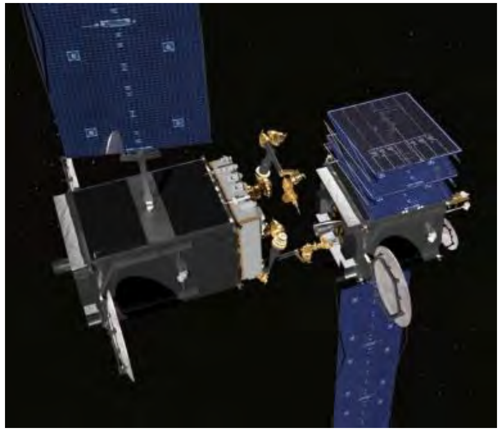
ORBITAL EXPRESS SPACE EXPERIMENT (DARPA)

Future

- Restore-L (NASA, 2022)
  - LEO
  - Landsat 7
  - Autonomous capture
  - Telerobotic refueling and relocation



- RSGS (DARPA, 2022+)
  - GEO
  - Resident space object
  - Autonomous and telerobotic capture, inspection, relocation, repair, upgrade



On-Orbit Servicing Challenges

General Challenges

- Rendezvous
  - Orbital dynamics
  - Relative navigation
  - Approach rotating or tumbling objects
- Capture
  - Multi-body dynamics
  - Capture mechanisms
- Testing: Verification and Validation

Robotics Challenges

- Capable robotic systems in space environment
- Handling delicate space hardware
- Flexibility required in dealing with failed spacecraft
- Unstructured work environment
- Spacecraft surfaces
- Lighting conditions
- Non-cooperative target objects
- Manipulation: Telerobotics vs. Autonomy

Rendezvous

Orbital Dynamics and Relative Navigation

Relative Motion EoM

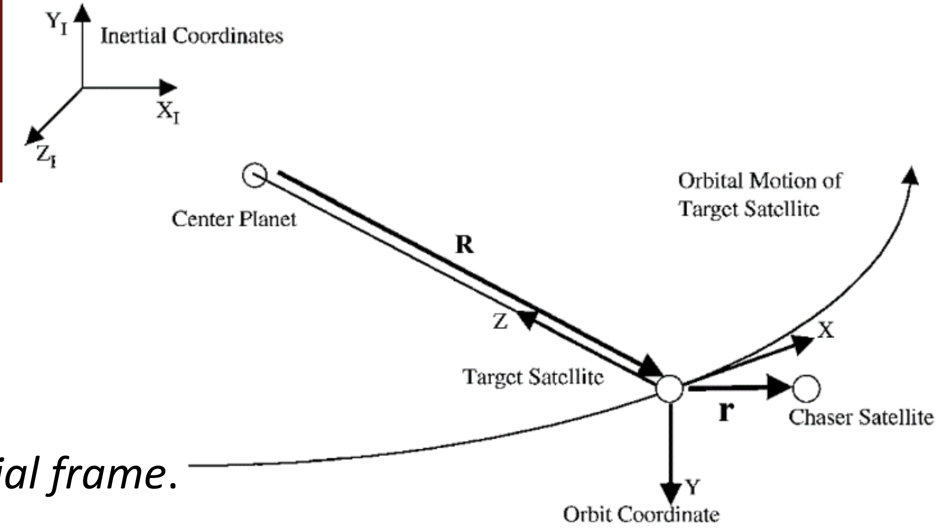
$$\ddot{\boldsymbol{R}} = -\frac{\mu}{R^3}\boldsymbol{R}$$

$$\ddot{\boldsymbol{R}} + \ddot{\boldsymbol{r}} = -\frac{\mu}{(R+r)^3}(\boldsymbol{R}+\boldsymbol{r}) + \frac{\boldsymbol{F}}{m_c}$$

$$\frac{\boldsymbol{R}+\boldsymbol{r}}{(R+r)^3} \approx \frac{1}{R^3}\left(\boldsymbol{R}+\boldsymbol{r} - 3\frac{\boldsymbol{R}^T\boldsymbol{r}}{R^2}\boldsymbol{R}\right)$$

$$\ddot{\boldsymbol{r}} = -\frac{\mu}{R^3}\left(\boldsymbol{r} - 3\frac{\boldsymbol{R}^T\boldsymbol{r}}{R^2}\boldsymbol{R}\right) + \frac{\boldsymbol{F}}{m_c}$$

Relative motion expressed in the *inertial frame*.



- We need to express the relative motion in the *target's local orbital frame*.
- The local orbital frame is rotating within the inertial frame with the orbital rate $\boldsymbol{\omega}$.
- The transformations of time derivatives of a vector $\boldsymbol{A}$ between a rotating coordinate system and an inertial coordinate system are given by:

$$\left.\frac{d\boldsymbol{A}}{dt}\right|_I = \left.\frac{d\boldsymbol{A}}{dt}\right|_{rot} + \boldsymbol{\omega}\times\boldsymbol{A}$$

$$\left.\frac{d^2\boldsymbol{A}}{dt^2}\right|_I = \left.\frac{d^2\boldsymbol{A}}{dt^2}\right|_{rot} + \boldsymbol{\omega}\times(\boldsymbol{\omega}\times\boldsymbol{A}) + 2\boldsymbol{\omega}\times\left.\frac{d\boldsymbol{A}}{dt}\right|_{rot} + \frac{d\boldsymbol{\omega}}{dt}\times\boldsymbol{A}$$

$$\ddot{\boldsymbol{r}} = -\frac{\mu}{R^3}\left(\boldsymbol{r} - 3\frac{\boldsymbol{R}^T\boldsymbol{r}}{R^2}\boldsymbol{R}\right) - 2(\boldsymbol{\omega}\times\dot{\boldsymbol{r}}) - \dot{\boldsymbol{\omega}}\times\boldsymbol{r} - \boldsymbol{\omega}\times(\boldsymbol{\omega}\times\boldsymbol{r}) + \frac{\boldsymbol{F}}{m_c}$$

Relative motion expressed in the target's local orbital frame.

Relative Motion EoM

In the target LVLH coordinate system:

$\boldsymbol{\omega} = \begin{pmatrix} 0 \\ -\omega \\ 0 \end{pmatrix}$	$\boldsymbol{R} = \begin{pmatrix} 0 \\ 0 \\ -R \end{pmatrix}$
$\boldsymbol{F} = \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix}$	$\boldsymbol{r} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}$
$\boldsymbol{\omega} \times \dot{\boldsymbol{r}} = \begin{pmatrix} -\omega\dot{z} \\ 0 \\ \omega\dot{x} \end{pmatrix}$	$\dot{\boldsymbol{\omega}} \times \boldsymbol{r} = \begin{pmatrix} -\dot{\omega}z \\ 0 \\ \dot{\omega}x \end{pmatrix}$
$\boldsymbol{\omega} \times (\boldsymbol{\omega} \times \boldsymbol{r}) = \begin{pmatrix} -\omega^2 x \\ 0 \\ -\omega^2 z \end{pmatrix}$	$\boldsymbol{r} - 3\frac{\boldsymbol{R}^T\boldsymbol{r}}{R^2}\boldsymbol{R} = \begin{pmatrix} x \\ y \\ -2z \end{pmatrix}$

- **Hill's Equation:**

$$\begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{pmatrix} = \begin{bmatrix} 2\omega\dot{z} + \dot{\omega}z \\ -\omega^2 y \\ 3\omega^2 z - 2\omega\dot{x} - \dot{\omega}x \end{bmatrix} + \frac{F}{m_c}$$

  - The out-of-plane motion y is independent of the in-plane motion xz.
  - In-plane and out-of-plane motion are decoupled and can be analyzed and controlled separately!
  - As most RVD missions occur in circular orbits, we'll focus on the circular case, with $\omega = const.$, so $\dot{\omega} = 0$.

Homogenous solution

(near) circular orbit

$$x(t) = \left(\frac{4\dot{x}_0}{\omega} - 6z_0\right)\sin(\omega\tau) - \frac{2\dot{z}_0}{\omega}\cos(\omega\tau) + (6\omega z_0 - 3\dot{x}_0)\tau + \left(x_0 + \frac{2\dot{z}_0}{\omega}\right)$$

$$y(t) = y_0\cos(\omega\tau) + \frac{\dot{y}_0}{\omega}\sin(\omega\tau)$$

$$z(t) = \left(\frac{2\dot{x}_0}{\omega} - 3z_0\right)\cos(\omega\tau) + \frac{\dot{z}_0}{\omega}\sin(\omega\tau) + \left(4z_0 - \frac{2\dot{x}_0}{\omega}\right)$$

Clohessy-Wiltshire (CW) Equations

V-bar Maneuver

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A V-bar maneuver is a burn parallel to the orbital velocity vector.

Initial conditions:

x_0, y_0, z_0	$\dot{x}_0 = \Delta V_x$
	$\dot{y}_0, \dot{z}_0 = 0$

$$x(t) = \frac{1}{\omega}\Delta V_x[4\sin(\omega t) - 3\omega t]$$

$$y(t) = 0$$

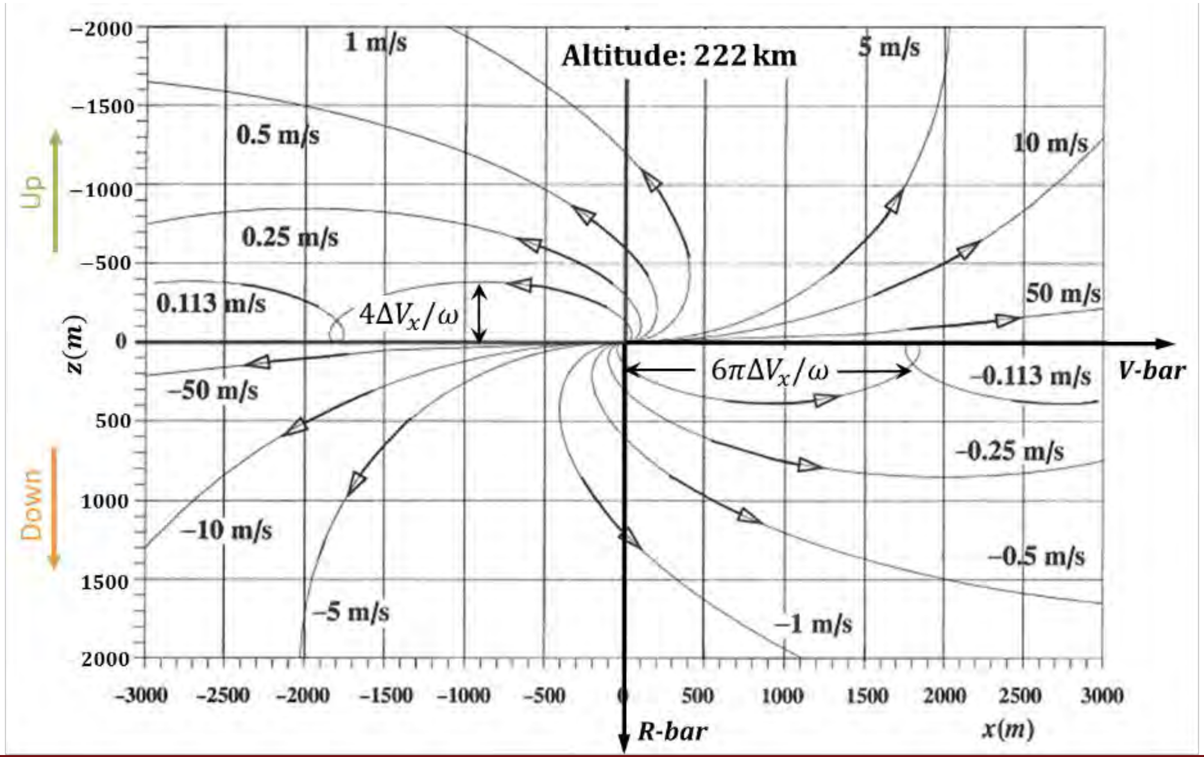
$$z(t) = \frac{2}{\omega}\Delta V_x[\cos(\omega t) - 1]$$

Counter-intuitive:

- Forward maneuver causes backwards motion.
- Backwards maneuver causes forward motion.

The resulting trajectory is a **prolate cycloid**

- If the ΔV was along the +V-bar (forward), the chaser will initially move forward and upward (-R-bar), then fall behind.
- If the ΔV was along the –V-bar (backward), the chaser will initially move back and down (+R-bar), then pass forward.



R-bar Maneuver

A R-bar maneuver is a burn up or down from Earth

Initial conditions:

$x_0, y_0, z_0 = 0$	$\dot{x}_0, \dot{y}_0 = 0$
	$\dot{z}_0 = \Delta V_z$

$$x(t) = \frac{2}{\omega}\Delta V_z[1 - \cos(\omega t)]$$

$$y(t) = 0$$

$$z(t) = \frac{1}{\omega}\Delta V_z \sin(\omega t)$$

- Upwards maneuver causes backward motion
- Downwards maneuver causes forward motion

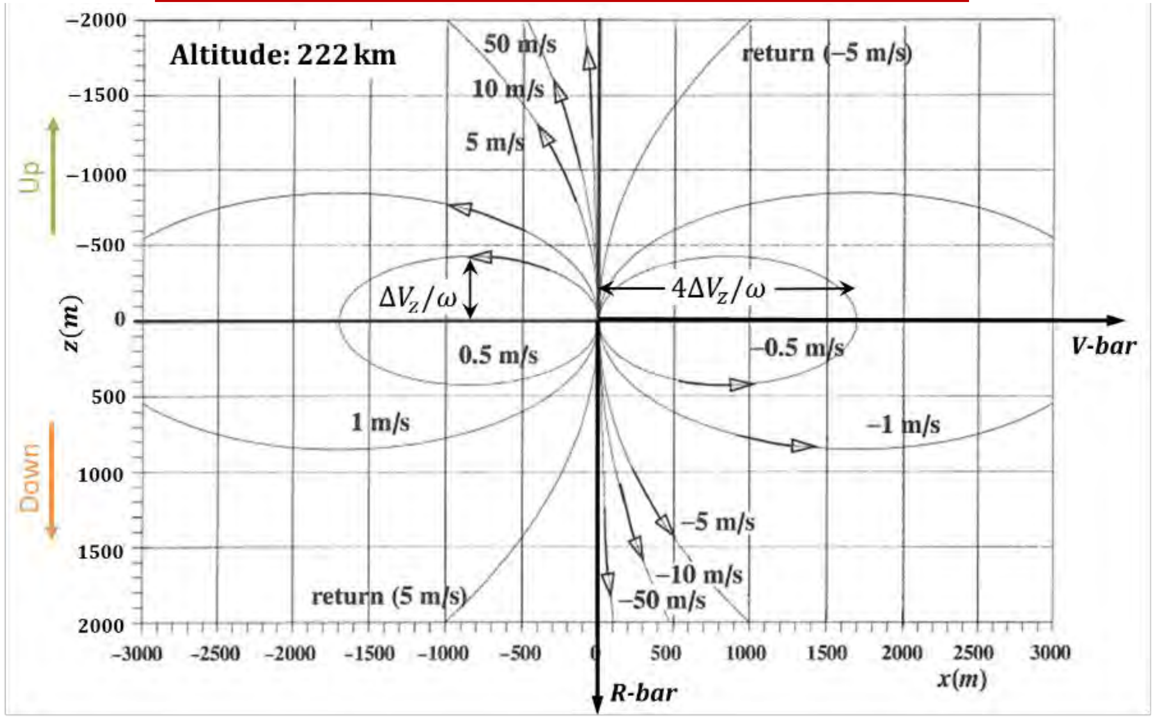
The resulting trajectory is an ellipse.

- Returns to the starting point after $t = T$.
- Maximum distance in x at $t = T/2$:

$$x_{T/2} = \frac{4}{\omega}\Delta V_z$$

- Maximum distance in z at $t = T/4$:

$$z_{T/4} = \frac{1}{\omega}\Delta V_z$$



Out-Of-Plane (H-bar) Maneuvers

An H-bar maneuver is a burn parallel to the horizon.

- Out-of-plane maneuvers serve the correction of the orbital plane.

Initial Conditions:

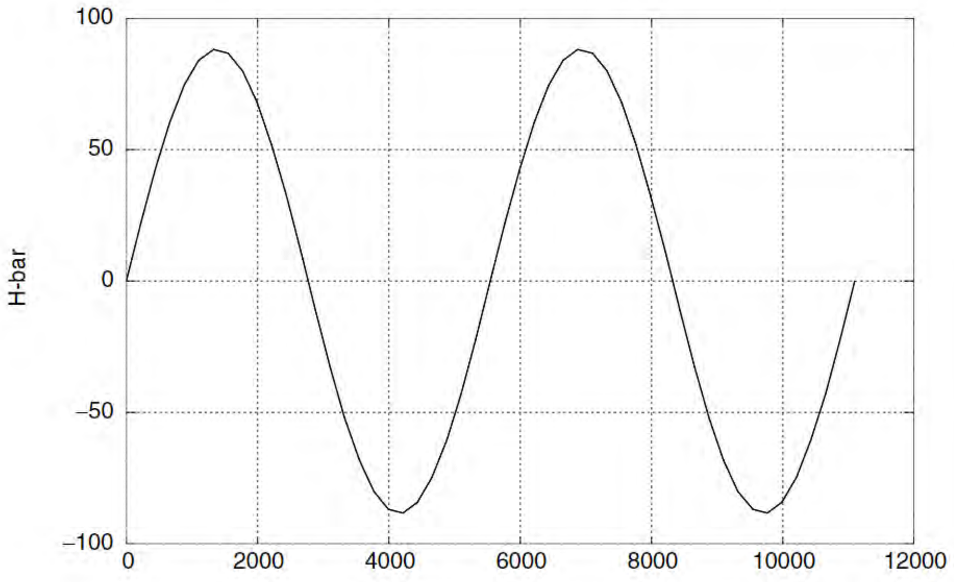
$x_0, y_0, z_0 = 0$	$\dot{x}_0, \dot{z}_0 = 0$
	$\dot{y}_0 = \Delta V_y$

Equations of Motion:

$$x(t) = 0$$

$$y(t) = \frac{\Delta V_y}{\omega}\sin(\omega t)$$

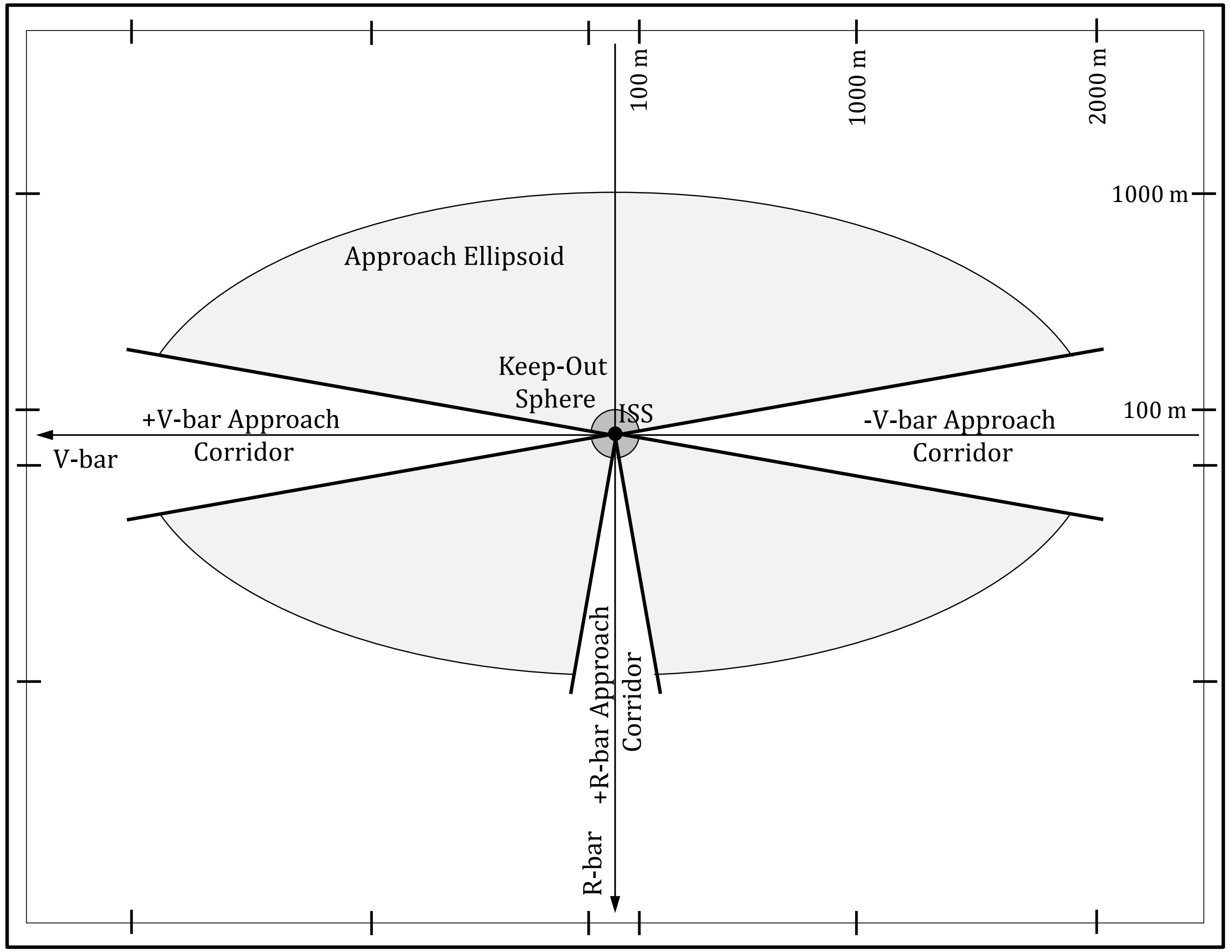
$$z(t) = 0$$



- Pure sinusoidal motion
- Decoupled from x-z motion

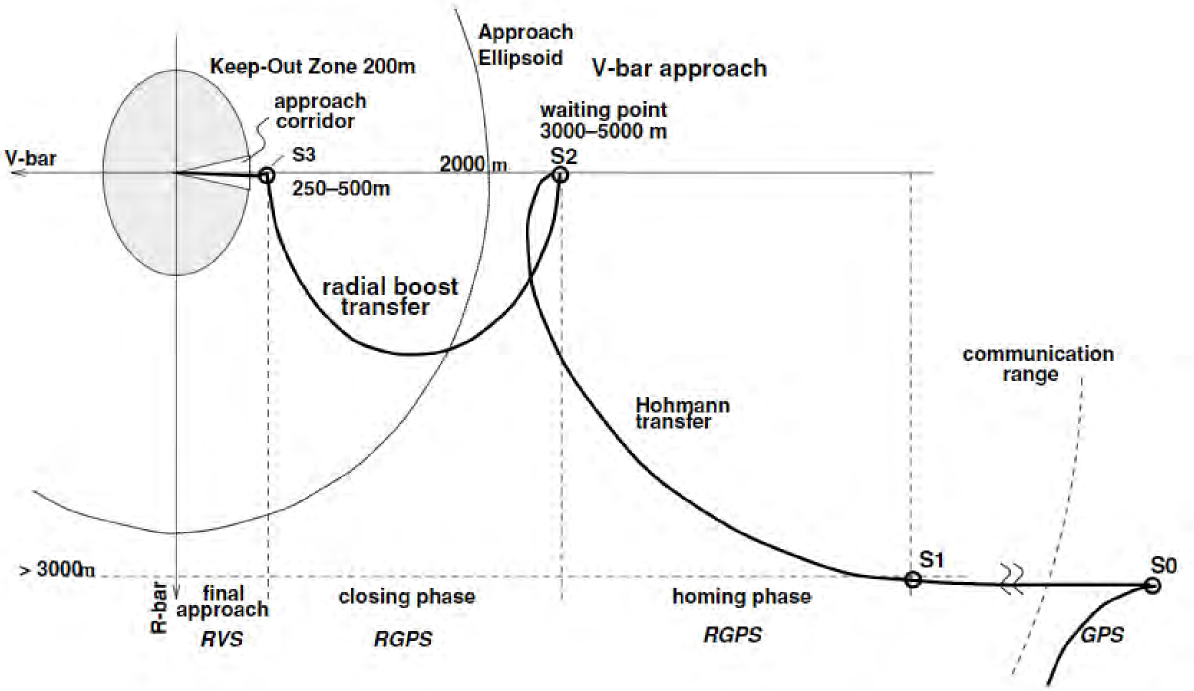
ISS Approach Safety

- Space stations restrict approach and departure to certain sectors:
  - Collision avoidance
  - Observability
  - Thermal loads and contamination
  - Communications
- The half cone angles for approach corridors are typically between $\pm 5°$ and $\pm 15°$.
- ISS Example:
  - ± 2000 m $\times$ ± 1000 m Approach Ellipsoid: ISS Control Center assumes command.
  - 200 m diameter Keep-Out Zone: Enter only through corridors.

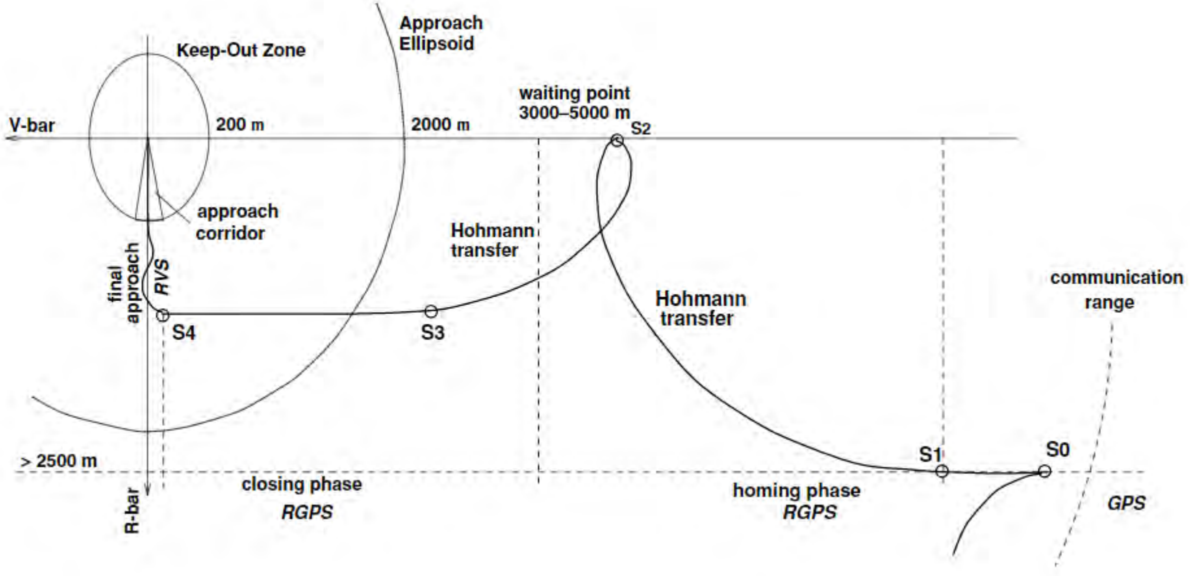


ISS: V-bar and R-bar Approaches

Approach along V-bar



Approach along R-bar

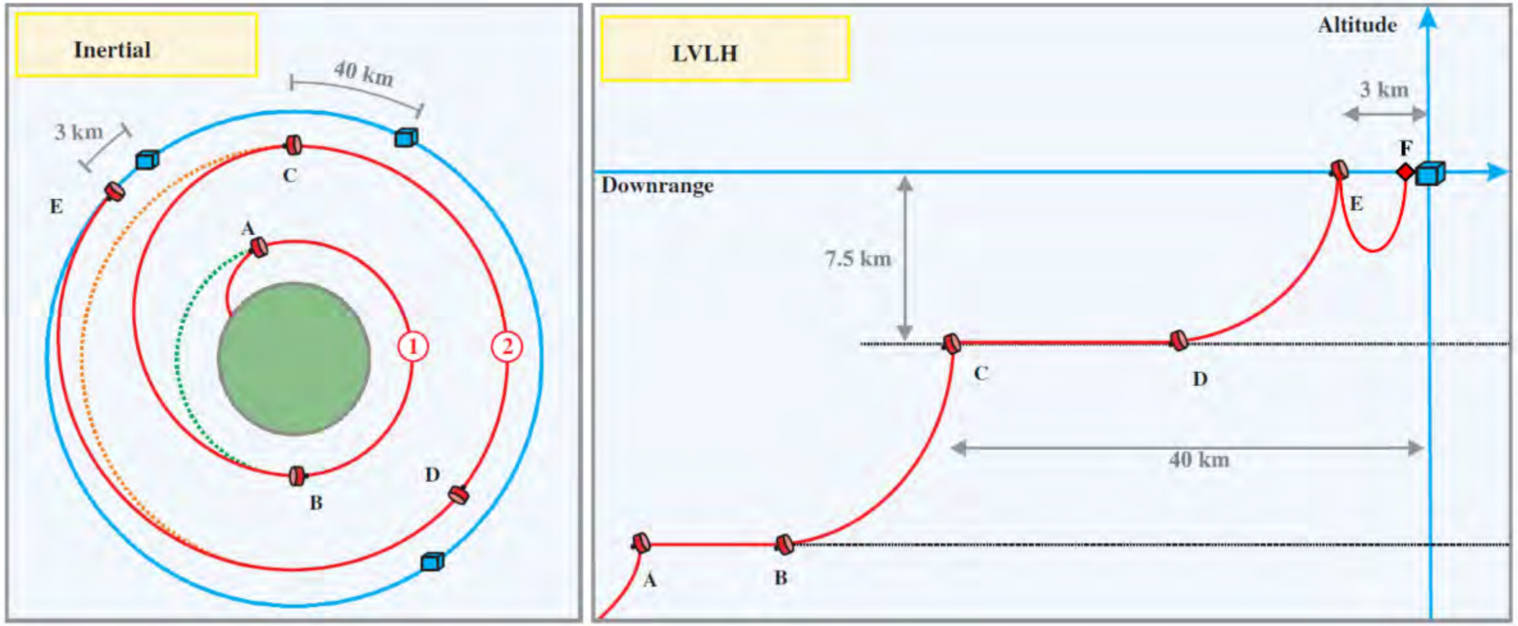


W. Fehse: Automated Rendezvous and Docking of Spacecraft

Example: DART Rendezvous

Demonstration of Autonomous Rendezvous Technology (NASA, 2005)

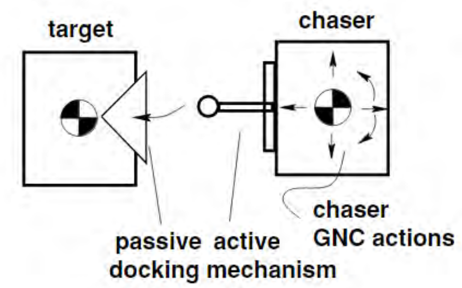
- A – B: Drift (Phasing in concentric orbits)
- B – C: Hohmann Transfer (V-bar maneuver)
- C – D: Drift (Phasing)
- D – E: Hohmann Transfer Δz = 7.5 km
- E – F: R-bar hop 3 km – 1 km



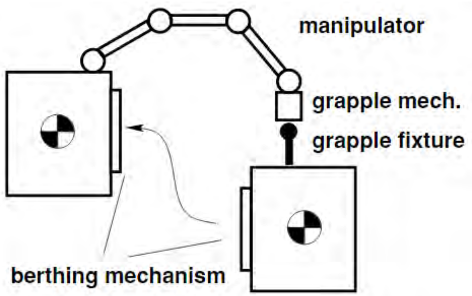
D. C. Woffinden, D. K. Geller: “Navigating the Road to Autonomous Orbital Rendezvous,” Journal of Spacecraft and Rockets, Vol. 44, No. 4, 2007

Measurement Requirements at Capture

Typically Required Performance



Docking:	
Approach Speed:	0.03 – 0.3 m/s
Lateral Alignment:	0.05 – 0.2 m
Lateral Speed:	0.01 – 0.05 m/s
Angular Misalignment:	1 – 5°
Angular Rate:	0.05 – 0.25°/s

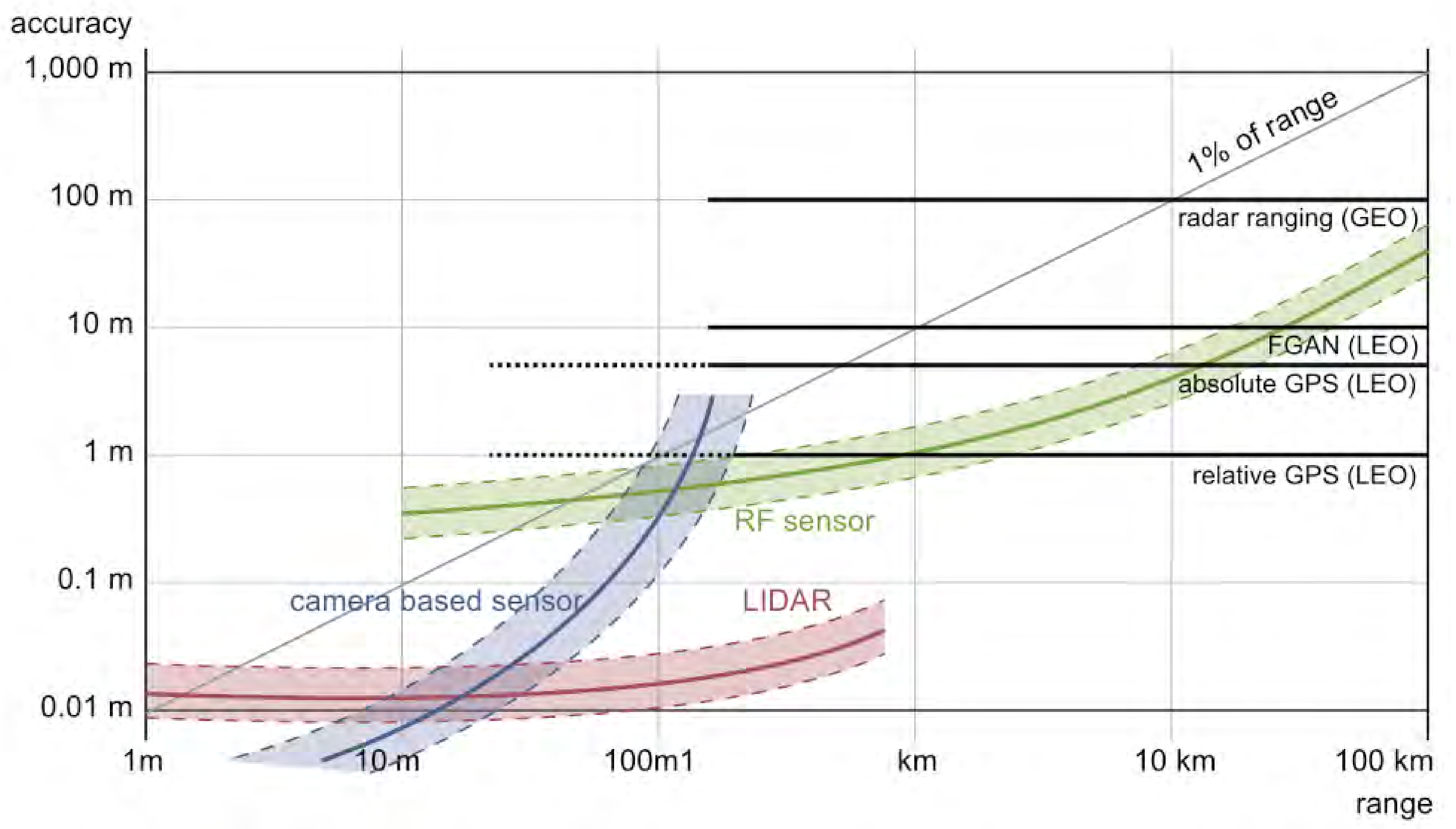


Berthing:	
Position (x, y, z):	0.1 – 0.5 m
Residual Speed:	$<$ 0.01 m/s
Lateral Speed:	0.01 – 0.05 m/s
Angular Misalignment:	$\leq$ 10°
Angular Rate:	$\leq$ 0.1°/s

Typical Measurement Requirements

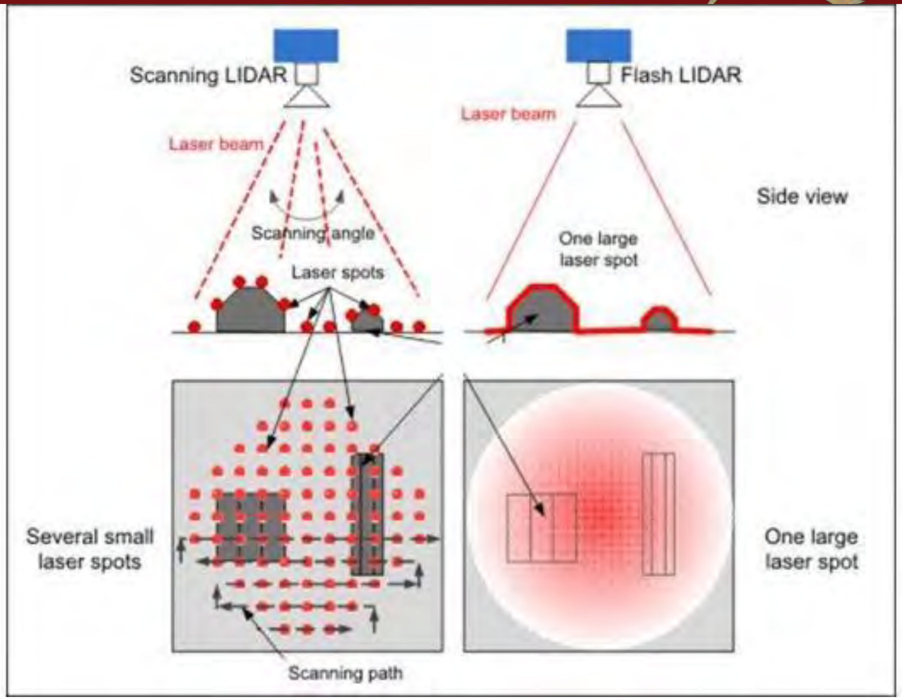
- Final position: factor of 2 – 5 below desired position accuracy.
- Velocity: factor of 2 – 10 below desired velocity accuracy.
- Range and LOS angles: Measured at $\geq$1Hz
- Relative attitude: $\approx$ 1°

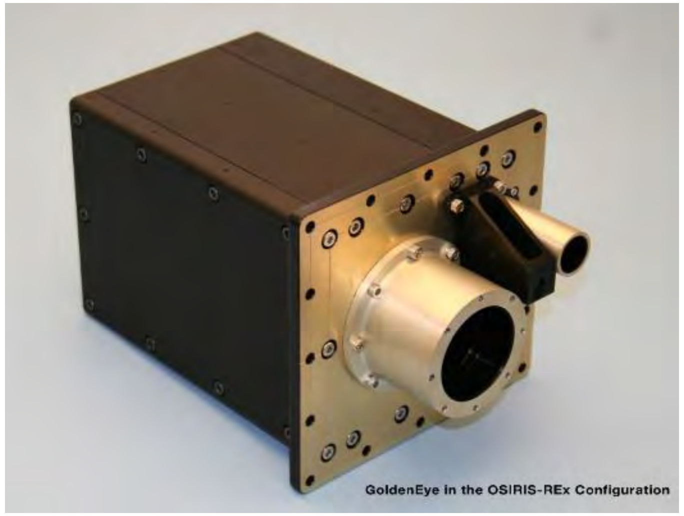
Sensor Capabilities

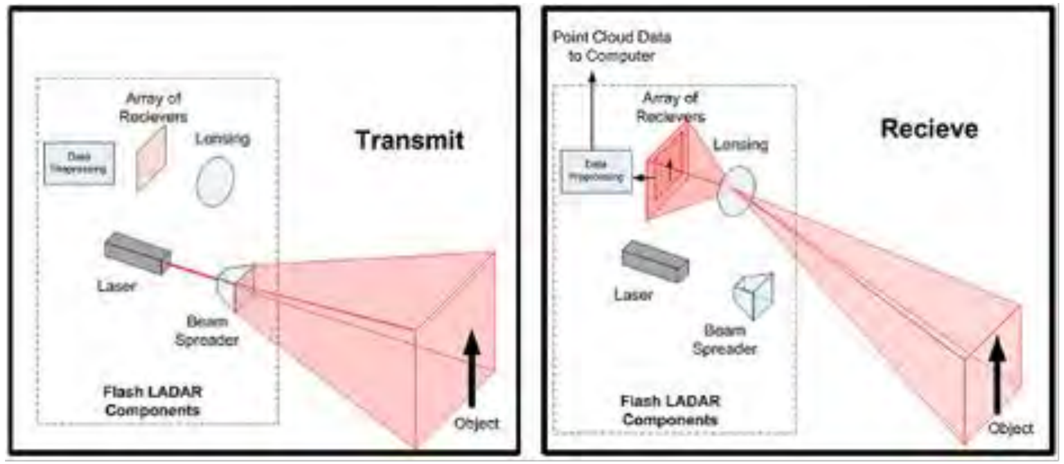


Flash Lidar

- Flash Lidar uses an array of laser diodes to capture a 3D snapshot.
- Example: OSIRIS-Rex GoldenEye
  - 128 x 128 detector array
  - Range $\approx$ 3 km
  - 5 – 10 Hz capture rate
  - Range bias < $\pm$ 10 cm
  - Range noise (3σ) < $\pm$ 15 cm

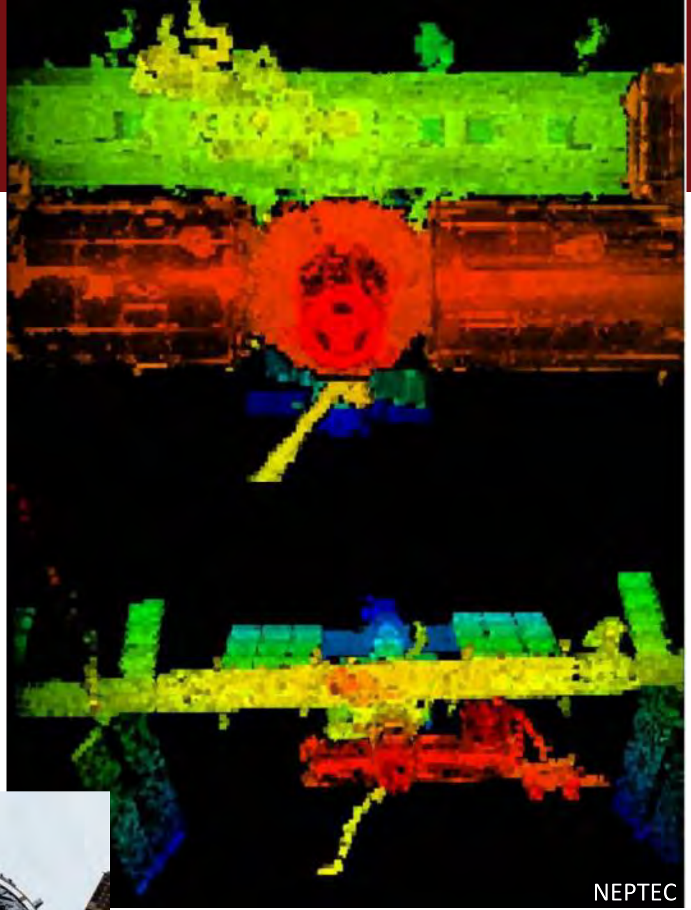


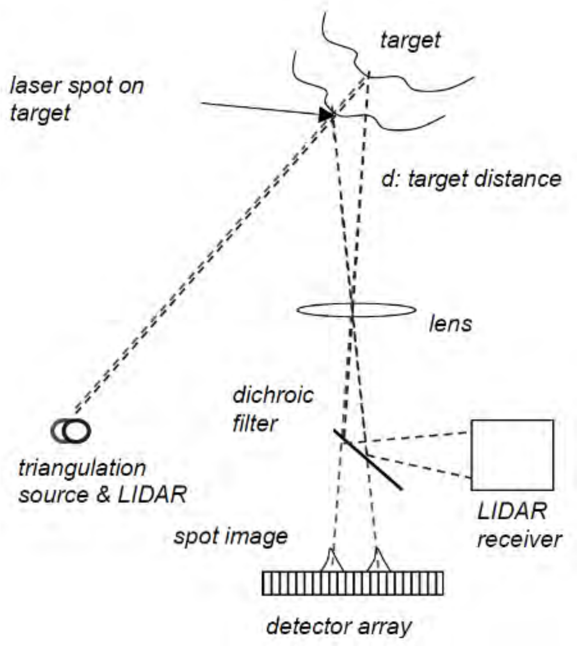


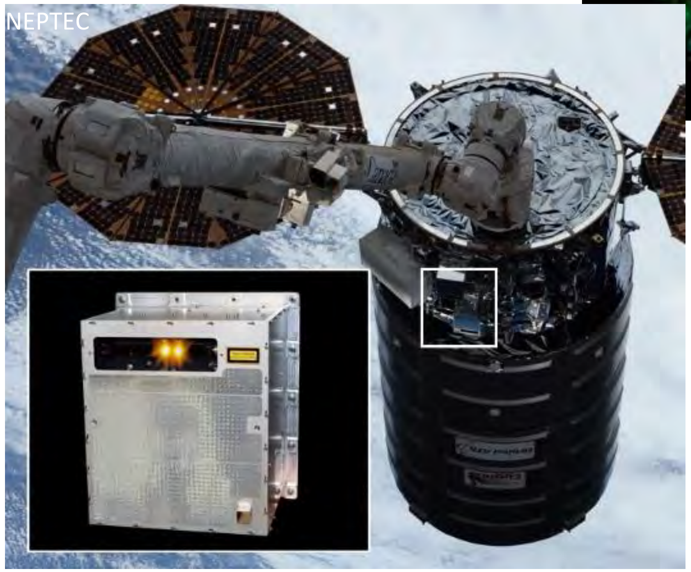


TriDAR

- Proprietary technology of NEPTEC.
- Specifically designed for the requirements of spacecraft proximity operations.
- Provides high sampling rate, range resolution, and lateral resolution from very short to mid ranges (few meters to few hundred meters)
- Combination of lidar and laser triangulation sensor.

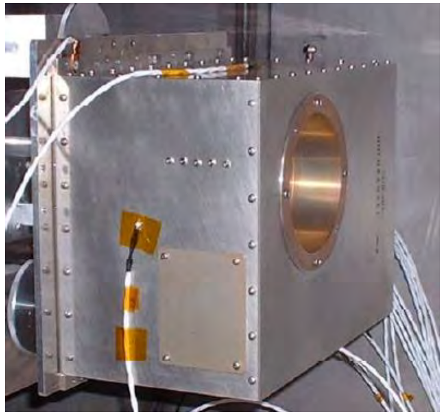




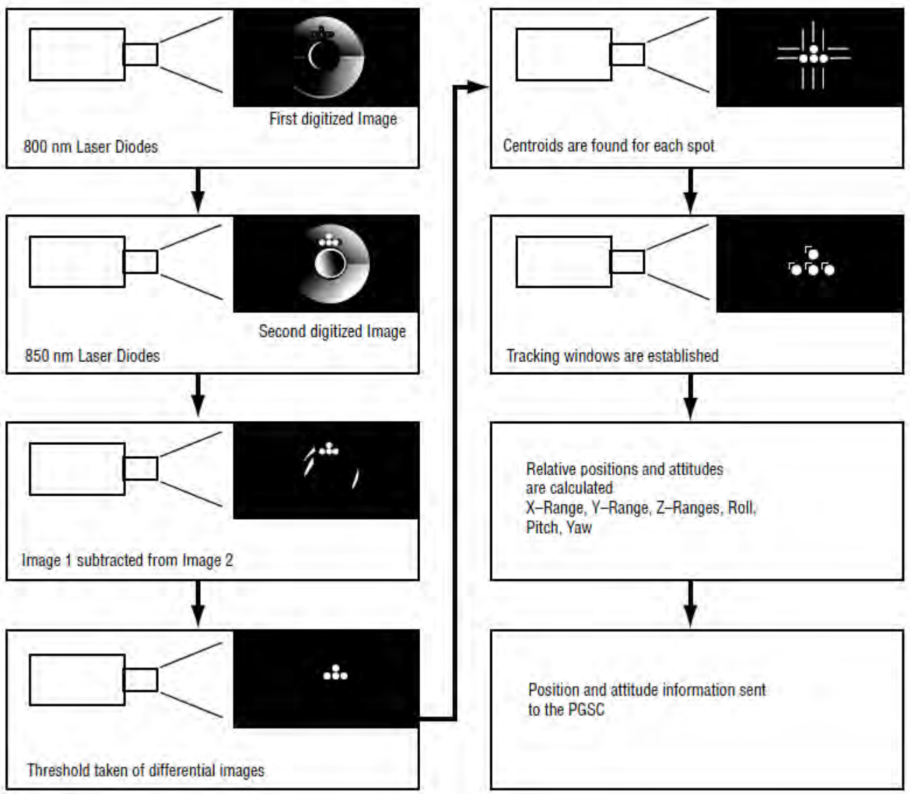


Advanced Video Guidance Sensor (AVGS)

- Used on Orbital Express
- Uses two sets of laser diodes (800 nm and 850 nm)
- The target pattern only reflects at 850 nm
- The images taken at both wavelengths are subtracted to eliminate the background

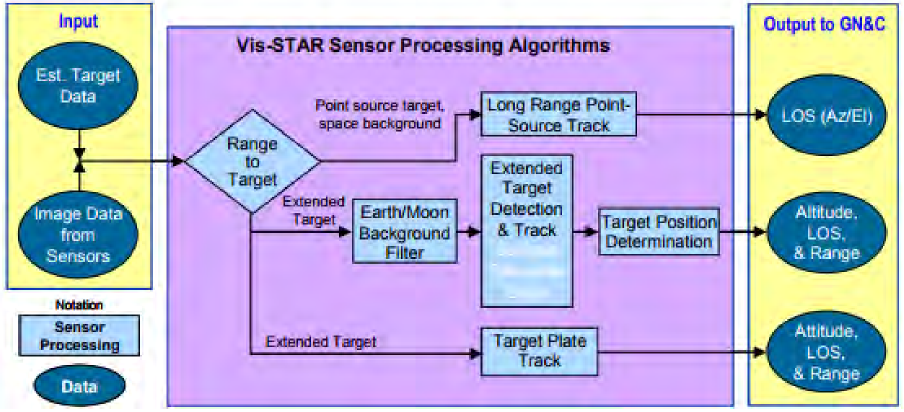


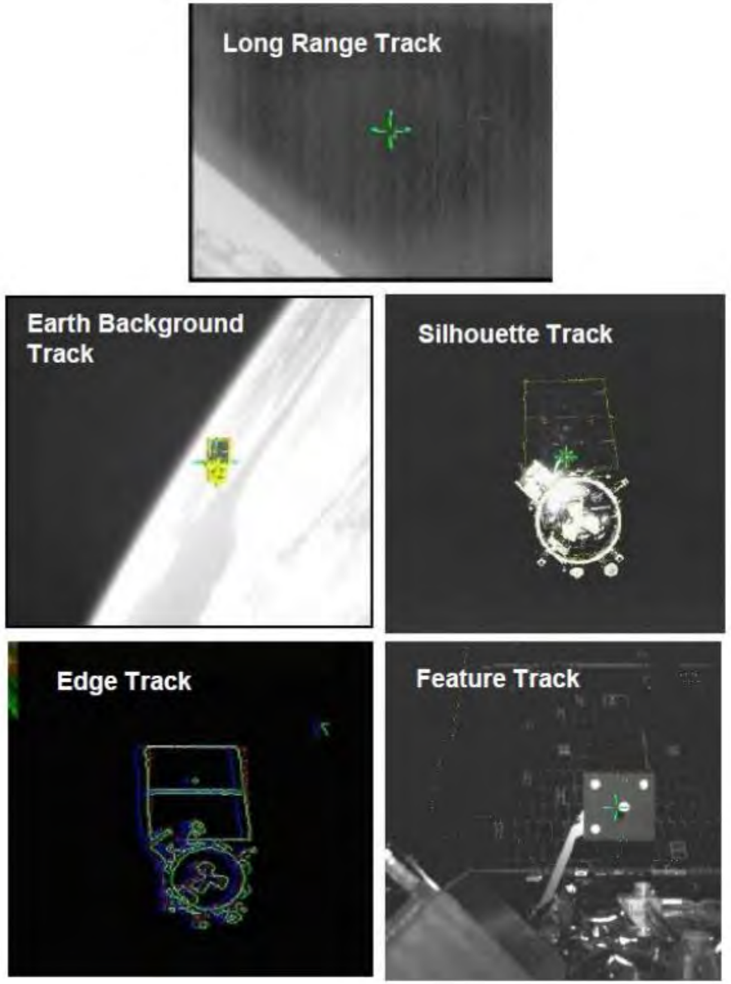
FOV	16° × 16°
Range	0.75 m – 300 m Short range target: 0.75 m – 20 m Long range target: 10 m – 300 m
Accuracy at docking	$\pm$ 13 mm $\pm$ 0.3°
Target angles	LRT: $\pm$ 27° SRT: $\pm$ 12°



Boeing Vis-STAR

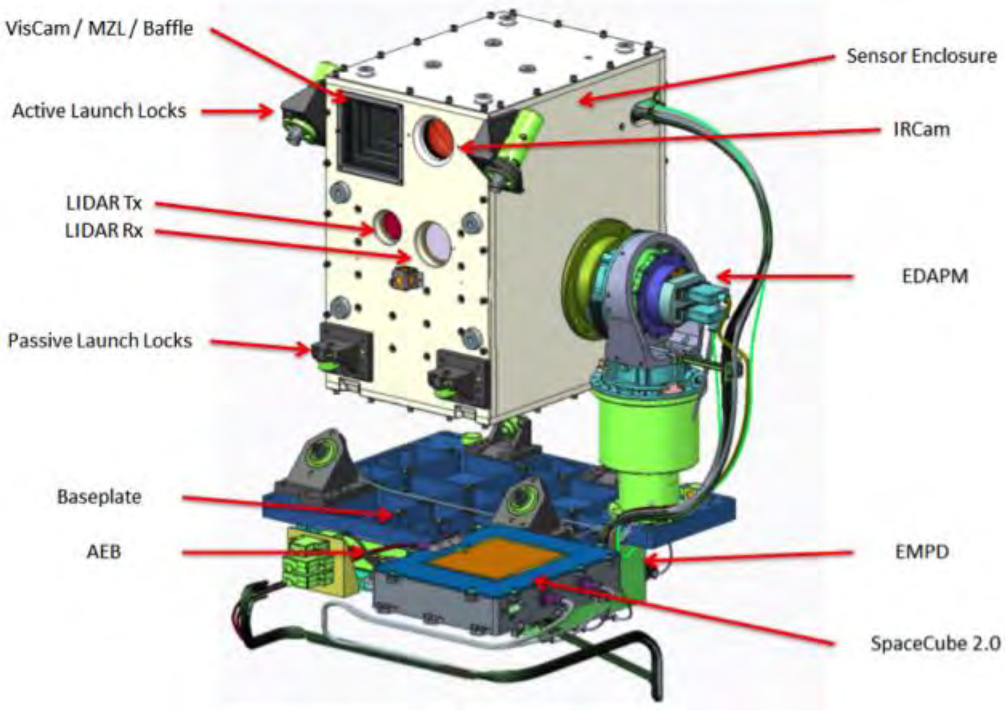
- Vision-based Software for Track, Attitude, and Ranging
- Used on Orbital Express
- At long ranges works as point source tracker.
- At close range uses a silhouette tracking method.
- Scales silhouette according to laser range finder distance data to match a set of reference images on file.
- For attitude calculations, the pixel image is compared pixelwise against the library images of the silhouette of the target at all attitudes.

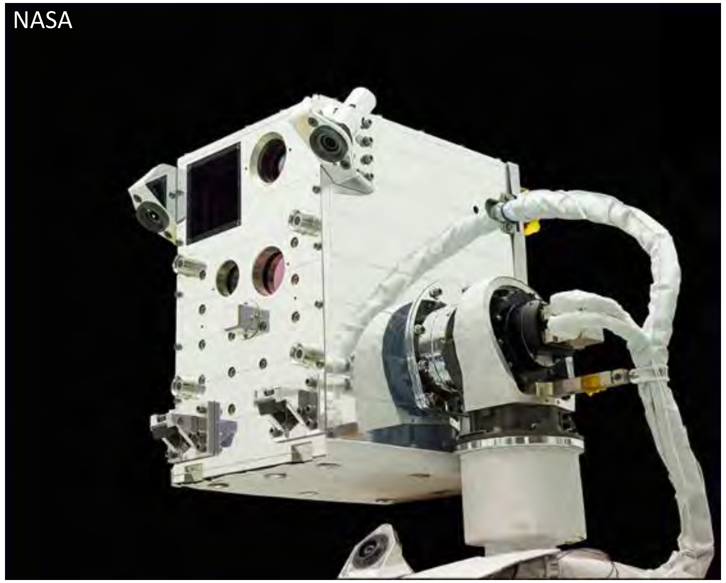




Raven

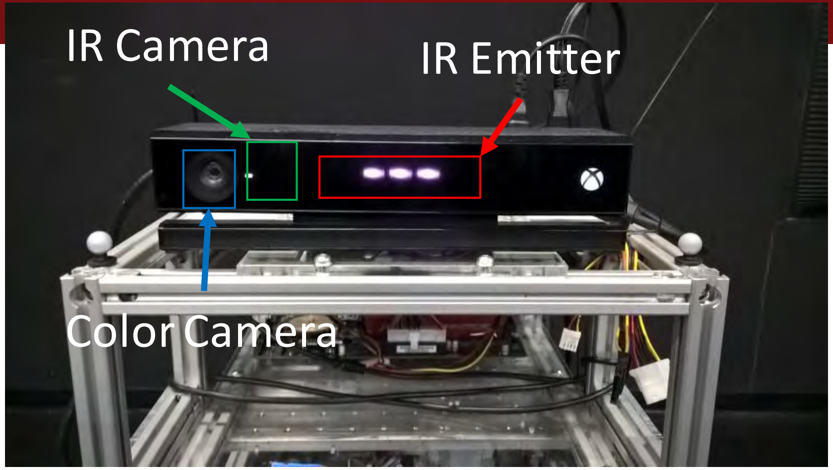
- To be used on the Restore-L mission
- Visible and IR cameras
- Flash lidar

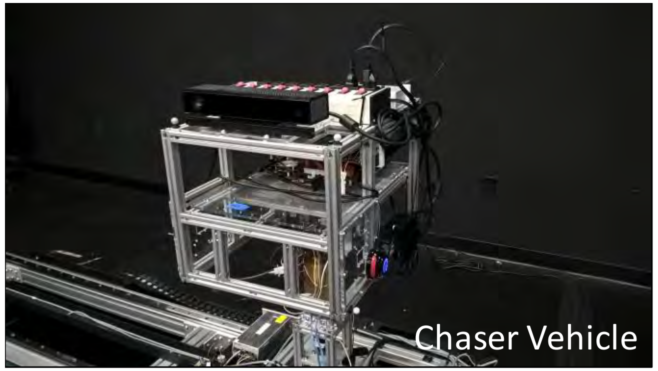


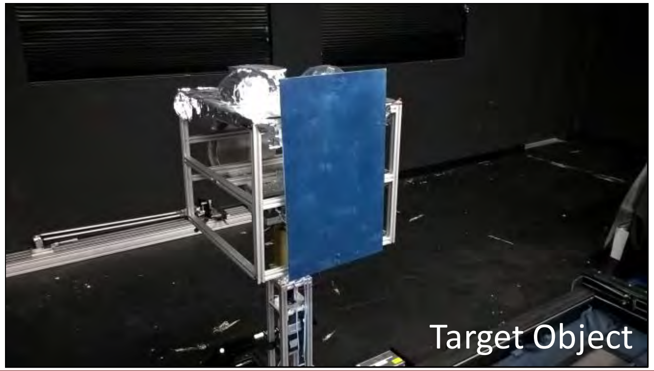


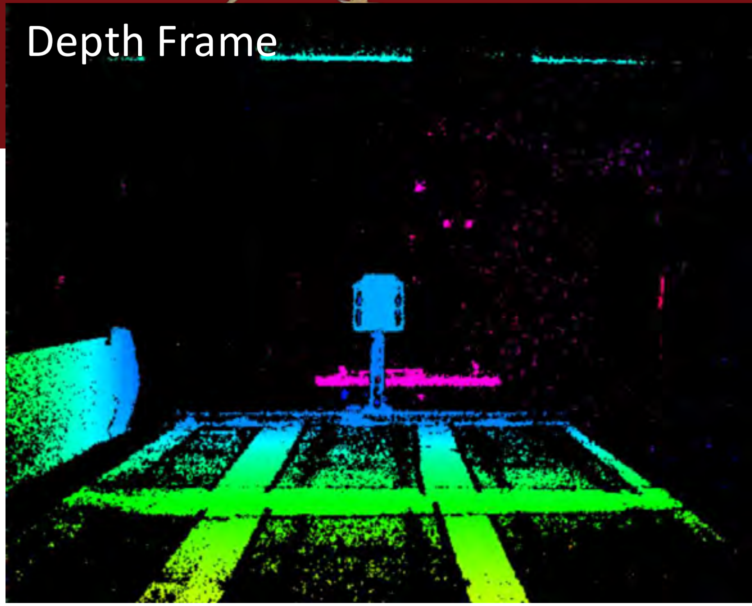
Point Cloud Based Relative Navigation

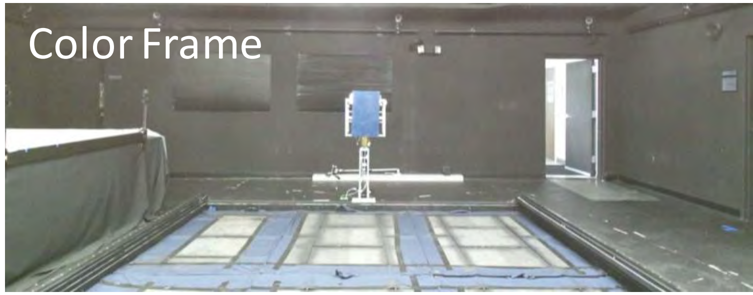
- Developed in Florida Tech Master's thesis
- Uses Microsoft Kinect2 time-of-flight sensor to generate point clouds of non-cooperative target object
- Uses Color Iterative Closest Point algorithm to identify transformation matrices between point clouds in successive frames
- Transformation matrices contain relative roll, pitch, yaw angles and position
- Laboratory tests show accuracy of 1-5 mm at distance of 3 m

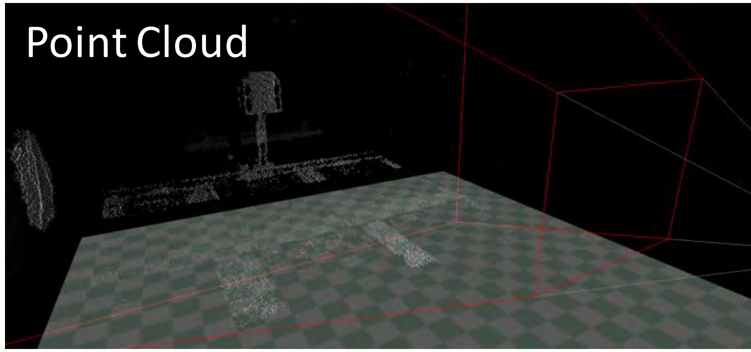












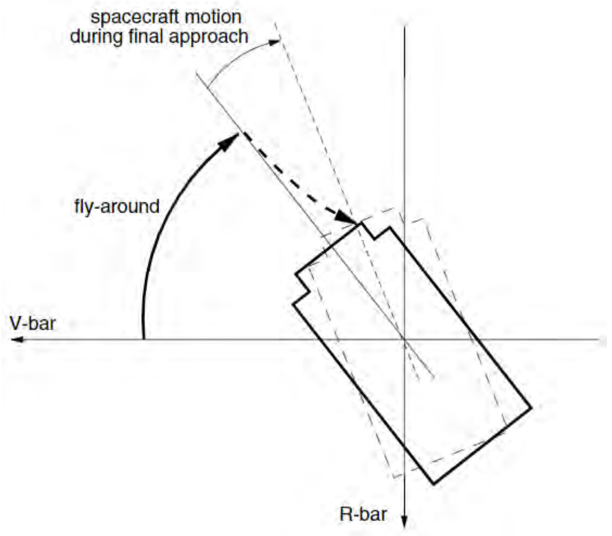
Rotating Targets

- In on-orbit servicing or debris removal scenarios, the majority of RVD targets is non-cooperative
  - No sensor fiducials
  - No capture interface
  - Rotation or tumbling motion
  - Exact geometry may not be known

- Typical rotation/tumbling rates
  - Inertial rotation: < 0.1°/s
  - Failed three-axis stabilization: 4 – 5°/s
  - Upper stage in flat spin: up to 40°/s

Slow Rotation Rates: Fly-Around

- To align with the capture axis, the chaser must match rotation rate and lateral velocity.
  - Radial fly-around
  - Multi-pulse fly-around
  - Forced motion circular flyaround



Forced motion in-plane flyaround at distance R_{fa} and angular rate $\dot{\alpha}$:

Equations of motion:

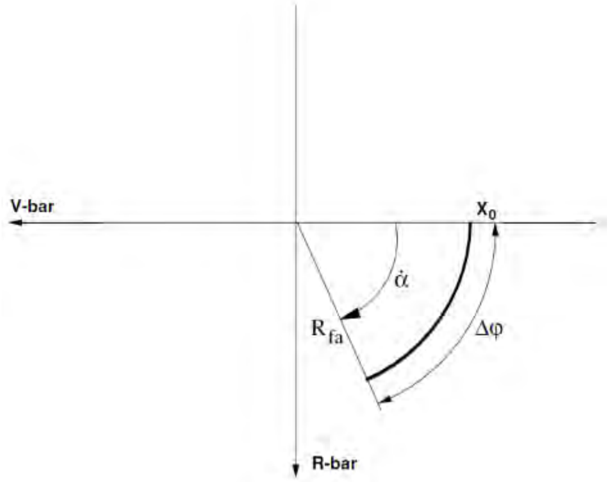
$x(t) = -R_{fa}\cos(\dot{\alpha}t)$

$y(t) = 0$

$z(t) = R_{fa}\sin(\dot{\alpha}t)$

Initial burn:

$\Delta V_{zi} = R_{fa}\dot{\alpha}$



Thrust profile:

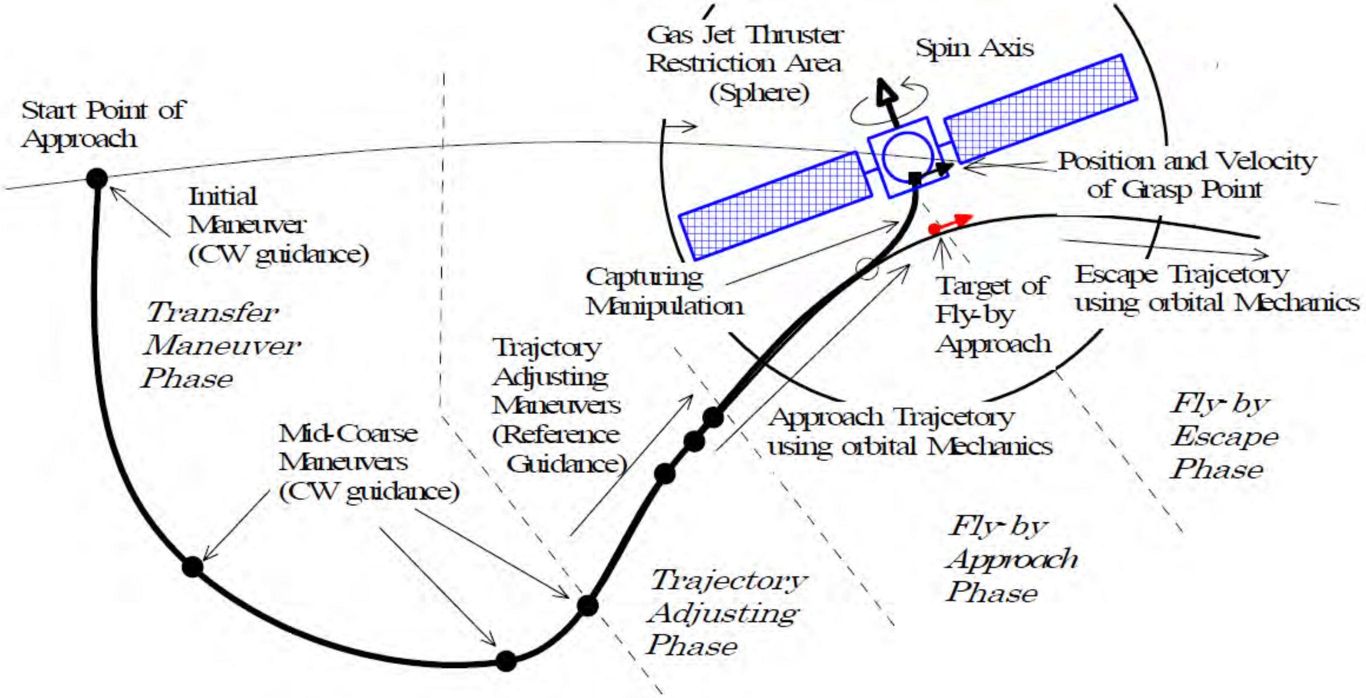
$\gamma_x(t) = -R_{fa}\dot{\alpha}(2\omega - \dot{\alpha})\cos(\dot{\alpha}t)$

$\gamma_z(t) = -R_{fa}(\dot{\alpha}^2 - 2\omega\dot{\alpha} + 3\omega^2)\sin(\dot{\alpha}t)$

W. Fehse: Automated Rendezvous and Docking of Spacecraft

Medium Rotation Rates: Flyby Approach

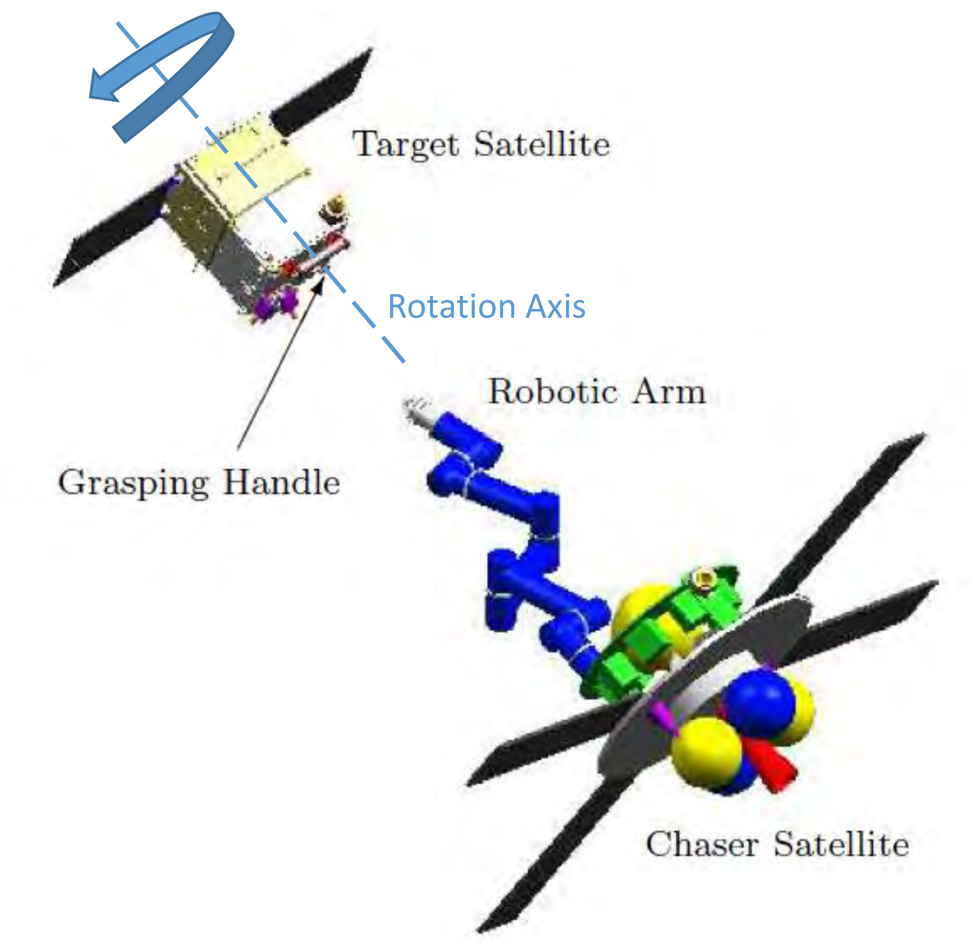
- Chaser is set on a free-drift flyby trajectory, bringing it to within capture range of the target with zero relative velocity.
- Minimizes plume impingement at close range.
- If capture fails, chaser naturally escapes.



Matsumoto, S., Jacobsen, S., Dubowsky, S, and Ohkami, Y., "Approach Planning and Guidance for Uncontrolled Rotating Satellite Capture Considering Collision Avoidance," *Proceedings of the 7th International Symposium on Artificial Intelligence, Robotics and Automation in Space: i-SAIRAS 2003*, Nara, Japan, 2003.

High Rotation Rates: Axis Approach

- For high rotation rates, trying to match the velocity of the capture point with a fly-around or a flyby maneuver would result in excessive propellant consumption and very large forces during capture.
- The alternative is to position the chaser spacecraft on the rotation axis of the target and then grasp the target with a robot manipulator.
- This results in low impact forces and more predictable contact dynamics.
- The challenge is: will there be a good capture feature on or near the rotation axis?



FIT Research: Sliding Mode Control

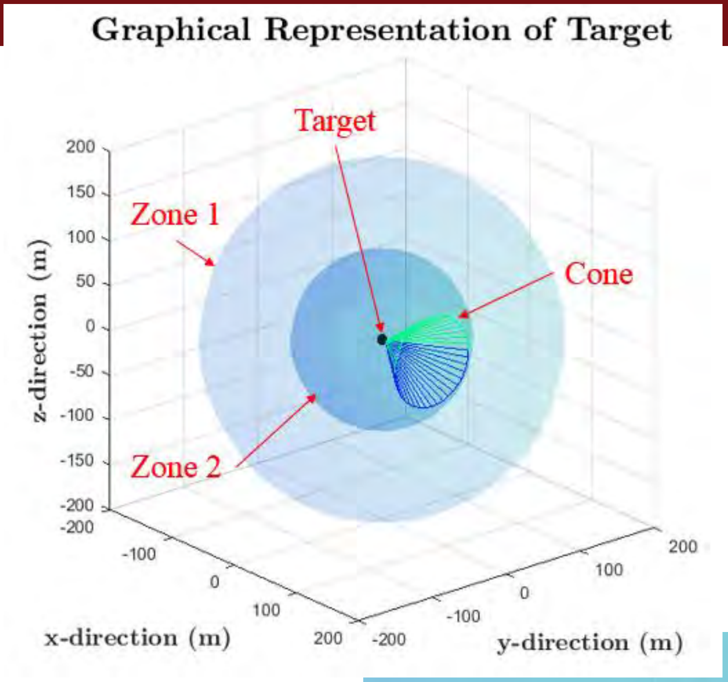
- Development and simulation of a sliding mode control to guide chaser through a maneuvering sphere into final approach cone
  - Cone: safe approach for chaser
  - Zone 2: Keep-out sphere, chaser must not enter
  - Zone 1: Maneuvering zone to match target orientation and rotation rates
- Builds on CW equations to describe Spacecraft motion

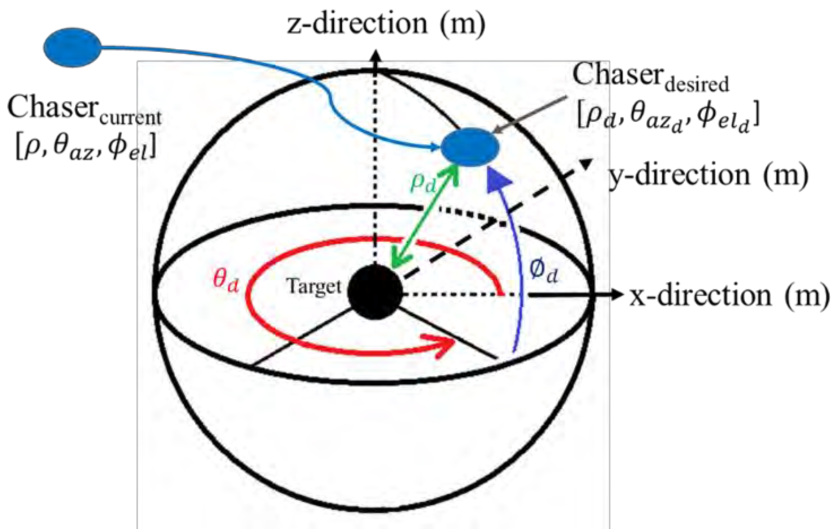
$$\boldsymbol{\tau_i} = \left[\widehat{\boldsymbol{H}}\ddot{\boldsymbol{q}}_{\boldsymbol{r}} + \widehat{\boldsymbol{C}}\dot{\boldsymbol{q}}_{\boldsymbol{r}} + \widehat{\boldsymbol{g}}\right]_i - [\,\boldsymbol{k}\,]_i \cdot \left[sat\left(\frac{s_i}{\delta_{bound}}\right)\right]_i$$

$$\boldsymbol{k_i} = \left|\left(\widetilde{\boldsymbol{H}}\ddot{\boldsymbol{q}}_{\boldsymbol{r}} + \widetilde{\boldsymbol{C}}\dot{\boldsymbol{q}}_{\boldsymbol{r}} + \widetilde{\boldsymbol{g}}\right)_i\right| + \boldsymbol{\eta_i}$$

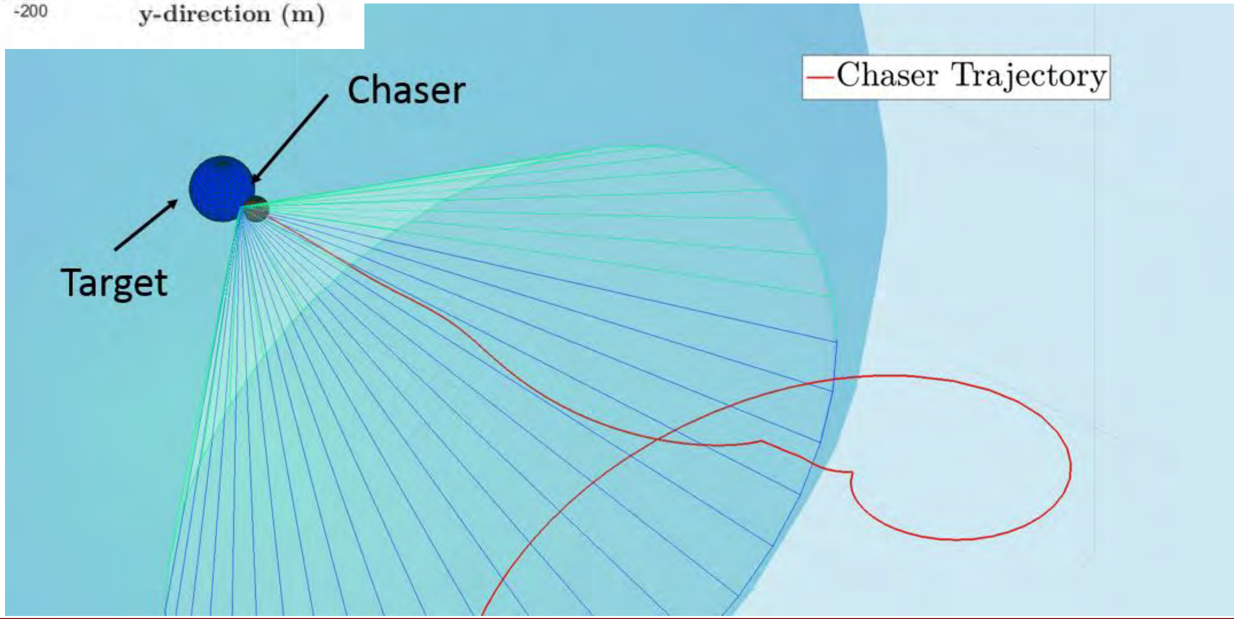
$$i = [x, y, z]^t$$

$$\widehat{\boldsymbol{H}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \widehat{\boldsymbol{C}} = \begin{bmatrix} 0 & -2\psi & 0 \\ 2\psi & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad \widehat{\boldsymbol{g}} = \begin{bmatrix} -3\psi^2 x \\ 0 \\ \psi^2 z \end{bmatrix}$$





S. Kwok-Choon, M. Wilde, and T. Go: “Modified sliding control for tumbling satellite capture with robotic arm,” 2016 *IEEE Aerospace Conference,* doi: 10.1109/AERO.2016.7500530



Capture

Multi-body Dynamics and Capture Mechanisms

Spacecraft-Manipulator Dynamics

- The mass of the manipulator pulls the center of mass of the system from the COM of the spacecraft.
- As the linear and angular momenta about the system's COM is conserved, any motion of the arm will cause translation and rotation in the base spacecraft.
- Contact between the end-effector and a grasping target will cause the whole system to rotate and translate, depending on the inertia distribution in the system and the rigidity of the robot joints.

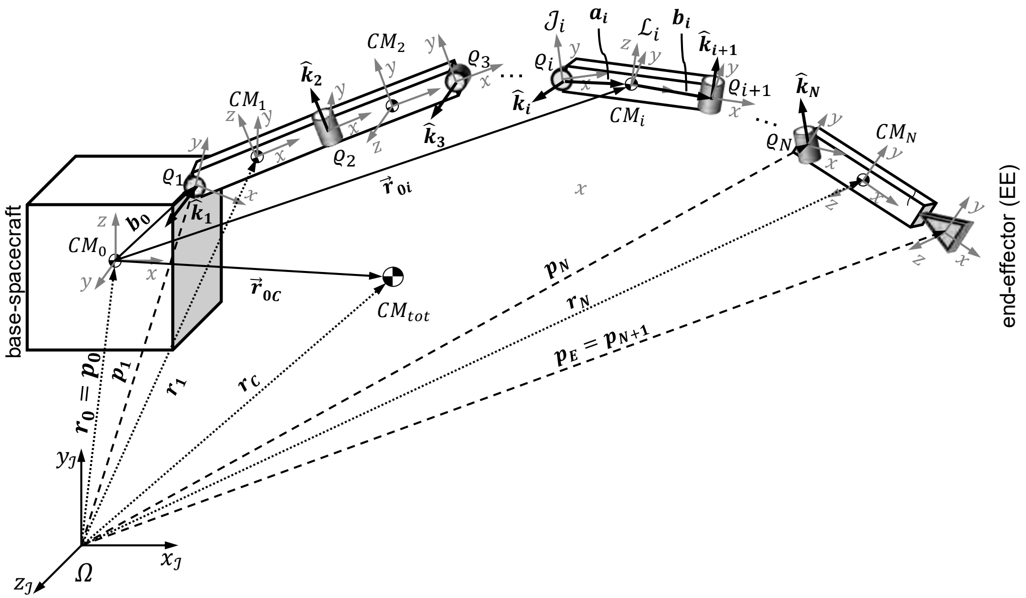
6 DOF Equations of Motion

M. Wilde, S. Kwok Choon, A. Grompone, and M. Romano: "Equations of Motion of Free-Floating Spacecraft-Manipulator Systems: An Engineer's Tutorial," *Frontiers in Robotics and AI*, 18 April 2018, doi: 10.3389/frobt.2018.00041.

- The EOM of a spacecraft manipulator system are given by:

$$\begin{bmatrix} \boldsymbol{H_0} & \boldsymbol{H_{0m}} \\ \boldsymbol{H_{0m}^T} & \boldsymbol{H_m} \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{x}}_0 \\ \ddot{\boldsymbol{q}} \end{bmatrix} + \begin{bmatrix} \dot{\boldsymbol{H}}_0 & \dot{\boldsymbol{H}}_{0m} \\ \dot{\boldsymbol{H}}_{0m}^T & \dot{\boldsymbol{H}}_m \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{x}}_0 \\ \dot{\boldsymbol{q}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{c_0} \\ \boldsymbol{c_m} \end{bmatrix} = \begin{bmatrix} 0 \\ \boldsymbol{\tau} \end{bmatrix}$$

$\boldsymbol{H_0}$:	base spacecraft inertia matrix (6 x 6)
$\boldsymbol{H_{0m}}$:	spacecraft manipulator coupling matrix (6 x N)
$\boldsymbol{H_m}$:	manipulator inertia matrix (N x N)
$\boldsymbol{c_0}, \boldsymbol{c_m}$:	non-linear coupling terms



- Linear and angular momenta are conserved, as long as there are no external forces and torques acting:

$$\begin{bmatrix} \boldsymbol{P} \\ \boldsymbol{L} \end{bmatrix} = \boldsymbol{H_0}\dot{\boldsymbol{x}}_0 + \boldsymbol{H_{0m}}\dot{\boldsymbol{q}} = \boldsymbol{M_0}$$

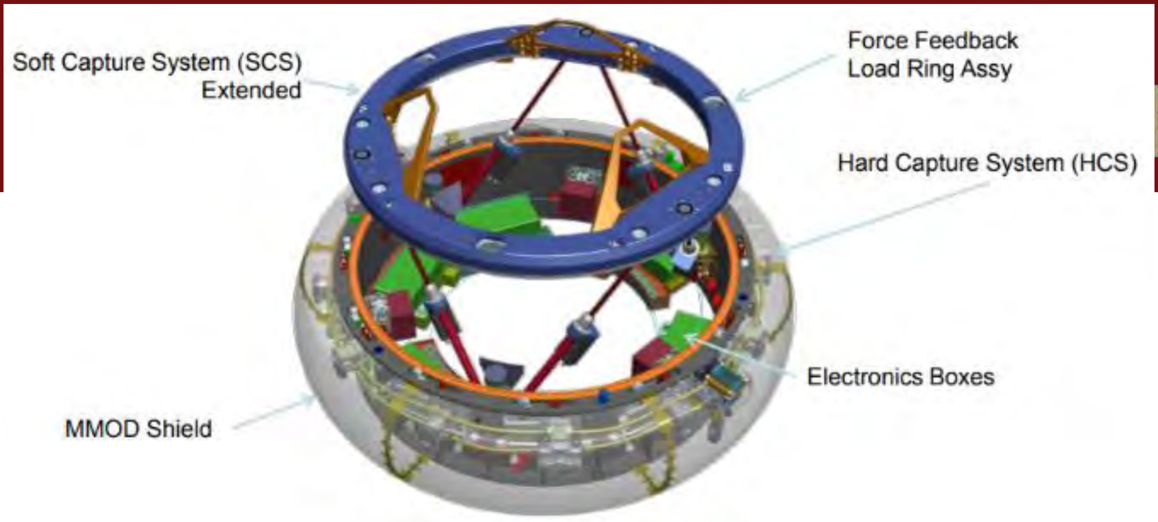
$$\frac{d}{dt}\begin{pmatrix} \boldsymbol{P} \\ \boldsymbol{L} \end{pmatrix} = \boldsymbol{H_0}\ddot{\boldsymbol{x}}_0 + \boldsymbol{H_{0m}}\ddot{\boldsymbol{q}} + \dot{\boldsymbol{H}}_0\dot{\boldsymbol{x}}_0 + \dot{\boldsymbol{H}}_{0m}\dot{\boldsymbol{q}} = 0$$

Generalized EOM:

$$\boldsymbol{H}^\star\ddot{\boldsymbol{q}} + \dot{\boldsymbol{H}}^\star\dot{\boldsymbol{q}} + \boldsymbol{c}^\star = \boldsymbol{\tau}$$

$\boldsymbol{H}^\star = \boldsymbol{H_m} - \boldsymbol{H_{0m}^T}\boldsymbol{H_0^{-1}}\boldsymbol{H_{0m}}$: Generalized Inertia Tensor

Crewed Spacecraft



NASA Docking System

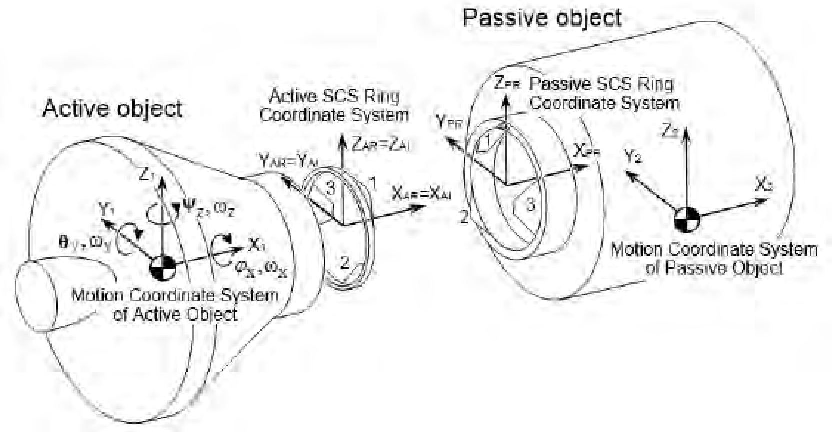
- Supports crewed spacecraft docking
  - ISS visitation
  - Exploration beyond LEO
  - Crew rescue
  - International cooperative missions
- Chaser vehicle sizes:
  - Light: 5,000 – 8,000 kg
  - Medium: 8,000 – 25,000 kg
- Target vehicle sizes
  - Large space complex: 100,000 – 375,000 kg
  - Earth departure stage: 33,000 kg – 170,000 kg

TABLE 3.3.1.1-2 INITIAL CONTACT CONDITIONS

Initial Condition	Limiting Value
Closing (axial) rate	0.05 to 0.10 m/sec
Lateral (radial) rate	0.04 m/sec
Pitch/Yaw rate	0.20 deg/sec (vector sum of pitch/yaw rate)
Roll rate	0.20 deg/sec
Lateral (radial) misalignment	0.10 m
Pitch/Yaw misalignment	4.0 deg (vector sum of pitch/yaw)
Roll Misalignment	4.0 deg

Notes:

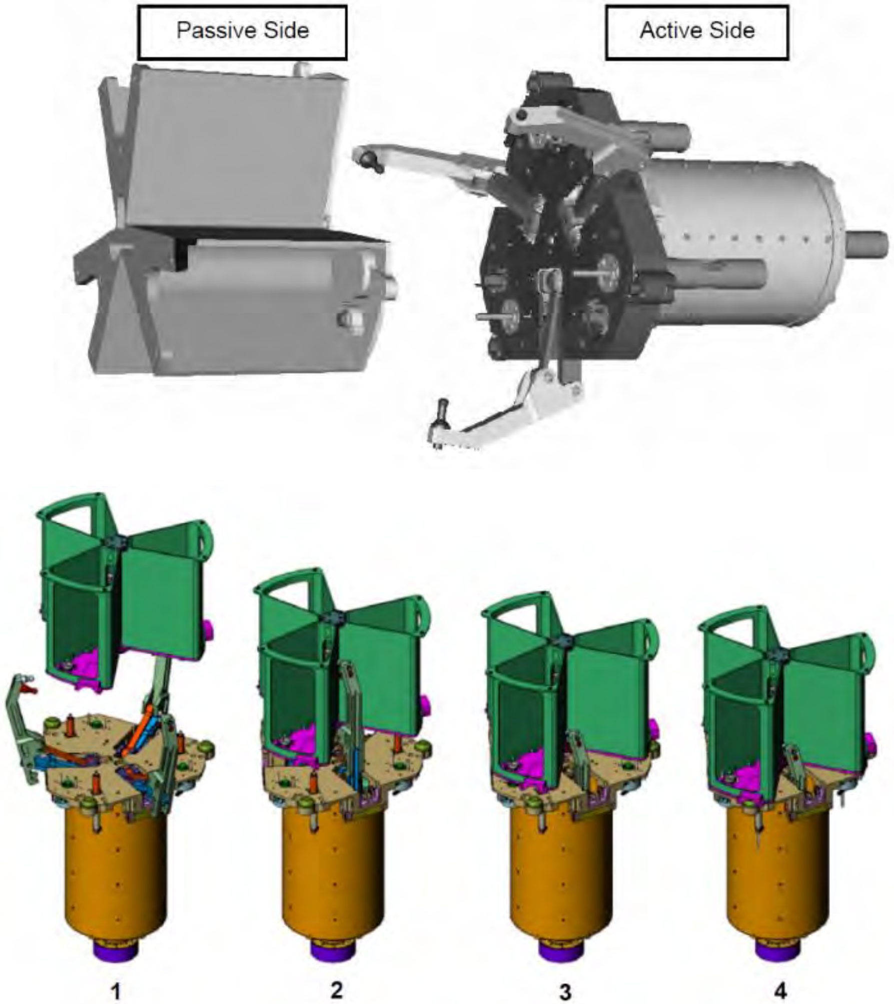
1. Initial contact conditions are independent and are to be applied simultaneously, with the exception that the lateral rate at the vehicle cg resulting from the combination of lateral (radial) rate and the pitch/yaw angular rate should not exceed the lateral (radial) rate limit.
2. Mean closing (axial) rate may be adjusted depending on vehicle mass combinations. Refer to Table 3.3.1.2-1.
3. Post contact thrust may be used to achieve necessary capture performance.
4. Lateral (radial) misalignment is defined as the minimum distance between the center of the active soft capture ring and the longitudinal axis of the passive soft capture ring at the moment of first contact between the guide petals.



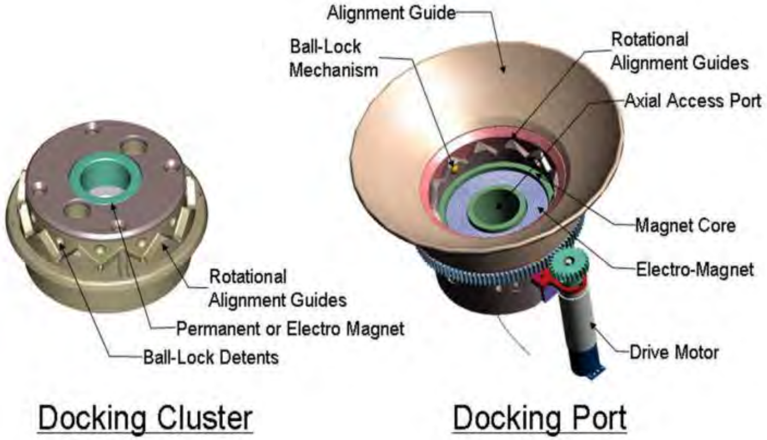
Robotic Spacecraft: Cooperative

FLORIDA TECH

Orbital Express Capture System



NASA Magnetic Capture Docking System

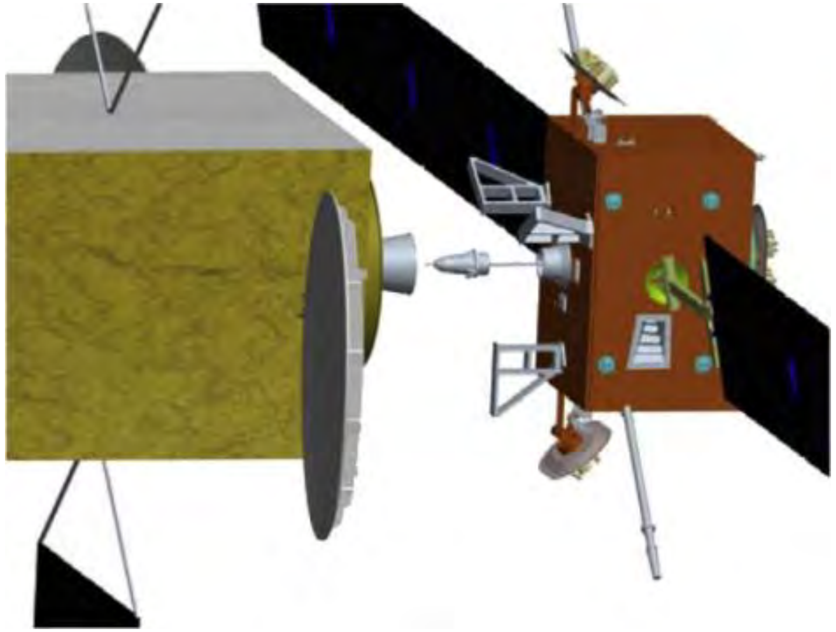


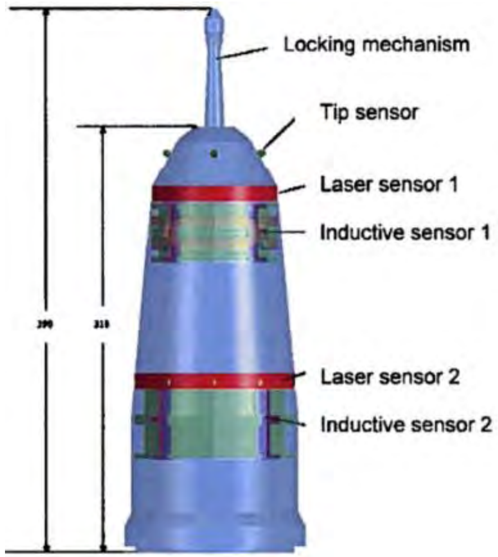
SPHERES Docking Port

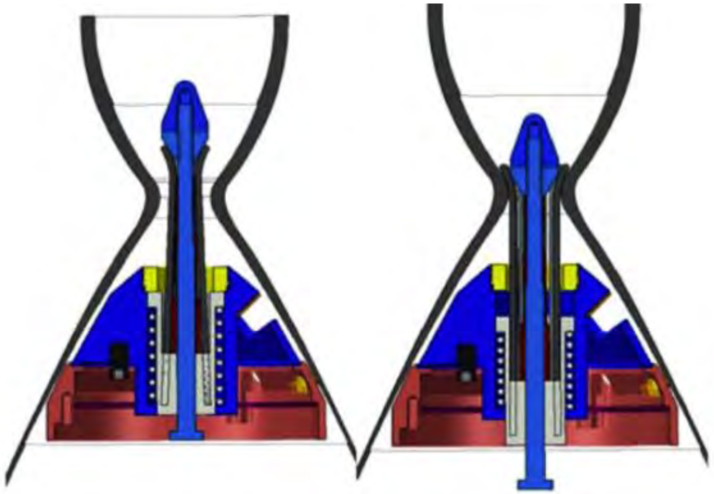
Non-Cooperative Capture

Rocket Nozzle Capture Tool

- Designed to dock with the current generation of GEO communication satellites
- Nozzle of apogee kick motor is reasonable docking interface for life extension missions
- Problem: Will be brittle after burn

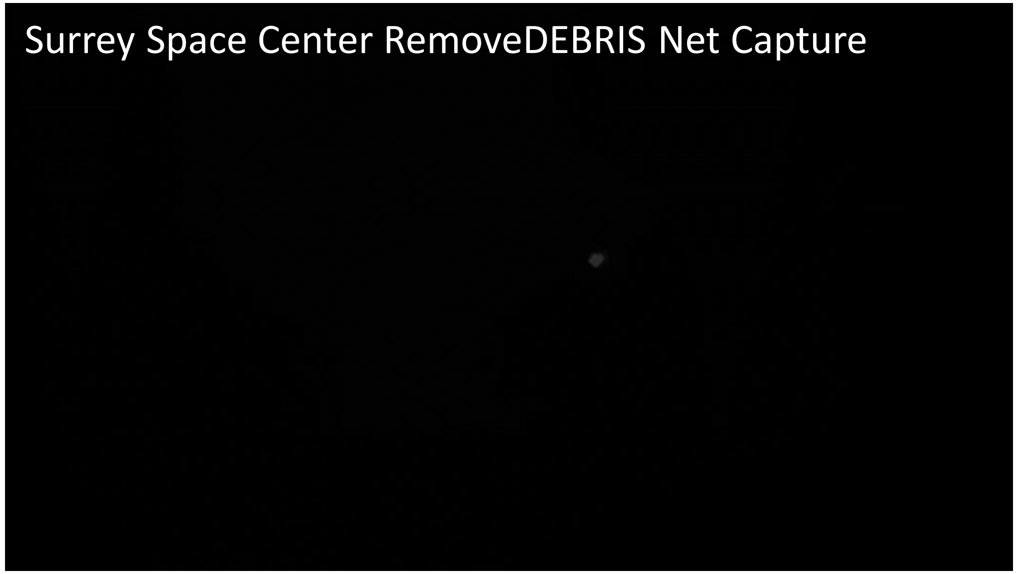






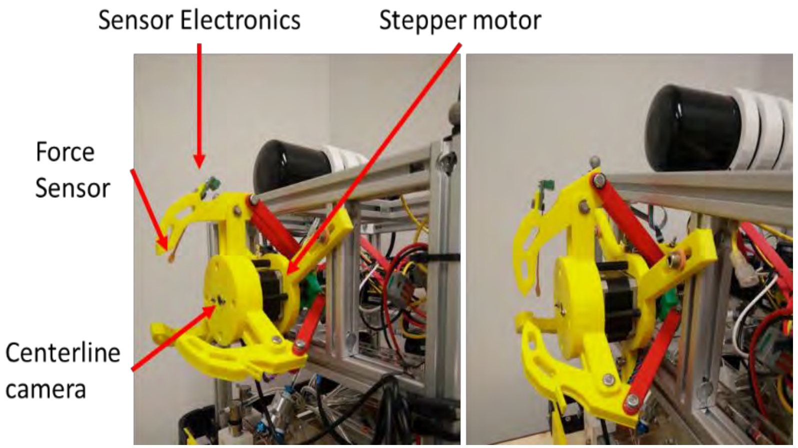
Space Debris Capture

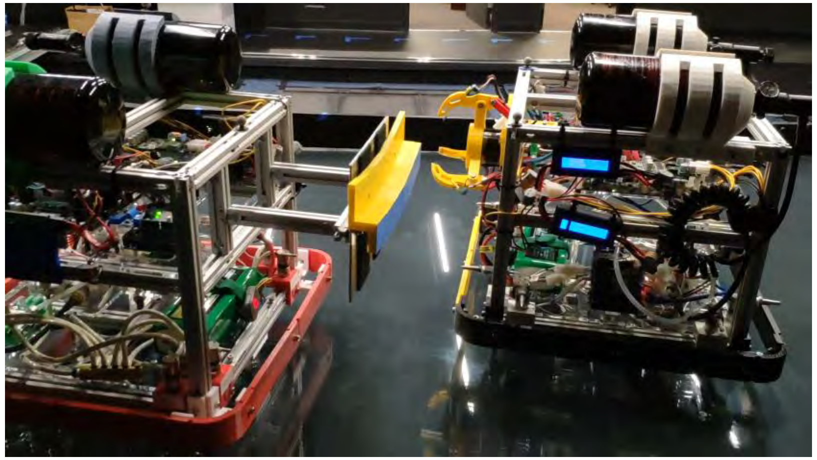
- Debris Capture Methods
  - Stiff Connection
    - Tentacles
    - Robotic Arm
      - Single Arm
      - Multiple Arms
  - Flexible Connection
    - Net
    - Tether-Gripper
    - Harpoon
    - Ropes
    - Bolos



FIT Capture Concepts & Prototypes

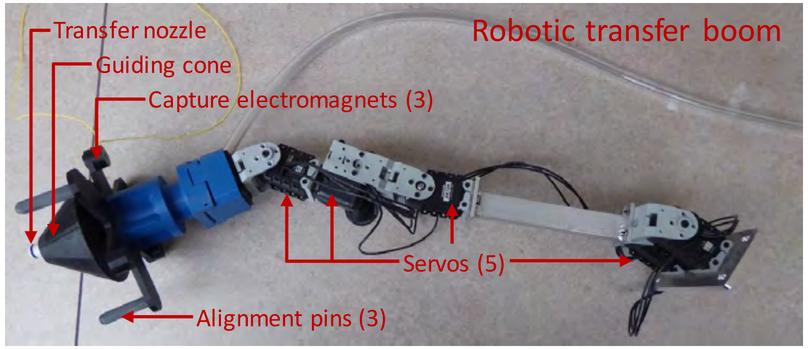
Capture Gripper

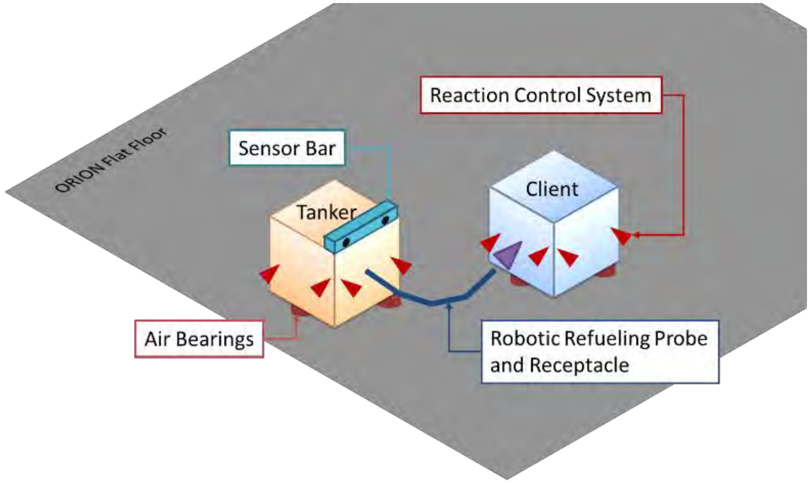


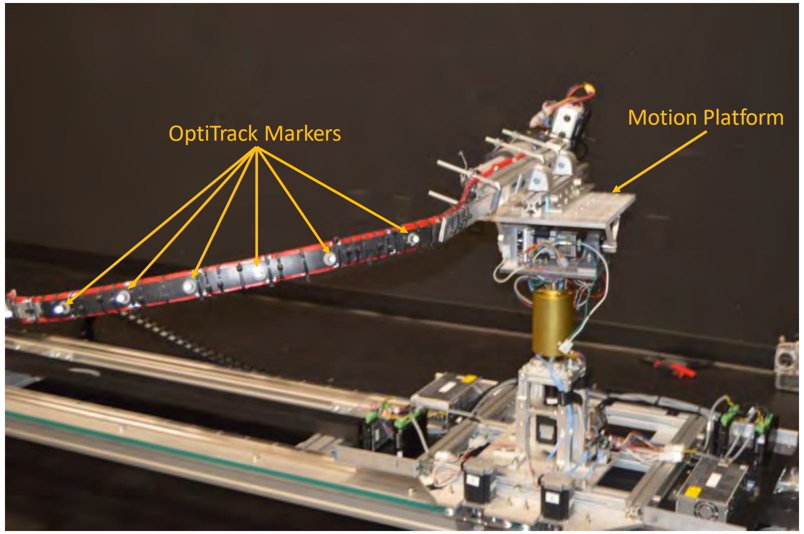


S Kwok Choon, K Buchala, B Blackwell, S Lopresti, M Wilde, and T Go: "Design , Fabrication , and Preliminary Testing of Air- Bearing Test Vehicles for the Study of Autonomous Satellite Maneuvers," *Florida Conference on Recent Advances in Robotics*, 2018

Robotic Refueling System







M. Wilde, I. Walker, S. Kwok Choon, and J. Near: "Using Tentacle Robots for Capturing Non-Cooperative Space Debris – A Proof of Concept", *AIAA SPACE and Astronautics Forum and Exposition*, 2017, doi: 10.2514/6.2017-5246

Testing

Verification & Validation

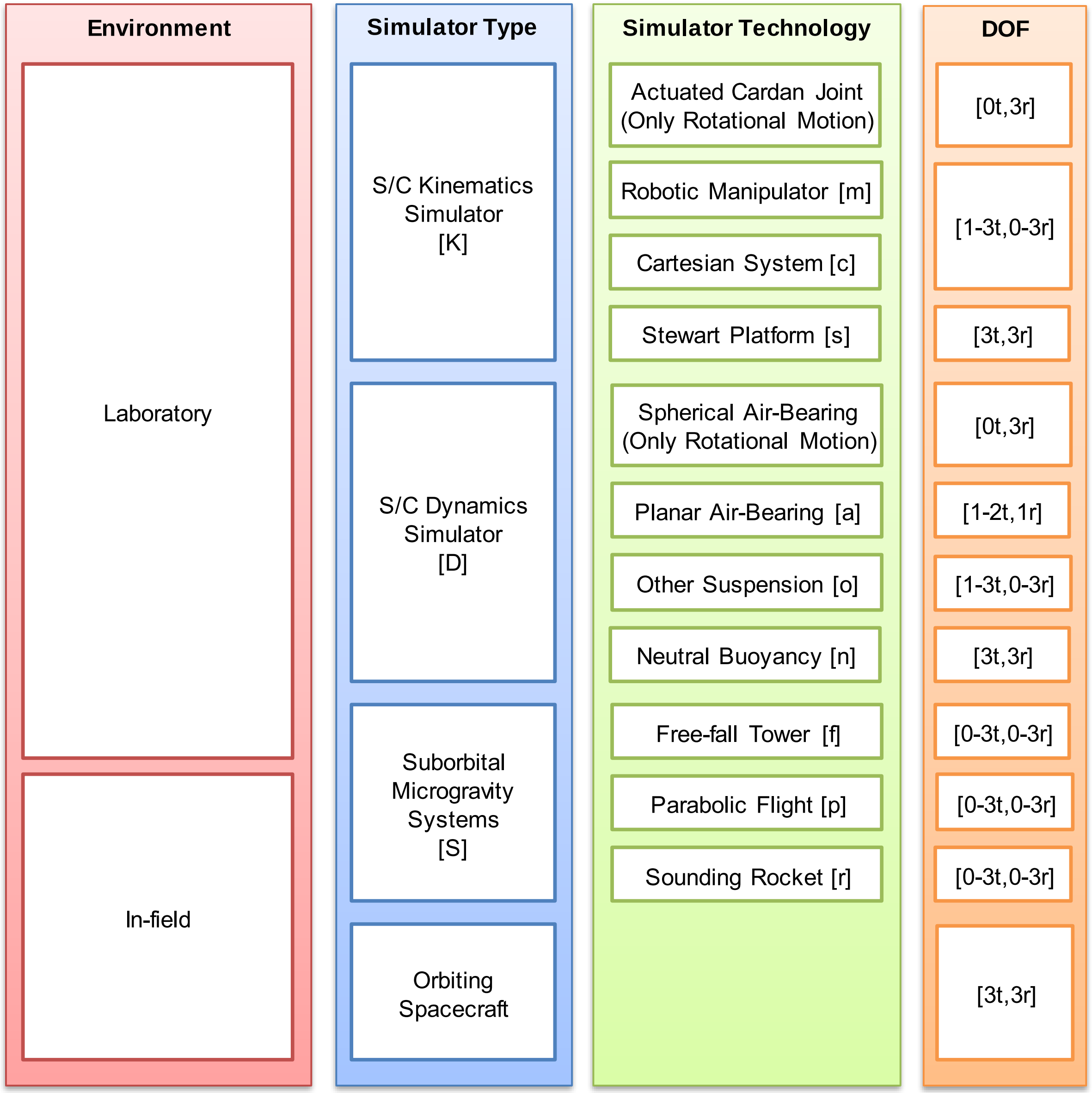
V&V Methods

- Goal: Reduction of mission risk to “acceptable” level.
- Hardware-in-the-loop testing with simulation of relevant environment parameters
- Does the test catch all the effects in the real world that could cause a risk during the operational phase?

	Analysis / Simulation	Experiment / Test	Remaining Uncertainty	
Orbital perturbation models	X		Low	
Plume interaction models		X	Low	
Thrusters	X	X	Low	
Mass, CoM position, inertia	X		Low	
Flexible appendages	X		Low	
Fuel sloshing	X		Moderate	
Sensors		X	Low	Relative Kinematics Simulator with Lighting Simulation
Sensor disturbance environment		X	Low	
Chaser / Target dynamics	X		Low	
S/C relative kinematics	X		Low	
Contact dynamics		X	Low	Spacecraft Dynamics Simulator
Capture latch kinematics		X	Low	

Spacecraft Motion Simulator Types

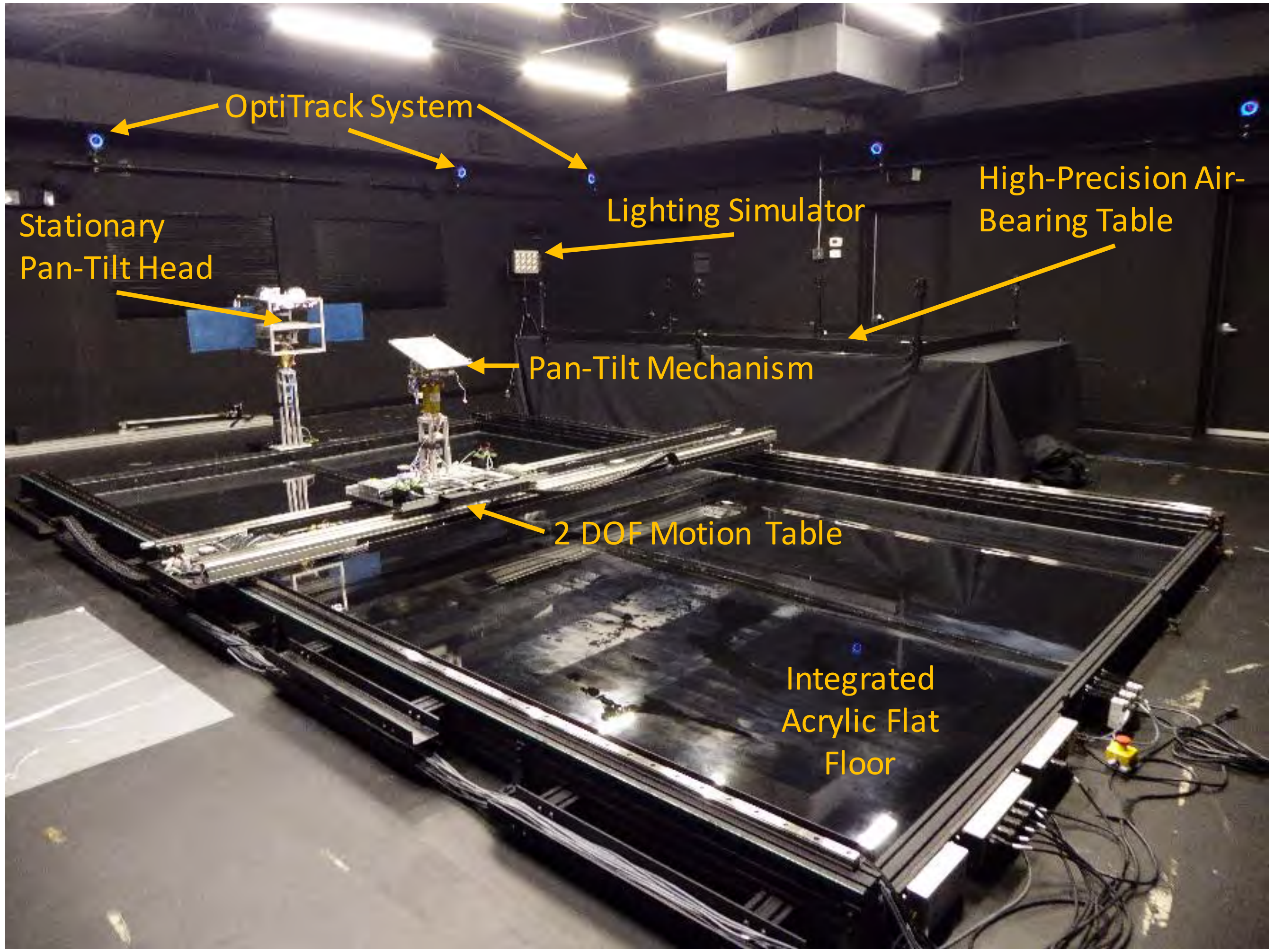
- Robotic rendezvous, capture and servicing systems require hardware-in-the-loop testing in motion simulators
  - Sensor performance
  - GNC systems
  - Mechanisms
  - Telerobotics and autonomy
- Simulators must recreate:
  - Maneuver kinematics
  - Multi-body dynamics, incl. contact dynamics
  - Lighting



Example: Florida Tech ORION Lab

Orbital **R**obotics **I**nteraction, **O**n-orbit servicing, and **N**avigation lab

- Maneuver kinematics simulator (4 + 2 DOF)
- Maneuver dynamics simulator (3 DOF)*
- Lighting simulation
- Object tracking system
- Control stations for telerobotics and supervised autonomy
- Use of air-bearing vehicles and quadcopters for spacecraft robotics experimentation and testing



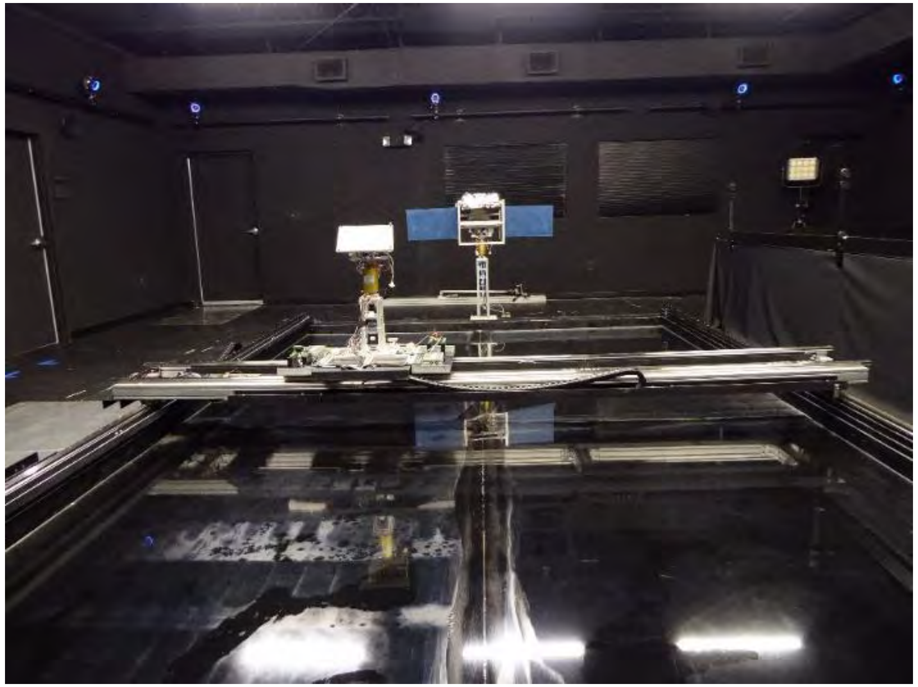
M. Wilde, B. Kaplinger, T. Go, H. Gutierrez, and D. Kirk: "ORION: A Simulation Environment for Spacecraft Formation Flight, Capture, and Orbital Robotics", *Proceedings of the 2016 IEEE Aerospace Conference*, Big Sky, MT, 2016, doi: 10.1109/AERO.2016.7500575

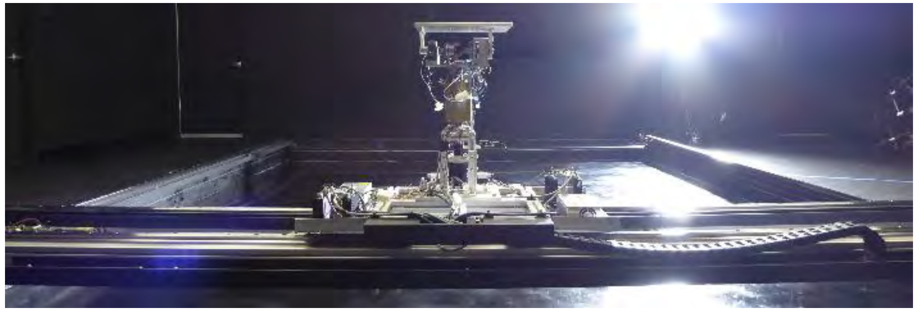
*6 DOF in development

Maneuver Kinematics Simulator

- Planar, gantry-based simulator for relative motion between two spacecraft
- Workspace: 5.5 m x 3.5 m
- Pan-tilt mechanisms for test articles of up to 20 kg, supplied with 120 V AC and Ethernet
- Pan-tilt heads can be removed to support other mechanisms, such as robotic manipulators
- Enables sensor testing, GNC law verification, teleoperation experiments, etc.
- Total 6 degrees of freedom

Degree of Freedom	Motion Range	Max. Vel.	Max. Accel.
Chaser x translation	5.5 m	0.25 m/s	1 m/s^2
Chaser y translation	3.5 m	0.25 m/s	1 m/s^2
Chaser pitch	±90°	60°/s	$60°/s^2$
Chaser yaw	inf.	60°/s	$60°/s^2$
Target pitch	±90°	60°/s	$60°/s^2$
Target yaw	inf.	60°/s	$60°/s^2$



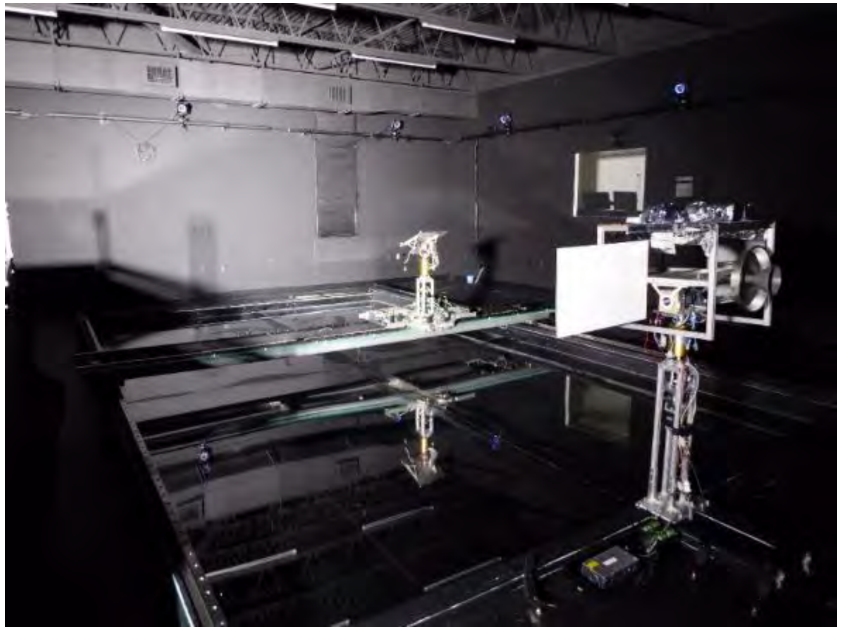


Maneuver Dynamics Simulators

Two air-bearing motion dynamics testbeds enable friction-free experiments of maneuver dynamics and contact dynamics of air-bearing vehicles.

Integrated Flat Floor

- 5.94 m x 3.60 m acrylic flat floor within the frames of the Maneuver Kinematics Simulator
- Enables coordinated use of gantry mechanism with air-bearing vehicles for kinematics/dynamics experiments such as robotic capture of debris objects

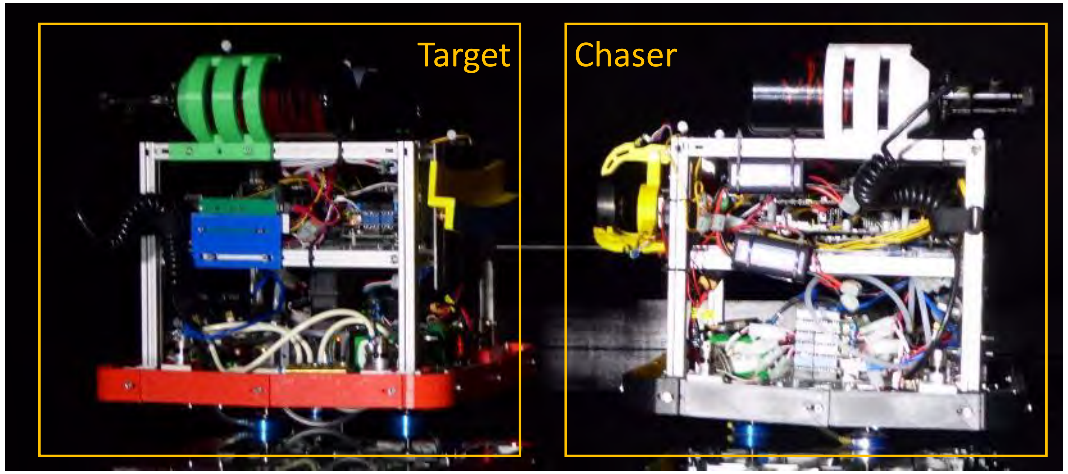


High-Precision Air-Bearing Table

- 3.6 m x 1.8 m tempered glass plate on optical bench with pneumatic vibration isolators
- Enables experiments in contact dynamics, spacecraft controls, formation flight, docking/capture, etc

Planar Air-Bearing Vehicles

- Planar air-bearing vehicles (ABV) are used for formation flight and docking/capture experiments
- Propulsion: custom thrusters using compressed N_2
- Attitude control: Thrusters or custom reaction wheels
- On-board computer: Intel i5
- Endurance: ~20 minutes
- Aluminum frame allows easy attachment of capture tools, docking interfaces, sensors, robot manipulators, etc.



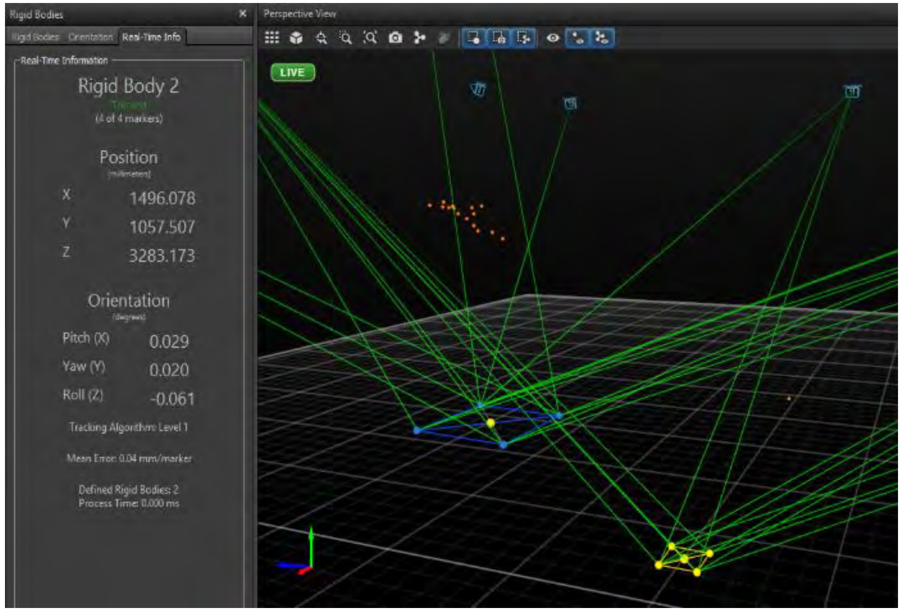
Chaser and target air-bearing vehicles (ABV)

Custom N_2 thrusters

Custom reaction wheel

OptiTrack System

- 12-camera OptiTrack Prime 17W system tracks objects within the ORION Lab with sub-millimeter and sub-degree accuracy
- Objects are defined by four infrared reflectors
- Used in closed-loop control of the Maneuver Kinematics Simulator
- For formation flight and docking experiments, OptiTrack can be used as stand-in for relative navigation sensors
- For sensor testing, the OptiTrack data serves as ground truth



Summary

- Space robotics will play an increasingly critical role in space science, commerce and exploration
  - On-orbit servicing
  - Debris removal
  - In-space assembly
- The critical technical challenges:
  - Relative navigation
  - GNC to capture non-cooperative objects
  - Capture dynamics
  - Capture mechanisms for non-cooperative objects
- Space robotics system require extensive, multi-disciplinary verification and validation, with substantial system-level, hardware-in-the-loop testing

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