"Front End Robotic Enabling Near-Term Demonstration (FREND) Technologies and Associated Servicing Architecture"

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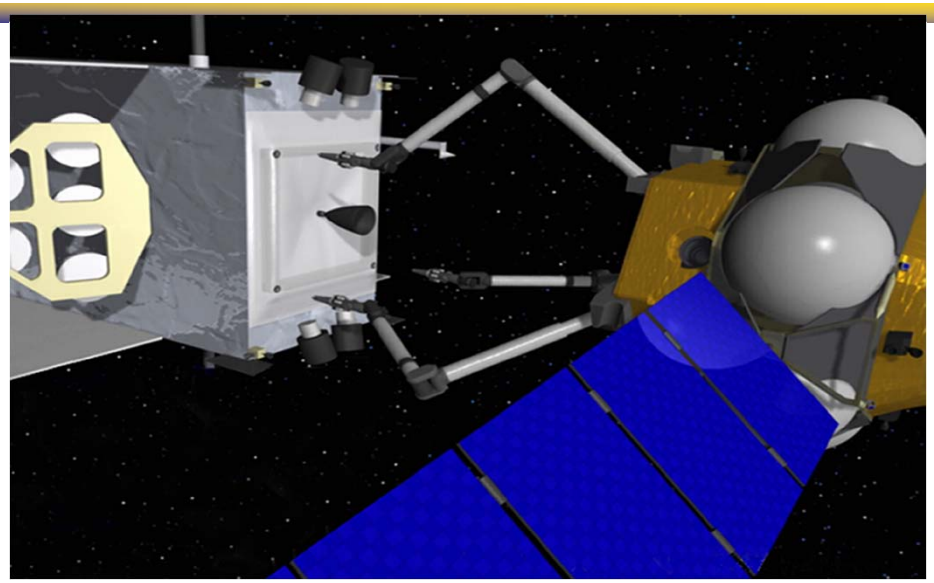
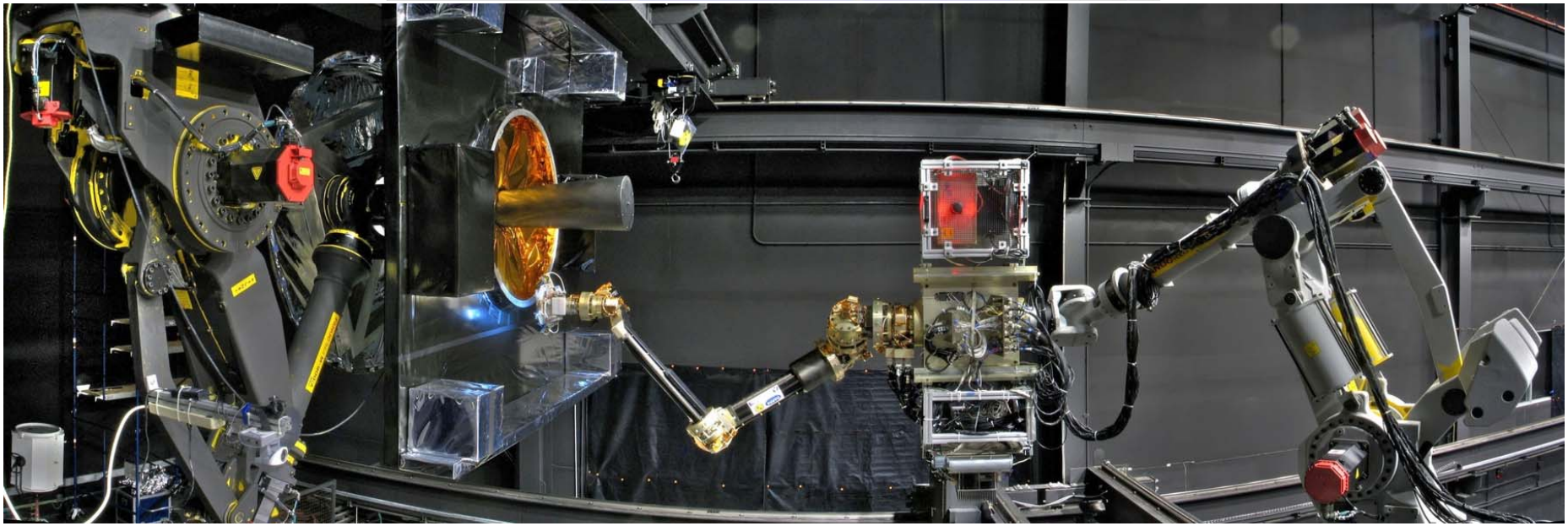
FREND Concept Vs. Reality





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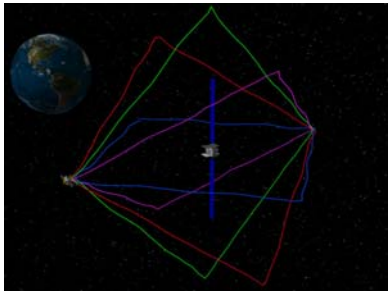
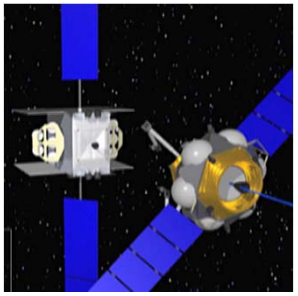
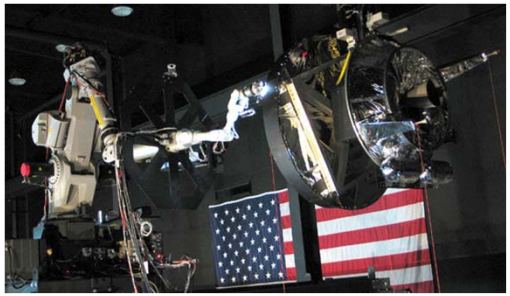
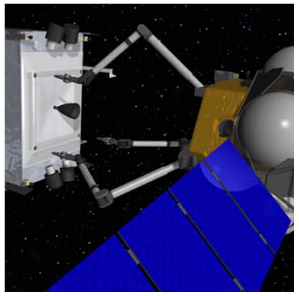
FREND Program Objectives

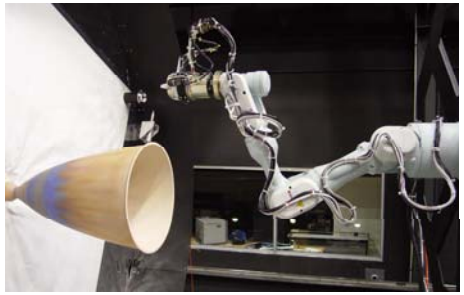
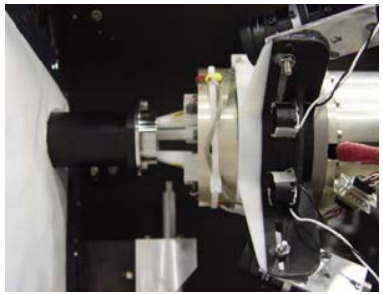
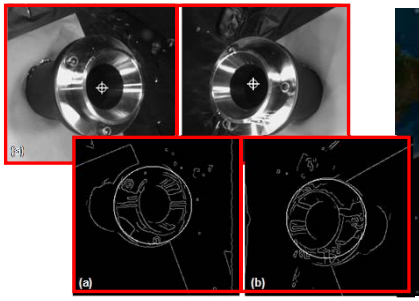
Advanced, Autonomous, Unaided Spacecraft Grappling

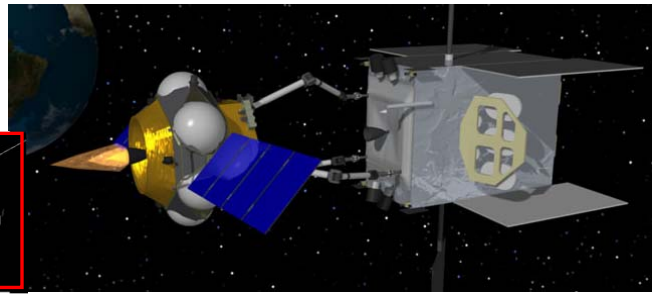
- Design a payload capable of autonomous rendezvous, capture, andboost of high value space assets
  - Require no modification of the customer spacecraft
  - Design one payload to service multiple customers
- Design, purchase, or investigate key subsystems necessary to meet program goals
  - Procure one 7+ DOF flight robotic arm
  - Develop a set of end effectors to allow capture of customer spacecraft structural hard points
  - Identify navigation sensor suite for long-range and close-proximity tracking, 3D imaging, and pose estimation
  - Determine flight processor requirements
  - Develop high-fidelity simulator for laboratory validation and orbit simulation
- Perform high-fidelity close-proximity testing under mission-like scenarios using NRL’s Proximity Operations Testbed

SUMO, Spacecraft for the Universal Modification of Orbits, 2003-2005

- **Design for GEO orbit change service for unaided assets**
  - **No pre-existing docking interface**
  - **No visual aids**
- **Supported by feasibility demo with full-scale hardware simulation**
  - **NRL proximity operations testbed**
  - **NRL developed control/vision algorithms**
  - **COTS non-flight robotics/sensors**



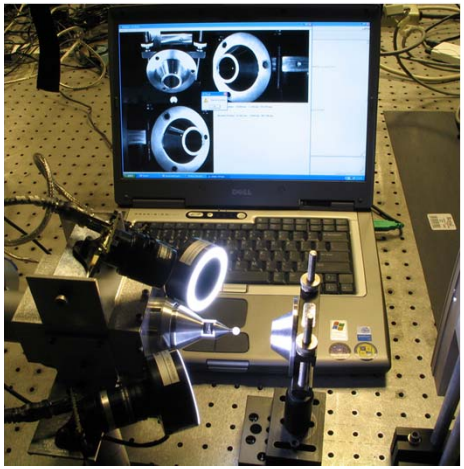
FREND, Front-end Robotics Enabling Near-term Demonstration, 2006-2008

- **Continue technology development towards spaceflight readiness, including moving to flight ready robotics, flight traceable sensors, processing, algorithms, autonomy, machine vision**

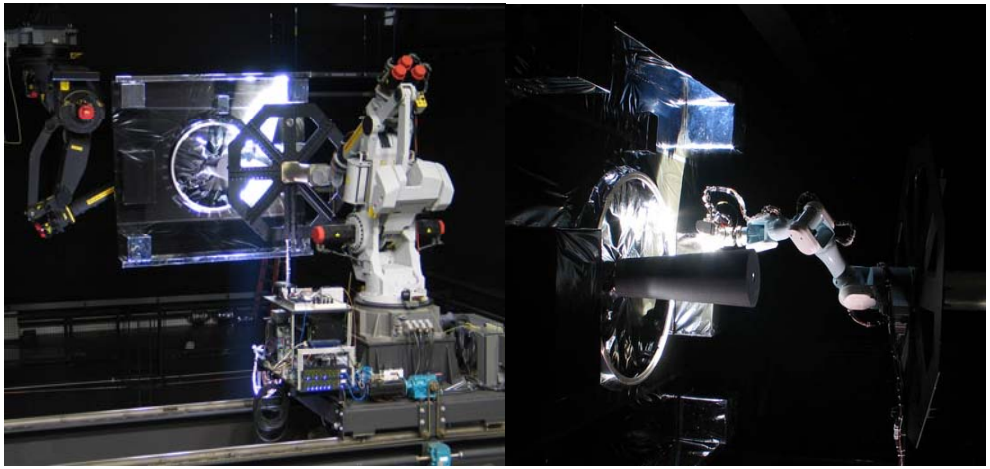
- **Procuring flight robotics from Alliance SpaceSystems**
  - **Designed and built to NRL’s specification**

- **Conducting full-scale tests of flight payload systems under increasingly realistic orbital conditions**

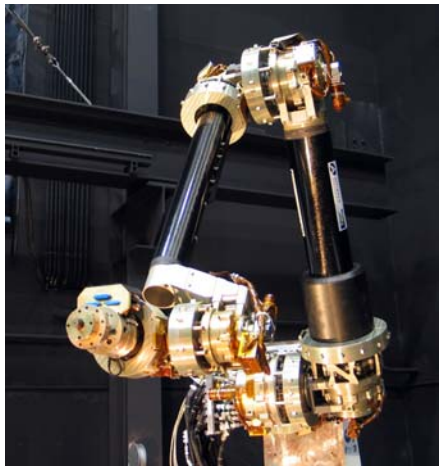
Machine Vision Testbed



Machine Full Scale Demo with Realistic Lighting



Prototype Robotic Arm



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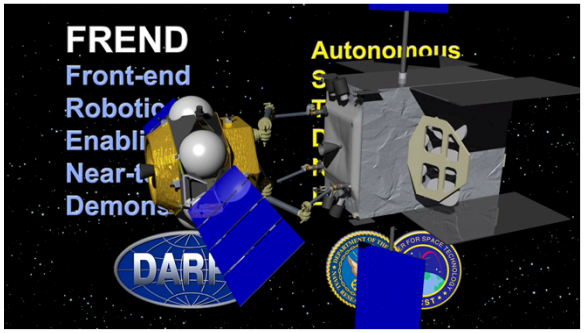
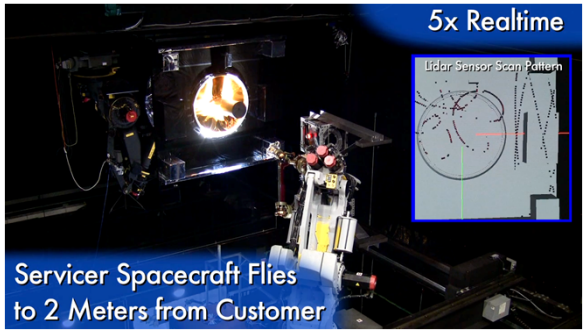
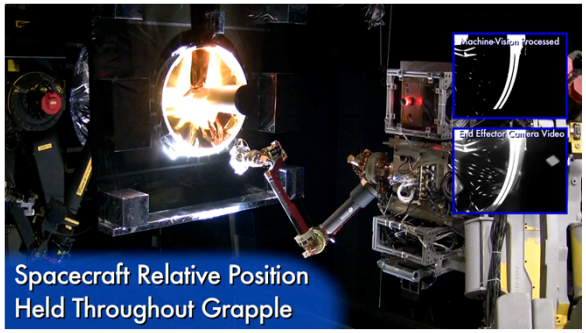
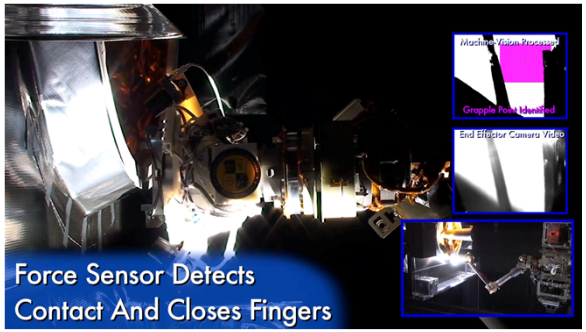
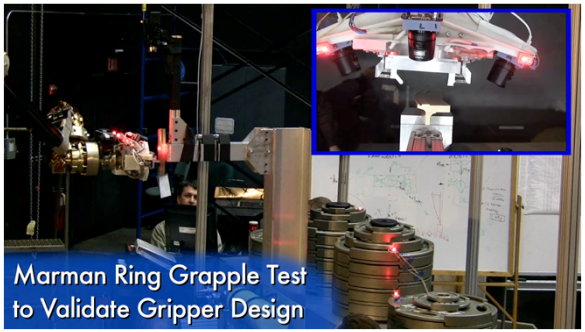
FREND System Demonstration Video

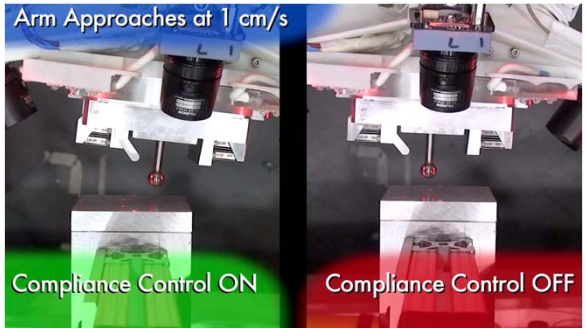


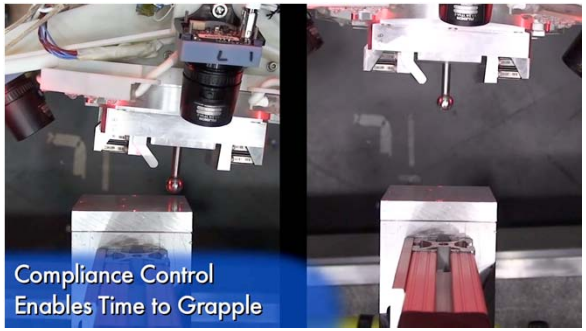


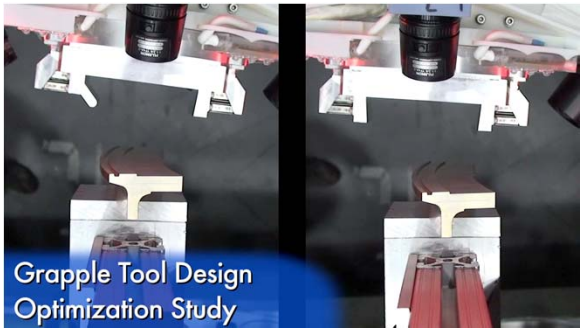












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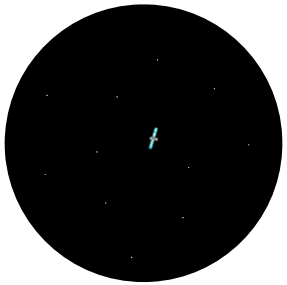
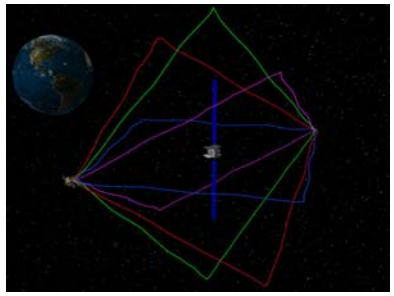
SUMO Mission Phases

Phase 0: Initial On-Orbit Deployment, Checkout, and Calibration

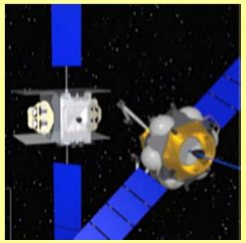
Phase 1: Acquire & Rendezvous
- 1.1: Long Range Navigation to 20 km Client Range and Bearing
- 1.2: Rendezvous 20 km ®1 km



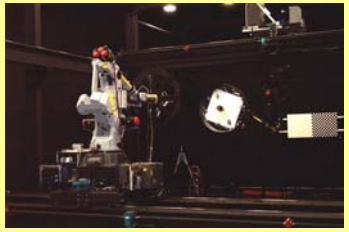
Phase 2: Survey & Inspection
- 2.1: Customer Survey
- 2.2: Data Downlink / Ground Process
- 2.3: Grapple Interface Detailed Survey



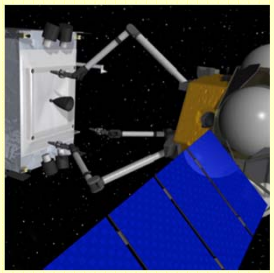
Phase 3: Approach to Capture
- 3.1: Grapple Final Preparation
- 3.2: Approach to Capture Box



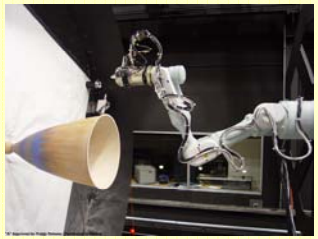
FREND Demo



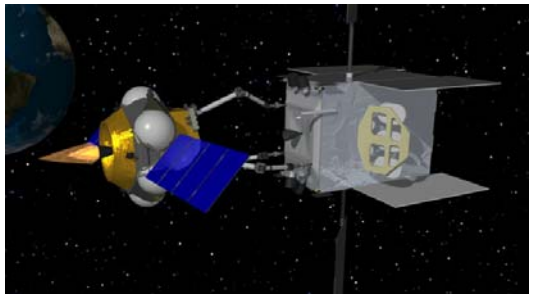
Phase 4: Grapple
- 4.1: First Arm Grapple
- 4.2: Three Arm Grapple
- 4.3: Grapple Rigidization



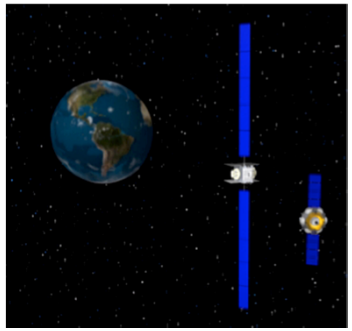
FREND Demo



Phase 5: Orbit Modification
- 5.1: Coupled Vehicle Checkout
- 5.2: Coupled Vehicle Steady State
- 5.3: Coupled Vehicle Thrusting

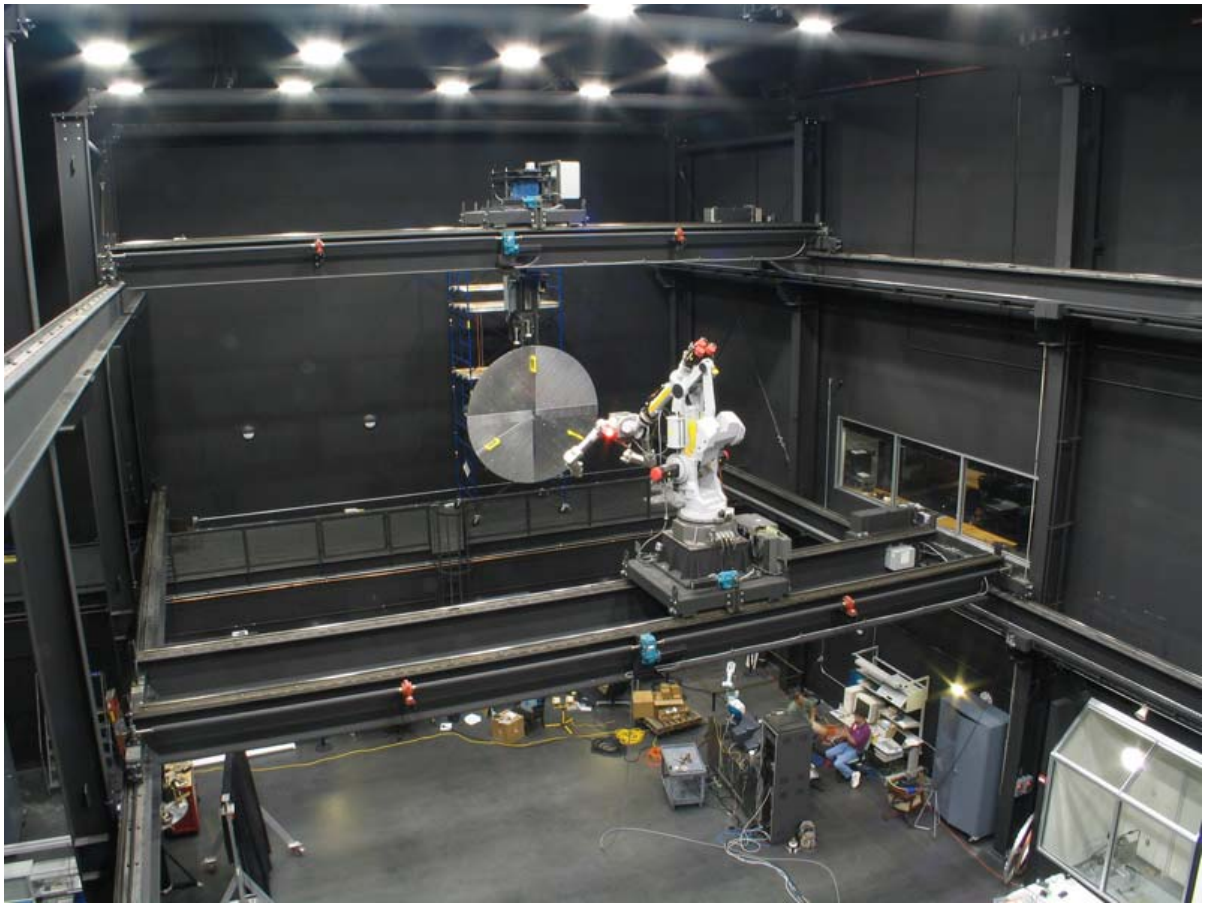


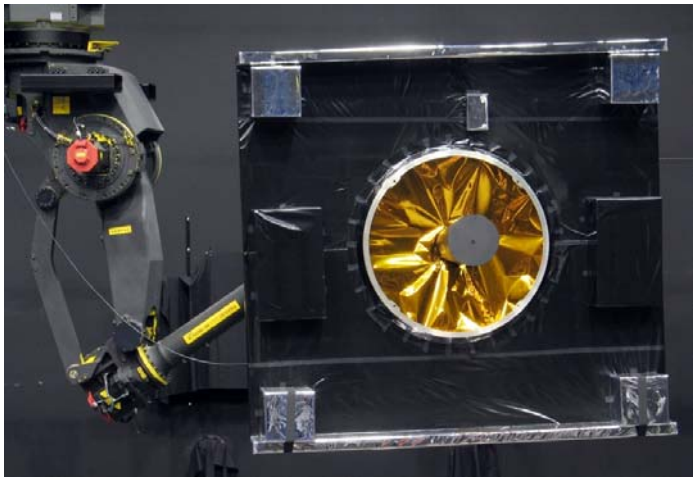
Phase 6: Safe Retreat
- 6.1: Nominal Grapple Release
- 6.2: Nominal Bus Retreat



Phase 7: Intra-Mission On-Orbit Hold / Secondary Missions

NRL Robotics Laboratory



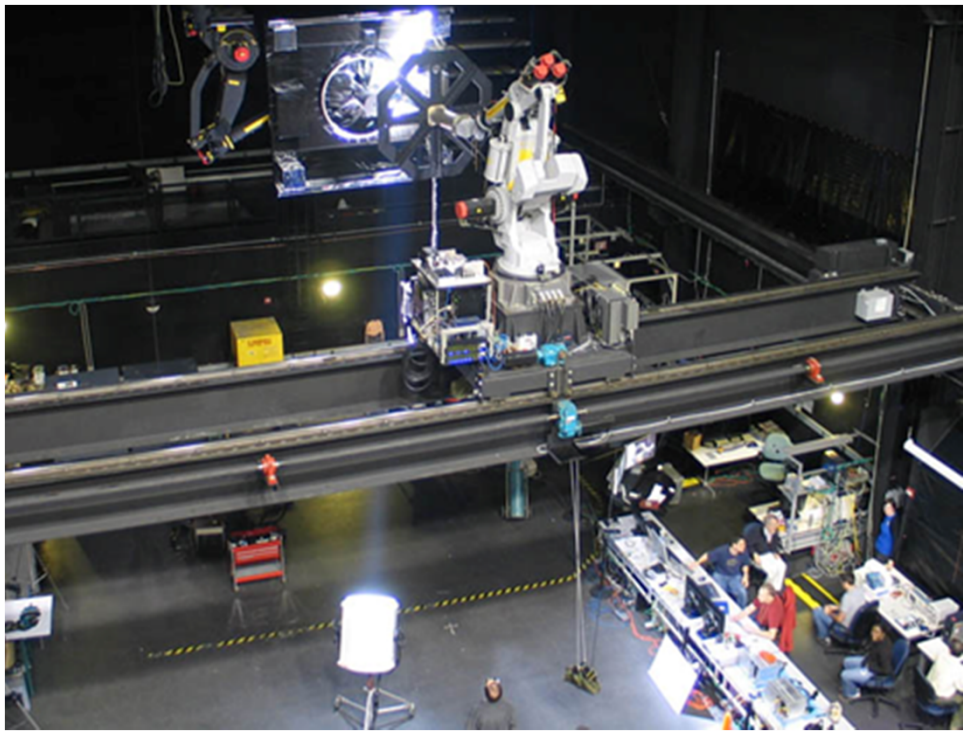


Proximity Operations Test Bed (POT)

- **Advanced Dual Platform Motion Simulator**
  - **Allows full three-dimensional (6-DOF) replication of spacecraft rendezvous and docking under realistic dynamic conditions**
  - **Allows developmental testing with hardware-in-the-loop robotic sensors, mechanisms, and flight code prior to launch**
  - **Allows full scale mission rehearsal with realistic satellite hardware**

Specifications

Specification	Pursuer Platform	Target Platform
Degrees of Freedom	6	6
Translational Range of Travel (X, Y, Z)	25, 10, 3 m	25, 10, 3 m
Rotational Range of Travel (ψ, θ, ϕ)	180, 180, 300 deg	180, 180, 360 deg
Absolute Positional Knowledge	1 cm	1 cm
Absolute Rotational Knowledge	0.01 deg	0.01 deg
Relative Positional Knowledge	0.003 cm	0.003 cm
Relative Rotational Knowledge	0.001 deg	0.001 deg
Relative Positional Control	0.5 cm	0.5 cm
Relative Rotational Control	0.001 deg	0.001 deg
Maximum Tanslational Velocity	45 cm/sec	45 cm/sec
Maximum Rotational Velocity	100 deg/sec	100 deg/sec
Maximum Payload Mass	400 kg	350 kg
Maximum Payload Moment	1372 N-m	1960 N-m



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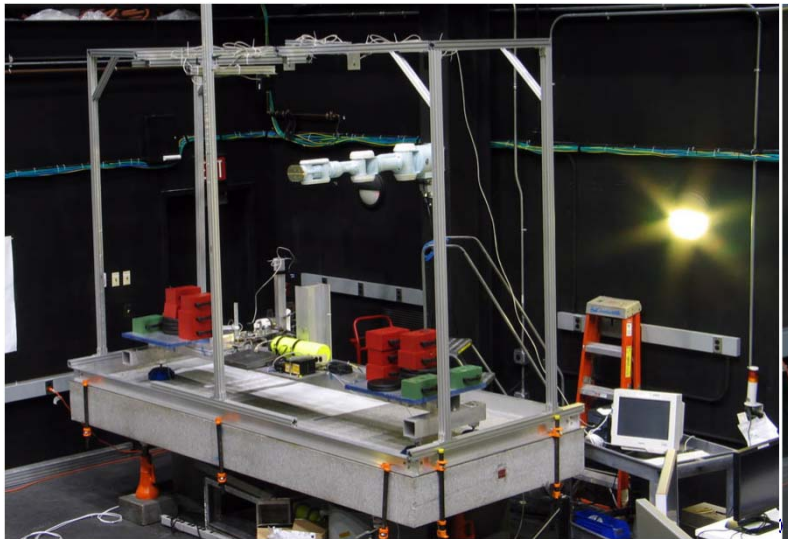
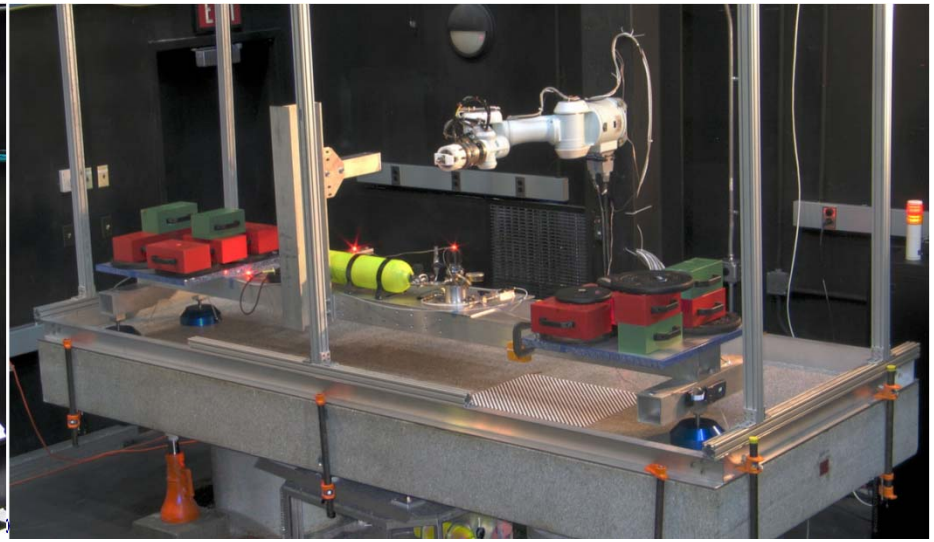
Gravity Offset Test Bed (GOT)

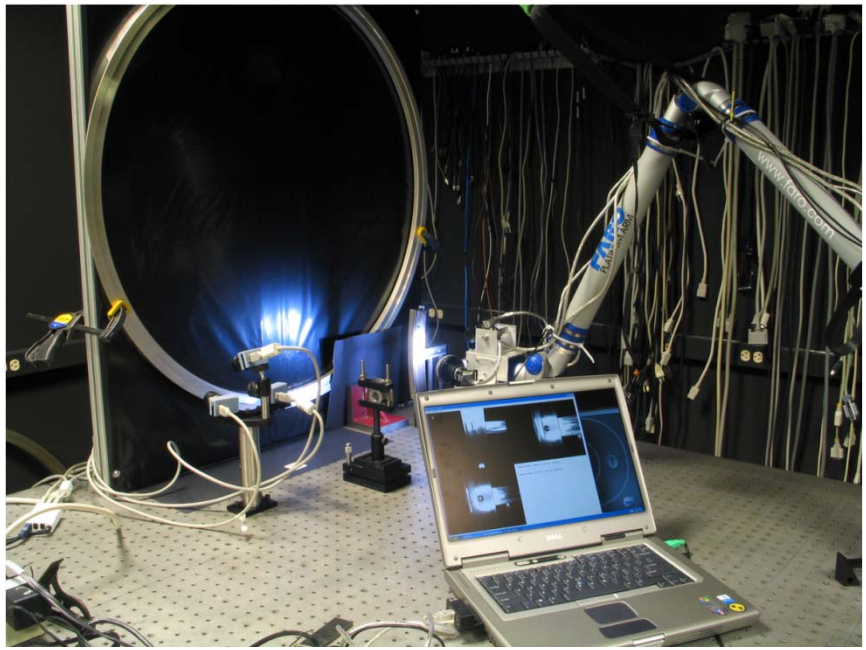
- 3 DOF, very low friction air bearing facility
- Allows high fidelity contact dynamics simulation to ensure ability to grapple in simulated zero-G conditions
- Realistic customer mass and inertias
- Used for developing, characterizing and validating
  - Robotics compliance control sensors and algorithms
  - End effector hardware design
  - Grapple control software
- Used for system integration and characterization of grapple related subsystems

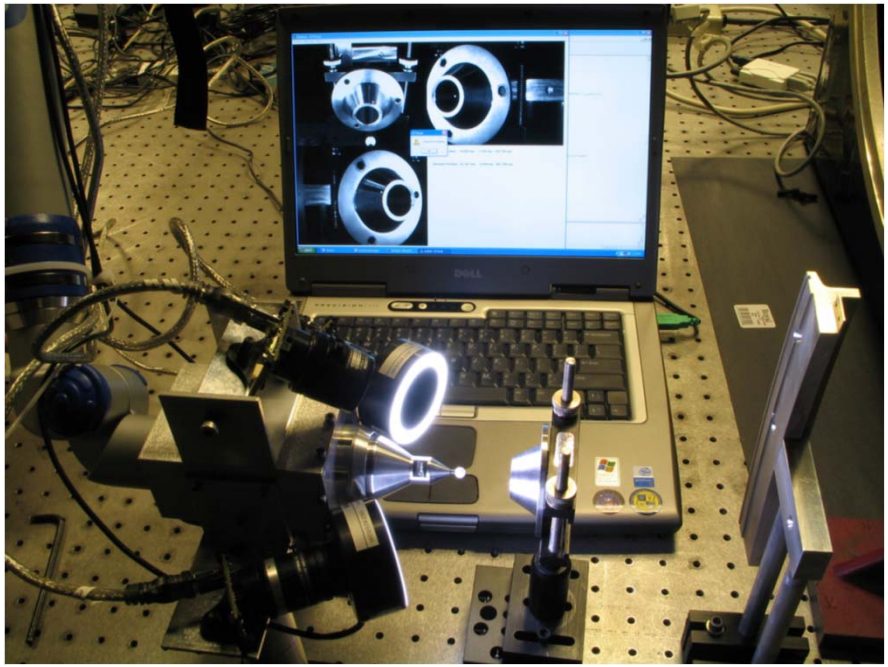


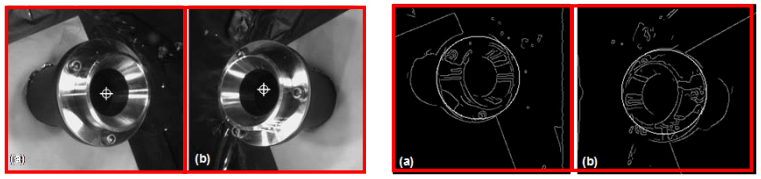


Grapple Feature Tracking Test Bed

- **Optical testbed for development and characterization facility for flight machine vision sensors, illuminators, and algorithms**
- **Allows high-fidelity orbital lighting simulation**
- **Testing against wide range of grapple features, blanketing materials, and lighting conditions**



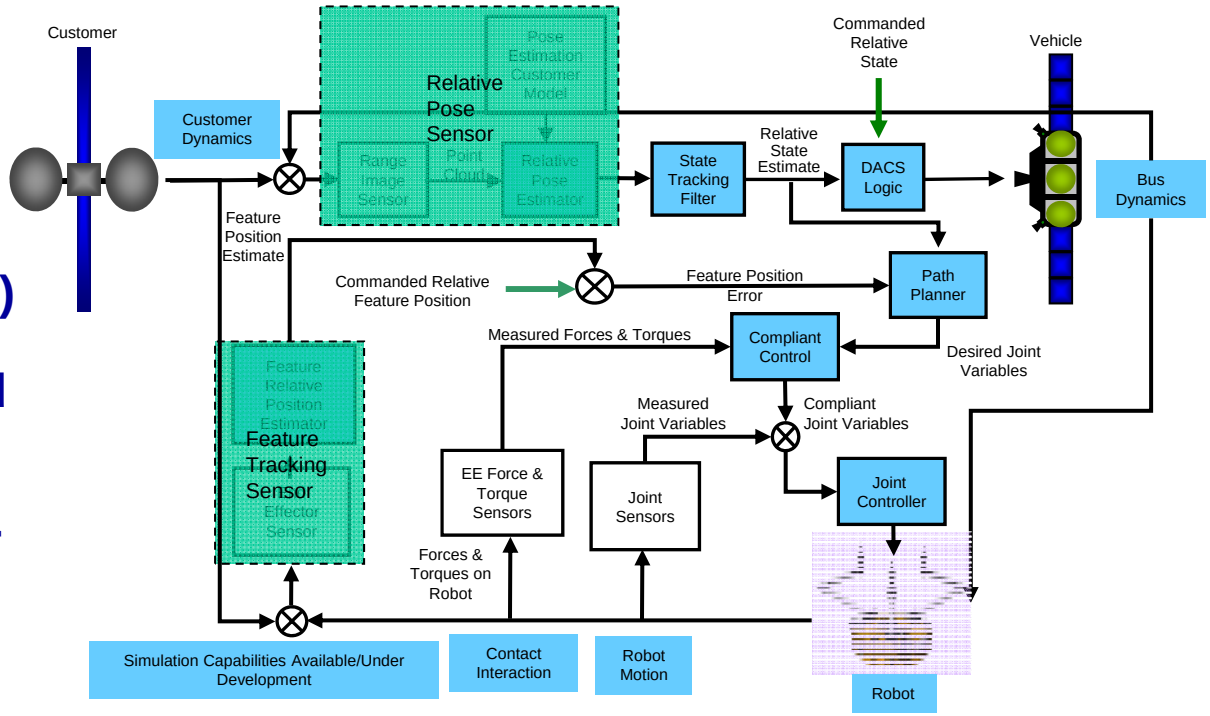


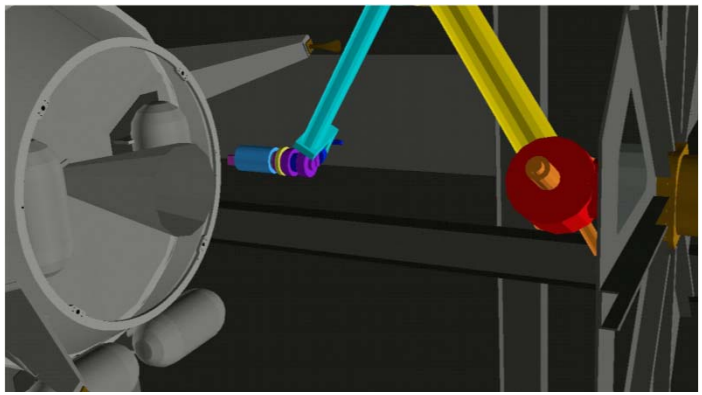


Machine Vision Identifies Grapple Feature

System Simulation Testbed

- **Full system dynamics simulation**
  - **Including sensors and lighting**
- **Software-in-loop (ultimately)**
- **Allows complete end-to-end scenario validation**
- **Validates results from other test facilities**
- **Development in progress**
  - **Currently has full system dynamics**
  - **Does not yet have sensor simulation capability**
  - **Not yet software-in-loop**



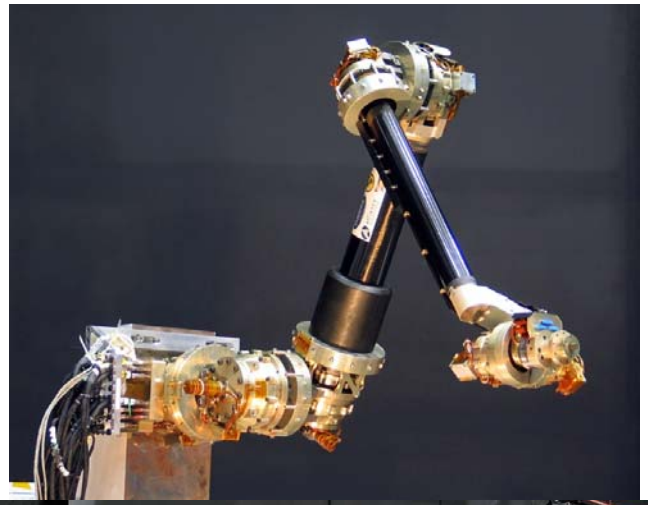


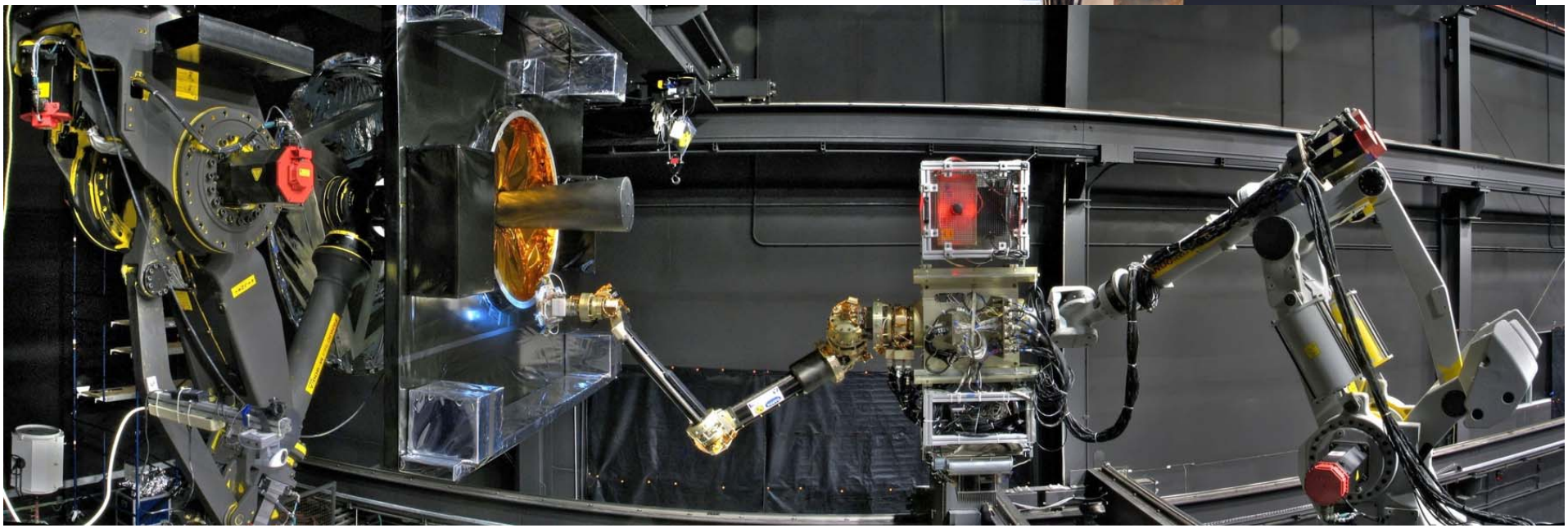
Graphical Simulation Limitations

- **Simulation does not contain dynamic model of arm**
  - **Models arm as a purely kinematic device, i.e. perfect command tracking**
  - **This assumption believed to be OK for teleoperation, as FREND arm tracking is quite good**
    - **< 5mm (0.5 degree/joint) tracking error**
    - **~3mm stiction effects observable at velocities < 1 cm/sec**
- **No contact dynamics or collision checking**

FREND Robotic Arm

- 7 DOF RPRPRPR manipulator
- 1.8 meters from shoulder to wrist
- ~80 kgs.
- Capable of supporting 5 kg end effector throughout workspace

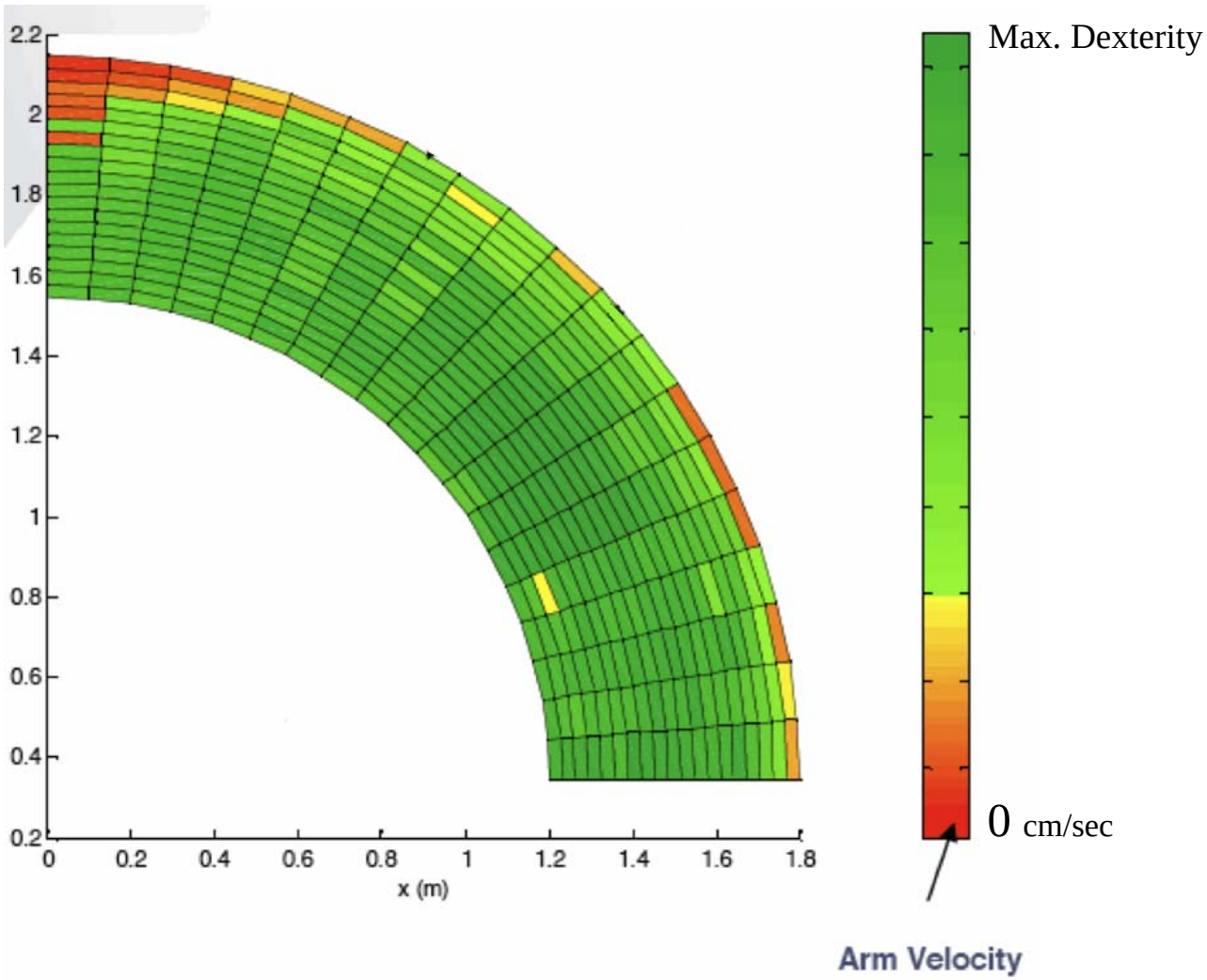




Singularities

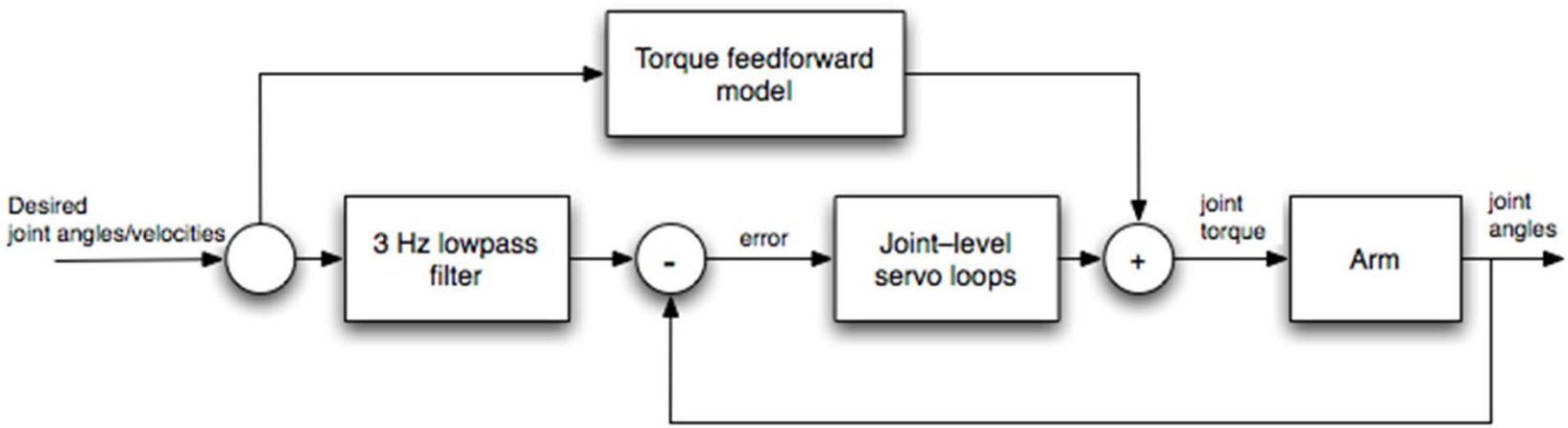
- **Throughout most of the workspace, the arm can move independently in translational and rotational axis *and* simultaneously control SEW angle (7 total degrees of freedom)**
- **In some orientations, two roll joints align and become redundant**
  - **Straight wrist**
  - **Straight upper arm**
- **When this happens only six DOF can be independently controlled**
- **Behavior of resolved–rate controller near singularities will not be catastrophic but may not yield desired results**
- **Method of flagging applications through network interface not yet determined**

Dexterous Workspace



Control Methodology

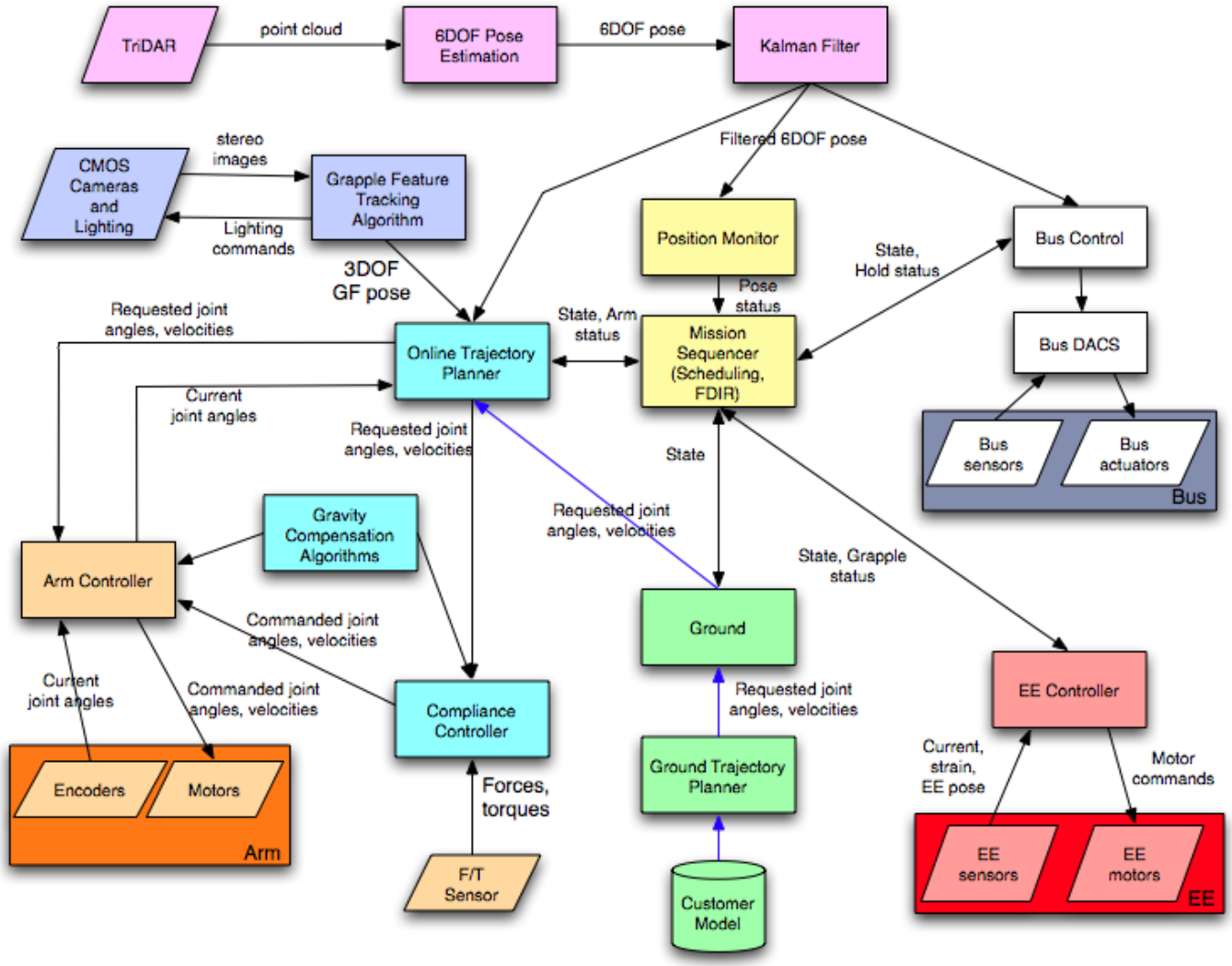
- Normal control performed at joint level
- Joint angles and velocities commanded at 20 Hz
- Low–pass 3 Hz filter to smooth commanded trajectories
- PID servo loops embedded in arm control electronics



Robotic Control Algorithms

- **Compliance Control for “soft dock” during grapple**
  - **Algorithm adjusts motion commands to reduce forces at contact to minimize customer disturbances, risk of damage, and to increase time for grapple**
- **Trajectory Planner for collision avoidance**
  - **Ground planning creates initial arm trajectory for grapple**
  - **Flight Trajectory Planner monitors arm and customer position and adjusts arm trajectory to minimize risk of contact**
- **Mission Sequencer for payload functional coordination**
  - **Provides system control over all payload functions**
  - **Provides fault detection, isolation, and recovery functionality**

FREND Algorithm Connectivity



Resolved–Rate Control

$$\dot{\theta}_d = J(\theta)^{-1}\left(\dot{x}_d + \gamma\left(x_d - x\right)\right)$$

- **Jacobian *J()* relates end effector velocity to joint velocity**
- **Invertible only in the case of 6DOF manipulators**
- **For 7 DOF manipulator an additional hard constraint may be added (SEW angle, for instance)**
- **Or a pseudoinverse can be taken**
  - **Infinite number of pseudoinverses typically exist**
  - **Specific pseudoinverse can be used to optimize secondary criteria**
    - **Deviation away from a specified pose**
    - **Minimize joint velocities**
    - **Obstacle avoidance**

Impedance Control

- **To control forces imparted on the customer spacecraft during grapple, FREND utilizes a joint–space impedance control law:**

$$\begin{aligned} \mathbf{C_m}\ddot{\tilde{\theta}} &= -\mathbf{C_p}\tilde{\theta} - \mathbf{C_d}\dot{\tilde{\theta}} + \tau \\ \tilde{\theta} &\doteq \theta_d - \theta \end{aligned}$$

- **The servo loops are standard uncoupled PID laws augmented by gravity and friction compensation:**

$$\mathbf{K_m}\tau_{PID} = -\mathbf{K_p}\left(\theta_\mathbf{c} - \theta\right) - \mathbf{K_i}\int\left(\theta_\mathbf{c} - \theta\right)\ dt - \mathbf{K_d}\dot{\theta}_\mathbf{c} + \tau_\mathbf{ff}$$

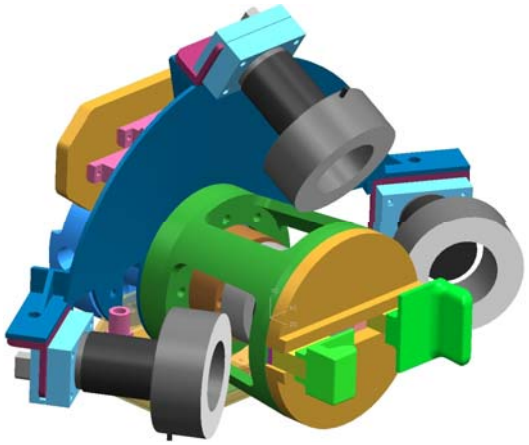
where

$$\tau_\mathbf{ff} = \begin{cases} \mathbf{K}_{col,pos}\mathrm{sign}(\theta_\mathbf{c}) + \mathbf{K}_{visc,pos}\theta_\mathbf{c} + \tau_g\mathbf{K}_{g,pos} & \text{if} \quad \mathrm{sign}(\theta_\mathbf{c}) \cdot \mathrm{sign}(\tau_\mathbf{g}) \geq 0 \\ \mathbf{K}_{col,neg}\mathrm{sign}(\theta_\mathbf{c}) + \mathbf{K}_{visc,neg}\theta_\mathbf{c} + \tau_g\mathbf{K}_{g,neg} & \text{if} \quad \mathrm{sign}(\theta_\mathbf{c}) \cdot \mathrm{sign}(\tau_\mathbf{g}) < 0 \end{cases}$$

Machine Vision Algorithms

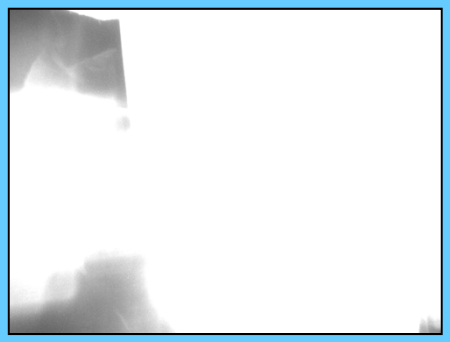
Machine Vision Algorithms recognize grapple features and provides final arm guidance for successful unaided grapples

- **Grapple Feature Tracking Algorithm(s)**
  - **Provides Grapple Location Feedback to Arm Trajectory During Final Approach**
    - **Corrects to 6DOF Pose Estimate Errors**
  - **Operating Range: 20 cm to 1.5 cm**
  - **5 Hz Update Rate**
  - **Accuracy:**
    - **± 2.0 cm 2s Noise and Bias at 20 cm**
    - **± 0.25 cm 2s Noise and Bias at 1.5 cm**
  - **Operating Parameters:**
    - **Grapple Features - Bolt Hole, Marman Ring, TBD Others**
    - **Variable Blankets - Black/Black, Gold/Black, Gold/Gold, Black/White**
    - **Variable Lighting - Eclipse, Variable Sun Angles at Variable Rates**
    - **Mono and Stereo Solutions Possible**

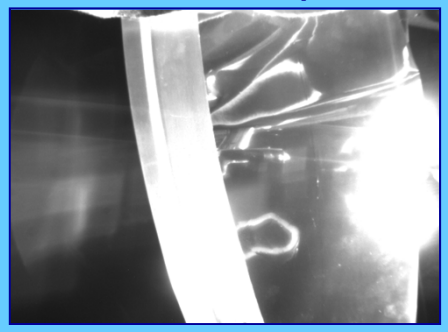


End Effector with 3 Cameras & Lighting

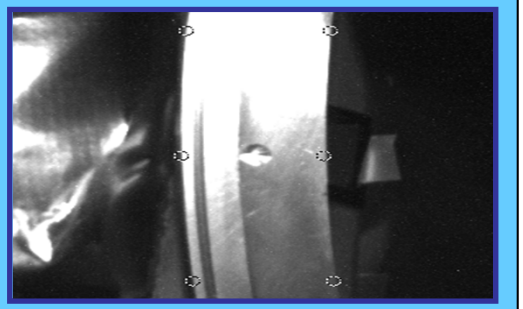
Before Autoexposure



After Autoexposure



GFTA Solution



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