Front End Robotic Enabling Near-Term Demonstration (FREND)

Mission Operations Considerations

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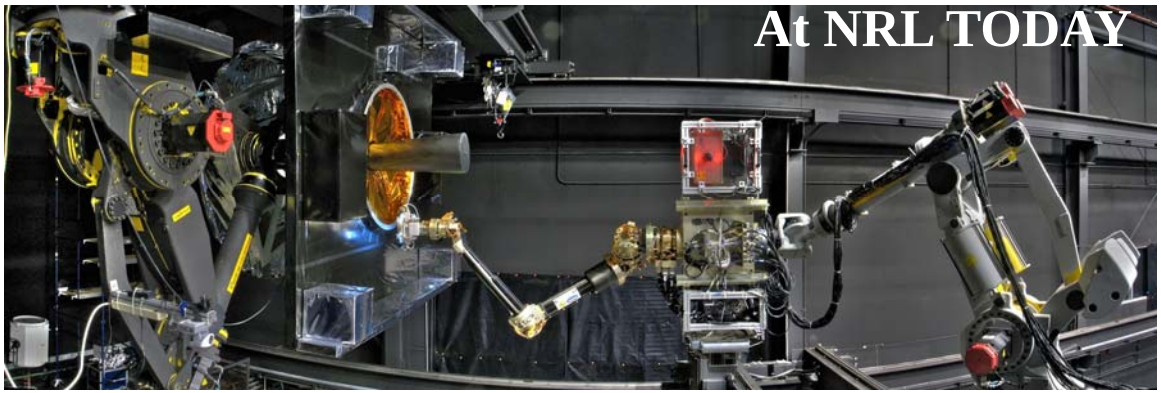
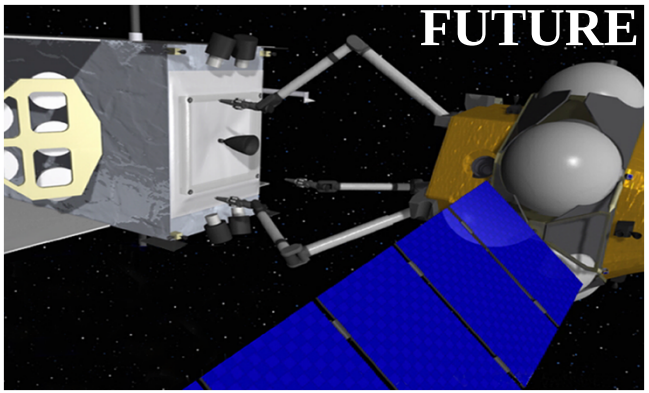
FREND Overview

- **Goal: Autonomous rendezvous, capture, and boost of high value space assets**
  - **Require no modification of the customer spacecraft**
    - **No pre-existing docking interface**
    - **No visual aids**
  - **Capable of servicing multiple customers**
- **Key payload subsystems:**
  - **7+ DOF flight robotic arm**
  - **Set of end effectors to allow capture of various customer spacecraft structural hard points**
  - **Navigation and rendezvous sensor suite for long-range and close-proximity tracking, 3D imaging, and pose estimation**
  - **High performance flight processor**
- **Perform high-fidelity close-proximity ground testing under mission-like scenarios**
  - **NRL Proximity Operations Testbed**





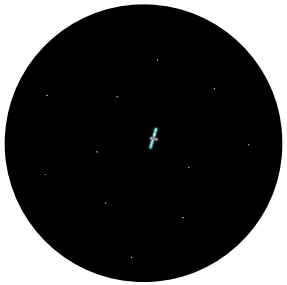
Notional Flight Demonstration Objectives

- Be capable of performing the following two reference missions
  - Geosynchronous or near-geosynchronous spacecraft capture and repositioning
  - Geosynchronous or near-geosynchronous spacecraft retirement to a supersynchronous orbit
- Be capable of performing both reference missions under all lighting conditions and at inclination angles < 10 degrees
- Be capable of performing no less than five instances of the reference missions during a one-year mission lifetime
- Be capable of rendezvous, proximity operations, capture, boost, and release of at least 3 types of commercial GEO communications satellites
- Incorporate an autonomous fault detection and recovery system which will be active throughout rendezvous, proximity operations, capture, boost, and release phases of the mission
- Demonstrate mitigation strategies designed to minimize the risk of damage to reference mission customer spacecraft, to include spacecraft charging differentials, collision and resulting mechanical damage, EMI/EMC, plume impingement, and contamination

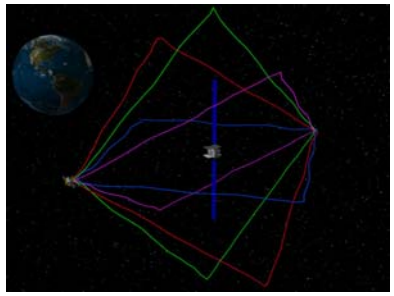
Notional Mission Phases

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

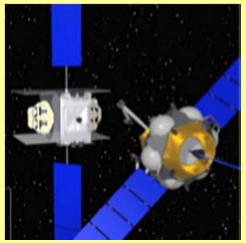
Phase 1: Acquire & Rendezvous
- 1.1: Long Range Navigation to 20 km Client Range and Bearing
- 1.2: Rendezvous 20 km ®1 km



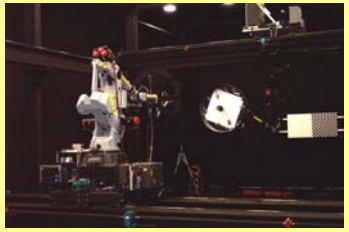
Phase 2: Survey & Inspection
- 2.1: Customer Survey
- 2.2: Data Downlink / Ground Process
- 2.3: Grapple Interface Detailed Survey



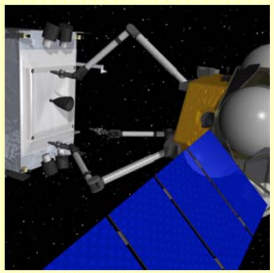
Phase 3: Approach to Capture
- 3.1: Grapple Final Preparation
- 3.2: Approach to Capture Box



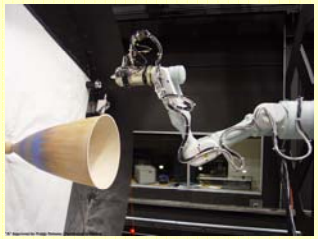
FREND Ground Demo



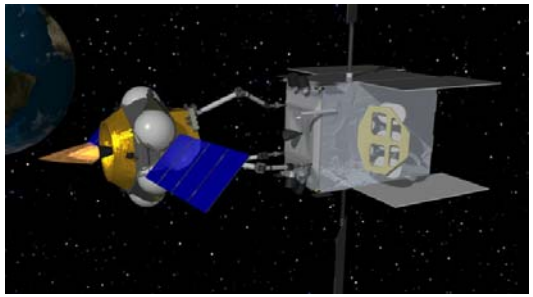
Phase 4: Grapple
- 4.1: First Arm Grapple
- 4.2: Three Arm Grapple
- 4.3: Grapple Rigidization



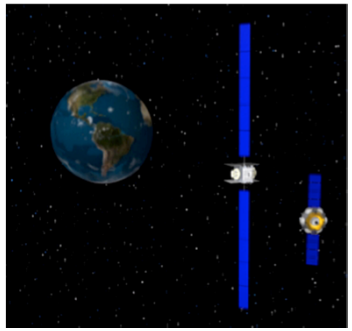
FREND Ground Demo



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

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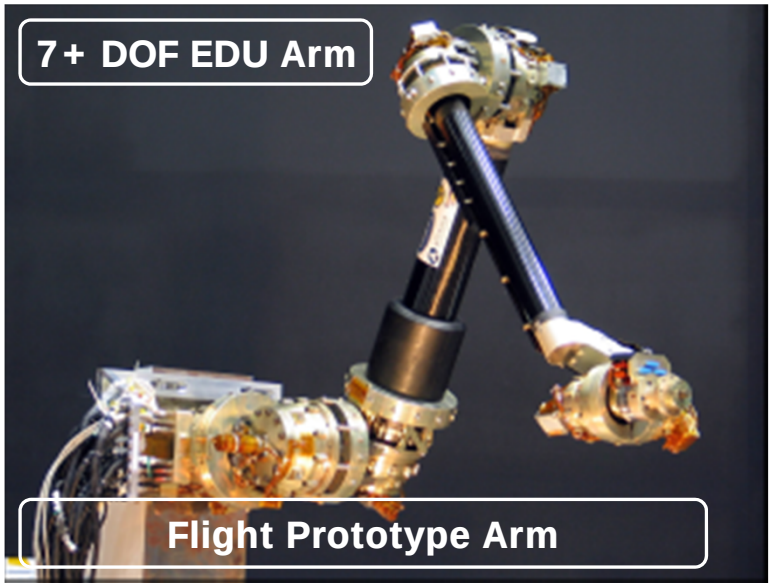
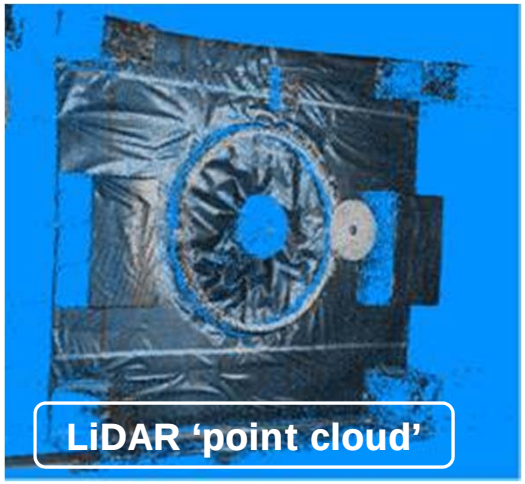
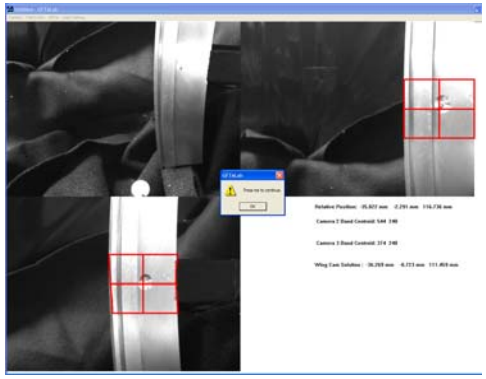
Key Technologies



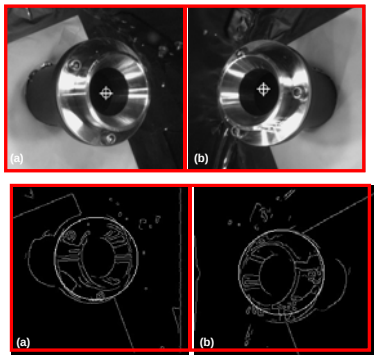
Scanning LiDAR with 6DOF Relative Pose



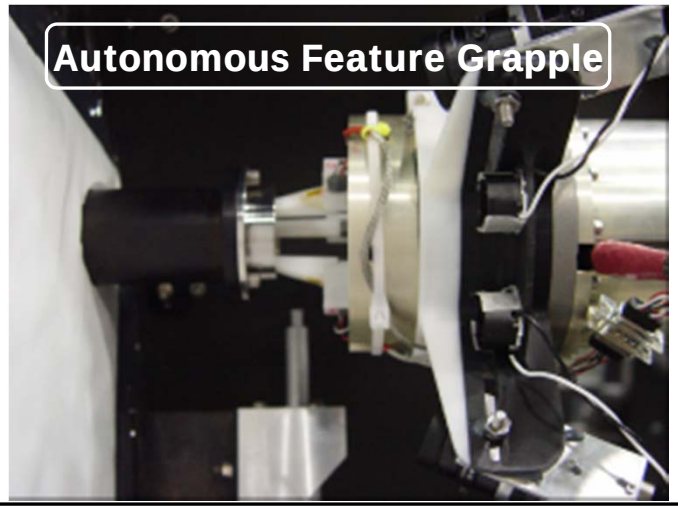
Machine Vision



Marman Rings



Bolt Holes



End Effector Tools and Robotic Algorithms

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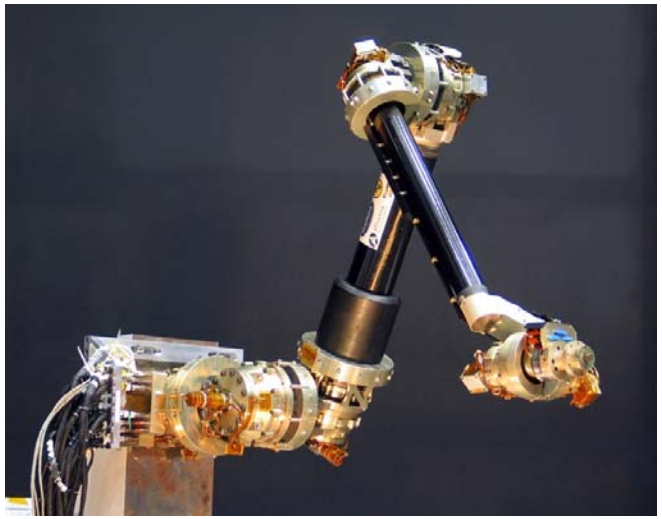
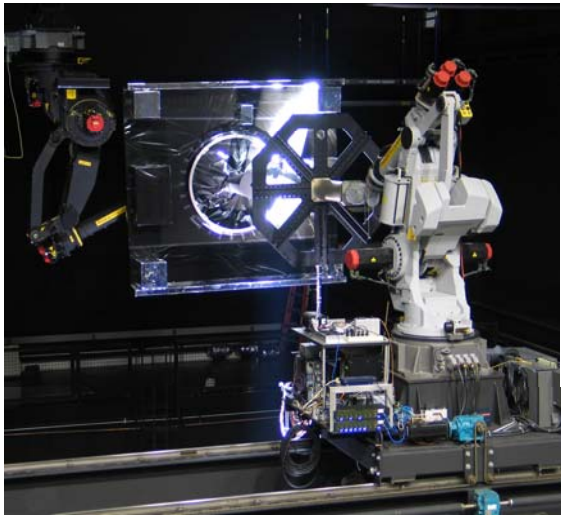
FREND Robotic Arm

- 7 DOF RPRPRPR manipulator
- 1.8 meters from shoulder to wrist,
- ~80 kgs. + 10 kg electronics
- Capable of supporting 5 kg end effector throughout workspace in 1g
- End of arm interfaces
  - Structural, rotary drive, power, and data

Prototype Arm



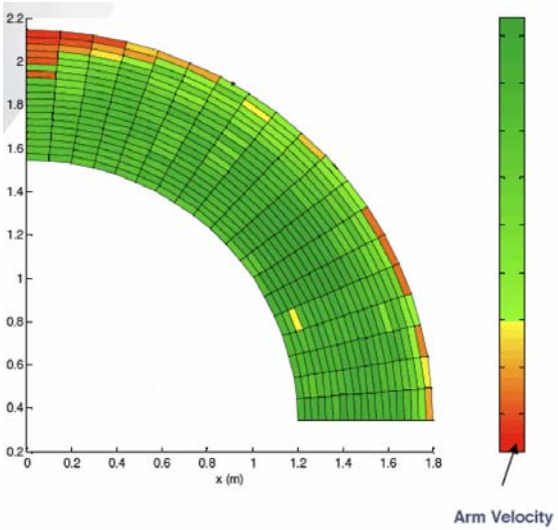
Full Scale Demo with Realistic Lighting



Demo	Date	Outcome	Note
COTS arm; bolt hole	February 2007	**Success**	**10 out of 10**
Improved autonomy; Marman ring	August 2007	**Success**	**12 out of 12**
EDU Arm; orbital lighting; contact dynamics	February 2008	**Success**	**12 out of 12**
Flight arm; improved FDIR	July 2008	**Success**	**12 out of 12**

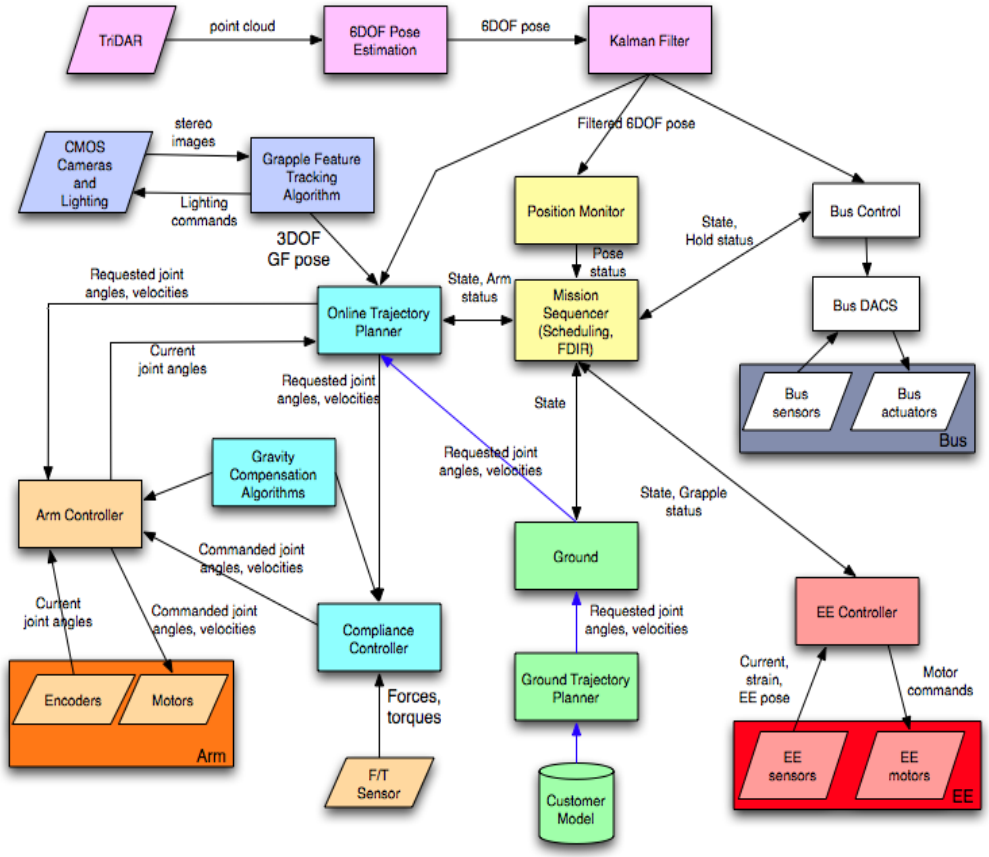
FREND Dexterous Workspace

- **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**



FREND Algorithm Connectivity

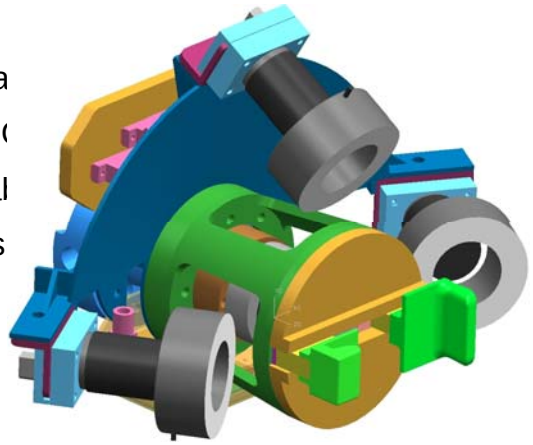
- Compliance Control for “soft dock” during grapple
  - Algorithm adjusts motion commands to reduce forces at contact to minimize customer disturbances, risk of damage, and to increase time for grapple
- Trajectory Planner for collision avoidance
  - Ground planning creates initial arm trajectory for 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



Machine Vision Algorithms

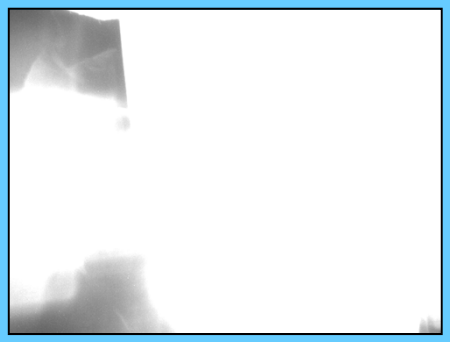
Machine Vision Algorithms recognize grapple features and provides final arm guidance for successful unaided grapples

- **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, Ma
    - Variable Blankets - Black/Black, (
    - Variable Lighting - Eclipse, Varial
    - Mono and Stereo Solutions Poss

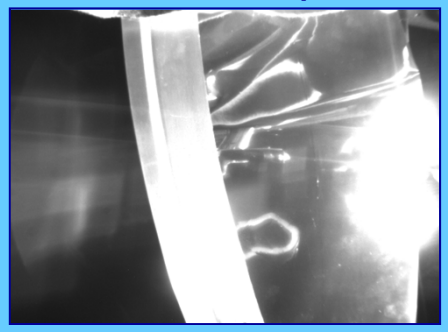


End Effector with 3 Cameras & Lighting

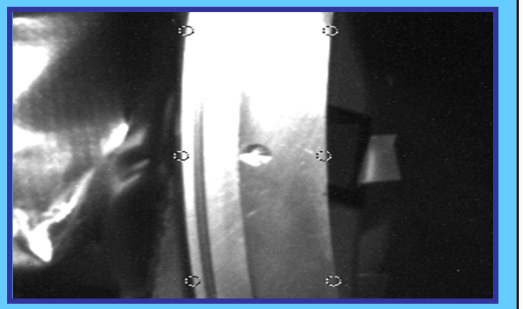
Before Autoexposure



After Autoexposure



GFTA Solution

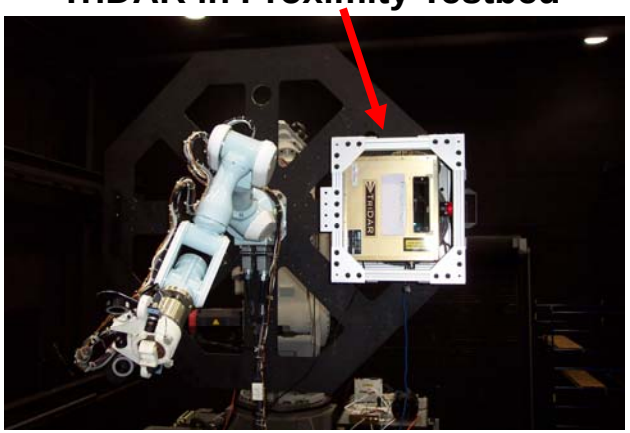


Scanning LiDAR with 6DOF Pose Algorithm

TriDAR sensor plus LASSO algorithm provides 6 DOF pose of customer satellite for proximity approach, stationkeeping, and robotic arm control

- TriDAR Performance
  - Triangulation Subsystem
    - Spatial Resolution:
      3 mm at 5 m, 2 mm at 2 m
    - Range Resolution:
      3 mm at 5 m, 0.5 mm at 2 m
  - TOF Subsystem
    - Spatial Resolution - <1 cm at 40 m
    - Range Resolution - 25 mm
  - Field of View - 30 deg. X 40 deg.
  - LASSO 6DOF Tracking Pose Update Rate - 5Hz
  - Operating Range - 0.5 meters to 2,000 meters

TriDAR in Proximity Testbed



Raster Point Cloud