JPL

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# TPF
# Formation Flying Technology

## Formation Control Testbed (FCT)


Asif Ahmed


2003 TPF Expo
October 14-16
Pasadena, CA


Jet Propulsion Laboratory
California Institute of Technology


Guidance Dynamics Corporation

DI-TEC INTERNATIONAL INC.

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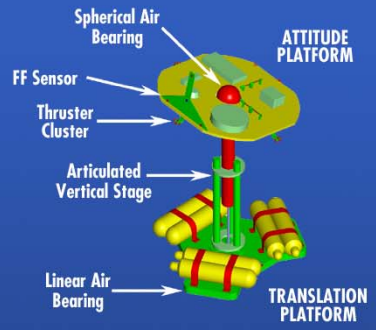
# FORMATION CONTROL TESTBED (FCT)

## SYSTEM-LEVEL VALIDATION OF FORMATION FLYING CONTROL IN A HARDWARE TESTBED

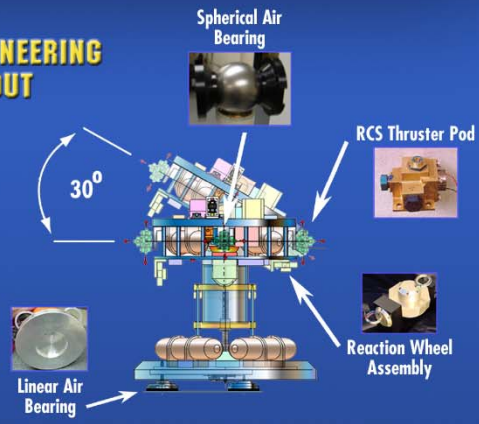
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

### CONCEPT

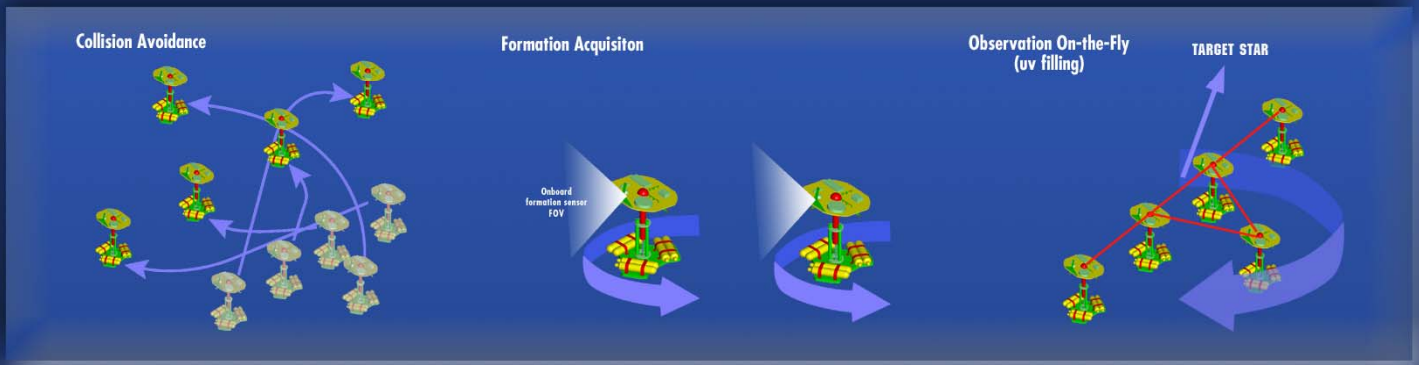



- Three robot formation
- Six degrees-of-freedom using spherical/linear air-bearings
- Robot Size/Weight: ~4 ft tall x 4ft diameter, ~780 lbs each
- Operation duration per charge of gas: ~1 hr
- Mechanical flat floor with glass top
- Operating area: ~30ft diameter
- Performance:
  - Formation Control: +/- 5cm
  - Attitude Control: +/- 5 arc-min
- On-board Avionics (each robot):
  - Avionics Computer (PPC750), Cold gas propulsion – 16 thrusters, Reaction Wheels – 3 single axis, Pseudo-Star Tracker, Formation Sensor (inter-s/c range/bearing), Wireless communication
- Flight-like commanding and telemetry

### ENGINEERING LAYOUT

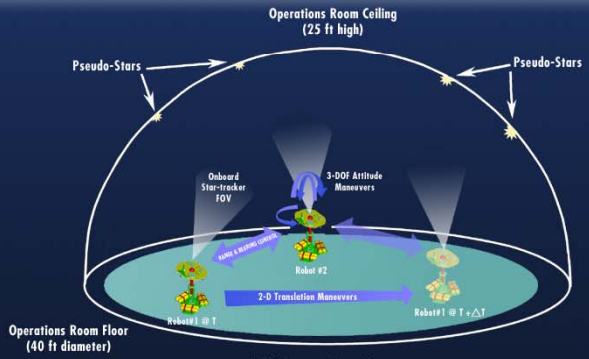



### FORMATION FLYING DEMONSTRATIONS

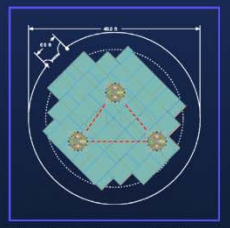



### FCT OPERATIONS

Formation Technology Lab (FTL)




FCT Operations Room



Mosaic Flat Floor with Glass Surface Panels (top view)

Single Flat Floor Panel (adjustable level)

# FCT Objectives

- Demonstrate formation flying as a viable mission architecture for TPF
- Validate Formation Algorithm and Simulation Testbed (FAST) for higher confidence performance predictions TPF Flight FFI

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# FCT – Functional Scope

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FCT is a ground hardware formation testbed for TPF, to demonstrate:

- An integrated end-to-end FF system
- Realistic FF Flight architecture - Sensing, Communication, Control and System Architecture
- Distributed multi-stage sensing, data fusion, estimation, and calibration
- Validate Formation Algorithms and Control System (FACS) developed by FAST
  - Lost-in-space formation acquisition
  - Collision avoidance
  - Integrated formation (range/bearing) & attitude guidance/control
  - Stable s/c & formation pointing for observation
  - On-the-fly observation (uv filling)
- Robustness demonstration with recovery from limited fault scenarios

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# FCT - Performance

- FCT will demonstrate autonomous TPF-like precision formation flying with three robots to a performance level of:
  - 10m diameter operating space
  - Up to 8 m separation
  - +/-5 cm range control
  - +/-5 arc minute attitude control
  - +/-60 arc-minute bearing control
  - 1 hr operations duration per charge

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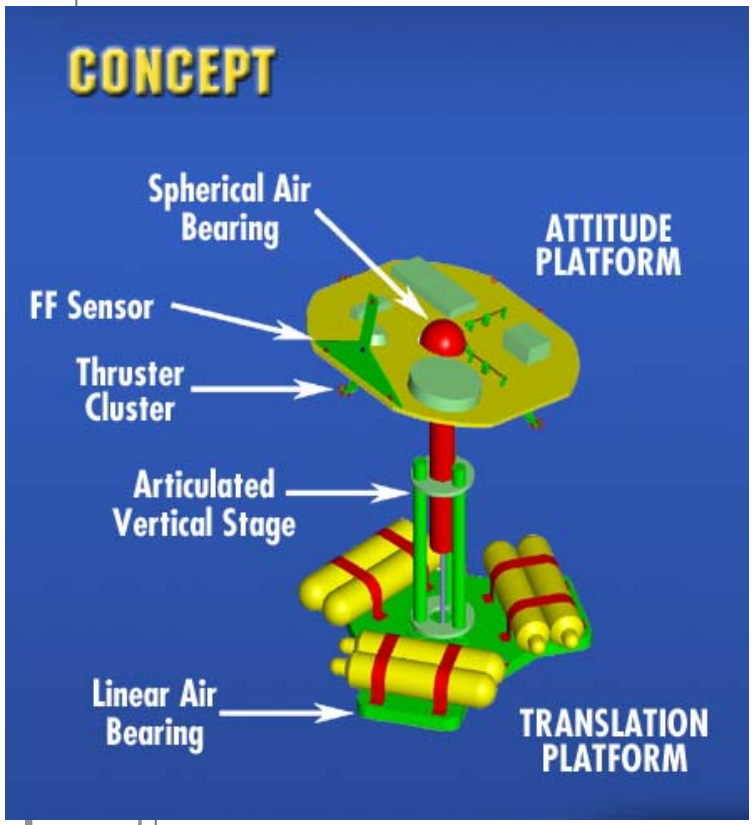
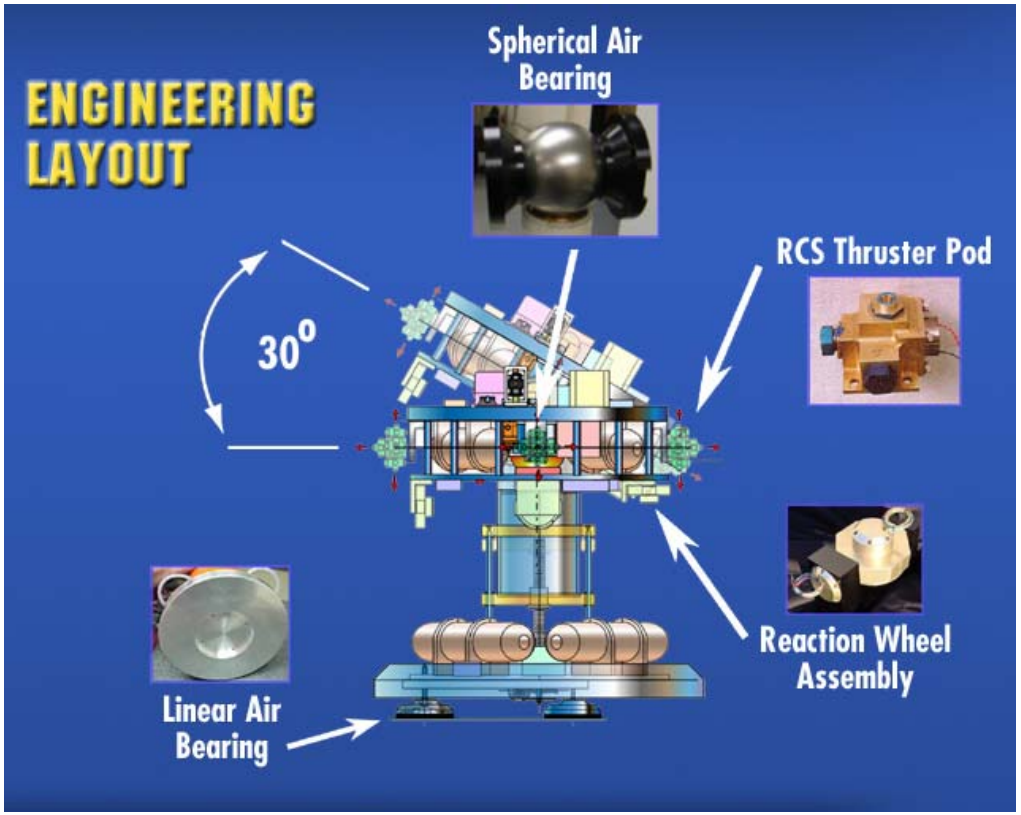
# FCT Robot




**Concept Briefing**
**April 14, 2003**

**CDR**
**September 19, 2003**

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# Similar Ground Testbeds

## Attitude Platform Inheritance - High


**3DOF Attitude only Testbeds with spherical airbearing**


**Tri-axial Attitude Control Testbed (TACT)**
**University of Michigan**
**Mass: 175—350 lbs (w/payload)**
**Dim.: 5 ft tip-to-tip**
**Avionics: fans**
**reaction wheels**

**Satellite Attitude Dynamics Simulator (SADS)**
**Naval Postgraduate School**
**Mass: ~350 lbs**
**Dimensions: 4 ft dia.**
**Avionics: cold gas thrusters**
**reaction wheels**


**Spacecraft Attitude Control Testbed**
**Georgia Tech.**
**Mass: ~450 lbs**
**Dim.: 1.2m**
**Avionics: cold gas thrusters**
**control moment gyro**

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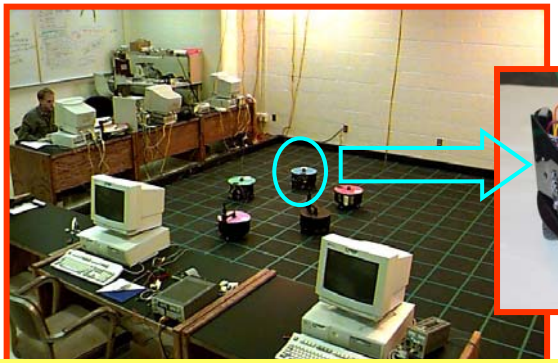
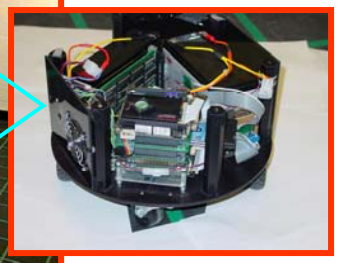
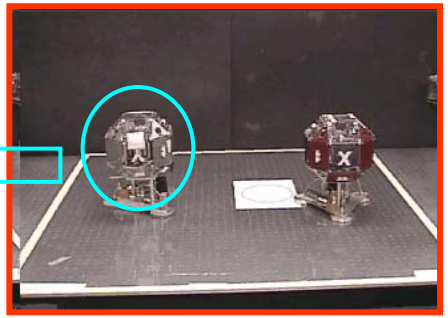
# Similar Ground Testbeds
## Translation Platform Inheritance - Low





Multi-Agent Intelligent Coordinated Control

BYU



MIT

Synchronized Position Hold Engage Reorient Experimental Satellites - SPHERES

JPL/UCLA

FORMATION ACQUISITION & ATTITUDE ALIGNMENT TESTBED (1998)

SYNCHRONIZED ROTATION TESTBED (2000)

FORMATION OPTICAL ALIGNMENT TESTBED (2002)

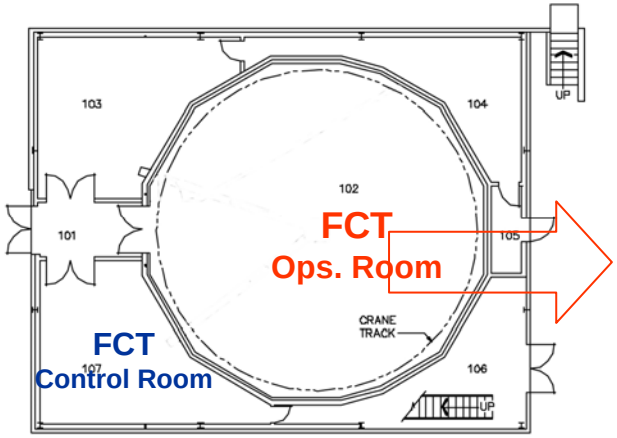
JPL Distributed Spacecraft Technology Program (NASA Code-R)

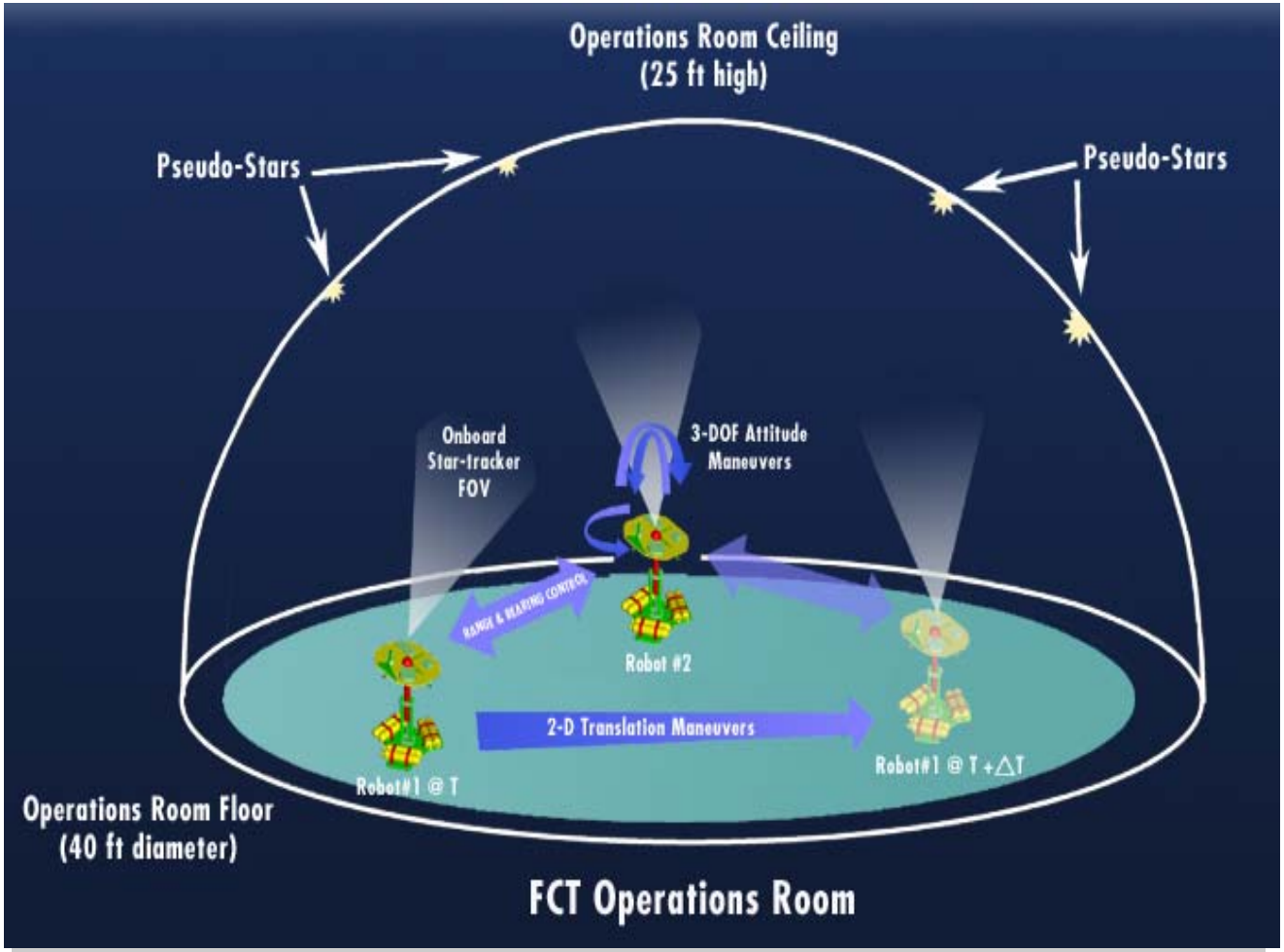
# FCT – Key Features

- **High fidelity**
  - Full rotation and translation degrees of freedoms (6DOF)
  - Realistic flight avionics architecture – sensors/actuators
- **Large area translation capability to support realistic formation flying relative maneuvers**
  - Flat floor (30ft diameter)
- **Total experiment run-time per charge of cold-gas**
  - 1 hr

# FCT – Operations Approach

Formation Technology Laboratory

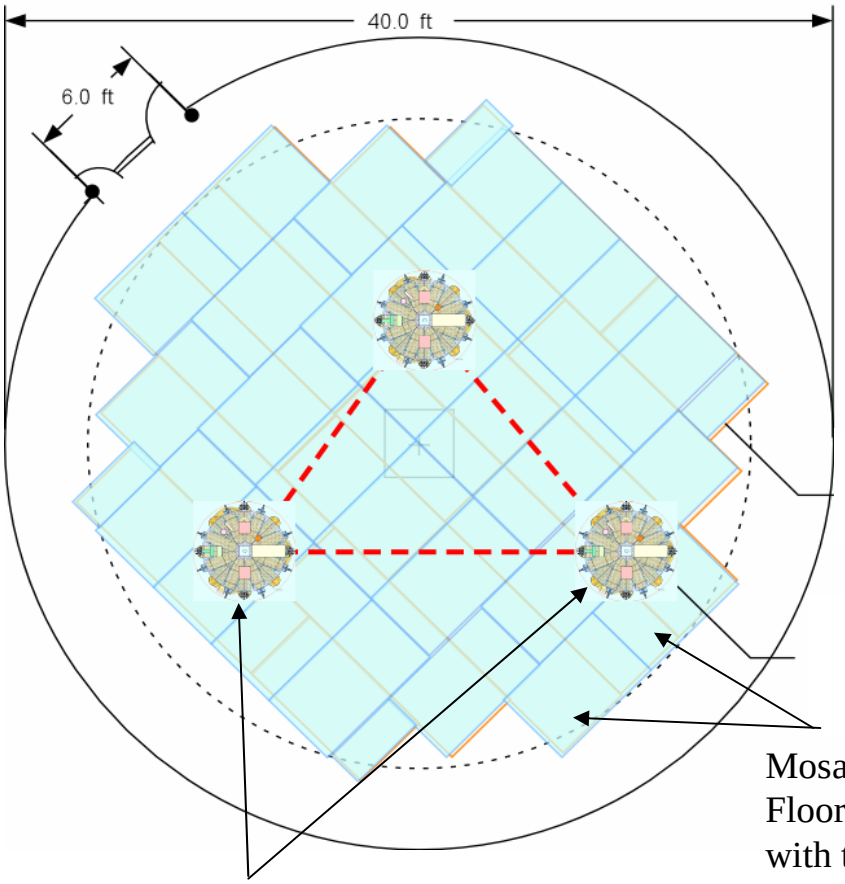



Click here for a movie

# FCT Ops. Room – Top View

## Facility is 40ft diameter circular room




**Requirements**:

- To minimize fuel needed to compensate floor slope induced drift
  - 160 μrad max slope
- Air-bearing traversal of panel-to-panel seams:
  - 0.0024" max step across panel seams

**Flat Floor**

- 16 Mosaic Panels with glass top
- Mosaiced sub-floor mechanical panels (4ftx12ft each)
  - Adjustable level (0.001 inches per turn of fine leveling screw)
- Top glass panels - cross-tiled
  - Evaluating other top surface materials

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# Floor

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Prototype

Design

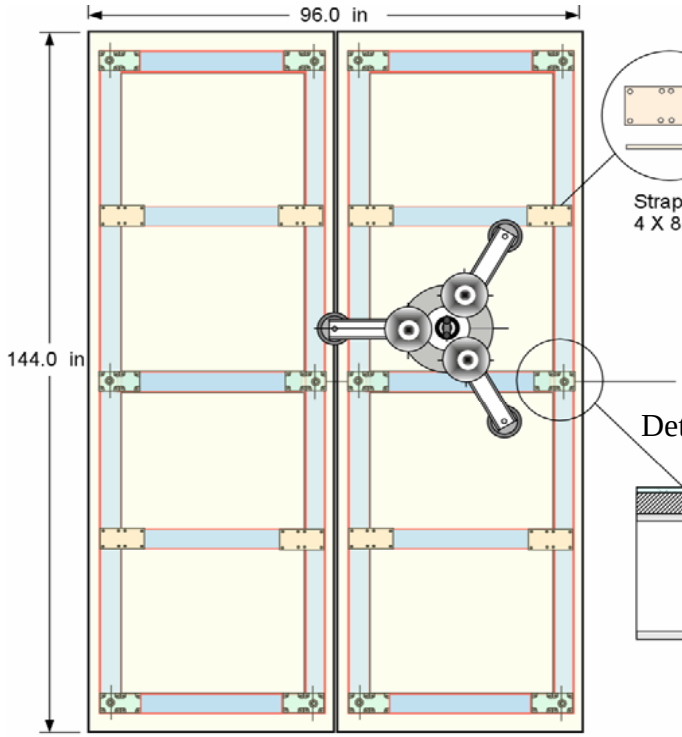
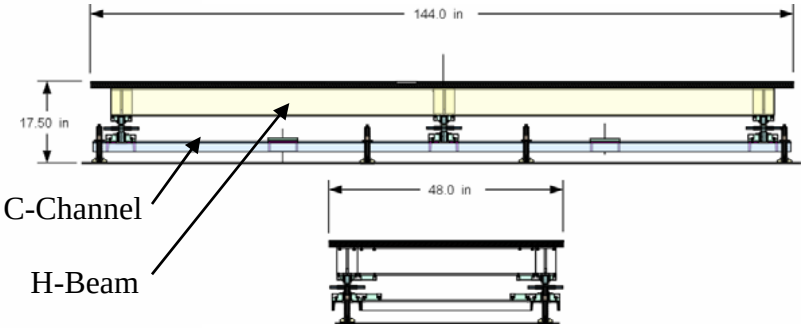
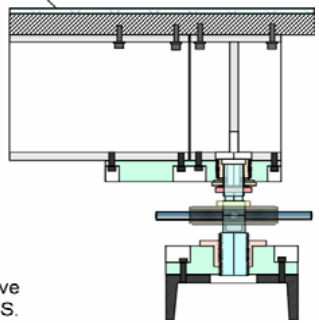



Table top as seen from above with H beams and mech. C.S.



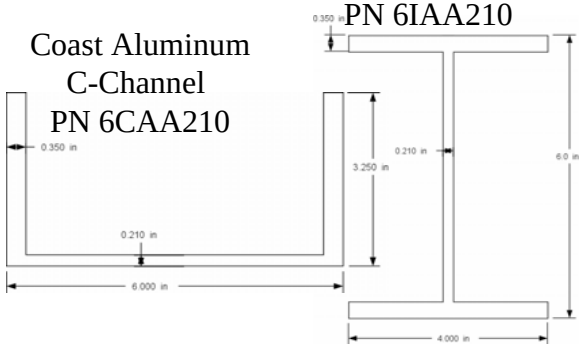




Detail – Compound Screw & Tie Plate



Coast Aluminum H-Beam PN 6IAA210

Coast Aluminum C-Channel PN 6CAA210

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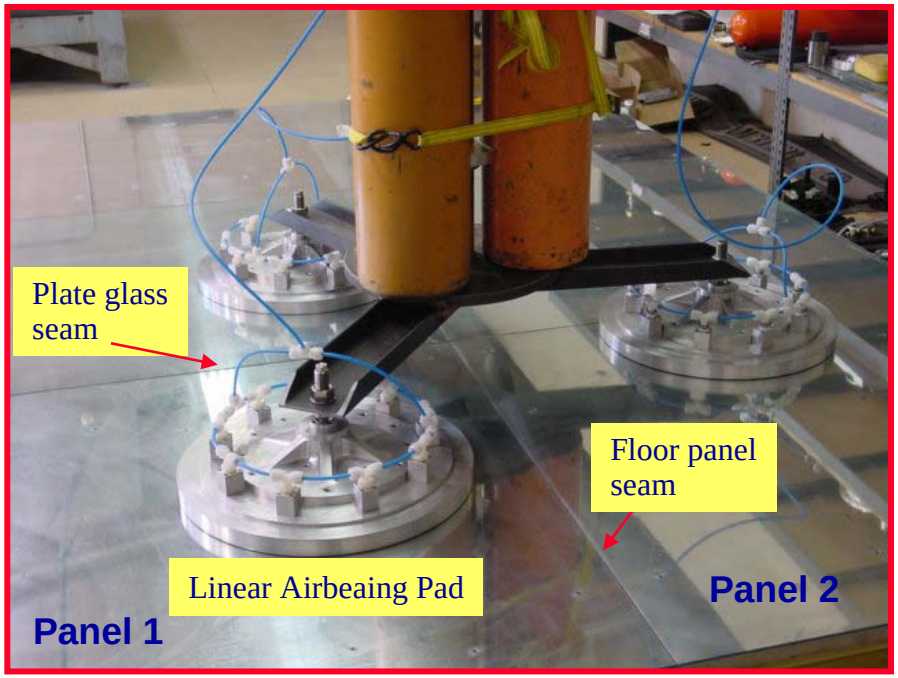
# Flat Floor – Prototype Testing

**Floor Prototype Testing using two as-built 4ft x12ft floor panels with top glass plate**

- Fully loaded air-pads successfully floated across glass seams
- Floor level variation to within +/- 0.002 in
- Characterizing the slope using actual 3 air-bearing test unit

Movie




**Linear airbearings loaded with full robot weight**

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# Summary

- Early prototyping of key risk elements: (April'03 – September'03)
  - flat floor, linear air-bearing, indoor star tracker
- Facility upgrade to house FCT nearing completion
  - end of October'03
- Transitioning into build/deployment phase

- First robot demo. - March '04
- Two-robot autonomous formation flying demo - June '05
- Three robot autonomous formation flying demo - April '06

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# Backup

# Poured Epoxy on Concrete Floor

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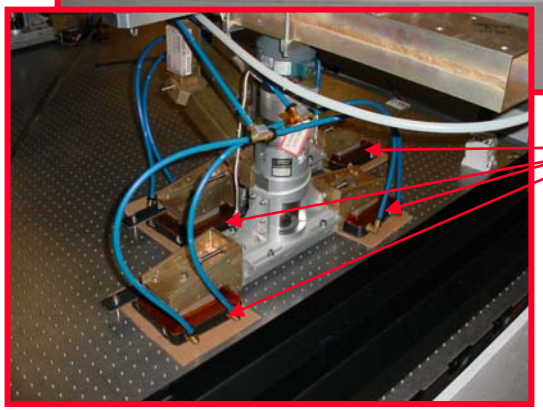
## ABLE Engineering Co. Inc.
## Flexible Space Structures Deployment Laboratory

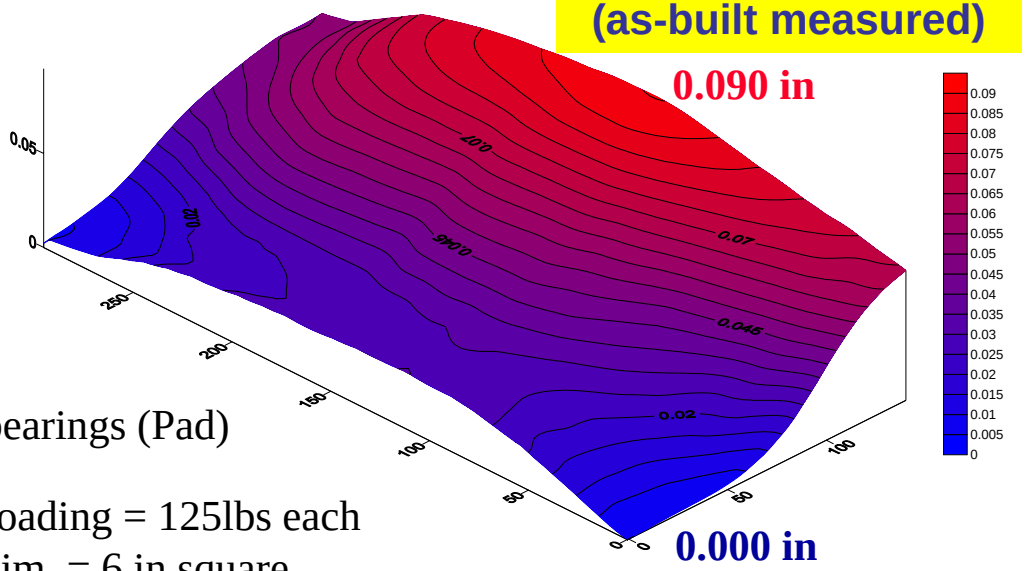
### Epoxy Floor



Air-bearings (Pad)

Finished Epoxy Floor

**Floor Level Variation (as-built measured)**




Pad Loading = 125lbs each
Pad Dim. = 6 in square
Epoxy Floor Thickness < 0.25in
Operating temperature: -60 to +90 C

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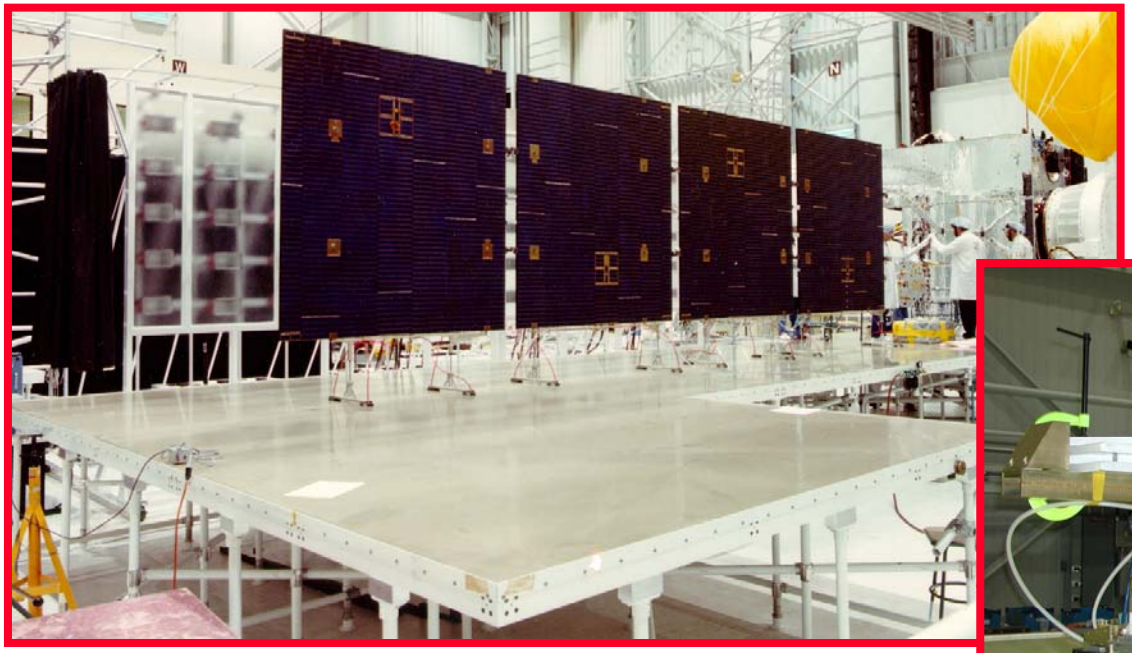
# Poured Epoxy on Raised Panels

**MD Robotics**
**Ontario, Canada**



**Deployment surface with small and large off-loaders**

**Raised honeycomb Panel With poured epoxy**

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