JPL

Terrestrial Planet Finder Mission

TPF

A NASA Origins Mission

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

DL-TEC INTERNATIONAL INC.

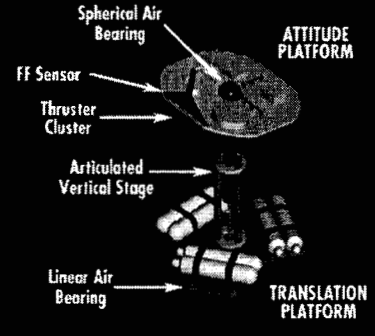
ACEi

FORMATION CONTROL TESTBED (FCT)

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

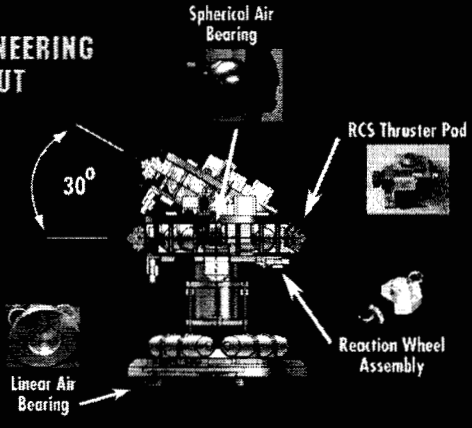
NASA National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

CONCEPT

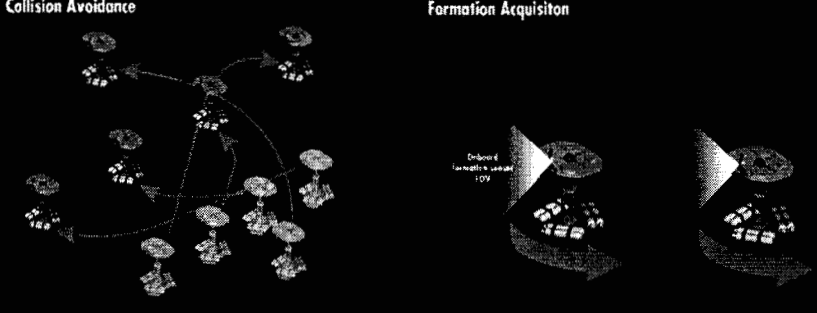


- Three robot formation
- Six degrees-of-freedom using spherical/linear air-bearings
- Robot Size/Weight: ~4 ft tall x 4ft diameter, ~780 lbs each
- Operation duration per charge of gas: ~1 hr
- Mechanical flat floor with glass top
- Operating area: ~30ft diameter
- Performance:
  - Formation Control: +/- 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

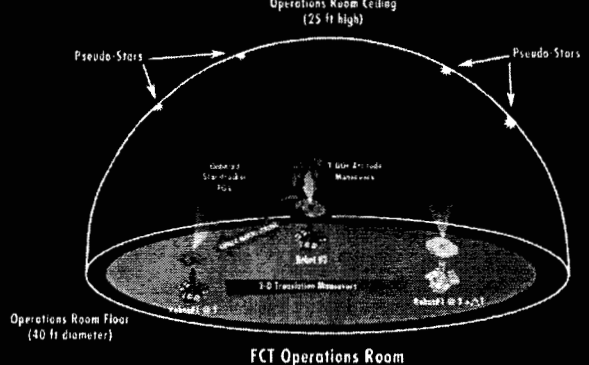


FORMATION FLYING DEMONSTRATIONS



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

Terrestrial Planet Finder Mission

TPF

A NASA Origins Mission

Guidance Dynamics Corporation

D-TEC INTERNATIONAL INC.

ACEi

FCT – Functional Scope

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

Terrestrial Planet Finder Mission

TPF

A NASA Origins Mission

Guidance Dynamics Corporation

DI-TEC INTERNATIONAL INC.

ACEi

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

Terrestrial Planet Finder Mission

TPF

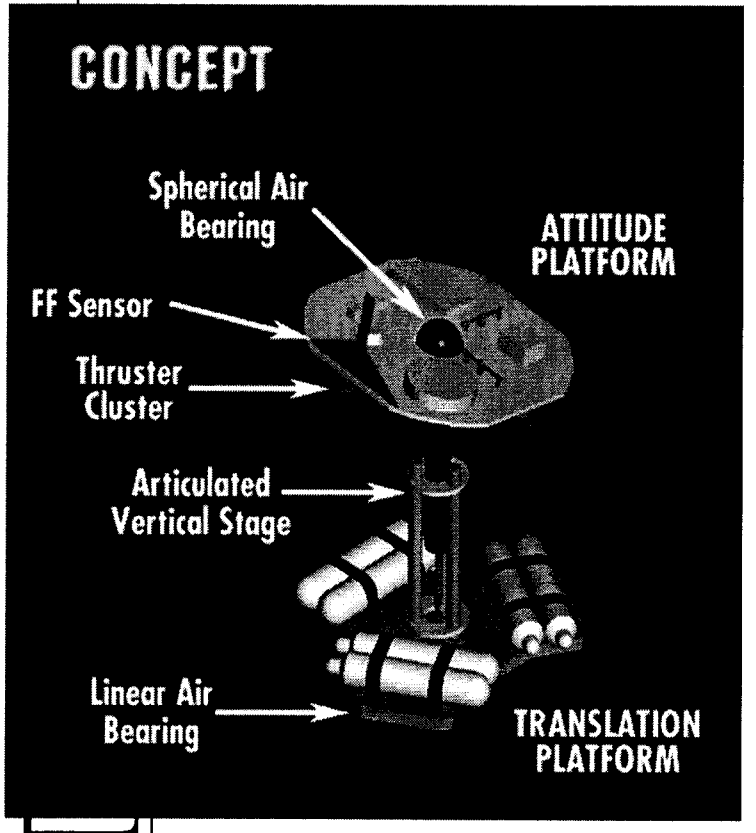
A NASA Origins Mission

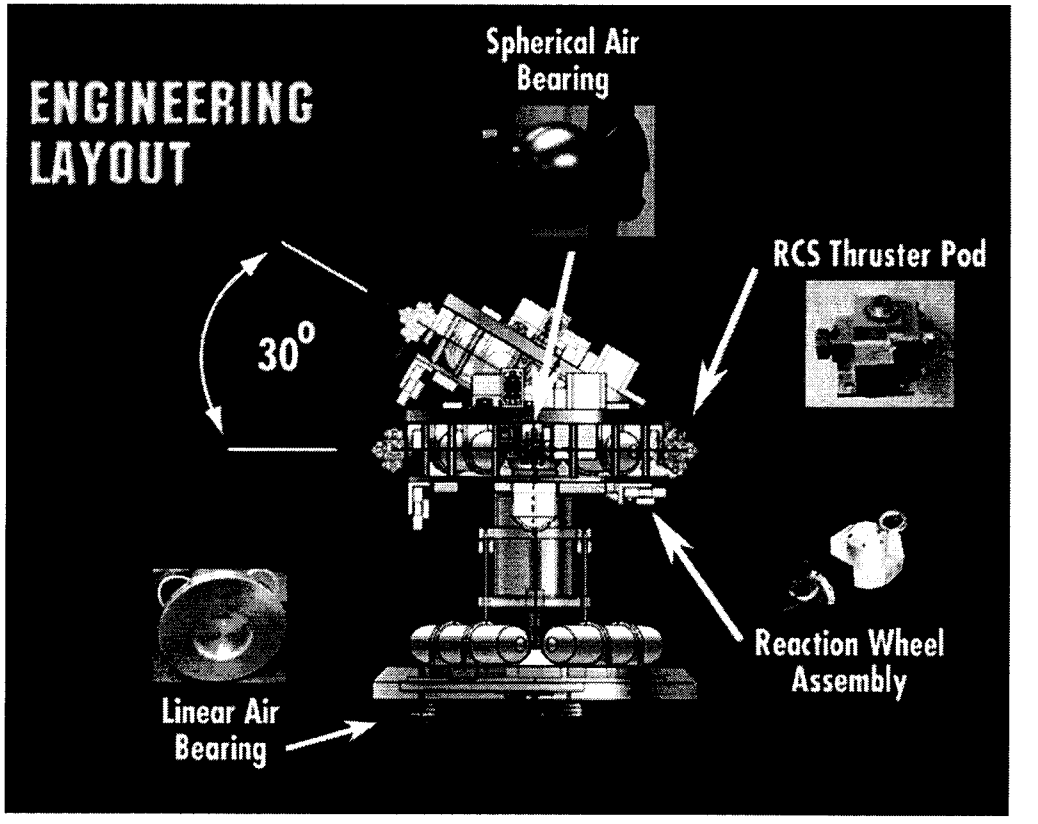
Guidance Dynamics Corporation

DL-TEC INTERNATIONAL INC.

ACEi

FCT Robot





Concept Briefing
April 14, 2003

CDR
September 19, 2003

A NASA Origins Mission

Guidance Dynamics Corporation

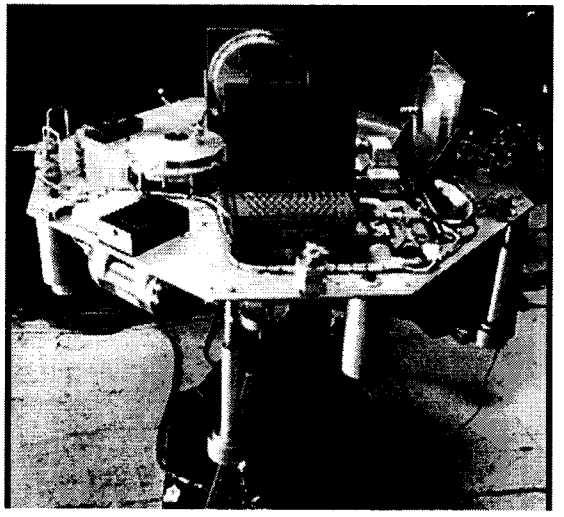
D-TEC INTERNATIONAL INC.

ACEi

Similar Ground Testbeds
Attitude Platform Inheritance - High

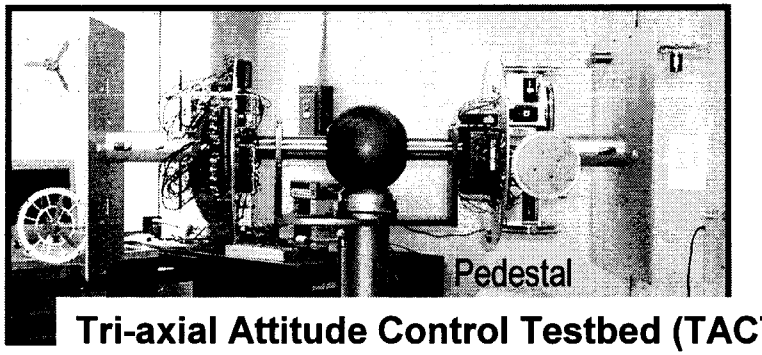
JPL

restrial Planet Finder Mission



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

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

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

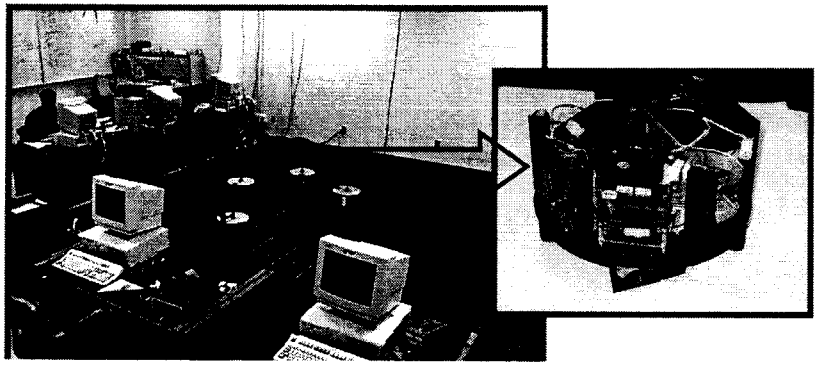
A NASA Origins Mission

Guidance Dynamics Corporation

DI-TEC INTERNATIONAL INC.

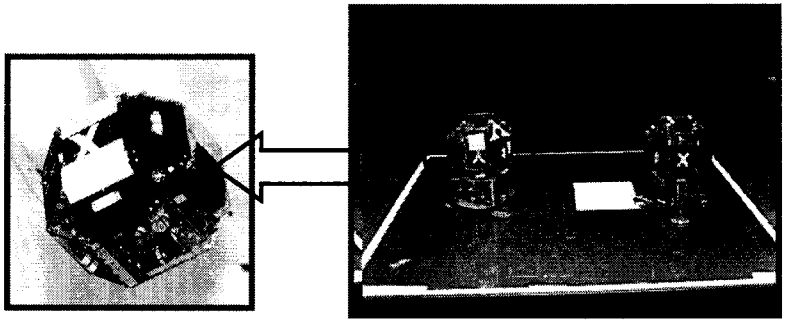
ACEi

Similar Ground Testbeds
Translation Platform Inheritance - Low



Multi-Agent Intelligent Coordinated Control

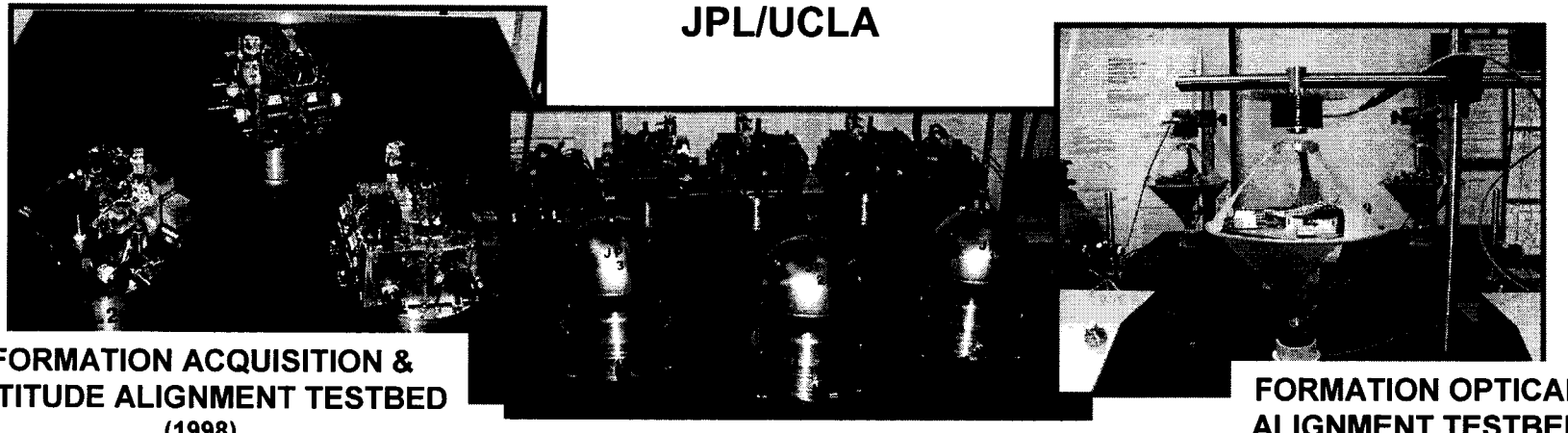
BYU



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)

Terrestrial Planet Finder Mission

TDE

A NA
Orig
Mission

Guidance Dynamics Corporation

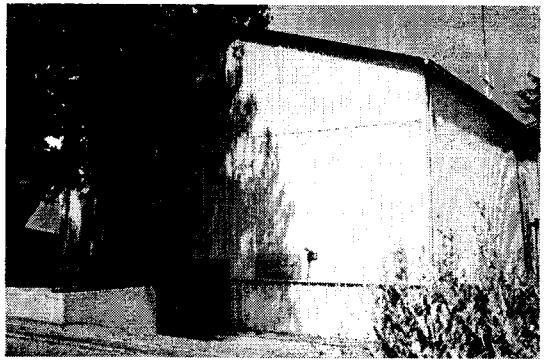
D-TEC INTERNATIONAL INC.

ACEi

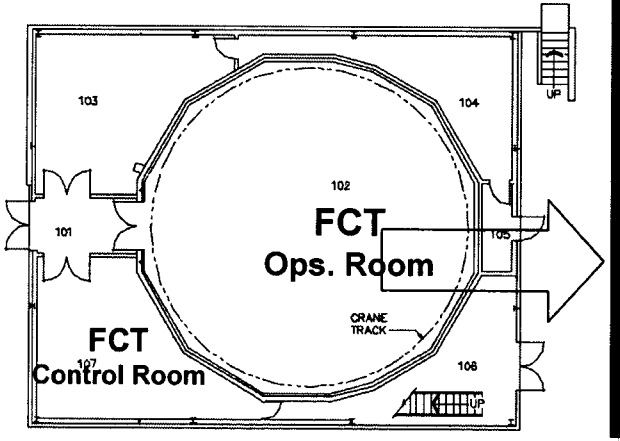
FCT – Key Features

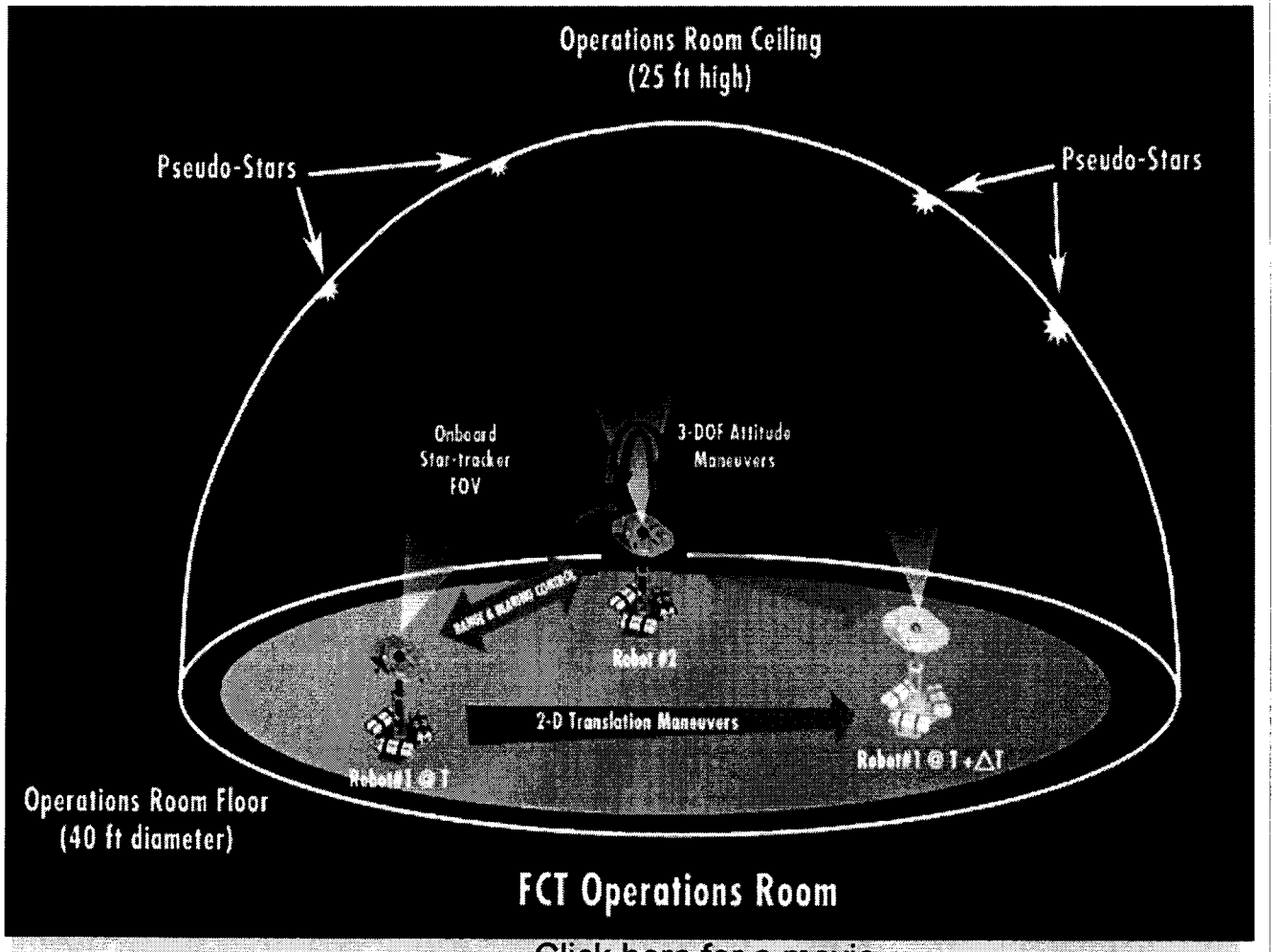
- **High fidelity**
  - Full rotation and translation degrees of freedoms (6DOF)
  - Realistic flight avionics architecture – sensors/actuators
- **Large area translation capability to support realistic formation flying relative maneuvers**
  - Flat floor (30ft diameter)
- **Total experiment run-time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

FCT – Operations Approach



Formation Technology Laboratory





Click here for a movie

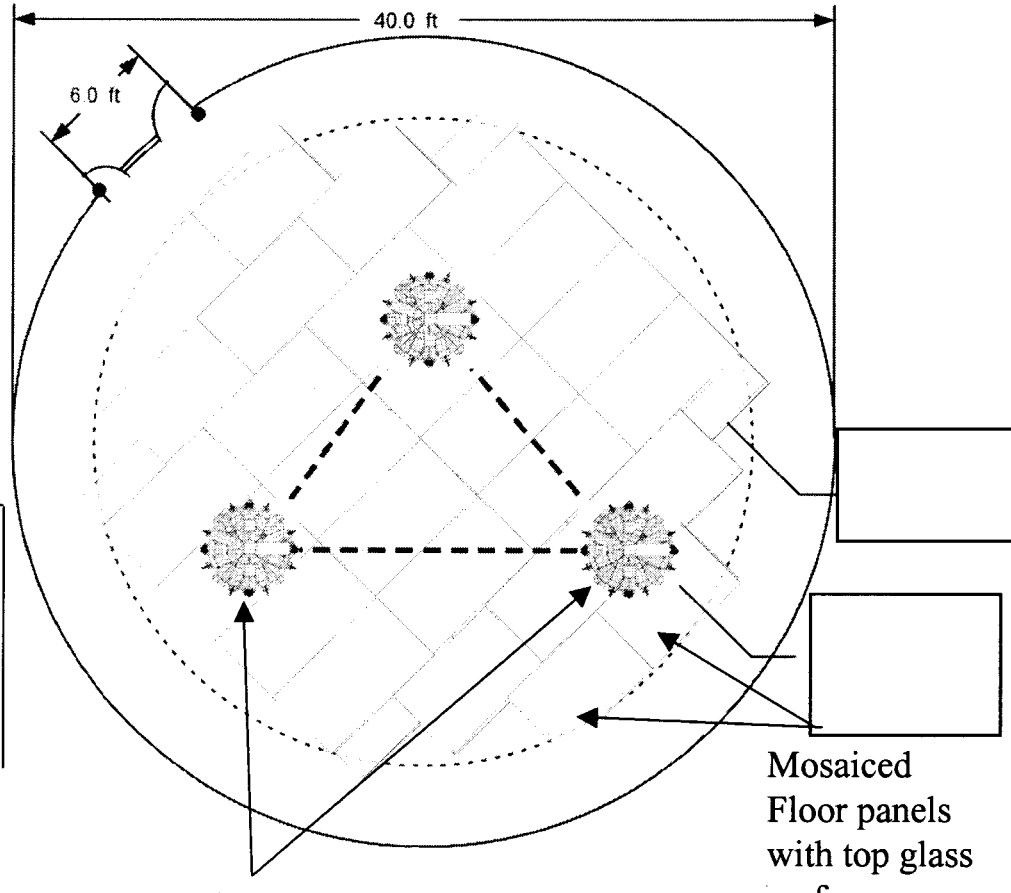
FCT Ops. Room – Top View

Terrestrial Planet Finder Mission

TPF

A NASA Origins Mission

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

Guidance Dynamics Corporation

DI-TEC INTERNATIONAL INC.

ACEi

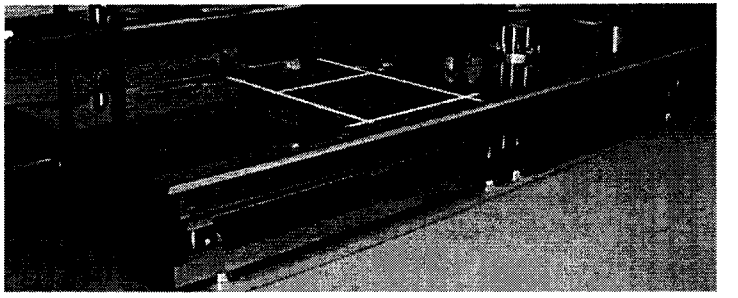
Floor

Terrestrial Planet Finder Mission

TPF

A NASA Origins Mission

Prototype



Design

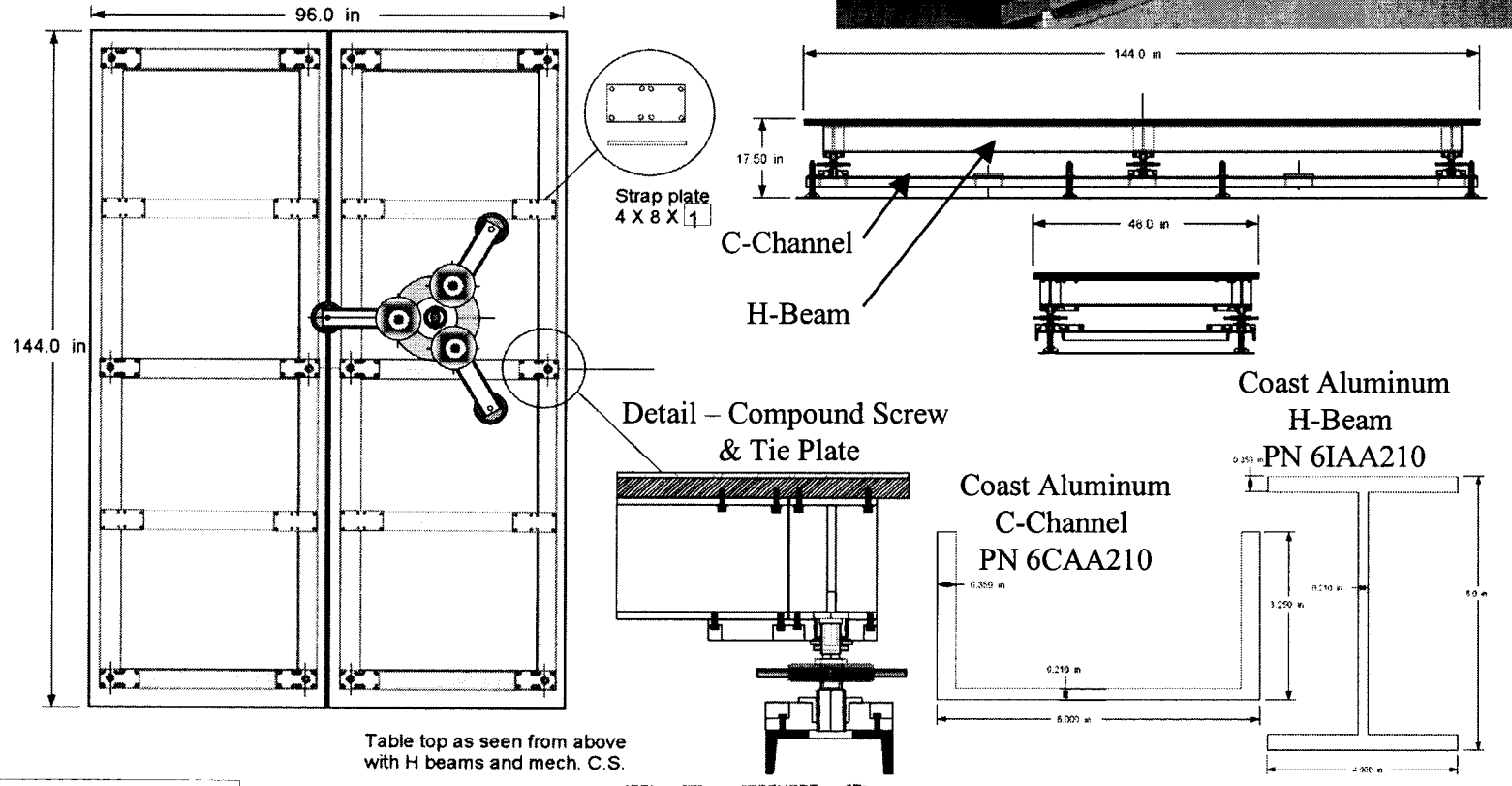


Table top as seen from above with H beams and mech. C.S.

Guidance Dynamics Corporation

D-TEC INTERNATIONAL INC.

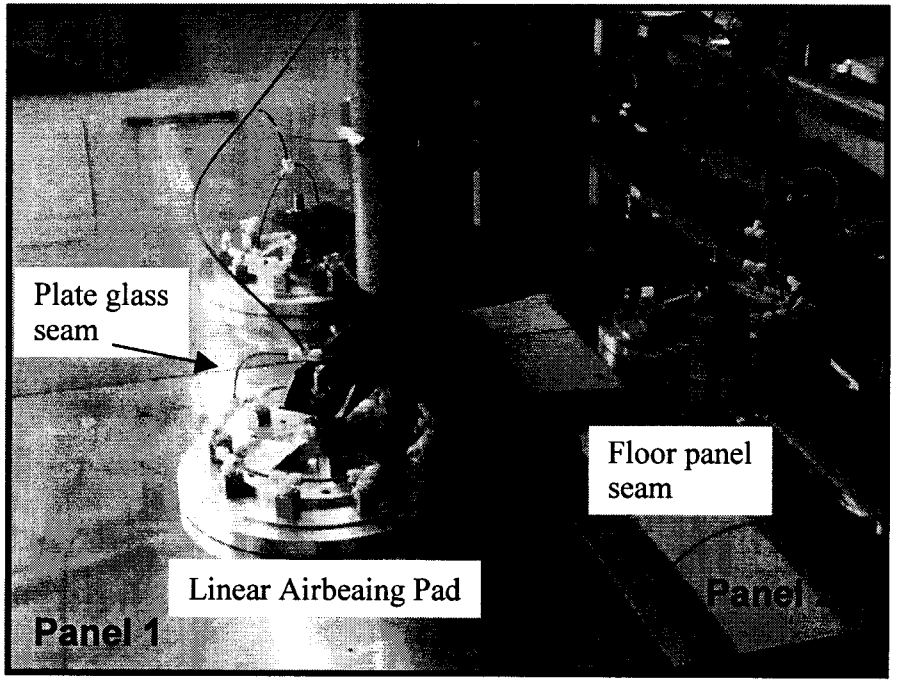
ACEi

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

Terrestrial Planet Finder Mission

TPF

A NASA Origins Mission

Guidance Dynamics Corporation

DI-TEC INTERNATIONAL INC.

ACEi

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. - FY'04
- Two-robot autonomous formation flying demo - FY'05
- Three robot autonomous formation flying demo - FY'06

Terrestrial Planet Finder Mission

TPF

A NASA Origins Mission

Guidance Dynamics Corporation

D-TEC INTERNATIONAL INC.

ACEi

JPL

Terrestrial Planet Finder Mission

TPF

A NASA Origins Mission

Backup

Guidance Dynamics Corporation

DI-TEC INTERNATIONAL INC.

ACEi

Poured Epoxy on Concrete Floor

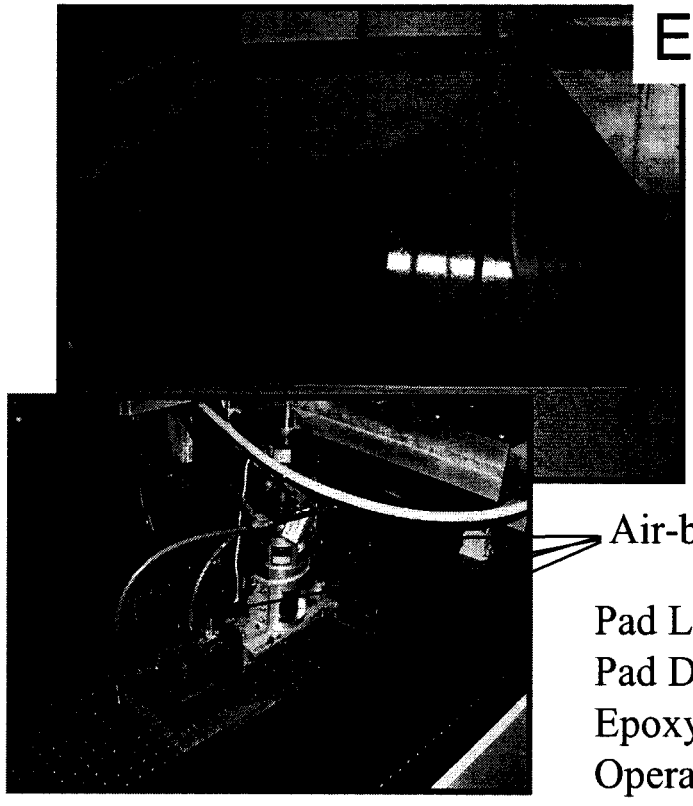
JPL

Terrestrial Planet Finder Mission

TPF

A NASA Origins Mission

ABLE Engineering Co. Inc.
Flexible Space Structures Deployment Laboratory

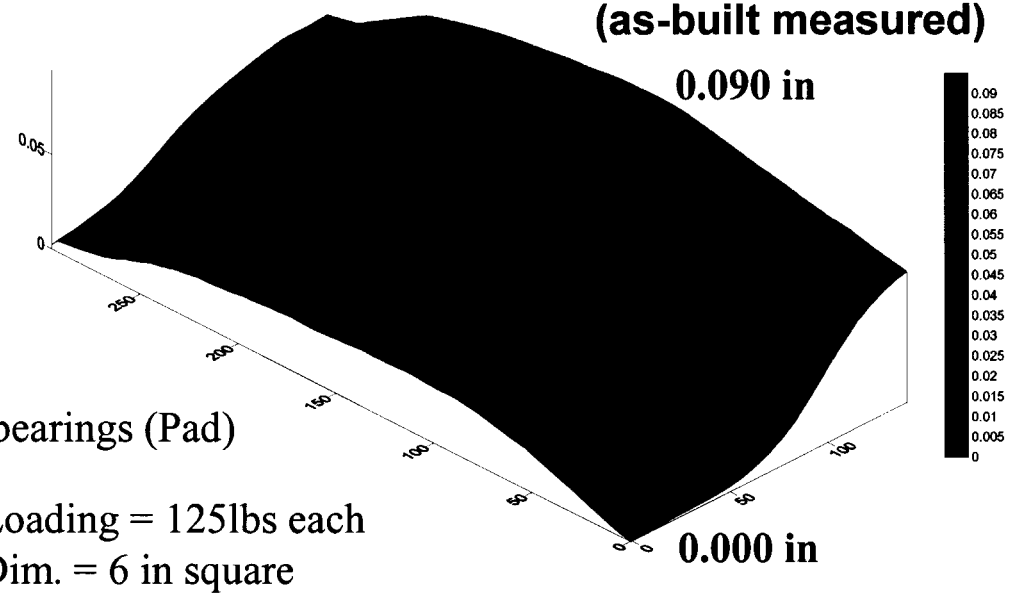


Epoxy Floor

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

Guidance Dynamics Corporation

DI-TEC INTERNATIONAL INC.

ACEi

Poured Epoxy on Raised Panels

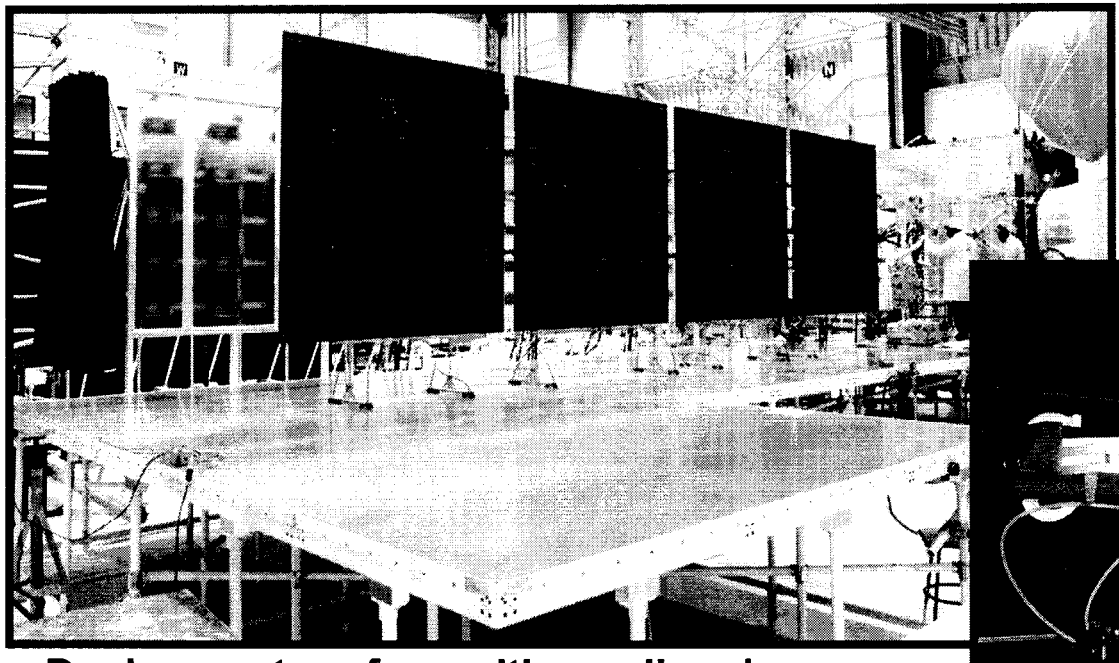
JPL

Terrestrial Planet Finder Mission

TPF

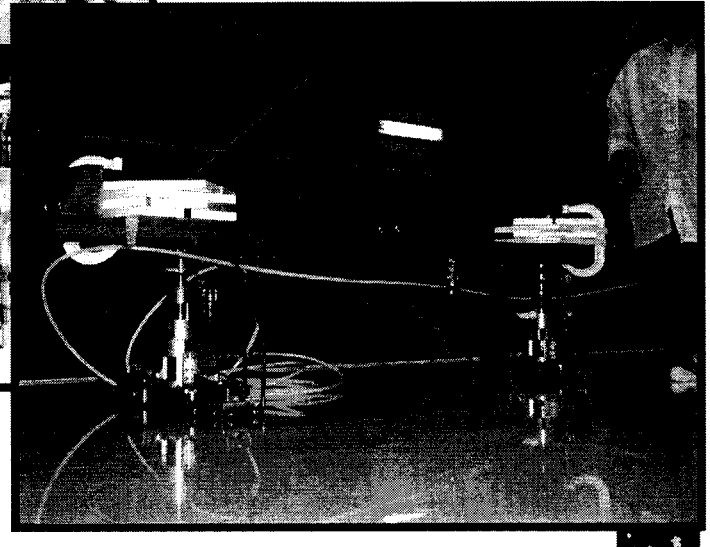
A NASA Origins Mission

MD Robotics
Ontario, Canada



Deployment surface with small and large off-loaders

Raised honeycomb Panel With poured epoxy



Guidance Dynamics Corporation

DI-TEC INTERNATIONAL INC.

ACEi