Teaming with the Terrestrial Planet Finder Formation Control Testbed

NASA Health & Safety Managers Meeting

March 3, 2005

Presented by Michael Swanson

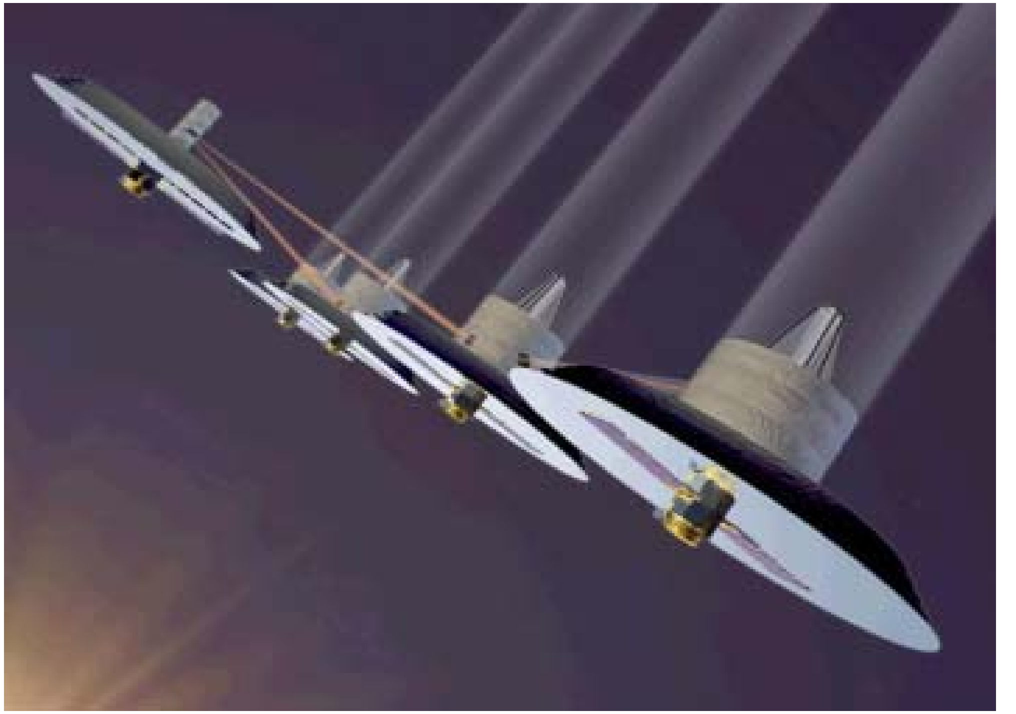
JPL Occupational Safety Program Office

Outline

- Introduction
- Overview
- Invitation to the Environmental, Health, and Safety (EH&S) Program Office
- Health & Safety Issues
- Health & Safety Approach
- Safety as "Value Added"
- Acknowledgements

Introduction

- Terrestrial Planet Finder (TPF) – NASA Origins
  - Two complementary observatories that will study all aspects of planets outside our solar system, searching for earth-like planets that might harbor life:
    - A visible-light coronagraph, to launch round 2014
    - A formation-flying infrared interferometer, to launch before 2020



Introduction

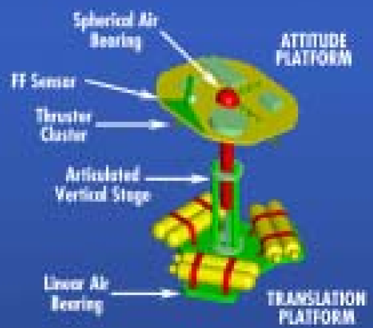
- Formation Control Testbed (FCT)
  - 6-DOF robotic testbed that will demonstrate an end-to-end precision formation flying system
  - Purpose:
    - Validate formation control architecture and algorithms
    - Demonstrate autonomous TPF-like precision formation flying with three robots to a performance level of:
      - 10 m diameter operating space
      - Up to 8 m separation
      - ± 5 cm range control
      - ± 5 arc minute attitude control
      - ± 60 arc-minute bearing control

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

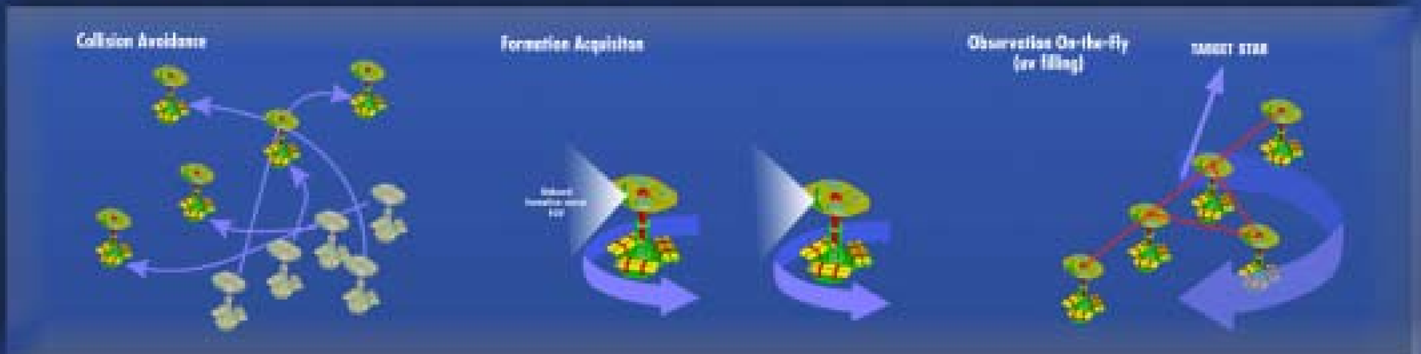
CONCEPT



- 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

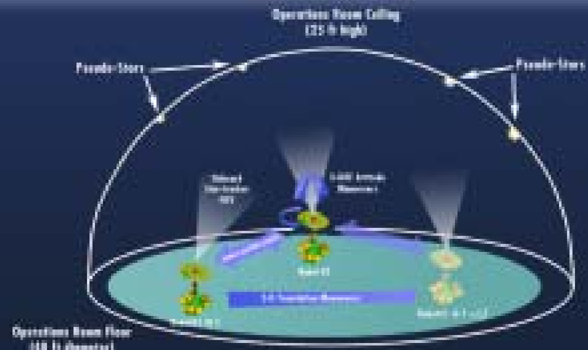
ENGINEERING LAYOUT

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)

Overview - Configuration

Total Mass: (lbs)

Wet = 663.1 lbs

Dry = 622.8 lbs

Attitude Platform(AP): (lbs)

Dry = 319.98 lbs

Wet = 328.6 lbs

Translation Platform (TP): (lbs)

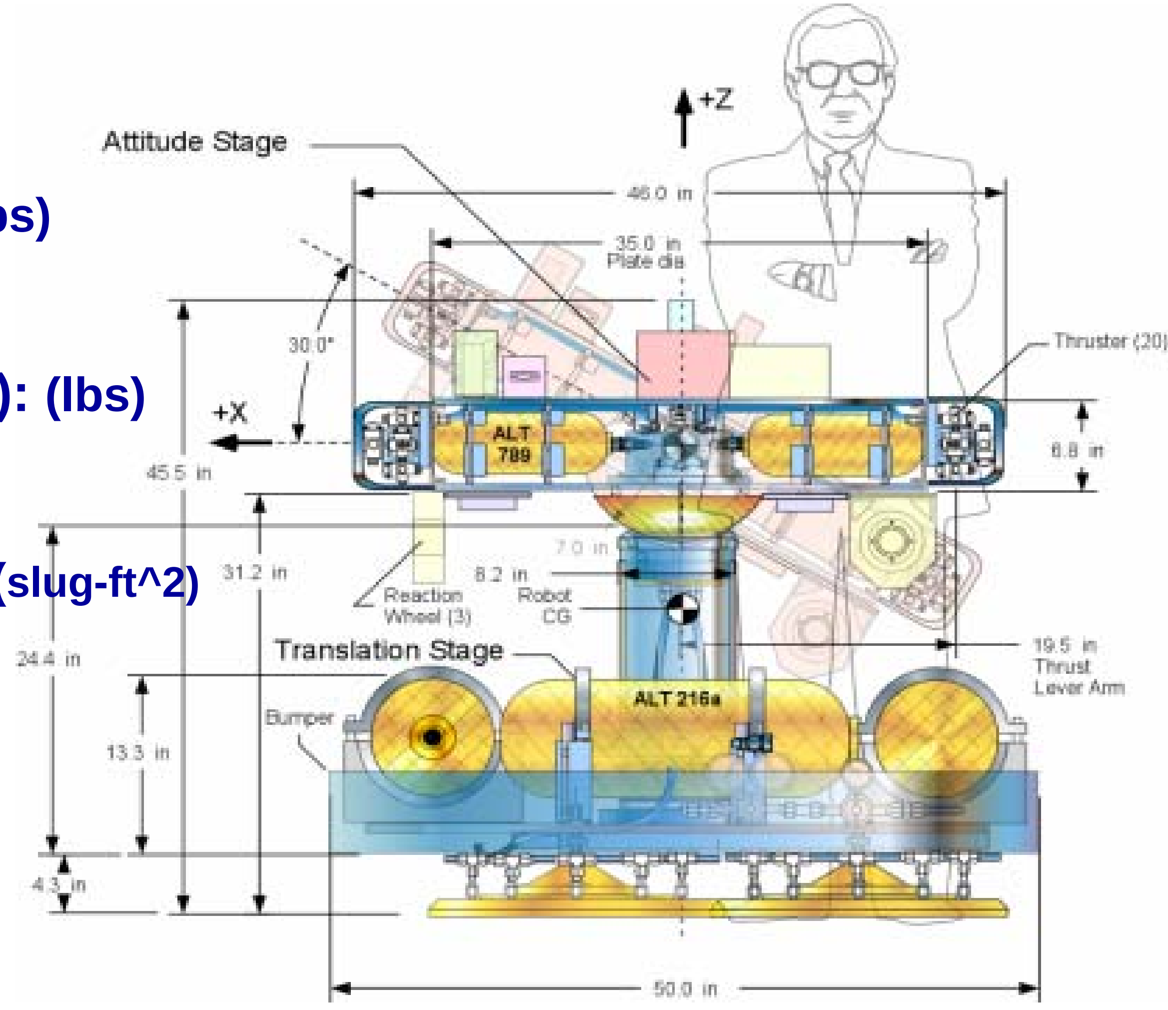
Dry = 288.14 lbs

Wet = 319.85 lbs

AP Inertia: [Ixx, Iyy, Izz] – (slug-ft^2)

Dry = [6.83 5.76 9.62]

Wet = [7.11 6.04 10.20]



Invitation to the EH&S Program Office

- FCT Personnel Invited the Occupational Safety Program Office (OSPO) and the Systems Safety Program Office (SSPO) to participate in the Preliminary Design Phase (April 2003)
  - Initial questions related to the high pressure systems for the air bearings and cold-gas thrusters.
- Contact was Suggested by Project Management!

Health & Safety Issues

- Operational Safety
  - Physical hazards of three 600-pound robots under remote and computer algorithm control
  - Noise from operational thrusters
- Pressure Safety
  - High pressure air (3000 psig) stored on each robot to power linear and spherical air bearings and thrusters
- Lifting Devices Safety
  - Robot and flat floor mobilization
- Systems Safety
  - Protect critical hardware

Safety Approach

1. **Safety through "Engineering design/build"**
   a. Designed in safety through selection of approved system components
   b. Designed in recommended safety margins
   c. Designed in pneumatic and electrical safety features
   d. Safety testing during Integration & Test phase (key milestones identified)

2. **Safety through "Administrative Procedures"**
   a. Safe Operating Procedures (SOPs)
   b. Pre-Operational Safety Review
   c. Task-Specific Health & Safety Plan
   d. Training/certification/indoctrination (institutional, site-specific)

3. **Safety through "Protective Equipment"**
   a. Eye glasses/face shields, gloves etc.
   b. Warning alarm (visible and/or audible)

Pressure Safety Design Features

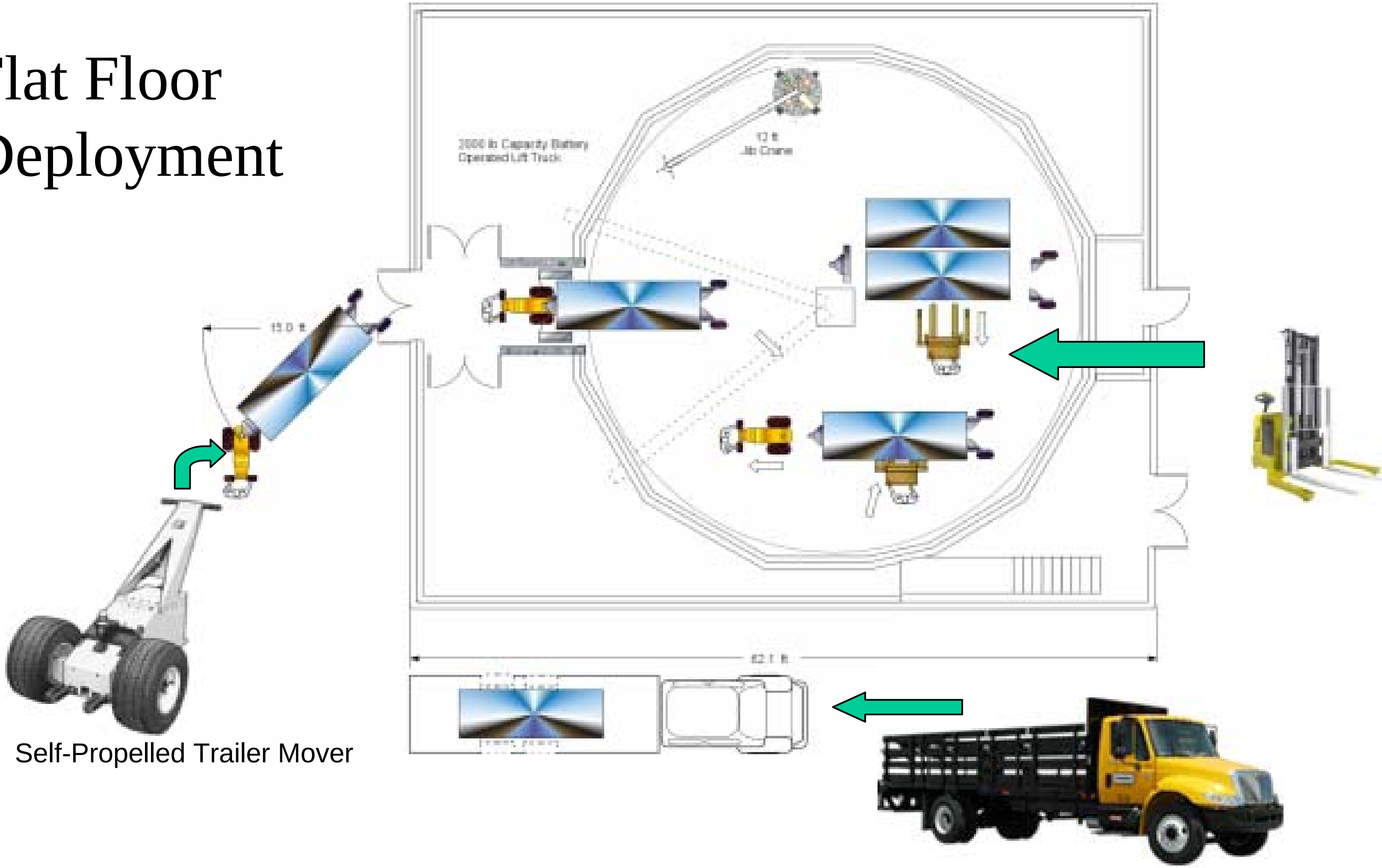
1. Different gender fill ports for the high and low pressure fill.
2. Extensive use of pneumatic safety devices (relief devices, check valves, vent valves etc.)
3. Extensive instrumentation of the system with pressure transducers, and gauges to provide enhanced visibility into the operational health of the system.
4. Color coded pneumatic lines for different pressure levels.
5. Refill System regulator to prevent overfilling the Robot on-board pressure vessels.
6. Positive hold-switch with a key at the Robot Refill Station, which requires the Refill Operator to hold the key in the on-position for the refill operation. Releasing the key will terminate the refill operation and vents the line via the three-way valve outside of the building.
7. Use of elastomeric gaskets under the band-clamp mounts of the pressure vessels, allowing the pressure vessels to expand during fill operational while still providing needed mechanical clamping force to keep the pressure vessels secure.
8. Use of mechanical stops to limit the radial adjustment of pressure vessels in the Attitude Platform to prevent inadvertent de-mating of a pressurized pressure vessel - during wet/dry center of gravity balancing.
9. An independent low pressure pressurization of the Robot(s) for manual floatation and/or powered operations without requiring filling the on-board pressure vessels. Enhanced safety during integration, test, and maintenance activities.

Mechanical/Electrical Design Features

1. Bumper ring around the FCT Robot Translation Platform using shock absorbers, to prevent direct collision and absorb impact forces in case of a collision.
2. Railing around the flat floor (panels) edges at the same height as the Robot bumper rings to prevent the robot to fall off the operating flat floor surface.
3. Protective cages around each of the four thruster clusters to protect against physical damage from impact.
4. Use of different size electric umbilical connectors for the Translation Platform and the Attitude Platform of the Robot external and recharge power.
5. Use of smart battery charger to recharge the on-board batteries, which adjusts the charging current based on the sensed level of battery charge.
6. Incorporation of a large easily accessible/visible panic button to shutdown the on-board avionics.
7. Use of work stand/support legs for the Attitude and Translation Platforms. These support legs allows for Attitude and Translation Platforms to kept off the work area surface for ease of maintenance as well as to minimize the possibility of damage to critical air-bearing components.

Storyboards Developed for Critical Activities

Flat Floor Deployment



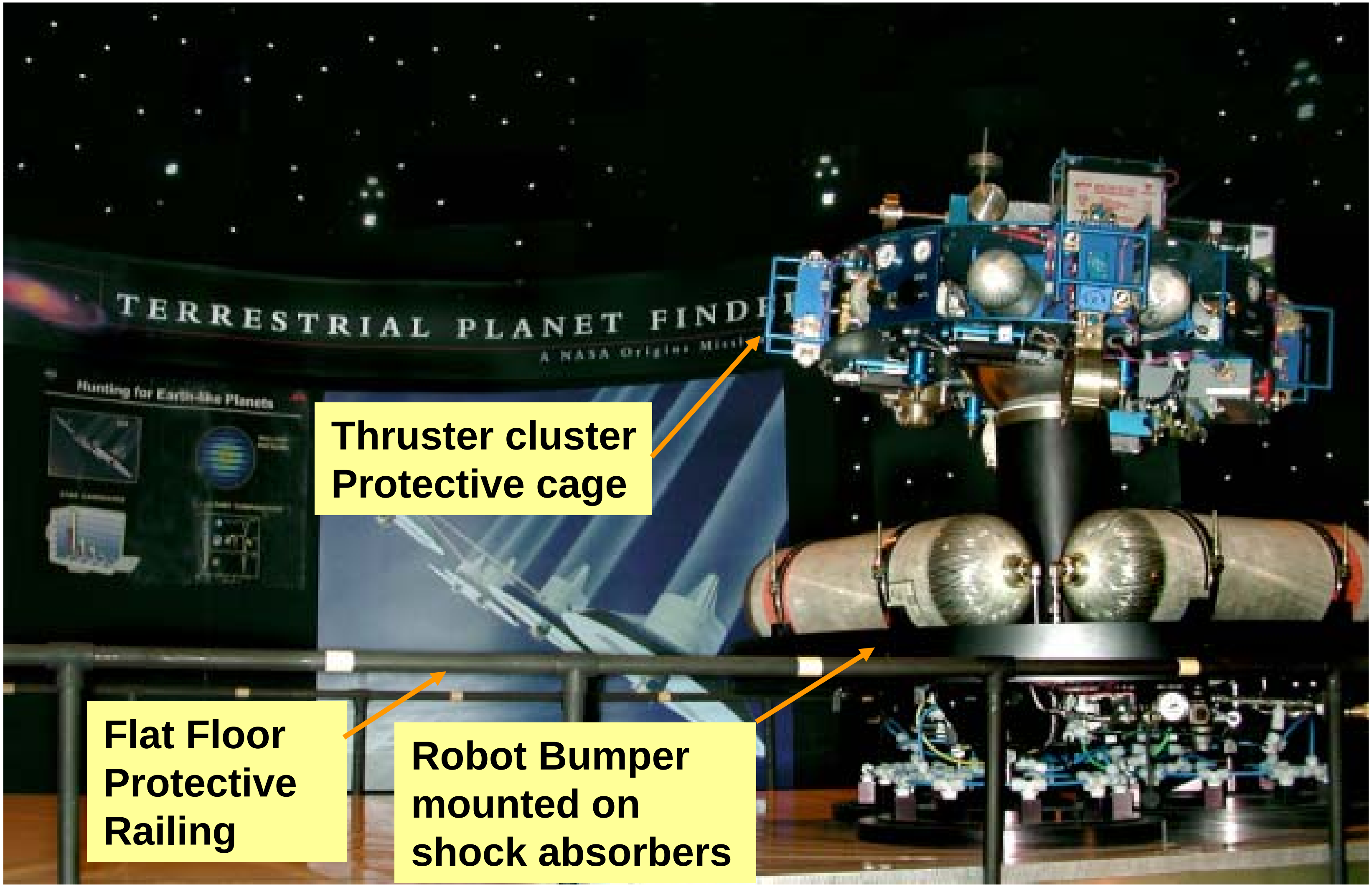
Scheduled Safety Review Points

Master Schedule Line No.	WBS No.	Task/Milestone Description	Task/MS	Start Date	Completion Date
54	1.1.1.1.3.4.1	Translation Stage Pneumatics Proof & Leak Tests	T	5/25/2004 8:00	5/25/2004 17:00
55	1.1.1.1.3.4.2	Translation Stage Floatation Tests	T	5/26/2004 8:00	5/28/2004 17:00
66	1.1.1.2.2.3	Switch Box Control Console	T	6/22/2004 10:40	6/24/2004 15:40
114	1.1.2.2.1	Integrated Attitude Stage Tests	T	6/3/2004 8:00	6/9/2004 17:00
119	1.1.2.2.5.1	Proof & Leak Test Attitude Stage Pneumatics	T	5/24/2004 8:00	5/25/2004 17:00
123	1.1.2.2.6.1	Thrusters	T	5/12/2004 8:00	5/25/2004 17:00
124	1.1.2.2.6.2	Reaction Wheels	T	6/9/2004 8:00	6/22/2004 17:00
148	1.1.3.1	Floor/Translation Integration at Di-Tec	T	5/26/2004 8:00	6/8/2004 17:00
149	1.1.3.2	Tranportation & Handling Check Out at Di-Tec	T	6/29/2004 8:00	7/12/2004 17:00
150	1.1.3.3	Final Float Tests at Di-Tec	T	7/22/2004 10:40	7/27/2004 10:40
152	1.1.3.4.1	Electronics/SW at ACEi	T	7/8/2004 10:40	7/15/2004 10:40
153	1.1.3.4.2	Full Robot ACEi	T	7/15/2004 10:40	7/22/2004 10:40
155	1.2	Robot & Floor Transportation & Installation	T	7/27/2004 10:40	7/30/2004 10:40
158	1.3.1	Installation & Checkout of Bauer Compressor	T	7/8/2004 8:00	7/12/2004 17:00
159	1.3.2	Installation & Checkout of Fill Stations	T	7/13/2004 8:00	7/14/2004 17:00
160	1.3.3	Proof and Leak Testing of Fill Pressurization System	T	7/15/2004 8:00	7/15/2004 17:00
161	1.3.4	Installation and Proof Loading of Jib Crane & Hoist	T	6/23/2004 8:00	6/24/2004 17:00
162	1.3.5	Installation of Floor Platforms	T	7/30/2004 10:40	8/2/2004 10:40
164	1.3.7	Installation & Emplacement of Robot 1	T	8/4/2004 10:40	8/6/2004 10:40
177	1.4.1.9	Transportation & Handling Design Details	T	4/19/2004 8:00	5/14/2004 17:00
211	1.5.3	Robot Functional Demonstration Software	T	7/8/2004 10:40	7/15/2004 10:40
216	1.6.1.2	COTS Parts	T	4/15/2004 8:00	7/7/2004 17:00
268	1.6.2.4	Laboratory Processor Functional Demo Software (1 ea	T	7/15/2004 10:40	7/20/2004 10:40
273	1.7.1.1	Develop Master Schedule	T	3/17/2004 8:00	4/13/2004 17:00
274	1.7.1.2	Develop Safety Data Package	T	5/3/2004 8:00	6/29/2004 17:00
275	1.7.1.2.1	Proof, Leak & Relief Pressure Test Procedure - Attitude	T	5/3/2004 8:00	5/21/2004 17:00
276	1.7.1.2.2	Proof, Leak & Relief Pressure Test Procedure -Transla	T	5/4/2004 8:00	5/24/2004 17:00
277	1.7.1.2.3	Proof, Leak & Relief Pressure Test Procedure - Robot	T	6/9/2004 8:00	6/29/2004 17:00
278	1.7.1.2.4	Jib Crane & Hoist Operation Procedure	T	6/9/2004 8:00	6/22/2004 17:00
279	1.7.1.2.5	Motorized Tow Operation Procedure	T	6/9/2004 8:00	6/22/2004 17:00
280	1.7.1.2.6	Self Propelled Lift Operation Procedure	T	6/9/2004 8:00	6/22/2004 17:00
282	1.7.2	System Engineering	T	3/17/2004 8:00	9/2/2004 17:00
283	1.7.2.1	Update Robot Mass Properties	T	3/17/2004 8:00	9/2/2004 17:00
284	1.7.2.2	Robot Operation and Maintenance Procedures	T	7/22/2004 10:40	8/19/2004 10:40
285	1.7.2.3	Robot Transportation & Handling Procedures	T	6/29/2004 8:00	7/26/2004 17:00
286	1.7.2.4	Floor Operation & Maintenance Procedures	T	5/26/2004 8:00	6/22/2004 17:00
287	1.7.2.5	Floor Transportation & Handling Procedures	T	6/29/2004 8:00	7/26/2004 17:00
288	1.7.2.6	Robot Fill System Operation and Maintenance Procedu	T	7/1/2004 10:40	7/29/2004 10:40
289	1.7.2.7	Robot Battery Charging Operation and Maintenance Pr	T	6/4/2004 8:00	6/17/2004 17:00
290	1.7.2.8	Laboratory Processor Operation and Maintenance Proc	T	7/20/2004 10:40	8/3/2004 10:40
291	1.7.2.9	As Built Drawing & Data Package	T	7/27/2004 10:40	8/24/2004 10:40
296	1.7.3.1.5	Pre-Operational Safety Readiness (OSR) Review	MS	7/9/2004 8:00	7/9/2004 17:00
297	1.7.3.1.7	Monthly Progress Reviews	T	4/12/2004 8:00	9/10/2004 17:00
299	1.7.3.1.8	Demonstration & Delivery Review	MS	7/21/2004 8:00	7/21/2004 17:00
301	1.7.3.1.2	Implementation Review	MS	3/31/2004 8:00	3/31/2004 17:00
302	1.7.3.1.3	Provide Project Schedule	MS	4/14/2004 8:00	4/14/2004 17:00
322	1.7.4.2.1	Attitude Stage Floatation Test	MS	6/23/2004 8:00	6/23/2004 17:00
323	1.7.4.2.2	Translation Stage Floatation Test	MS	5/31/2004 8:00	5/31/2004 17:00
326	1.7.4.3.2	Power system design complete	MS	6/2/2004 10:40	6/2/2004 10:40
333	1.7.4.4.1	Internal Pre Operational Safety Review	MS	6/30/2004 8:00	6/30/2004 17:00

First Robot Deployment
August 24, 2004

Flight Technician Team
Logistics and Materials Team
Protective Services Team

First Robot Operational September 2004



Safety as “Value-Added” Rather than “Hindrance”

1. Carbon Dioxide initially considered and rejected due to concerns with building ventilation and fill logistics – air compressor and storage system used instead.
2. Initial pressure system design did not have pressure relief to protect against regulator failure – additional relief devices added.
3. Initial cylinders proposed for Translation Stage limited to 100 cycles by the DOT exemption – replaced with cylinders with unlimited cycles.
4. Review of proposed pressure component list revealed high pressure gauge with no pressure relief – replaced with gauge with built-in pressure relief.
5. Testing of as-delivered relief devices on the storage pressure vessels revealed lower than expected relief pressure setting on a number of them – replaced/reset with the proper relief setting and certified prior to installation.
6. On-site check during installation revealed thinner than required tubing for Refill System high-pressure (5000 psig) lines – upgraded to thicker wall thickness in compliance with ASME standards.
7. Eliminated the use of Jib crane for critical lift early in the design phase to stay compliant with NASA Standard – an alternate approach developed in a timely manner.
8. Facility flooding risk identified, documented and communicated to management months prior to FCT hardware deployment – interim steps taken during rainy periods by deploying roof tarp and sandbags to safeguard against leaks and flooding, while detailed design was completed for roof rework and re-grading with new concrete for proper drainage.

Acknowledgements

- Director for Astronomy and Physics: Larry Simmons
- TPF Project Manager: Dan Coulter
- FCT Team: