Micro-Inspector Spacecraft for Space Exploration Missions

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Team Members:

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Boeing Phantom Work
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Overview

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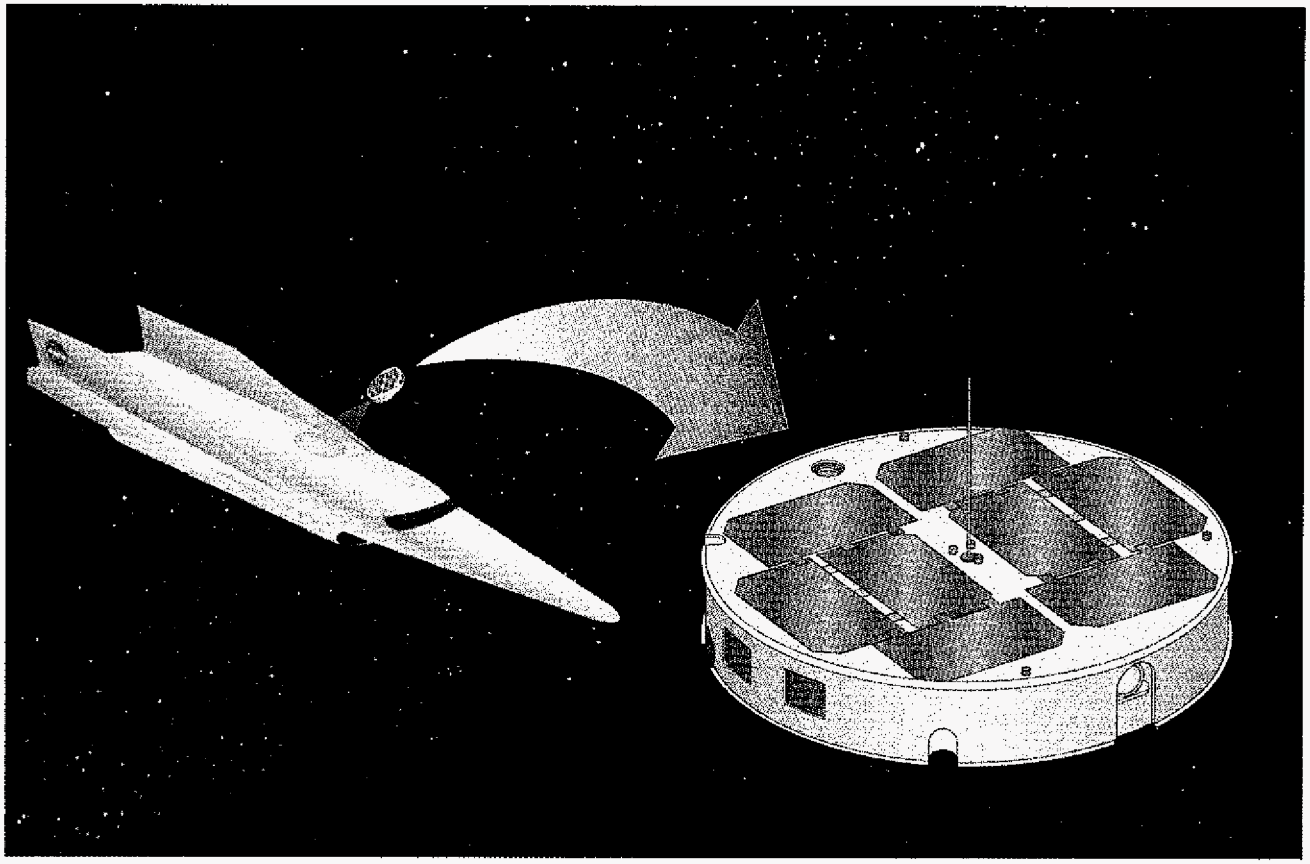
Introduction

Micro Inspector Spacecraft Improves Safety of Flight Vehicles



We will mature the technology of highly miniaturized micro-inspectors for remote inspection of space vehicles, enhancing safety and reliability of future ESR&T missions.

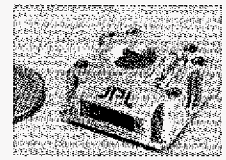
Project Outline

Micro-Inspector Concept

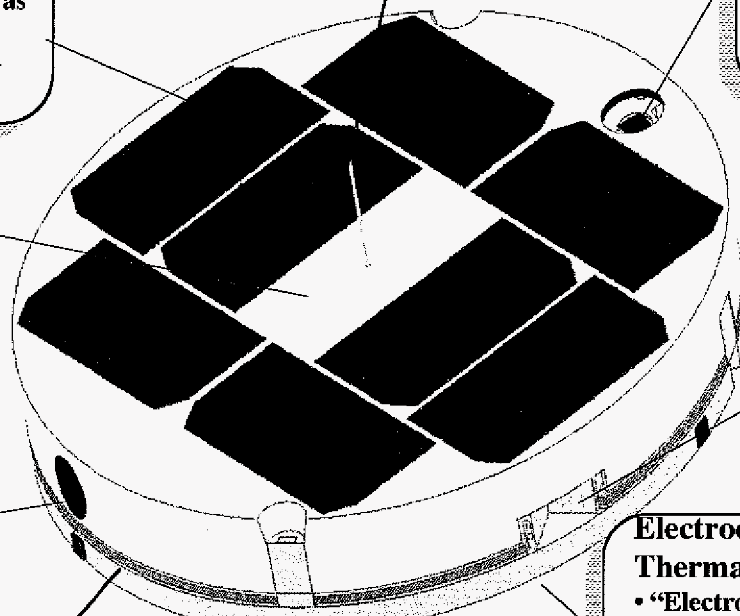
Solar Cells for Continuous Operation In Sun
- GaInP2/GaAs/Ge cells
- Two Li-Ion batteries as back-up
- 3.6 Ah, ~ 4-hr charge

Quarter-Wave Monopole Antenna For Telecom
- 30-m range

Sun Sensor for Celestial Navigation



3-Axis Micro-Gyro (Mounted Internally) (Draper)



Low Pressure Butane Propulsion System for ACS and small delta-v (15 m/s)
- 1 mN thrust
- 50 sec Isp
- MEOP = 40 psi

Camera (1 of 3) for Imaging, Relative Navigation and Collision Avoidance

Electrochromic Surface for Thermal Control (Mounted Below)
- "Electrostatic Louver"
- No moving parts
- Thin Film 0.08 g/cm^2
- ε = 0.35 - 0.8

Multi-Functional Tank
- Forms main spacecraft structure
- Supports electronic circuit board, electrochromic surface
- Factor of safety > 5 MEOP

- The micro-inspector is based on the FY'04 Low-Cost Adjunct Microspacecraft (LCAM) testbed, shown in the attached graphics, but may ultimately vary in design pending sponsor needs.
- Final deliverable on the micro-inspector project is a demonstration model (TRL 6) to be ground-tested in a space-related environment. No flight article will be delivered.

Anticipated Impact on Exploration Systems

STC #	STC Description	Project Support or Impact
1	Margins & Redundancy: "significant improvements in robustness in operations, reliability and safety".	The micro-inspector spacecraft will be able to perform routine safety or anomaly inspections, increasing safety.
2	ASARA: "making it possible for humans to operate affordably and effectivley in deep space…for sustainable periods of operations - while ensuring that they are "as safe as reasonably achievable"	The micro-inspector spacecraft may be used to inspect spacecraft prior to critical mission phases (e.g. reentry, landings) without the need to resort to human EVAs, representing an affordable option to ensure "as safe as reasonably achievable " operations.
3	In-Space Assembly: "docking vehicles and systems together on orbit including space maintenance, servicing, " etc.	One or several micro-inspectors may be deployed to provide imagery from multiple, hard to reach viewing angles to supervise assemblies, reducing risk.
4	Modularity: "employing common, redundant components, subsystems, and/or systems that can improve reliability and support multiple vehicles, applications, and/or destinations".	The micro-inspector represents an inherently modular component that may be attached to multiple host vehicles systems.
5	Robotic Networks: "extend the reach of human explorers".	The micro-inspector will reduce the need for complex and costly human EVAs.

Task Description

Demonstrate, in a ground-based space related environment at TRL 6, an ultra-low mass micro-inspector spacecraft demonstration model for vehicle inspection to enhance safety and reduce risk of future human and robotic space exploration missions. Key features include:

Ultra-Low Mass and Size (<3.0 kg/20cm):
- Through use of a unique multi-functional system design.

Celestial Attitude Determination:
- Allowing operations beyond Earth orbit

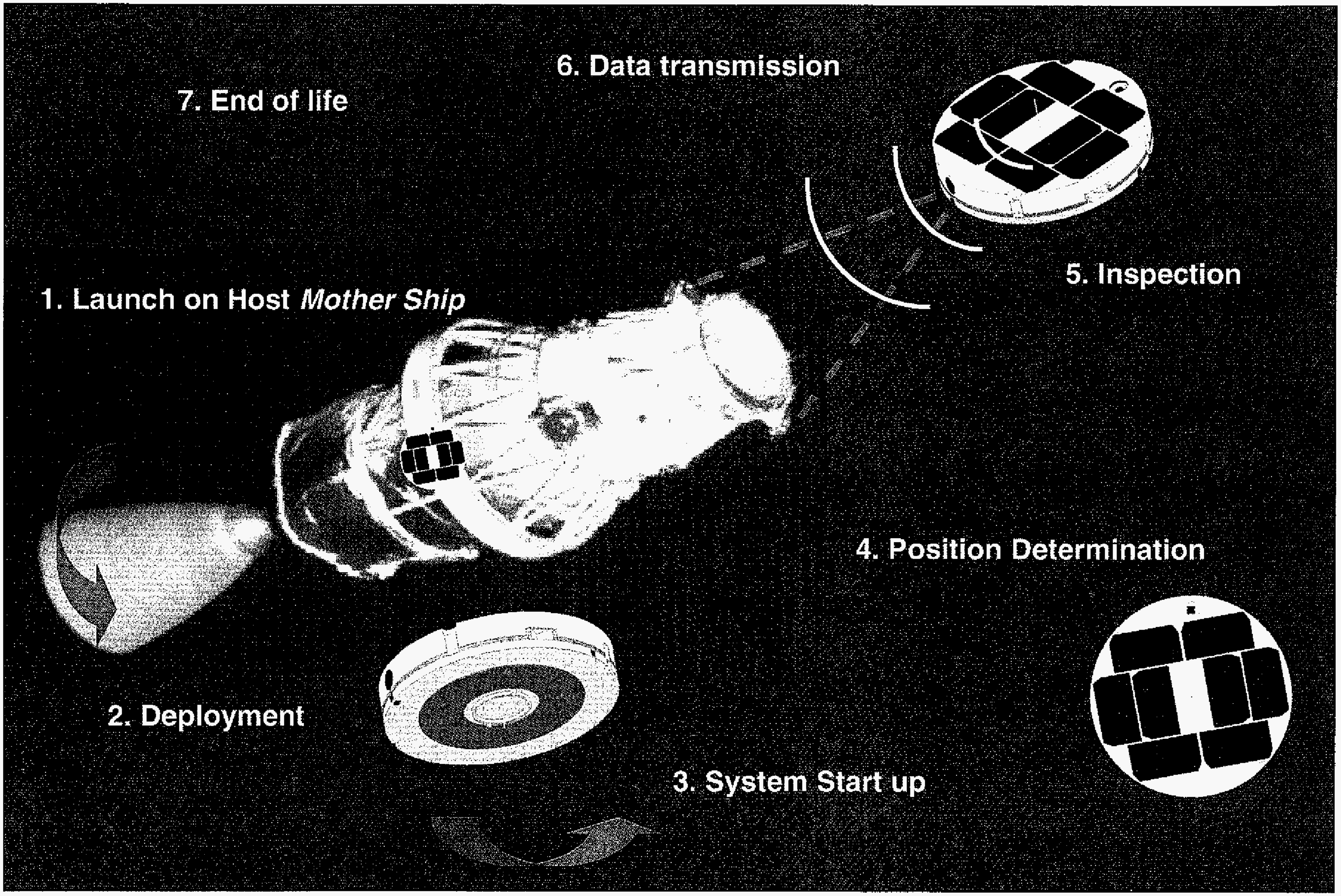
Continued Operation in Sun at 1 AU:
- Solar powered with Li-Ion battery backup
- Ultra-low power consumption (4-5 W): Xilinx Virtex II processor, piezoelectric propellant valves

Safety:
- Collision avoidance system
- Low-pressure, low leakage liquid butane propulsion system
- Low delta-v (14 m/s) and spacecraft accelerations

Imaging:
- Wide and narrow angle cameras.

Final deliverable is micro-inspector hardware for a ground demonstration. No flight article will be delivered.

Notional CONOPS of Micro-Inspector



Notional CONOPS of Microinspector - cont'd

<u>Launch</u>

Initial State: Inspector-sat integrated and tested on host s/c passes health test prior to launch.

Action: Host s/c issues Test command to initiate self-test of inspector-sat. Inspector-sat performs on-board health assessment, and reports system and sub-system state of health to s/c.

End State: <Health State Vector>

During Launch inspector-sat is powered off; mechanical and electrical power, data, com i/f to s/c.

<u>Deployment</u>

Initial State: <Healthy State Vector>

Action: Host s/c issues Release command initiating inspector-sat release mechanism.

End State: <Released, Power-on State>

Connection between microinspector and host is severed, releasing microinspector away from the host. Full power to the microinspector is initiated at this time and all systems are powered on.

<u>System Start-up</u>

Initial State: <Released, Power-on State>

Action: Collision Avoidance algorithm ensures inspector-sat is kept at a safe distance from host;

End State: <System Boot Successful, Collision Avoidance in place, host is safe>

<u>Position Determination and Control</u>

Initial State: <System Boot Successful, Collision Avoidance in place, host is safe>

Action: Determine inspector-sat position relative to host, and relative to stars, sun, Earth;

Final State: <Relative, Absolute position determined at a safe distance from host>

The microinspector knows its position and is at a safe distance from the host (1-10 m).

<u>Inspection</u>

Initial State: <Relative, Absolute position determined at a safe distance from host>

Action: Inspector-sat receives Inspect Command from host s/c.

Final State: <Active Inspection Process; check for safety; collision avoidance; navigate; collect inspection data>

<u>Data transmission to host</u>

Initial State: < Active Inspection Process; check for safety; collision avoidance; navigate; collect inspection data>

Action: Inspector-sat receives Transmit Command from host s/c.

Final State: <Inspect and Transmit Inspection Data>

Pictures and other data is transmitted via short range communications to the host vehicle.

<u>End of life</u>

Safe and dispose of inspector-sat;

Key Deliverables

Phase I (Year 1):

- Review and define ESR&T relevant space environment and mission requirements, including human rating (JPL with NASA JSC).
- Critical Components Assessment (propulsion, thermal, collision avoidance) (JPL).
- Define and perform proximity simulations and derive key micro-inspector design parameters (with Boeing Inc.).
- System level design of a micro-inspector at PDR level (JPL and team)
- Detailed roadmap and implementation plan for Phase II.

Phase II (Year 1):

- Detailed component and system level design
- Component and system breadboard development and test to CDR level

Phase II (Year 2):

- Fabrication and assembly of engineering model micro-inspector
- Demonstration of a <3 kg micro-inspector demonstration model, including environmental testing (solar thermal vac, vibe, shock, EMI, air table).

Phase II (Year 3):

- Final modifications, retests (if necessary), and documentation
- Final delivery of 1-3 kg micro-inspector demonstration model ground-tested in a relevant environment (TRL 6).

Team Members

JPL:

- Overall Project Lead & System Engineering Lead
- Subsystem Engineering
- Environmental Testing (Vibe, Shock, Thermal, EMI, Rad.)

NASA Johnson Space Center (JSC):

- ESR&T requirements definition support (human rating)
- Air-bearing Table (ABT) facility tests to study 2-D proximity ops.

Boeing Phantom Works, Inc.:

- Proximity operation simulations
- Commercialization assessment

Vacco Industries, Inc.:

- Piezovalve and Butane thruster design & fabrication
- Selected sub-component and component acceptance tests

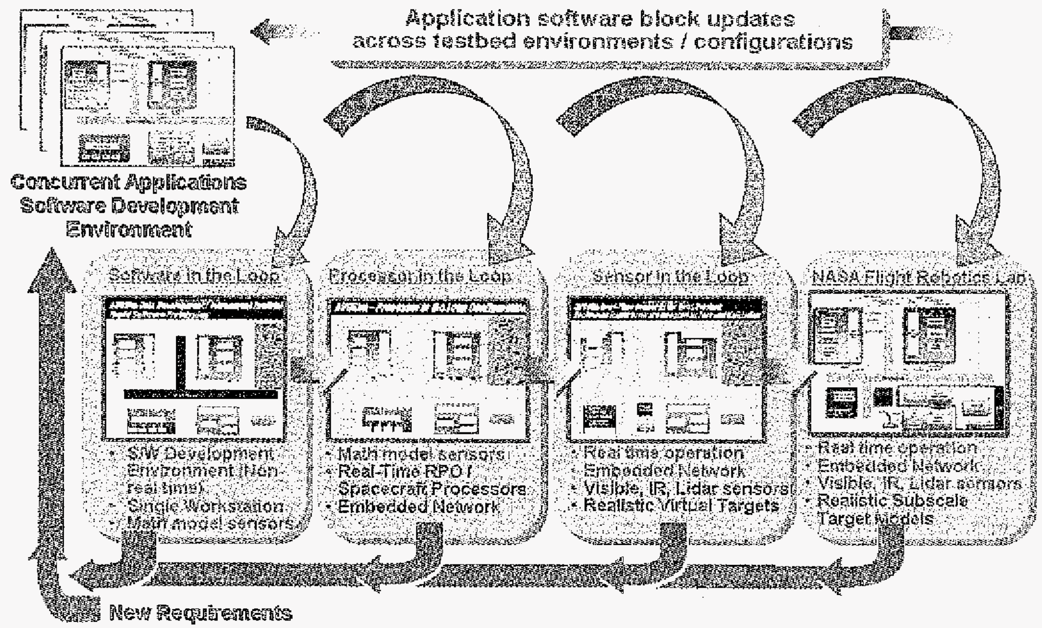
Ashwin-Ushas Inc.:

- Electrochromic surface design, manufacture & test for thermal subsystem
- Environmental test support.

Overview of Key Technology Approaches

Boeing - Proximity Operation Simulations

Boeing will perform proximity simulations of the micro-inspector design using a software package developed for Orbital Express:



B-STAMPS (Boeing Spacecraft Trajectory Analysis and Mission Planning Simulation Tool):

- **Support mission planning and analysis to aid development of CONOPS**
- **Derive system/subsystem requirements: sensor performance, thruster performance, power (solar angles during maneuvering), etc.**
- **Continued trade studies for system/ subsystem engineering technologies and architectures.**
- **Can provide transition to flight projects through mission rehearsal tarining and real-time control and monitoring of on-orbit vehicle.**

AVOSim (Autonomous Vehicle Operations Simulation) will provide high-fidelity rendezvous simulation including hardware/software in the loop testing:

- **High fidelity scene generation**
- **Six DOF environment to support integration and validation of hardware and software.**
- **Spiral development: start with math models of systems/algorithms, proceed to processor-in-the-loop, hardware sensors in-the-loop.**

NASA JSC - Air Bearing Table Testing

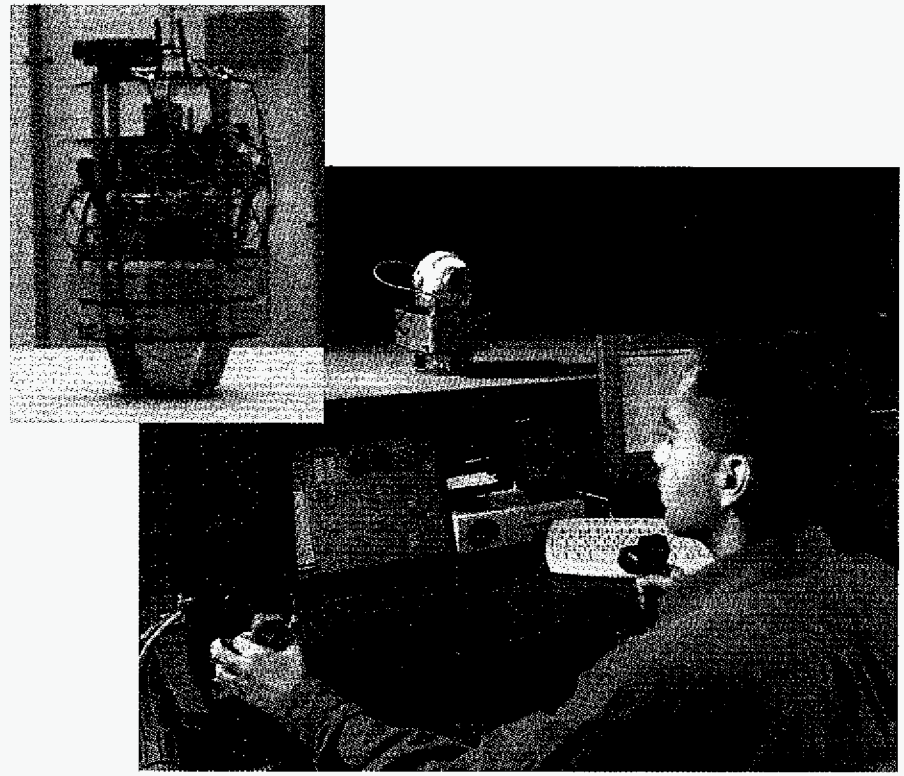
NASA JSC will provide air-bearing table testing to experimentally verify 2-D proximity operation simulations and collision avoidance:

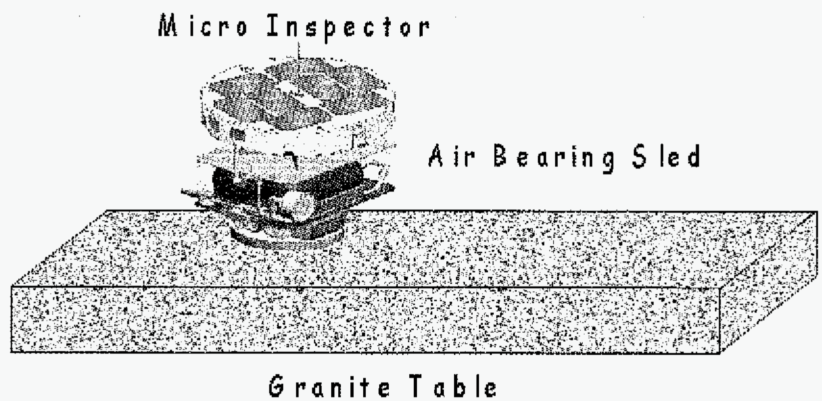
Plate: Available facilities previously used in AERCam program.

- **8’ x 10’ x 20” granite plate**
- **precision flat: max. 17 micro-g lateral acceleration**

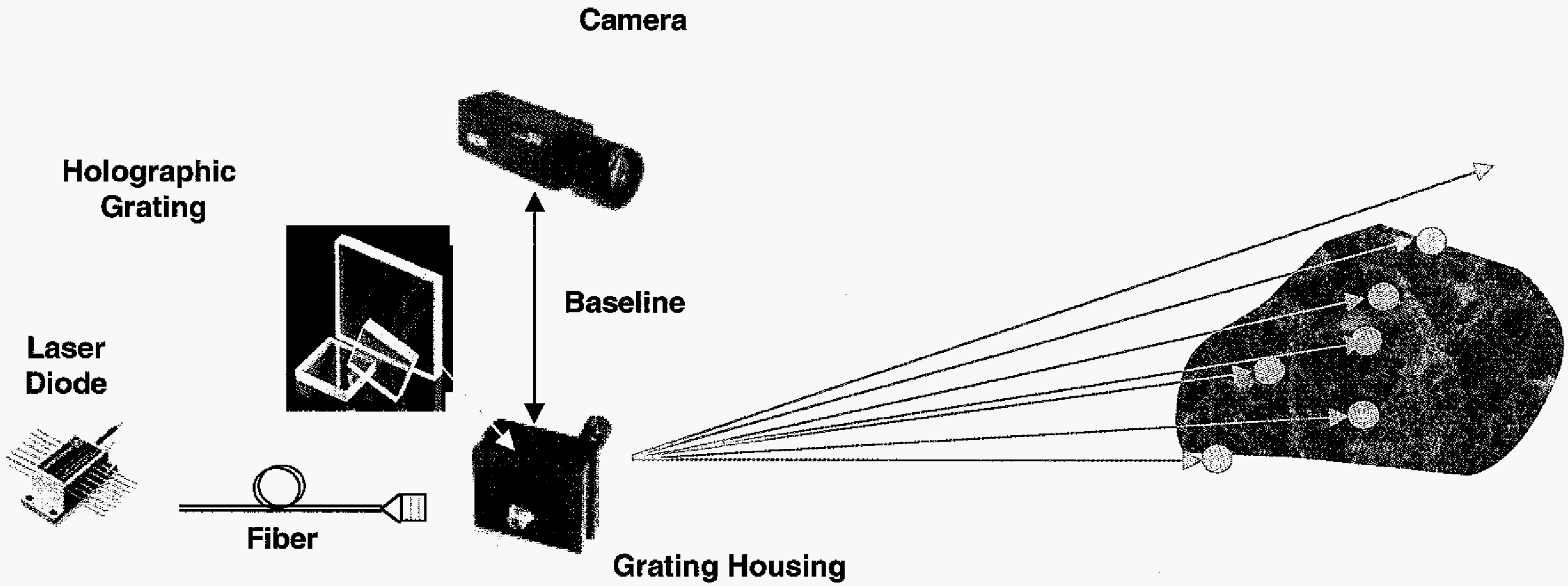
Air-Bearing Sled: A dedicated sled will be designed and built by NASA JSC for Micro-Inspector.

- **Contains a pressurized gas system and necessary support structure, propellant, batteries and electronics to float the micro-inspector payload**
- **Approx. 2 lb mass including fuel and batteries.**
- **Up to 5 kg payload capability**
- **Minimum of 30 minute test run depending on battery and propellant supply.**





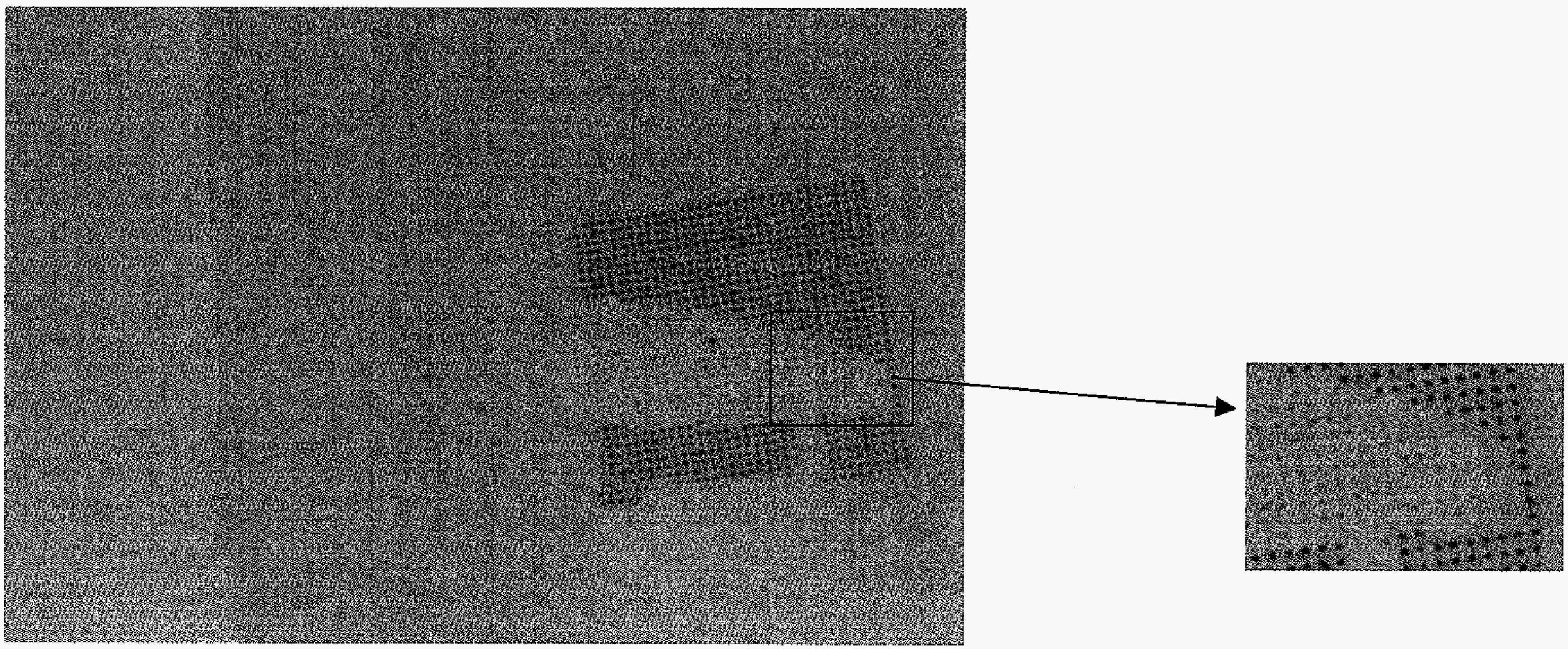
Collision Avoidance Approach



- Standard stereo system setup (offset camera)
- A periodic pattern is projected on to a scene using a laser & grating
- The spots in the scene are located and identified
- Camera offset is used to triangulate position of spots in scene to extract 3D information. Use same cameras as used for inspection with suitable filter to increase signal-to-noise ratio.
- Laser: 2 W laser diode, duty-cycled, flight-qualified, commercially available
- Approx. 4 cm range accuracy at 0.25 W laser power between 4-10 m range

Collision Avoidance Approach - cont'd

Rock imaged with Demo setup. Highlight shows displacement of spots on foreground object. The projector was a standard laser pointer (red) and a 33x33 spot grid.



Additional Micro-Inspector Safety Features

Safe Sequencing:
- Adequate distance from host
- Low Velocities and turn rates

Onboard Constraints Checks:
- Limited delta-v and burn times

Anomaly detection & Response:
- Significant and/or unexpected increase in angular rates disables all valves

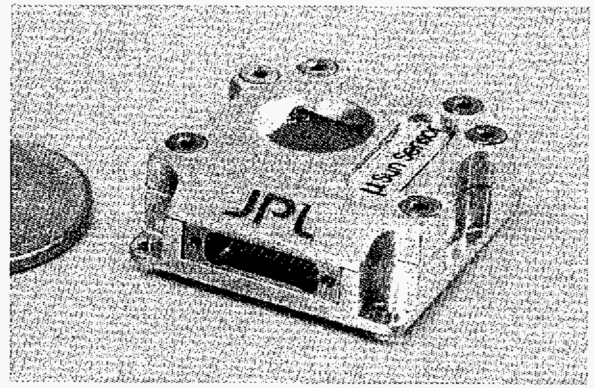
Inherent Hardware System Design Safety Features:
- Low mass and velocity = low kinetic energy
- Thruster only access plenum tank directly, not main propellant supply. Main tank separated from plenum tank by an additional valve in series with thruster valves.
- Alternate logic to valve drivers remains enabled if avionics fails
- Heartbeat required for active system
- No thrust vector goes through the center-of-mass of the micro-inspector.

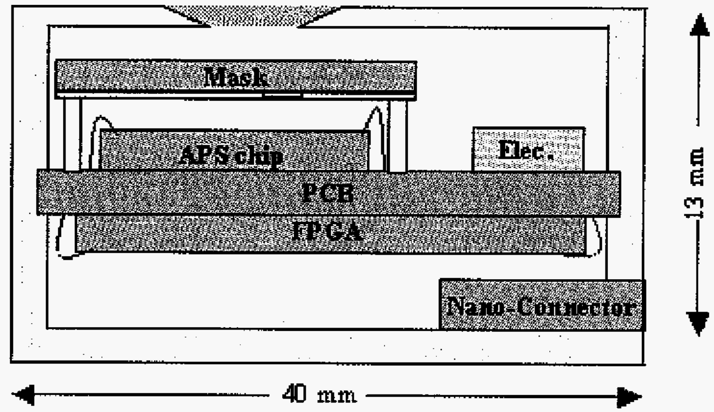
Attitude Control System Approach

Sun presence sensors (diodes) and micro-sun sensor will provide line of reference to sun, and allow spacecraft to orient its solar arrays facing the sun.

Sun Sensor is TRL 5 and being developed under Mars Technology Program:

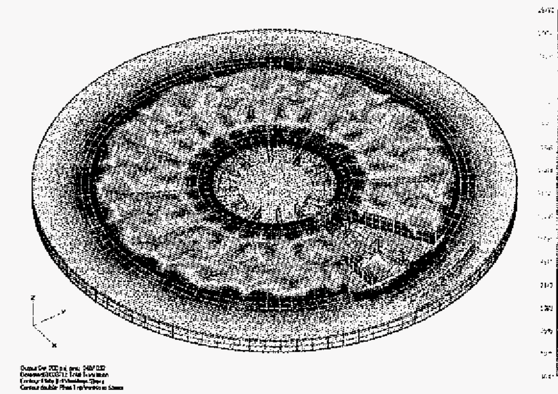
- MEMS pinhole mask and Active Pixel Array chip allow determination of solar direction.
- Internal FPGA based processing electronics.
- 40 grams
- 280 mW
- 40 x 40 x 13 mm
- FOV 128 degree
- 2.4 arc-min pointing knowledge accuracy.



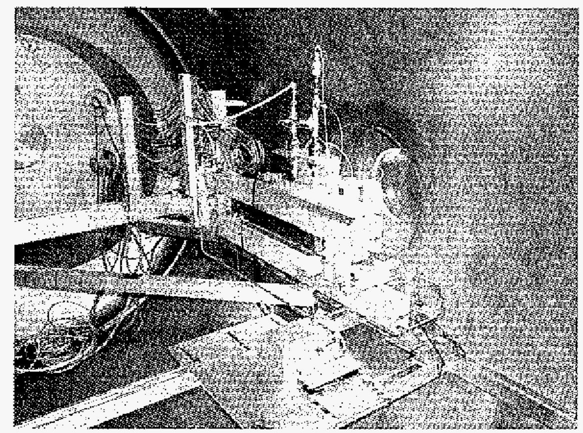


Mechanical Subsystems

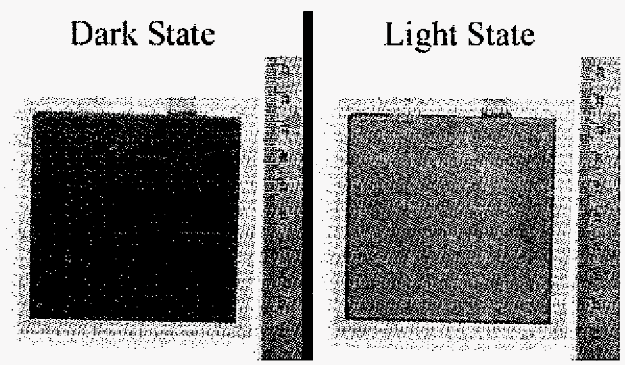
- **Multi-Functional Tank:**
  - Combines main spacecraft structure, propellant tank, thermal control and electronics circuit board.
  - Realizes very low spacecraft mass (< 3 kg)
  - Significant safety factors of > 5 for MEOP of 40 psi.
  - Significant heritage through previous Code R funded task.



- **Butane Propulsion System:**
  - Compact liquid storage.
  - Low pressure (40 psi) provides inherent safety.
  - Liquid storage reduces risk of leaks vs. cold gas systems.
  - Vacco Industries Corp. will serve as industry partner (design and fab. lead) in the development of a TRL 6 system based on ultra-low power piezovalve technology.
  - JPL responsible for integration and test, incl. unique micro-thrust stand diagnostics with < 0.5 μN resolution.



- **Thermal Control:**
  - Electrochromic variable emittance film
  - Application of electric voltage changes emittance by up to 0.5.
  - Emittance ranges available between 0.15 and 0.85
  - Ultra light-weight: 0.08 g/cm^2
  - No moving parts.
  - Industry partner: Ashwin-Ushas Corp.



Power & Telecom

Power & telecom relying on commercial parts. Current design envisions:

Power:

- **GaInP2/GaAS/Ge triple junction cells, 26.5 % efficiency**
- **Li-Ion batteries enabling cold temperature operation**
- **Power conditioning is a dedicated design effort requring unique voltages, such as approx. 50V supply to propulsion piezovalves, and low-voltage buses (1.5, 2.5, 5.0 V potentially).**
- **Heritage through previous Code R funded microspacecraft testbed task**

Telecom:

- **Short range, low-cost (30-m) UHF system (916.5 MHz)**
- **Quarter wave monopole antenna**
- **115.2 kb/s**

Summary & Conclusions

- Micro-Inspector spacecraft will serve key strategic technical challenge areas of ESR&T, such as safety and reliability, ASARA, and in-space assembly.
- Micro-inspector design is inherently modular and flexible, allowing applications on multiple missions to multiple destinations, incl. beyond Earth-orbit, expanding capabilities of micro-inspector presently under development.
- Effective teaming between JPL, NASA JSC, Boeing Phantom Works Inc., Vacco Industries Inc., and Ashwin-Ushas Inc. utilizes unique experiences and skills at each institution.
- Significant heritage due to previous Code R funded microspacecraft testbed activity will be utilized in this technology maturation efforts to deliver a demonstration model of the micro-inspector ground tested in a space-relevant environment (TRL 6)within 3.5 yrs.