Micro-Inspector Spacecraft: An Overview

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ABSTRACT: JPL has developed a small (<5 kg) spacecraft capable of visual inspection of a host vehicle with support from NASA's Exploration Systems Mission Directorate (ESMD). The Micro-Inspector is designed to have a minimal impact on the host with respect to mass, size, cost, interface, and integration. On orbit, the host provides the separation signal to the Micro-Inspector, ejecting it to autonomously maneuver about the host taking images and communicating them back to the host in real-time. The Micro-Inspector is capable of receiving commands for additional utility. After operations are complete, the Micro-Inspector will go through an end of life disposal, ensuring it is at a safe distance and minimal risk to the host. The Micro-Inspector spacecraft features an FPGA based avionics design with embedded processors, miniaturized celestial sensors and a MEMS-based IMU for navigation, structured light system for hazard avoidance, triple-junction solar cells for power generation and lithium-ion batteries for power storage, and a low pressure butane propulsion system, all in a compact and integrated structure, allowing the Micro-Inspector to operate in close proximity to another space object. Extra mass and volume can be used for additional sensors other than visual inspection to provide a more complete analysis of the local space environment. This paper describes the multi-mission utility of the Micro-Inspector and presents an overview of the spacecraft system and subsystem designs, description of a typical inspection mission scenario, and initial hardware demonstrations of key subsystems, partially integrated with each other in a Micro-Inspector testbed at JPL.

INTRODUCTION

Throughout the 1980s and 1990s, JPL has been in the business of developing advanced micro-systems and micro-electronics technologies and components for future space applications. Examples included the development of spacecraft subsystem components such as Micro Electro Mechanical Systems (MEMS) gyros, sun-sensors, star-trackers, micro-valves and thrusters, thermal heat-pipes, power storage and distribution, and many others. There have been also occasional micro flight system developments such as the New Millennium Program Deep-Space 2 Probe (Ref) or the MUSES-C Nano-Rover (Ref). Furthermore, there have been many mission studies that did not result in a flight system development (ref prior work by Dave Collins and others such as Jim Burke in 80s, etc.).

The work presented in this paper builds upon prior system studies and research at JPL, such as the Low Cost Adjunct Micro-spacecraft (LCAM) (Ref. Collins et. al.), which prototyped a 1.5 kg autonomous inspector satellite for the simple, visual inspection of a remote vehicle. Subsequently, NASA awarded JPL the current Micro-Inspector Satellite Project to perform technology maturation of the proposed remote vehicle inspection capability.

It should be noted that this topic is not new, nor unique to work at JPL. In particular NASA JSC had previously developed and demonstrated the AERCam microspacecraft for the similar purpose of inspecting the International Space Station or Space Shuttle (Ref). Whereas the AERCam was designed for operation by an astronaut in Earth orbit (uses GPS for position determination) our goal was to design a system that can operate autonomously in deep-space, on its way to the Moon or Mars and beyond.

This paper provides an overview of the Micro Inspector Satellite Project which has completed its preliminary design phase in March 2006. Moreover, all sub-systems have been prototyped and demonstrated in a flight system testbed at JPL. This paper is organized as follows. We first describe the operational overview of the Micro Inspector Satellite application, followed by the Micro-Spacecraft System and Sub-System descriptions. We conclude with an overview of the current flight system testbed, opportunities for future work and collaboration with universities and other interested parties.

MISSION OVERVIEW

The JPL Micro-Inspector spacecraft is designed to be launched attached to its host vehicle. At a desired time in the host mission, the host will deploy the inspector away from its docking port via a gentle spring-loaded ejection system and thermal separator. The Micro-Inspector spacecraft will initialize its subsystems and then autonomously navigate about the host, beginning its inspection mode. The Micro-Inspector is capable of circumnavigating the host for full vehicle inspection coverage or to investigate specific spacecraft anomalies to enhance mission safety. The Micro-Inspector is also capable of holding position and attitude to monitor a particular event on the host (mechanical deployment or docking). The Micro-Inspector is propellant limited in its lifetime resources, so the duration of inspection capable is dependant on the dynamics of the inspection profile.

During the inspection phase of the mission, the Micro-Inspector maintains bi-directional communication with the host, relaying images and spacecraft health data and uploading commands and command sequences.

Once the Micro-Inspector mission is complete, it performs an end of life disposal to ensure safety to the host vehicle. Depending upon the host mission, the end of life disposal can be achieved by re-docking to the host, or placing the Micro-Inspector in an orbit in which a collision with the host or other spacecraft is not possible for an extended duration, or which ensures burn-up in the atmosphere over time for Earth orbiting missions.

It is possible, due to the low mass of the Micro-Inspector, and its minimal impact to host resources, to have multiple inspectors being carried along by a single host. Multiple inspectors could be released simultaneously providing different viewing angles for a particular event, or as a stereo pair. Multiple inspectors could also be released in sequence to provide data on the effects of the space environment over a longer period of time, including radiation effects and micrometeorite impacts, or at particular anomaly events to increase mission safety.

Potential host spacecraft include the Crew Exploration Vehicle, NASA's replacement for the Space Shuttle, or any other robotic spacecraft in Earth orbit, heading to the moon, Mars, or beyond. The Micro-Inspector spacecraft is capable of operation in Low Earth Orbit, but its lifetime decreases due to added fuel consumption to make up for atmospheric drag effects.

SPACECRAFT OVERVIEW

The JPL developed nano-scale spacecraft is a rectangular box approximately 8"x8"x2" with a mass of just 5 kg, made up of all subsystems of a typical spacecraft including thermal, propulsion, command and data handling, power, telecommunications, and attitude determination and control.

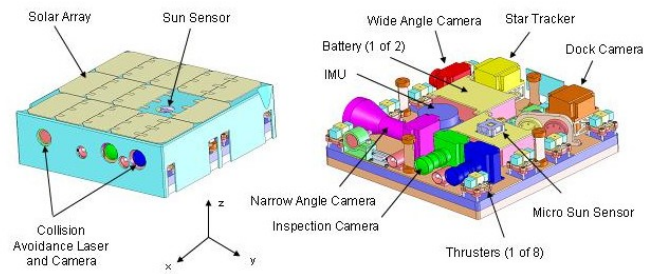


Figure 1. Spacecraft Components

The spacecraft is composed of a sandwich structure consisting of the propellant tank, multilayer circuit board, and payload components. All subsystem electronics are integrated onto one circuit board reducing the need for cables and harnesses. On top of the tank and circuit board is the solar panel assembly, a mushroom cap top mounted on fiberglass standoffs which thermally isolate the panel from the main structure. The solar array is housed on the top of the solar panel assembly, providing the main source of power to the spacecraft electronics. All spacecraft subsystems are located in the interior of the spacecraft mounted on top of the multifunctional tank below the solar panel assembly. Figure 1 shows a CAD model of the spacecraft with components identified.

Mechanical Design

All spacecraft components are mounted to the multifunctional tank (MFT). The MFT not only serves as the primary structure of the spacecraft, it also has a number of other uses including the liquid propellant storage, propellant vaporizer, vapor plenum, some nutation damping, dock interface, heat transfer, controlled heat radiation, and –Z-axis EMI and radiation shielding. Figure 3 shows a cross-section of the tank with liquid propellant storage and plenum areas shown.

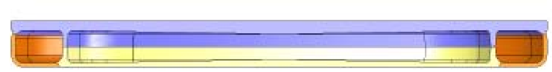


Figure 2. Multifunctional Tank Showing Central Liquid Propellant Storage and Outer Plenum Ring

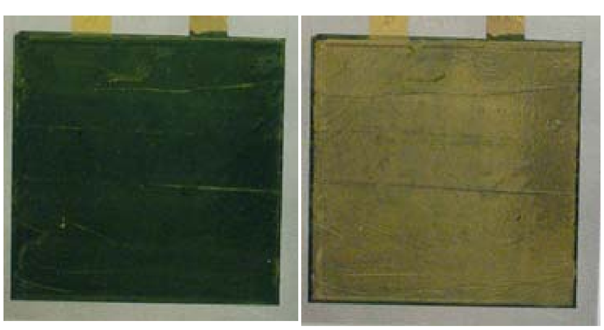
The inner cylindrical tank section is the liquid tank, which contains the bulk of the butane propellant in its liquid stage. The outer, annular section is the plenum tank. Via an isolation and flow control valve (see propulsion section), liquid butane is bled into the plenum, and is stored there in a purely gaseous state until needed by the thrusters, which will bleed gaseous butane directly from the plenum. The plenum and liquid tank arrangement is such that the plenum tank surrounds the liquid tank, and in particular, the single orbital weld of the liquid tank. Should leakage occur at this liquid tank weld, butane will leak into the plenum tank, which now doubles as a containment vessel for the butane, provided added safety.

Thermal

The Micro-Inspector spacecraft consists of two thermally isolated parts. The solar panel assembly provides the cover of the spacecraft. The assembly is a thin cover dense with solar cells on its top side. Aside from some cut-outs for the cameras and thrusters, the solar panel assembly is painted white to reject as much heat as possible and keep the solar array at its specified operating temperature range. To minimize the heat transfer from the solar panel assembly to the circuit board and tank, the two are connected with thin fiberglass stand-offs and the underside of the panel is a gold-plated (low-ε) surface.

The multifunctional tank is designed to be an iso-thermal mass which absorbs waste heat from the circuit board, vaporizes the butane propellant, and radiates the waste heat to space. In order to maximize the heat transfer from the circuit board, the bottom side of the tank contains a variable-emittance electrochromic surface to modulate the radiated heat.

The electrochromic device we are using is a thin-film dual-electrode device developed by Ashwin-Ushas. By applying a slightly positive or negative voltage on the electrodes, the reflectance in the IR wavelength changes between a high-ε (0.85, IR-absorbing) dark state and low-ε (0.15, IR-reflective) light state.



Dark State (+0.2 V) Light State (-1.0 V)

Figure 3. Dual-electrode Electrochromic Device (Ashwin-Ushas Corp., Inc.)

Although the electrochromic surface has not flown in space, qualification testing has been performed to see the effects of time, temperature, radiation, and material compatibility on the emissive states. The devices have shown resistance to vacuum environments (little to no outgassing), ultraviolet exposure (over 500 hours), gamma radiation (up to 8 Mrad), thermal cycling between -10 to +30^{o}C, and were shown to be chemically compatible with the butane propellant.

Propulsion

The propulsion system uses iso-butane as propellant and low power piezoelectric valves as thruster and flow regulation valves, developed by Vacco Industries Inc. of South El Monte, CA in collaboration with JPL. Butane was chosen because of its relatively low vapor pressure of approximately 100 psia at 50 ^{o}C, allowing for a flat, disk-shaped tank design as shown in Figure 2. Higher pressure propellants such as nitrogen or xenon require spherical or cylindrical tanks, with which the integrated design of the multifunctional tank would not be possible.

A block-diagram of the propulsion system is shown in Figure 4. The system consists of the liquid butane tank in which the butane self-pressurizes depending upon spacecraft temperature. Downstream of the liquid tank, a Vacco latching valve and piezoelectric valve regulates propellant flow into the plenum tank. Inside the plenum, the butane vaporizes and is held in a gaseous phase at approximately 15 psia, although the pressure can be adjusted to meet the spacecraft thrust needs. Pressure and temperature sensors measuring plenum pressure allow for a closed-loop control of the system, allowing the piezoelectric flow control valve to be cycled to maintain a plenum pressure with a given deadband as the thrusters fire for maneuvers.

From the plenum, gaseous butane is fed into the thrusters, which consist of a piezoelectric valves and an integrated nozzle provided by Vacco Industries. The valves require an actuation voltage of approximately 150 V to fully open.

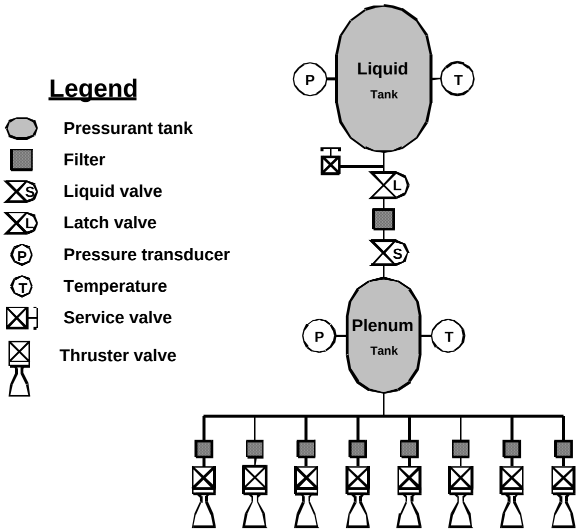


Figure 4. Butane Propulsion System Block Diagram

The Micro-Inspector piezovalve was tested over temperature from +10 to +50 ^{o}C and gamma radiation of doses up to 100 kRad (Si). Small changes in actuation responses (stroke vs. applied voltage) were observed, but all remained within a few microns, accounting for a small percentage of the full stroke (200 micron maximum). The valve design by Vacco compensates for these small changes in the peizoactuator stroke, and valve performance is thus un-affected.

A prototype of the Vacco thruster was tested on the micro-Newton thrust stand at JPL as shown in Figure 5. The prototype thruster featured the same actuator, actuation mechanism and design as the Micro-Inspector flight unit, but was larger in scale due to some threaded inlet and outlet tube fittings to allow for the attachment of flow measurement devices to the unit. Thruster performances of 10 mN at 10 psia inlet pressure and 25 mN at 25 psia inlet pressure were measured, as specified in the initiation of this project. Specific impulse was estimated at 60 sec, measuring pressure decay (and hence mass loss and flow rate) from the plenum tank.

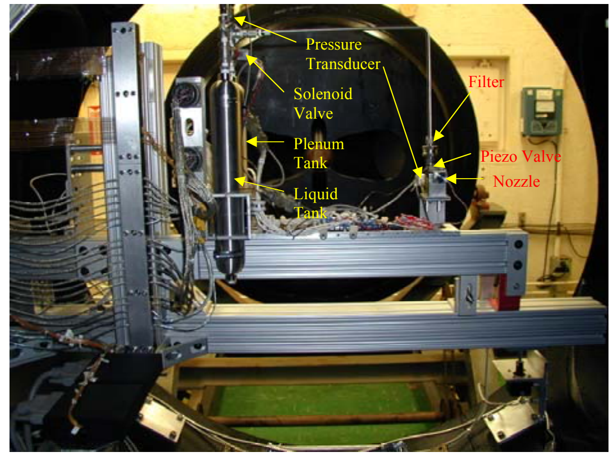


Figure 5. Vacco Prototype Butane Thruster on the JPL Micro-Newton Thrust Stand

Avionics

The Micro-Inspector Avionics platform provides a self contained reconfigurable package with the capability to perform signal processing, telecommunication, control algorithms, distributed processing, and SEU tolerate processing at significantly lower power consumption, lower mass, and higher MIPS throughput than existing space qualified avionics.

The heart of the Micro-Inspector avionics is a Virtex II Pro FPGA with two embedded PowerPC 405 processors. Processor SEU mitigation is achieved by running the two processors in a lock-step and compare configuration. By using 7-bits of the 16-provided Error Correction Coding (ECC) bits for implementing Error Detection and Correction (EDAC), two-bit detection and one-bit correction is achieved. In the future, the full 16-bits can be utilized to accommodate high error control functions such as 8-bit correction and detection using Reed Solomon algorithms.

A development avionics board was fabricated based on previous internally funded efforts at JPL in Mobility Avionics. The board contains the Xilinx FPGA, 256 MB DDR SRAM, 128 MB flash memory storage and file system, Linux OS, and fast Ethernet and RS-232 user interfaces.

These processors run the commands and sequences to control the Micro-Inspector to provide inspection services and monitor internal spacecraft health sensors.

Power and Electrical

Spacecraft power is generated using triple-junction solar cells in an array on the top of the solar panel assembly. Inside the structure, the Micro-Inspector contains four lithium-ion batteries (based on Sony's 18650 design) for energy storage.

In order to achieve its small form-factor, the Micro-Inspector does not have open area for a large solar array or added mass for large batteries, so there is not an excess of power. In order to achieve capable performance in such a small form-factor, all electronic circuits are designed for efficiency. A novel peak power tracking approach for energy transfer to improve array loading and lower heat dissipation is employed. This method maintains a regulated stiff bus voltage of 5V minimizing additional conversions for a majority of the operating electronics. DC/DC converters regulate the voltage to 1.5V, 2.5V, and 3.3V for the FPGA and digital electronics. Finally, a 150V supply powers the piezoactuators for the thruster valves.

Voltage is measured on all of the buses and reported back in the spacecraft health telemetry. Current is measured on the solar array and batteries to help maintain the efficient operation of the peak power tracker. Solar array current and voltage measurements are used as a backup of the attitude control subsystem as described later. Remaining health sensors include multiple temperature sensors on various locations of the spacecraft and pressure sensors on the liquid and plenum sides of the multifunctional tank to help regulate propellant flow.

Telecommunications

Communication with the Micro-Inspector is performed via short range UHF communication to the host. There is no capability for communication directly to Earth. The Micro-Inspector transceiver is a low-power transceiver built for the Mars program at JPL. The Mars Micro Transceiver consists of a custom designed RFIC and digital baseband/control IC. It is a half-duplex system capable of supporting data transmission rates greater than 2 Mbps and receives commands and control instructions at up to 8 kbps.

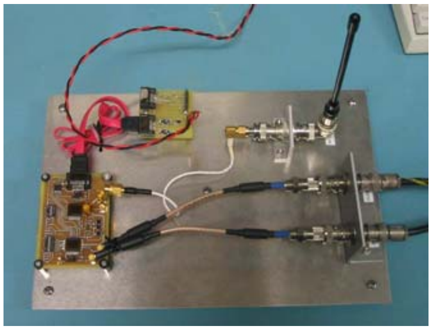


Figure 6. Prototype Transceiver

The Micro-Inspector uses high data rates to transmit inspection images and spacecraft health data back to the host. Commands and command sequences are sent from the host to the Micro-Inspector using the low data rate uplink.

Attitude Determination Sensors

The Micro-Inspector uses a number of miniaturized sensors to determine the spacecraft attitude. The center is a MEMS-based Inertial Measurement Unit (IMU) made by Honeywell consisting of three gyroscopes and three accelerometers. One of the six Micro-Inspector cameras can be used as a star camera. A JPL developed micro sun sensor provides two axis sun angle data when the solar array is illuminated. Also, as a back-up, the current and voltage measurements of the solar array, along with five coarse sun sensors located on each side of the spacecraft can roughly determine attitude assuming typical cosine losses. Spacecraft attitude is processed using a 6-state Kalman filter. A combination of thruster command integration, accelerometers, and range measurements from the hazard avoidance structured light system provide data into the relative position to the host.

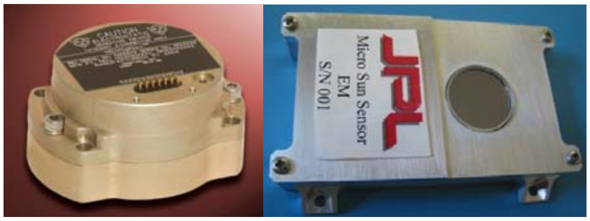


Figure 7. Left: Honeywell MEMS-based IMU Right: JPL-developed Micro Sun Sensor

Celestial navigation is a key feature of the Micro-Inspector, allowing for operation beyond Earth orbit as required for future exploration missions to the Moon or Mars. Most other inspectors developed rely on differential GPS to determine the relative position to the host, restricting them to Earth orbiting missions.

Imaging

There are a total of six cameras boresight about three axis on the Micro-Inspector. All cameras are designed at JPL using a custom interface to a commercial APS detector made by Cypress, the FillFactory STAR250. This permits only one interface to be developed for the avionics board, but more imaging capability. Two cameras are located along the +X-axis of the spacecraft. These are the main inspection camera and the hazard avoidance camera. The +X-axis will face the host during most of the inspection mission lifetime. Both cameras have a 25° field of view, the only difference in optics is the addition of the narrow pass band filter over the hazard avoidance camera. Two secondary inspection cameras are located on the –Y-axis. These are the narrow and wide angle cameras employing 8^o and 45^o degree field of views respectively. These cameras will be used for inspection of the host when higher resolution data is needed. The narrow angle camera will be able to view the host at high resolution, with the wide angle camera putting the scene in perspective of the larger vehicle. These cameras are capable of doubling as star cameras if necessary. Finally, there are two cameras oriented in the –Z-direction looking through cut-out portions of the multifunctional tank. These cameras both have 40^o field of view optics. One camera will be used as the primary star camera since it is opposite of the solar panel array and most likely to be looking into deep space during the inspection mission. The final camera on the –Z-axis is used during separation and docking maneuvers. This camera locates fiducials located on the host dock to determine the relative velocity and tip-off rates immediately prior to separation from the host.

Although cameras operating in the visible range have been baselined for the Micro-Inspector, other imaging payloads could be accommodated such as uncooled IR cameras or mini mass spectrometers, once host vehicle requirements are sufficiently defined.

Hazard Avoidance Subsystem

Structured light was selected for the hazard avoidance subsystem because of its low mass and cost. Structured light is a method of remote sensing a 3-dimensional structure in close proximity utilizing a laser, holographic grating, and single camera. The laser beam is split into 400 different beams by a diffractive grating to form a regularly spaced grid of laser beams that is projected into the field of view of an APS camera. The laser source and camera are separated by a known distance, forming the base of a triangle. As the Micro-Inspector moves closer or further from the host, the spots move horizontally in the camera field of view. Triangulation is used to calculate the distance to each spot in the grid recreating a 3D representation of the structure in view.

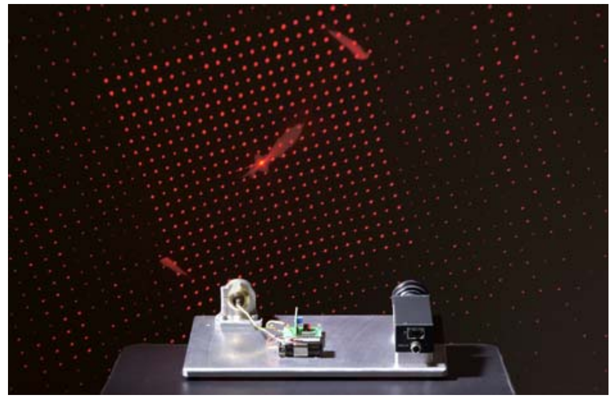


Figure 8. Structured Light Hazard Avoidance Subsystem Showing Laser Projection

A breadboard system was developed and characterized for the Micro-Inspector project. The breadboard system used a 1 W eye-safe laser. The diffractive holographic grating was developed in JPL's Micro Devices Lab. It produces a square array of 21 x 21 spots with a full divergence angle of 26.2^o. This angle matches the field of view of the camera. The camera is also contains a narrow band pass filter (10 nm) to increase the signal to noise of the spots. The filter enables the sensor to be used in the sunlight.

Safety Features

The Micro-Inspector design is focused on safe operation to the host vehicle and its crew. On board constraints and anomaly detection are driven by safe operation. The Micro-Inspector employs a laser based hazard avoidance sensor to provide relative range measurements to the host and indicate whether a collision with the host is imminent. The spacecraft avionics can then react to maintain a safe keep-out-sphere about the host such that a collision is mitigated.

The mass of the Micro-Inspector is kept as low as possible. Coupled with low velocity, accelerations, and turn rate, this results in a low kinetic energy in the result of a collision. The inspector's physical properties include curved surfaces to eliminate damage from sharp or protruding features in the event of a collision. All spacecraft components with the exception of the flexible UHF antenna are mounted inside of the spacecraft structure underneath the solar panel assembly. The solar panel assembly acts as a cushion to any possible impact through its thin fiberglass standoffs, which also play a critical role in the spacecraft thermal design.

The propulsion system has a number of safety features to minimize the momentum the inspector can build during its maneuvers. The thrusters feed from a plenum which contains only a small portion of the stored propellant. The bulk of the propellant is isolated and regulated through two valves in series. In the event of a loss of power, or anomaly within the flight processor, the valves to all thrusters closed.

Impact testing is in progress at JSC using an air bearing sled to collide a prototype of the sharpest corner of the Micro-Inspector with brittle materials that could be on a host vehicle. Our current test article is a portion of shuttle tile. During testing, the air bearing sled is released via an electromagnet. Optical sensors determine the horizontal velocity of the sled and force transducers behind the test article measure the impact. The tile is then visually inspected for potential damage. The test is repeated for a variety of impact velocities.

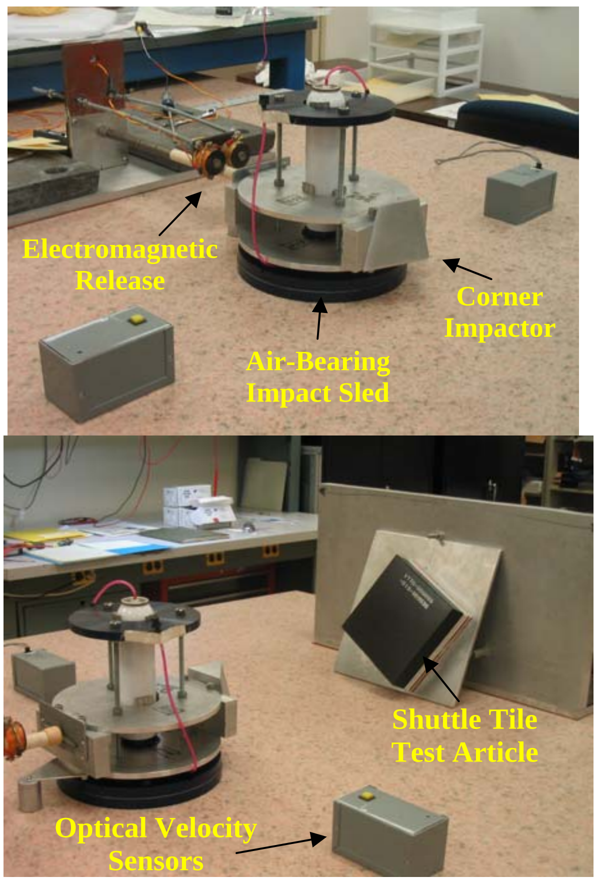


Figure 9. Top: Air Bearing Sled Showing Corner Impactor and Release Mechanism, Bottom: Air Bearing Sled and Shuttle Tile Test Article

CURRENT STATUS- HARDWARE TESTBED

As of the writing of this paper, the project is at a PDR level and is searching for customers to accommodate a flight demonstration of the Micro-Inspector technology and mission concept. A hardware testbed has been created to develop the subsystem hardware and interfaces. The development avionics board allows for easy integration of candidate sensors and microspacecraft technologies. Another goal of this testbed is to be used as a learning platform for new employees at JPL. The small form factor allows an individual to see more of the systems challenges of a related to spacecraft design.

Figure 10 shows a portion of the Micro-Inspector testbed, specifically the integration of the Honeywell IMU with the avionics board. In this particular case, the FPGA is programmed to read data from the IMU and command the thrusters with a simple equation based on IMU attitude. The thruster commands are verified using a thruster control box with LED indicator lights in the orientation of the thrusters on the spacecraft. Also integrated in the testbed is the control of the electrochromic surface allowing the FPGA to toggle between a dark and light state.

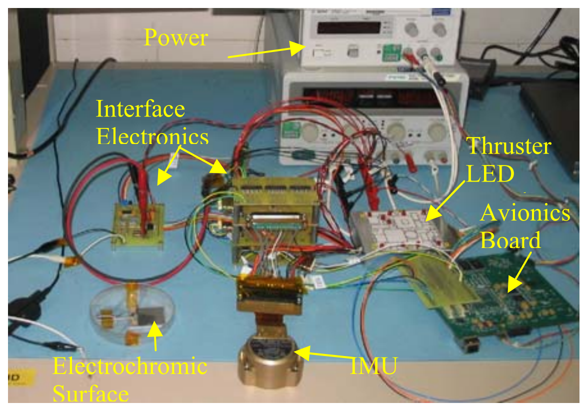


Figure 10. IMU and Electrochromics Sample Integrated with Avionics FPGA Board in Testbed

The project hopes to continue development on the hardware testbed to integrate more spacecraft subsystems. Once integrated, the subsystems can be tested on a systems level either using an air bearing sled similar to the one being used for impact testing at JSC allowing 2-dimensional motion, or the electronics can be integrated onto a 6 DOF robotic test platform located in the JPL Formation Control Laboratory currently used for the development of formation flying algorithms and hardware.

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