Low Cost Lunar Exploration Mission
Concepts using Micro Satellite Systems and Technologies

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Outline

• Motivation for Topic of Briefing
  – IAA Symposium on Small Satellites for Earth Observation, Berlin, Germany, April 2\textsuperscript{nd} 2005, “Special Session on Micro-Satellites for Low-Cost Lunar Exploration.”

• Micro Spacecraft Technologies & Spacecraft Systems

• CubeSats growing in popularity

• Two Case Studies at JPL:
  – Lunar Gravity Mapping micro-sat science instrument
  – Remote Vehicle Inspection for lunar exploration missions

• Vision of micro-spacecraft and lunar exploration
  – To be presented at the 56th International Astronautical Congress, 2005, Fukuoka, Japan.
Micro Spacecraft Components and Sub-System Development funded by NASA, DOD, etc.

- MEMS Gyros & Accelerometers (IMU)
- MEMS and APS based Sun sensors & Star Trackers
- MEMS Micro Thrusters & MEMS Micro Valves
- MEMS Piezo-Electric Actuators
- Integrated micro-electronics & digital/analog
- Multi-Functional Structures
- Advanced Thermal Management Techniques
- On-board Spacecraft Autonomy
- Advanced Lil Batteries for low temperatures
- Advanced Solar Array Architectures and Cells
- Re-configurable Avionics Hardware
- Science and Spacecraft Sensors and Instruments
Advanced Microsystems Enable Future New Mission Capabilities

Global Coverage (RF, Visible) using Micro Sat Constellations

Planetary Ascent Vehicles

Micro-Spacecraft Inspectors

Sub Surface Probes

Advanced Micro-Systems will enable new capabilities for future space exploration missions.

Advanced Aerial Mobility

Advanced Surface Mobility
CubeSat Overview

- Practical platform for experimentation
  - Standardization and ridesharing
  - Students participate in entire mission life cycle
- CubeSat standard defines 10 cm / 1 kg cube
- P-POD deployer carries 3 single CubeSats
  - Protects primary payload, spring reliable ejection
  - Compatible with multiple LV
CubeSats

- Initiated in 1999 by Stanford and Cal Poly
- 60+ universities, private companies & government labs building picosatellites
- Multiple manifest & repetition reduces costs to $40K/cube
  - Includes CubeSat/P-POD launch fee, launch interface & campaign, licensing and export fees
- First launch in 06/03: Eurokot / 6 CubeSats
- Upcoming launches (dates to be confirmed)
  - 10/05: Dnepr / 14 CubeSats
  - 03/06: Dnepr / 7 CubeSats
- Future US launch capability
  - ESPA, Falcon-1, FALCON, Delta-2, Pegasus, Shuttle
MEMS Picosat Inspector (MEPSI) Stack

- All boards conformal coated (Uralane 5750)

- DC DC converter
- IMU bottom board
- IMU upper board
- Radio Board (RF)
- Radio board (digital)
- Flight Computer
- Memory
- IMU daughterboard (1 of 2)
- Spacers
MEPSI-1 STS113: Launch

PICOSATs

Launcher is the gold box
Two Micro-Spacecraft Case Studies

1. Lunar Gravity Subsatellite Concept
2. Inspector Micro-Satellite Project
Lunar Gravity Subsatellite
Mission Concept and Assumptions

- Consider a low-altitude lunar polar orbiter
- Orbiter deploys a small ‘cube-sat’ corner-cube reflector
  - Launcher mounted in +velocity direction on spacecraft
  - Subsatellite has small delta-V imparted by launcher (~ 1 cm/sec)
- Laser tracking system pointed in -velocity direction on spacecraft
- Subsatellite Initially enters FOV of fixed-direction coarse-acquisition 3-degree laser near end of first relative orbit
  - Dwells in FOV for approx. 20 minutes before departing
- Phasing of orbit brings it approximately 300 m further behind after each rev
- 1 month of laser tracking data will yield high precision gravity field of entire moon
- For 28 days of measurements, approx 63 days of operations, assuming:
  - Subsat 1: 7 day deployment walk-out, plus 14 day measurement phase
  - Subsat 2: 21 day “wait” before deploy, 7 day walk-out, plus 14 day measurement phase
- Gravity measurement subsystem: < 10 kg total mass, < 10 Watts power
Subsatellite Initial Deploy Orbital Geometry

Subsatellite Local Vertical vs Local Horizontal Relative Position

(1) Spring-launch at ~ 1 m/sec

(2) First entry into 3-deg laser FOV

S/C motion

Distance (km)

Deploy Trajectory
3 deg Half Angle
3 deg Half Angle
Subsatellite Deploy Orbit

Subsatellite Local Vertical vs Local Horizontal Relative Position

Distance (km)

Subsatellite walk-out

-32.0 -27.0 -22.0 -17.0 -12.0 -7.0 -2.0

LDO Local Horizontal (km)

0.75 deg Half Angle

3 deg Half Angle

Deploy Trajectory

0.75 deg Half Angle

3 deg Half Angle
Relative Motion of Subsatellite over 30 Days - LDO LVLH z vs x

(LDO stationkeep maneuver sized to cause subsat “walkoff”)

Subsat Meas Phase Traject.
15 arcmin Half Ang
30 arcmin Half Ang
45 arcmin Half Ang

Assumptions:
1. 28 km initial altitude
2. 10x10 lunar gravity
3. initial separation 30 km
4. differential solar rad force
5. Earth and Sun n-body gravity forces

Subsatellite Visibility during Measurement Phase

LVLH X (negative behind main s/c), km

-120 -100 -80 -60 -40 -20 0 20 30

t = 5 days
x = -43.8 km
z = 622 m

t = 10 days
x = -56.9 km
z = 566 m
Gravity Subsatellite Components

Transmitter:
- Passively Q-switched microchip laser pump diode:
  - ~3W input, ~1.5 W output, 1500 Hz firing rate
- frequency doubling crystal, and thermoelectric cooler
- variable-beam-divergence transmitter (3 deg to 45 arcmin half-angle)

Receiver:
- Telescope with time-of-flight electronics
- Range rate precision (1-sec averaging) of approx. 140 microns/sec over range of 30 to 70 km

Corner Cube Micro-Satellite:
- Passive Subsatellite is octahedral, with 8 cube-corner faces
- Dimensions of each subsatellite = 3-4 inches in diameter
- Subsatellite mass = < 0.8 kg

Launcher:
- Spring-based ejection system mass < 5 kg
Summary of Gravity Subsatellite Concept

• A gravity subsatellite is currently under study for high-precision lunar gravity mapping
• Total system is estimated at < 10 kg and < 10 watts
• A gravity subsatellite is passive
• Precision tracking is performed using existing laser ranging technology
• A cube-sat launcher is used to deploy 1 or more subsatellites.
• A more capable system may use an active subsatellite with a beacon, imaging, etc.
Micro-Inspector Spacecraft for Space Exploration Missions

**Project Management:**
Juergen Mueller (PI), Leon Alkalai (PM), Hannah Goldberg (PSE)

**Team Members:**
NASA Johnson Space Center, Boeing Phantom Works, Vacco Industries Inc., Ashwin-Ushas Inc.

**Project Overview:**
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.

**Features:**
- **Ultra-Low Mass and Size:** 3-5 kg
- **Celestial Attitude Determination:** Operations beyond Earth orbit
- **Continued Operation in Sun at 1 AU:** Solar powered with Li-Ion battery backup
- **Ultra-low power consumption:** Xilinx Virtex II processor, piezo propellant valves
- **Safety:** Collision avoidance system, Low-pressure, low leakage liquid butane propulsion system, Low delta-v (15 m/s)
- **Imaging:** Wide and narrow angle cameras, hazard detection
- **Communications:** Real-time video, UHF - Local com to host
Mission Operations Overview

5. End of Mission Disposal
Final maneuvers place μIns. safely away from the host. This helps mitigate additional risk to the host with the presence of a non-operational hazard.

1. Launch and Transport
μIns. launches attached to host and powered off until needed

2. Deployment
After verifying μIns. health, the host severs electrical/mechanical connection and μIns. is ejected away from the host

3. Orientation and Calibration
μIns. locates and tracks the position of both the host and sun and performs on orbit calibrations as necessary

4. Inspection and Communication
μIns. performs through commanded sequences for external inspection of the host vehicle. Downlink of inspection pictures and health data telemetry, uplink of commands.

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# Performance and Capabilities

- **Free-Flying remote vehicle inspector:**
  - Autonomous ops – uplinked sequences – host in the loop
- **Visual Inspection resolution:**
  - 1 cm (at 10 m range)
- **Monitoring:**
  - Real-time video
- **Lifetime:**
  - 6 hours min operation
  - 2 hours lifetime from battery power
  - Unlimited operating power in full sun
- **Attitude Determination, Celestial Navigation:**
  - Micro Sun Sensor, Gyro, Star Tracker
- **Pointing control accuracy:**
  - 1 degree
- **Position control accuracy:**
  - 1 m; 10 mN thrusters
- **Power:**
  - Solar Arrays, LiI Batteries
- **Communications:**
  - 1 Mbit/sec downlink, 5 kbits/sec uplink
- **Propulsion:**
  - Cold gas prop, plenum
- **Thermal Management:**
  - Passive, Active: Electro-chromics
- **Hazard Avoidance:**
  - Laser ranging, HW/SW checks, low delta-V, impact analysis, etc.
- **Human Rated performance:**
  - Designed for use in human missions
Flight System Block Diagram

- Solar Array
- Batteries (x4)
- Peak Power Tracker
- Power Switch
- Voltage Converters (x5)
- Step-Up Converter (x2)
- Regulated 5V Bus
- Optional Power When Docked
- Liquid Reservoir
- Butane Plenum
- Microthrusters
- Valve Drivers
- Electrochromics Controller
- Heaters
- MUX/ADC
- Avionics Hardware
  - 2 Processor Xilinx Virtex-II Pro FPGA w/EDAC, SDRAM, Flash, config. Mem.
- Voltages (x7), Currents (x2), Pressure (x2), Temperatures (x8), Sun Presence Sensors (x5)
- Controlled Emissivity Surface
- Antenna
- Transceiver
- GSE Connector
- UART
- 3-axis Gyro
- Micro Sun Sensor
- -Z axis Camera (x2)
- -Y axis Camera (x2)
- +X axis Camera
- LED Flash
- Coll. Av. Camera
- Laser Spot Generation
- RS422
System Description

- Sandwich structure (8.4” x 8.4” x 2.6”)
  - Multifunctional Tank (MFT)
  - Multilayer Circuit Board (MCB)
  - Solar Panel Assembly (SPA)
- Solar panel is thermally isolated from tank
  - Thin fiberglass standoffs provide structural support
  - Long, small gauge wires connect antenna, solar cells, and temperature sensor from SPA to circuit board
- Electrochromic surface mounted to bottom side of tank
- Payload components mounted on standoffs over circuit board underneath solar panel and mounted through tank
  - Battery assemblies (x2)
  - Gyro
  - Cameras (x6)
  - Micro Sun Sensor
  - Laser
System Integration

- Wide Angle Camera
- Sun Sensor
- Gyroscope
- Narrow Angle Camera
- Laser Grating
- + X Camera
- Flash
- Collision Avoidance Camera
- 4 X Battery
- -Z Camera
- Laser Radiator
- Laser
- -Z Camera
- Latching/liquid Valve Manifold
- 4 X Stand Off
- 8 X Thruster
- Multifunctional Tank
- 14 X Solar Cell
- Solar Cell Array

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ILC, 2005, Toronto, Canada
The Micro-Inspector Multifunctional tank has two chambers. (1) The liquid butane tank and (2) the Plenum. The liquid butane is converted to vapor using the heat of the electronics and transferred into the plenum using the latching/liquid valves. The thrusters use the vapor in the plenum to propel the spacecraft.
Avionics Block Diagram
Key Technical Resource Margins

- **Inspector Satellite Mass:**
  - < 10 kg
  - CBE < 4 kg (> 100% margin)
- **Power**
  - 13.3 W power available from solar array: 30% margin
  - Assumes cooler operating temperature than what is probable
- **Propellant mass**
  - 100 g propellant, equivalent to 15 m/s delta-V
  - Propellant usage dependant upon operations
  - Tank sized for 300 g propellant (45 m/s delta-V): 200 % margin
- **HW and SW Computer**
  - Xillinx Virtex II Pro, dual-CPU for SEU detection
  - Extensive features for radiation tolerance, fault tolerance
  - 300 MHz CPU > 75% margin
- **Communications**
  - 1 Mbit/sec downlink: 45% margin
Summary of Micro Inspector Satellite

- Micro-Inspector satellite designed for remote vehicle inspection in space beyond Earth orbit: Moon, Mars, etc.
  - CBE < 4 kg
- System directly applicable to ESAS
  - Vehicle remote inspection
  - Monitoring of vehicle docking and rendezvous
  - E/PO
- Schedule:
  - Project just completed its System Requirements Review
  - PDR is scheduled for January 2006
  - Project Schedule: 3.5 years to full TRL 6 including qual test and demonstration in ground testbed
- Cost:
  - Phase 1: 2.7 M$
  - Phase 2: 15.3 M$
Vision

- Highly miniaturized (nano/pico) satellites can be used effectively to perform useful science and exploration objectives at the moon.
- CubeSats or other forms of pico-sats are affordable to a broad group of international (small) space agencies, universities, small businesses, etc.
- Consider a ‘World Lunar Project’:
  - A single integrating organization (company) provides the s/c bus,
  - Other institutions may support operations, navigation, management
  - Vehicle carries multiple (10-12) individual ‘CubeSats’
    - Each CubeSat is from a different institution
    - Functions vary from imagers, beacons, penetrators, orbiters, etc.
  - Mission engages the world, including universities, high-schools, public
  - Project is funded by a combination of government funds and private investors