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Miniature Wide Field-of-View Star Trackers for Spacecraft Attitude Sensing & Navigation

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Abstract:

Introducing a family of miniature, wide field-of-view Star Trackers for low cost, high performance spacecraft attitude determination and navigation applications. These devices, derivative of the WFOV Star Tracker Camera developed cooperatively by OCA Applied Optics and the Lawrence Livermore National Laboratory for the Brilliant Pebbles program, offer a suite of options addressing a wide range of spacecraft attitude measurement and control requirements. These novel sensors employ much wider fields than are customary (ranging between 20 and 60 degrees) to assure enough bright stars for quick and accurate attitude determinations without long integration intervals. The key benefits of this approach are light weight, low power, reduced data processing loads and high information carrier rates for wide ACS bandwidths.

Devices described range from the proven OCA/LLNL WFOV Star Tracker Camera (a low-cost, space-qualified star-field imager utilizing the spacecraft's own computer for centroiding and position-finding), to a new autonomous subsystem design featuring dual-redundant cameras and completely self-contained star-field data processing with output quaternion solutions accurate to 100 μrad, 3σ, for stand-alone applications.

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1.0 LLNL/OCA STAR TRACKER CAMERA

The LLNL/OCA Star Tracker Camera was developed in support of the SDI Brilliant Pebbles (BP) program by the Lawrence Livermore National Laboratory and OCA. The BP Star Tracker Camera was designed to acquire star-field imagery from which spacecraft attitude information could be derived for navigation and to update and calibrate Inertial Measurement Unit (IMU) attitude data. The WFOV Star Tracker Camera is unusual in that it employs very wide field-of-view optics (nearly 60°), much greater than is customary for Star Trackers. This wide-field design evolved from trade-studies early in the BP program that showed this approach to be significantly more mass-efficient than traditional narrow field designs. It's advantage results from the unique balance the design achieves between FOV, aperture, focal plane sensitivity and the spatial distribution of bright stars in the sky. Prototypes of this new class of sensor weighing just a few hundred grams routinely achieve better than 200 microradian accuracy as reported recently by Lewis et al[1].

The generic WFOV Star Tracker Camera uses a 55° FOV concentric lens. The concentric design-form maximizes relative aperture and eliminates lateral color effects that can introduce stellar color temperature dependent centroid shifts. The focal surface in this design is spherical, requiring the use of a fiber-optic faceplate (FOFP) with a spherically curved front surface to flatten the field for interface to the CCD imaging device. This design approach delivers a fast optical system in a very compact, low mass package with a relative aperture almost twice as large as flat-field design-forms of comparable performance.

Both intensified and unintensified versions of the WFOV Star Tracker Camera have been prototyped and tested. The intensified variants employ a gated, second-generation, proximity-focused image intensifier between the lens and the CCD to increase sensitivity enough to allow a corresponding decrease in integration time. This configuration assures full performance on vehicles with relatively high attitude drift rates by using its short integration time (typically, 30 to 50 msec) to avoid degradation from image smear. Unintensified versions are much lighter (weighing less than 130 grams) and achieve full performance on platforms with drift rates up to about 1°/hour (where integration periods as long as 400 msec are practical). With current commercial focal plane readout noise levels as low as 40 to 60 electrons, unintensified cameras perform well with integration periods of about 100 msec. Advanced technology focal planes reduce that period considerably. In the presence of limiting background flux (where the net signal-to-noise ratio becomes background limited), the unintensified array will actually allow shorter integration times than an intensified camera because of its superior quantum efficiency and broader spectral bandwidth.

The basic Wide Field-of-view Star Tracker concept has several important advantages over traditional approaches. Key among them is that the probability of finding bright stars increases with the solid angle surveyed (FOV). Therefore, as field-of view increases, so too will the number of bright stars included within it. Further, since there are relatively few bright stars in the sky (less than 500 brighter than $M_v = 4$), a large FOV assures that only a small catalog of the very brightest need be considered for navigation. With such a small star map to manage, it is quite practical to use fast pattern-matching techniques to reliably determine the orientation of a spacecraft in near real-time.

With the focal plane stray light flux distributions anticipated in typical service, WFOV Star Tracker imagery ordinarily requires processing to subtract the average local background signal from each pixel. This is automatic where the signal amplitude distribution of a cluster of pixels is found to match the nominal blur energy distribution of an imaged point source (probable star). Star Tracker maximum stray light limits are imposed by either saturation effects (where the sum of signal and background fluxes exceed CCD well capacity or the dynamic range of subsequent signal electronics) or by the shot noise of the background. In the case of dim stars, shot noise limits the maximum background flux before saturation becomes a problem. Stray light analyses using the APART code indicate maximum point source transmittance (PST) for a typical baffle is about 1×10^{-7} for all sun angles beyond the solar exclusion angle. For sun positions just approaching the solar exclusion angle, the exact magnitude of the stray light becomes a major factor in determining minimum integration times for both the intensified and unintensified sensors. Inside the solar exclusion angle, one or more optical surfaces will be directly illuminated by the sun and the stray light signal increases dramatically, overwhelming the dimmer stars.

The image processing algorithm identifies stars by evaluating the amplitude characteristics of candidate pixel clusters. The key discrimination criteria require that, 1), the peak pixel amplitude(s) remain below saturation (normally the case, except for the very brightest stars) and 2) that the character of the intensity profile of the pixel cluster match the expected point-spread function (PSF) of a normal image. Thus, a single, isolated pixel will not be identified as a star, even though it exhibits appropriate signal amplitude, because the amplitude of its neighboring pixels won't conform to the expected PSF intensity contour. It is important to note that the sub-pixel centroiding accuracy of the Star Tracker's image processing algorithms, nominally about 1/10 pixel, would not be possible if the star's blur diameter were not larger than a single pixel. The unique concentric optic of the WFOV Star Tracker Camera not only provides the proper image scale for optimum centroiding, but maintains essentially perfect scale uniformity across its full working format.

Once all of the potential star images within a data field have been located, the brightest are grouped into candidate star-triangles, iteratively compared against star catalog data and ultimately resolved into confirmed star-triangle matches. The algorithm typically uses a minimum of five star-triangle matches (requiring at least five detectable stars per data field) in order to establish the attitude of the sensor within prescribed error limits. The orientation of the Star Tracker's optical axis (and thus the spacecraft's attitude) is ultimately expressed as an output quaternian developed from the individual rotation quaternians for each of the star triangle matches in the ensemble (and in which any residual star position errors have been evenly distributed).

WFOV Star Trackers can reliably establish their orientation with only a relatively simple corrective term to standardize the position-finding algorithm for hardware variances. Just three quantities are needed for this correction; 1) the as-manufactured effective focal length, 2) static boresight position error and 3) the two-dimensional distortion characteristics of the basic optical design (each quantity being referenced to the origin of the focal plane coordinate system and expressed to an accuracy ≤3 μm). No special measurement or specific correlation of actual (individually measured) PSF variations across the field-of-view is needed to achieve nominal angular precision.

1.1 WFOV Star Tracker Optics Assy

The generic WFOV Star Tracker optic is a 3 element $f/1.26$ design yielding a 55 degree diagonal working field. The central, spherical (ball) element is of Schott SSK4 glass and the front and rear concentric shell elements are Ohara SLF02 and Schott LaF20, respectively. A fiber-optic faceplate provides the curved image surface to interface the spherical image front of the lens to the planar CCD array.

1.2 WFOV Star Tracker Focal Plane Electronics

The baseline focal plane detector device for the WFOV Star Tracker Camera is a Thomson-CSF TH7883 CCD array. The TH7883 is derived from the TH7863 array by transforming its storage zone into an imaging area, identical and adjacent to the original imaging zone, thereby doubling its active imaging area. The array is read out as a single field of 576 active lines with 384 active pixels per line. Pixels measure 23 μm by 23 μm, yielding an active imaging area of 8.832 mm by 13.248 mm. The pixel instantaneous field-of-view (IFOV) is 1.3 milliradians, square. The array, with its surface-mount readout electronics, is packaged into a compact space-qualified focal plane assembly on a multi-layer flex-print circuit board. Power, control and digital video interfaces are implemented through a single miniature 50-pin connector.

2.0 OCA ADVANCED STAR TRACKER ASSEMBLY

OCA's Advanced Star Tracker Assembly (ASTA) is a new, completely self-contained, light-weight, high-performance star tracker system for space applications. The ASTA design has evolved from its WFOV Star Tracker origins in response to needs for a fully integrated star tracker system able to meet the demanding mass, power and performance goals of next-generation light-weight spacecraft. This new design capitalizes on the unique attributes of the LLNL/OCA Wide Field-of-view Star Tracker Camera, developed originally for the SDI Brilliant Pebbles program, and extends that heritage to realize a wholly self-contained attitude measurement system weighing less than 1.2 kg and nominally accurate to ± 100 microradians, 3σ.

2.1 System Overview

The OCA ASTA is based on dual-redundant CCD star cameras. The analog outputs of the camera's CCD arrays are digitized and uniformity corrected to better than 0.2% of full scale. System control and star image processing is implemented using a 32-bit MIPS R3000 compatible LSI Logic LR33000 microprocessor. The computer manages all internal functions including camera control, analog to digital conversion, pixel uniformity correction, sub-pixel star centroiding, housekeeping, BIT and communications to and from the spacecraft under the RS-422 communications protocol. Star identification and attitude solutions are implemented using Intelligent Decisions, Inc. "Stellar Compass" software. This code, developed for the LLNL Brilliant Pebbles program and proven on all BP test flights to date, has been specifically engineered for this new class of wide-field star tracker and is ideally suited to the task.

ASTA is configured around an orthogonally mounted pair of 23 degree FOV cameras. This narrower, flat-field optical design-form takes advantage of BP simulation and flight-test experience showing that the WFOV Star Tracker Camera's working field could be reduced without compromising performance. Early WFOV Star Tracker operational doctrine was very conservative in its baseline demand for 10 cataloged stars in any given field to assure that a minimum of 5 would be ultimately useful for attitude determination. In practice, PSF matching has turned out to be an excellent way to distinguish legitimate star images from other objects, artifacts and noise spikes. In fact, so fast and robust is this "star-finding" method that ASTA was designed with a significantly narrower field-of-view (now based on a minimum of 5 stars per field in the least well populated high galactic latitudes) and so benefits in three important ways:

- ASTA's flat-field, low distortion lens weighs less and also eliminates the cost, mass and additional complexity of a fiber-optic field flattener.
- Better than 90% optical transmission over its full working field
- Reduced probability of the sun's intrusion into the working field

Figure 2.1-1 illustrates OCA's Advanced Star Tracker Assembly. Prominently visible are the two, orthogonally oriented lens assemblies and (through the cut-away) a portion of the main circuit board inside the housing. Figure 2.1-2 presents a cross-sectional view of the ASTA in orthographic projection. The dual-redundant camera configuration is ASTA's most obvious physical feature. This configuration not only provides the basic redundancy of two separate and complete cameras (independent optics, focal plane and analog video circuitry) but, more importantly, assures reliable high-accuracy attitude data irrespective of the spacecraft's orientation or rotational axis. If the sun should happen to intrude into one camera's field, attitude measurements may be conveniently made using the other camera rather than by re-orienting the spacecraft. Even more importantly, the dual-camera design avoids the potential for large errors resulting when the spacecraft's instantaneous axis of rotation lies near the optical axis of one of the cameras. This problem arises from the sharply increasing influence of residual star centroid errors on the output quaternian's roll component as the spacecraft's roll axis approaches the sensor's line-of-sight. In practice, ASTA's control software features can select the proper camera based on IMU attitude data from the spacecraft or will automatically switch to the alternate field if the roll axis is found to lie too close to the current sensor's optical axis.

The ASTA optics use the same 14 mm entrance pupil diameter (aperture) typical of the WFOV Camera but take advantage of improved net optical transmission (gained by eliminating the WFOV Star Camera's FOFP field flattener) and new low noise read-out electronics to extend its working range down to stars of $M_v = 5.1$ with normal integration periods of only 20 msec. This configuration still allows a conveniently small star catalog (1024 stars) to assure attitude updates at 33 msec intervals with completely deterministic data latency characteristics.

As an illustration of its robustness it is significant to note that ASTA is designed to deliver its specified performance under worst-case conditions but, in actual practice the statistical distribution of stars is such that it is only necessary to use stars fainter the $M_v = 4.5$ about 4% of the time and, normally, fully half of the stars will be brighter than $M_v = 3.6$.

ASTA optics are baffled externally by a single-stage multi-vane sun-shade with integral capping shutter. The shutter protects against the long-term build-up of scattering contaminants (and atomic oxygen erosion in LEO) and, when closed, provides an active diffuse radiometric calibration stimulus for in situ CCD gain normalization.

Stray light analyses reliably predict a sun equivalent PSNIT = 1×10^{-8} for these optics with the Sun at its closest working (exclusion) angle of 30 degrees. This allows sufficient margin to assure specified performance even with a realistic allowance for degradation due to space contamination build-up over time.

The 6 element, thin section optical design is based on generally available Schott radiation-tolerant (anti-browning) glasses.

2.2 Summary Specifications

Optics	Equivalent Focal Length:	22 mm
	Entrance Pupil Diameter:	14 mm
	Focal ratio:	$f/1.57$
	PSF Energy Distribution:	~70% central pixel, ~30 % adjacent eight pixels
	Ensquared Energy:	≥ 60% everywhere within working field
	Field of View (FOV):	23°, circular
	Instantaneous Field of View (IFOV):	~1 mrad
	Spectral Range:	500 - 1000 nm (full spectrum)
	Transmission:	≥ 90% within working field (full spectrum)
	Image Format:	8.84 mm, square
CCD	Imaging Device:	Thomson-CSF TH7883 CCD
	Quantum Efficiency:	≥ 35%
	Pixel dimensions:	23 μm, square
	Pixel arrangement:	384 (V) x 384 (H) (usable pixels)
	Array dimensions:	8.83 mm (V) x 8.83 mm (H) (usable area)
	Readout Noise:	≤ 40 e-, 1σ, rms
	Integration Time:	variable, 20 msec nominal
	Frame Rate:	30 fps (max, full field)
Image Processing	Data Latency:	Integration time dependent, fully deterministic
	Stellar Compass Processing Time:	2 msec (quaternian computation)
	Attitude Accuracy:	±100 μradians, 3σ, for drift rates ≤10°/min
	Video Quantization:	9 bits effective (dim stars)
	Offset Uniformity:	Corrected to 0.2% full scale
	Gain Uniformity:	Corrected to 0.2% full scale
Power	Operating Voltages:	±5.0, ±15.0, 28.0 ±6 VDC
	Nominal Operating Power:	6.5 W (worst case peak)
	Shutter Actuation Power:	2.2 W peak, 0.5 W holding
	Stand-by (idle) Mode:	0.7 W
Mass	Optical Subassembly:	89 g
	Electronics Subassembly:	640 g
	Mechanical Subassembly:	317 g
	STA, Total Mass:	1,046 g

[1] I.Lewis, A.Ledebuher, T.Axelrod, J.Kordas and R.Hills, "WFOV Star Tracker Camera, UCRL-JC-105345, proc. SPIE International Symposium on Optical Engineering & Photonics in Aerospace Sensing, Orlando, FL, April 1-5, 1991.

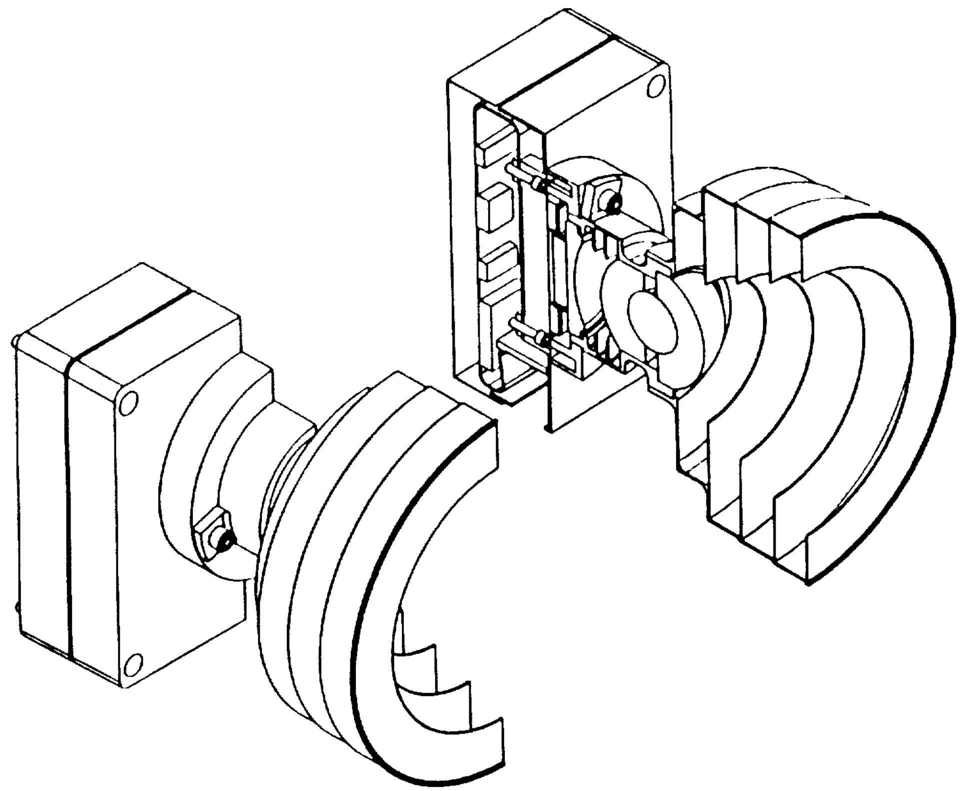

Figure 1.0-1 Cut-away view of the OCA/LLNL Wide Field-of-View Star Tracker Camera showing (in order, front to rear) the multi-vane baffle, WFOV concentric lens, fiber-optic field flattner, CCD and camera electronics.

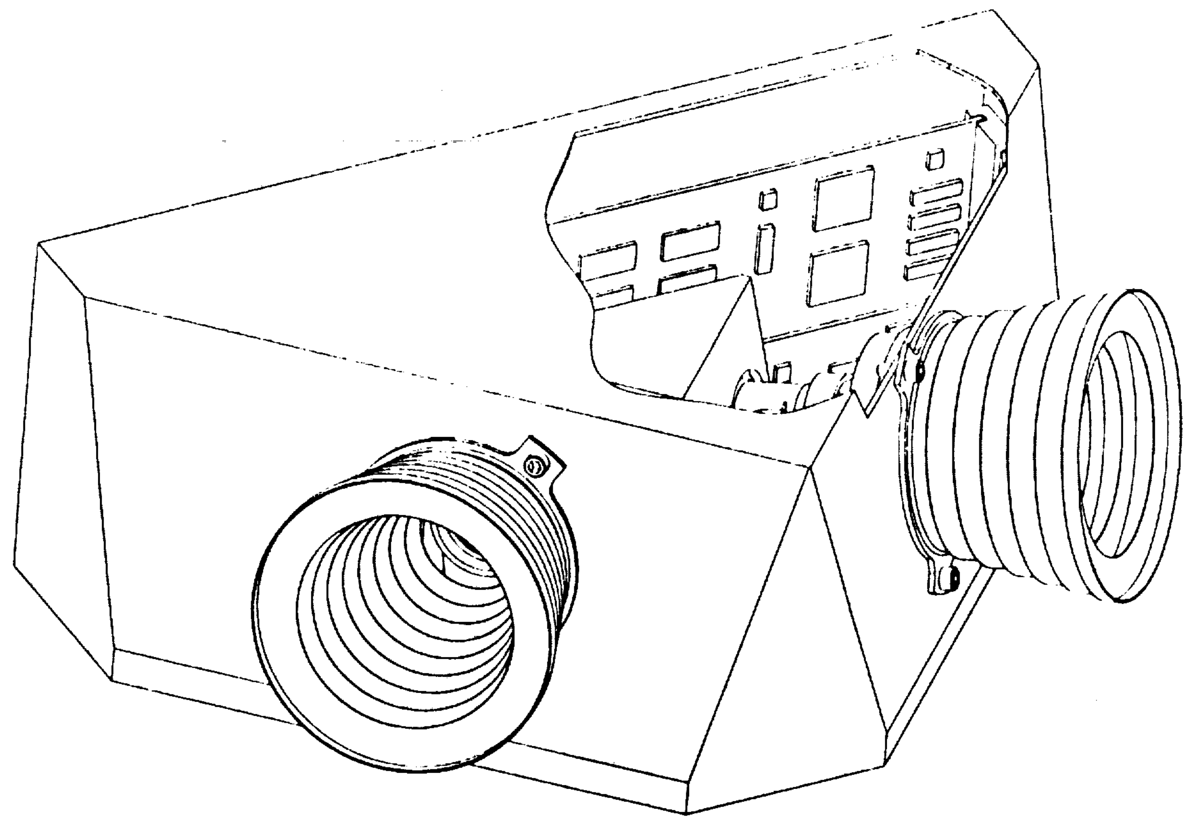

Figure 2.1-1 Cut-away view of the OCA Advanced Star Tracker Assembly (ASTA) illustrating the orthogonally oriented, dual-redundant cameras with optics and baffles.

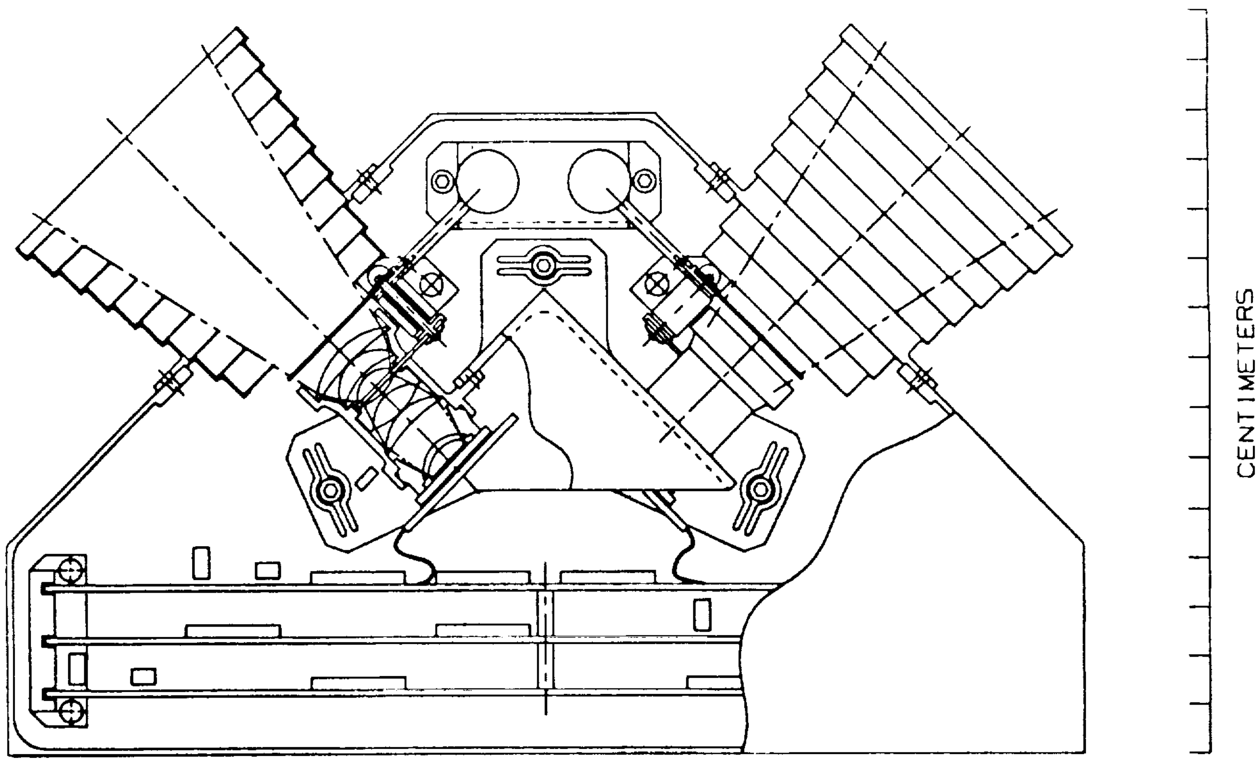

Figure 2.1-2 Cross-sectional orthographic projection of the OCA Advanced Star Tracker Assembly (ASTA) showing details of its 6-element, wide angle, flat-field lens with baffle and integral capping shutter.

NOVEL POSITION SENSOR TECHNOLOGIES FOR MICRO ACCELEROMETERS*

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ABSTRACT

An important new approach for vehicle guidance and control is based on the use of compact, low-mass, low-cost sensors integrated with the vehicle structure. Many advantages of this approach lead to new capabilities. However, the development of compact guidance and control sensors leads to a variety of fundamental physical problems associated with sensor sensitivity and noise. For example, as sensor size is reduced, it becomes necessary to improve the sensitivity of the sensor signal detection mechanism. For an accelerometer, the position sensor must be more sensitive if the accelerometer proof mass is to be reduced. In addition, as accelerometer proof mass is reduced, thermal noise appears in the motion of the proof mass, thus degrading the resolution of the accelerometer. These challenges to sensor development will be described.

Recent developments at JPL, based on new position sensor principles such as electron tunneling, have produced a series of novel, ultra-high sensitivity microsensors and microinstruments. Included among the applications demonstrated are a high-sensitivity micro-seismometer and micro-accelerometer. In this presentation, the principles and performance of these devices will be described. It will be shown that the implementation of micro instruments using these principles produces systems having performance equivalent to previous conventional instruments, but, with major reductions in mass, volume, and power consumption.

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Microtechnologies
and
Applications to Space Systems Workshop

SUMMARY REPORTS

REPORT OF THE MICROSPACECRAFT PANEL

Chairmen
Ross M. Jones
Jet Propulsion Laboratory, California Institute of Technology

Denis Connolly
NASA Lewis Research Center

This report is based in part on material presented at the workshop on

MICROTECHNOLOGIES AND APPLICATIONS TO SPACE SYSTEMS
Jet Propulsion Laboratory
California Institute of Technology
May 27 & 28, 1992

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National Aeronautics and Space Administration
Office of Aeronautics and Space Technology

REPORT OF THE MICROSPACECRAFT PANEL

INTRODUCTION

These findings and recommendations are based solely on the material presented during the Microtechnologies and Applications to Space Systems Workshop, 5/27 & 28/92, and the personal knowledge and judgment of the panel members. These findings and recommendations represent the consensus views of the committee. The mission utility of microspacecraft for NASA space science missions was not an issue that the panel addressed. For the purposes of this panel, a microspacecraft was defined to be a fully functional spacecraft, intended for use on NASA space science missions, whose mass is on the order of 10 kg. During the panel discussions the microspacecraft mass definition was used somewhat loosely to be not less than 10 kg but certainly not more than 100, dependent upon the mission requirements.

PANEL SCOPE

The scope of the panel is presented here in order to put the panel report into context.

> "The panel report will attempt to identify areas that need additional development to enable a microspacecraft for NASA space science missions. These areas will span technology development through space qualification of the microspacecraft system. The panel will deal with two top level issues: 1) integrating advances in technology into the microspacecraft system and 2) identifying present limits of obstacles to achieving a microspacecraft. These limits or obstacles will be further defined as either fundamental or only based upon the present state of technology, and therefore a fertile area for improvement with increased resources. The panel will be concerned with all spacecraft subsystems, i.e., instruments, power, propulsion, attitude control, command & data, telecommunications, thermal and structure/cabling/mechanisms."

The scope of the panel evolved somewhat from the above during the discussions on 5/29. Contrary to the what is written above, the panel did not concern itself specifically with (science) instruments.

FINDINGS

1) The panel identified no fundamental engineering or physics limitations that would preclude the construction of a microspacecraft.

2) There is a large amount of available technology (up to technology readiness level (TRL) 7 which can support microspacecraft given the proper amount of design, validation and qualification.

   2a) Some of this technology can be directly and immediately applied to microspacecraft and some will require modification to NASA needs.

   2b) This same technology can also be applied to the larger NASA space systems.

3) The majority of the technology that can support microspacecraft is programmatically located in the DOD (SDIO, DARPA, etc.) and their contractors.

4) There are certain spacecraft components that could be applied to or may be required for certain NASA space science microspacecraft and that have not been addressed by the DOD. Foremost among these components are micro-RTGs, electric propulsion and telecommunications equipment developed for the frequencies used by NASA.

5) The following subsystem/box level technologies (see table 1) can support a microspacecraft and are relatively mature (up to TRL 7) in the DOD community.

6) Microspacecraft have certain unique technical challenges/needs at the system integration level (see table 2).

7) The panel's assessment is that the first application of Micro Electro Mechanical Systems (MEMS) technology to microspacecraft will probably be in the area of sensors (e.g. pressure and temperature), and micro gyros and micro-accelerometers.

Table 1
Technologies Resident at DOD Contractors
that Could Support a NASA Microspacecraft

<u>Structures/Mechanisms</u>

shaped memory actuators - d
composite sandwich panel & trusses (metal & polymer matrix composites) - d
high thermal conductivity composites & phase change material - d

<u>Power</u>

high efficiency solar cells - d
high energy density battery cells - m

<u>Command and Data</u>

data compression - d/m
opto electronics - m
high capacity bulk data storage parts - d

<u>Telecommunications</u>

active arrays - m
digital receivers - m
Ka band and higher frequencies -m
optical communications - m

<u>Attitude Control</u>

fiber optic and ring laser gyros - d
miniature star cameras/trackers - d
lightweight reaction/momentum wheels - d

<u>Propulsion</u>

mono and bi-prop engines - m
high pressure fiber overwrapped propellant & pressurant tanks - d
lightweight valves and regulators - m/d

<u>Electronic Packaging</u>

surface mount technology - d
multichip modules - d
3-D packaging - d
wafer scale integration - m
MMIC - d

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d = can be directly applied to NASA microspacecraft (may require re-qualification for a NASA mission)
m = requires modification and qualification for NASA needs

Table 2
System Level Technology Issues Unique to Microspacecraft

1) Improved/Re-partitioned system architectures
2) minimization of interconnections (e.g. cabling/connectors)
3) common mechanical/electrical/thermal packaging
4) power distribution and use at lower system voltages

RECOMMENDATIONS TO NASA
(ranked according to priority)

1) Establish a program to flight demonstrate microspacecraft.

1a) Vigorously pursue the transfer, qualification and insertion of DOD developed technologies (defined in finding #5) to NASA missions, systems and subsystems.

1b) In cooperation with NASA codes SL, SS, SZ, SE and QE, support system/mission studies of the microspacecraft concept with the goal of more effectively presenting the applications, requirements and pros and cons of microspacecraft.

1c) Support the development of microspacecraft technologies which are either unique to microspacecraft or which have not been supported by the DOD (defined in findings # 4 & 6).

2) Support the MEMS community with a small (~$0.5) program and encourage investigations into NASA applications.

3) Convene a microspacecraft working group to increase communication between users and technologists. This working group should consist of representatives from NASA user centers, NASA technology centers, codes R, S and Q and the DOD contractor community.

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MICRO GUIDANCE AND CONTROL PANEL RECOMMENDATIONS

μG&C

JOHN DIBATTISTA, CHAIR, NASA HQ CODE RSR
FRED Y. HADAEGH, CO-CHAIR, JPL
CLAUDE KECKLER, CO-CHAIR, LaRC

MAY 29, 1992

WORKSHOP ON MICROTECHNOLOGIES & APPLICATIONS TO SPACE SYSTEMS

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MICRO G & C TECHNOLOGY
DEFINITION

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WHAT IS MICRO GUIDANCE AND CONTROL?

- MICRO-MINIATURIZED GUIDANCE AND CONTROL COMPONENTS AND SUBSYSTEM (SENSORS, ACTUATORS, CONTROL ELECTRONICS)
- MICRO GUIDANCE AND CONTROL ARCHITECTURE REALIZED BY INTEGRATION OF MICRO-MACHINED DEVICES, ON-CHIP VLSI CIRCUITS AND GUIDANCE AND CONTROL FUNCTIONS

MICRO G&C TECHNOLOGY
PANEL SCOPE

THE GUIDANCE AND CONTROL PANEL WILL FOCUS ON EMERGING MICRO-GUIDANCE AND CONTROL TECHNOLOGIES, USERS AND SYSTEMS ISSUES WITH THE FOLLOWING EMPHASIS.

- MICRODEVICE G&C SUBSYSTEMS FOR SPACECRAFT WILL BE EXAMINED WITH EMPHASIS ON COMPONENT TECHNOLOGY, ATTITUDE AND ARTICULATION CONTROL CAPABILITIES, HEALTH MONITORING AND RECOVERY.
    - MICROSENSOR AND MICROACTUATOR DESIGN AND THE ATTENDANT ELECTRONICS, POWER AND INFORMATION PROCESSING WILL BE ADDRESSED. ALSO INCLUDED WILL BE VEHICLE HEALTH MONITORING FOR TRANSPORTATION SYSTEMS.
    - FABRICATION TECHNOLOGIES, INCLUDING SILICON PROCESSING, MICRO-MACHINING, TUNNELING TECHNOLOGY, MATERIAL SCIENCE, VLSI OF DEVICES AND SUPPORTING CIRCUITRY "ON-CHIP" WILL BE COVERED.
    - DISTRIBUTED ARCHITECTURE ISSUES WILL BE DISCUSSED INCLUDING DATA HANDLING, POWER TRANSMISSION AND DISTRIBUTED MICROSENSING ARCHITECTURES.
- PLATFORM APPLICATIONS WILL INCLUDE
    - SYSTEM IDENTIFICATION, HEALTH MONITORING, AND REMOTE SENSING APPLICATIONS
    - VEHICLE GUIDANCE, NAVIGATION AND CONTROL, AND SHAPE CONTROL FOR MULTI-USE VEHICLES AND LARGE INSTRUMENTS LIKE RADIOMETERS
- THE SCIENCE MISSION APPLICATIONS WILL INCLUDE SYSTEM IDENTIFICATION, OPTICAL FIGURE CONTROL FOR GROUND/SPACEBORNE TELESCOPES AND INTERFEROMETERS, AND INSTRUMENT POINTING/SENSING/ISOLATION.

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MICRO G & C TECHNOLOGY

PURPOSE AND OBJECTIVES

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OVERALL PURPOSE:

- DEVELOP NEW MINI/MICRO GUIDANCE AND CONTROL SYSTEM ARCHITECTURES AND COMPONENTS THAT MEET THE NEEDS OF FUTURE SPACE SYSTEMS

KEY OBJECTIVES:

- DEVELOP THE GUIDANCE AND CONTROL MICRO-SENSING, COMPUTATION, AND CONTROL ARCHITECTURES AND COMPONENTS THAT WILL ENABLE:

- INCREASED RELIABILITY VIA
  - SOLID STATE TECHNOLOGY
  - MASSIVE REDUNDANCY OF MICRO-COMPUTERS

  REDUCTIONS
  - 100/1 OR MORE IN SIZE, MASS AND POWER
  - 10/1 OR MORE IN RECURRING COST AND COST GROWTH RATES

- ARCHITECTURES WITH
  - ROBUST PERFORMANCE OVER TEMPERATURE, VIBRATION, AND RADIATION RANGES
  - EMBEDDED HEALTH MONITORING
  - VIABLE DISTRIBUTED FAULT TOLERANT G & C

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MICRO G & C TECHNOLOGY
G & C APPLICATION NEEDS FOR FUTURE SPACE SYSTEMS

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MICRO-SPACECRAFT, MICRO-LANDERS, MICRO ROVERS

- ATTITUDE & MANEUVER CONTROL SYSTEM
- MICRO-INERTIAL REFERENCES
- MICROELECTRO-OPTICS FOR MINIATURE CAMERAS & REMOTE SENSORS
- INERTIAL/CELESTIAL NAVIGATION SYSTEMS
- HEADING REFERENCE UNITS
- MINI-CAMERA POINTING, ARTICULATION & STABILIZATION
- ANTENNA POINTING, ARTICULATION & STABILIZATION
- INTEGRATED OPTICAL TRACKING

REMOTE SENSING PLATFORMS, INTERFEROMETERS, & DEPLOYABLE REFLECTORS

- DISTRIBUTED MICRO-SENSOR SYSTEM IDENTIFICATION
- MULTIVARIABLE CONTROL OF STRUCTURAL DYNAMICS
- DISTRIBUTED SHAPE & POSITION CONTROL OF MIRROR ARRAYS
- EMBEDDED ARTICULATION AND STABILIZATION OF TELESCOPE & INSTRUMENT OPTICS
- DISTRIBUTED MICRO-INERTIAL REFERENCES
- EMBEDDED HEALTH MONITORING OF G&C EFFECTORS
- INTEGRATED OPTICAL TRACKING

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MICRO G & C TECHNOLOGY
CORE BUILDING BLOCKS

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- CORE INNOVATIONS NEEDED FOR THE NEW MICRO-G & C ARCHITECTURES
  - MASSIVELY DISTRIBUTED MICROSENSING FOR SYSTEM ID AND CONTROL
  - LIGHT POWERED REMOTE PROCESSING NETWORK FOR MICROSENSING
  - MICRO-G & C FOR MICRO-SPACECRAFT AND MICRO-ROVERS
  - SIX DEGREE-OF-FREEDOM MICRO-INERTIAL MEASUREMENT UNIT
  - ACTIVELY CONTROLLED MICROMACHINED DEFORMABLE MIRRORS
  - EMBEDDED HEALTH MONITORING FOR G & C EFFECTORS
  - NEW ARCHITECTURES FOR FAULT TOLERANCE AND TO INTEGRATE DIVERSE SUBSYSTEMS

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MICRO G&C TECHNOLOGY

TECHNOLOGY AVAILABILITY

μG&C

CURRENT READINESS LEVEL:	2-3 (COMPONENT), 1 (SYSTEM)
LAB DEMONSTRATION:	3 YEARS FROM FUNDING START
FLIGHT DEMONSTRATION:	5 YEARS FROM FUNDING START (SUBSYSTEM LEVEL)

JPL

MICRO G&C TECHNOLOGY

G & C PANEL RECOMMENDATION

μG&C

THE GUIDANCE AND CONTROL PANEL CONCLUDES THAT THE DEVELOPMENT OF MICRO GUIDANCE AND CONTROL TECHNOLOGIES WILL HAVE A REVOLUTIONARY IMPACT ON NASA SPACECRAFT AND MISSIONS.

THE PANEL RECOMMENDS THAT NASA UNDERTAKE AS SOON AS POSSIBLE THE DEVELOPMENT OF THE MICRO G&C TECHNOLOGY CORE BUILDING BLOCKS, IDENTIFIED IN THIS REPORT, IN ORDER TO EXPLOIT AND SHAPE THE DIRECTION OF INDUSTRIAL AND ACADEMIC ADVANCES IN MICROTECHNOLOGIES.

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MICRO G&C TECHNOLOGY
IMPLEMENTATIONS

μG&C

EXPEDITE CRITICAL ANALYSIS OF MICROTECHNOLOGY VIABILITY FOR G&C

- EXAMINE STATE-OF-THE-ART IN MICRO-DEVICES ACROSS VARIOUS DISCIPLINES AND AGENCIES FOR LEVERAGING INTO G & C INCLUDING MEDICAL, AUTOMOTIVE, BIOLOGICAL, AVIATION AND CONSUMER PRODUCT ADVANCES
- CONDUCT G & C BENEFITS, APPLICATIONS AND CONCEPTUAL STUDIES TAKING INTO ACCOUNT THE MULTIDISCIPLINARY TECHNOLOGIES INVOLVED

FABRICATE

- PURSUE AND SUCCOR PROMISING DEVICES, CONCEPTS (E.G., ELECTROSTATIC, ELECTROMAGNETIC, ETC.)
- BUILD AND TEST PROTOTYPE INTEGRATED SYSTEMS

VALIDATE

- SUBJECT PROMISING SUBSYSTEMS TO REALISTIC ENVIRONMENT
- CONDUCT FLIGHT EXPERIMENTS (GET-AWAY SPECIALS, PIGGY-BACK, ETC.) FOR VALIDATIONS

WORKSHOP PROCEEDINGS:
MICROTECHNOLOGIES AND APPLICATIONS TO SPACE SYSTEMS

Workshop Summary Report

Study Coordinator and Proceedings Editor: B.A. Wilson
Jet Propulsion Laboratory, California Institute of Technology

Workshop Chairs: F.Y. Hadaegh, W.J. Kaiser and B.A. Wilson
Jet Propulsion Laboratory, California Institute of Technology

Microtechnologies offer the potential of enabling or enhancing NASA missions in a variety of ways. Following in the footsteps of the microelectronics revolution, the emerging micro–electro-mechanical systems (MEMS) technology, which offers the integration of recent advances in micromachining and nanofabrication techniques with microelectronics in a mass-producible format, is viewed as the next step in device and instrument miniaturization. In the course of identifying the major areas of impact for future space missions, the following three categories emerged:

- **Miniaturization of components and systems, where the primary benefit is a reduction in size, mass and/or power. (Example: Microspacecraft.)**
- **New capabilities and enhanced performance, where the most significant impact is in performance, regardless of system size. (Example: Optical domain image processing.)**
- **Distributed (multi-node) systems and missions, a new system paradigm in which the functionality is enabled through a multiplicity of elements. (Examples: Distributed networks of sensors for mapping, constellations of microspacecraft, or distributed health management sensor systems.)**

The first category is the most obvious, and, not surprisingly, encompasses many of the important applications identified in this report. Nevertheless, there are also numerous examples of significant impact in the other two categories, and because they are more likely to be overlooked in a cursory survey, represent some of the most significant contributions of this study.

MINIATURIZATION OF COMPONENTS AND SYSTEMS

It is generally recognized that future large flagship missions will be fewer and farther between, and that we have entered an era in which smaller, lower budget missions will dominate NASA's space exploration suite. Consequently, there is a critical focus on making everything smaller, lower mass and lower power, preferably with little or no sacrifice in capability or performance. The near-term targets are for Pegasus-launched microspacecraft, for which the total mass allocation, all subsystems and instruments combined, is 10 - 400 kg. Instruments for microspacecraft missions must be concomitantly small, typically under 1 kg. The feasibility of small (< 20 kg) and miniature (< 2 kg) planetary rovers is also being considered.

The Microspacecraft panel reviewed requirements for and obstacles to achieving a 10 - 400 kg, first-generation microspacecraft, and no *fundamental* engineering or physics limitations were identified. Much of the required technology has already been developed, primarily within the DoD community. Key technology developments yet required include micro radioisotope thermoelectric power generators, electric propulsion, Ka–band communication systems, and embedded physical sensors. Space and mass limitations on a microspacecraft may preclude conventional modular approaches, calling for additional systems integration issues to be addressed. Other technologies such as high-density batteries, data compression techniques, mono–, bi– and solid propellant engines and various mechanical, optoelectronic and communication systems, require further modification to meet specific NASA requirements.

A number of overall recommendations were generated concerning the development and implementation of a first-generation microspacecraft. Ranked in order of priority, these are:

- Establish a program to flight demonstrate microspacecraft.
  - Vigorously pursue the transfer, qualification and insertion of DoD-developed technologies to NASA missions, systems and subsystems.
  - In cooperation with NASA Codes SL, SS, SZ, SE and QE, support system/mission studies of the microspacecraft concept with the goal of more effectively presenting applications, requirements, and pros and cons of microspacecraft.
  - Support the development of microspacecraft technologies that are either unique to NASA or have not been adequately supported by DoD.
- Support the micro–electro-mechanical systems R&D community with small programs and encourage investigation into NASA applications.
- Convene a Microspacecraft Working Group to increase communication between users and technologists. This working group should consist of representatives from NASA user centers, NASA technology centers, Codes R, S and Q, and the DoD contractor community.

The Guidance and Control (G&C) Panel concluded that the development of micro G&C technologies will have a revolutionary impact on future generations of NASA spacecraft and missions. Micro G&C architectures can be achieved through the integration of micromachined devices, on-chip VLSI circuitry and guidance and control functions. The core building blocks include a six-degree-of-freedom micro inertial measurement unit (IMU), actively controlled deformable mirrors, distributed microsensor systems, embedded health monitoring, and light-powered, fault-tolerant processing networks. The overall recommendations in the area of G&C encompass three phases from the planning stages to the flight experiments:

- Expedite critical analysis of microtechnology viability for G&C:
  - Examine emerging state-of-the-art microdevice technologies across various disciplines and agencies for leveraging into G&C implementations, including medical, automotive, biological, aviation and consumer product advances.
  - Conduct studies on micro G&C conceptual development, applications, and benefits, taking into account the multidisciplinary technologies involved.
- Develop and fabricate components & systems:
  - Pursue and succor promising concepts and devices, e.g. electrostatic, electromagnetic, etc.
  - Build and test prototype integrated systems.
- Validate system performance:
  - Subject promising subsystems to realistic environments and operating conditions.
  - Conduct flight experiments for validation, e.g. "get-away specials," "piggy-back," etc.

Miniaturization of planetary rovers will enable a wide range of future planetary exploration missions. Rovers can be considered planetary surface "spacecraft," and much of the discussion in the spacecraft section applies equally to rovers. There are also some additional requirements, primarily in the areas of motility, including path planning and navigation, and articulation of components. Enhanced autonomy is also desirable, which requires additional microsensors and on-board processing capabilities.

The implementation of microtechnologies in sensors and science instruments is already under way, and represents a rapidly evolving area of development with the promise of additional revolutionary advances in the future. The primary impact on science instrument size is expected to result from the development of micromachined transducers, micromechanical structures, and chip-level photonics coupled with fiber optics. The integration of electronics, photonics, and micromechanical functionalities into "instruments-on-a-chip" will provide the ultimate size advantage. The near-term advantages will most likely occur through the insertion of micromachined sensors and actuators, on-focal-plane electronics, discrete photonic components, and nanofabricated optical elements. Overall, the Science Instruments Panel of the workshop found reason for excitement in the potential of emerging microtechnologies to significantly reduce the size and power of future science instruments. Just as in the microelectronics revolution of the previous 20 years, during the next 20 years we may witness vast reductions in the cost of mass-produced items, in this case based on micromechanical and integrated MEMS technologies. This is particularly encouraging as we enter a future in which we anticipate significantly smaller missions with concomitantly reduced cost ceilings. Consequently, this panel strongly urged NASA to focus attention on the development of these technologies to permit their insertion into space missions as rapidly as possible.

NEW CAPABILITIES AND ENHANCED PERFORMANCE

In many cases, the insertion of microtechnologies and/or miniaturized systems can actually *improve* system performance or even enable new science returns. In the case of microspacecraft, for example, the smaller mass and potentially increased robustness against higher accelerations, can be translated into increased maneuverability. This can mean more direct trajectories and shorter trips, which, in turn, reduces restrictions on the viability of instruments suffering from limited component lifetimes. It also increases the possibilities for multi-destination missions. Enhanced performance may also be possible for individual spacecraft subsystems such as communications, data management, G&C, and embedded sensor systems, which could be used to advantage in micro and conventionally sized spacecraft alike. Micromechanical structures are particularly promising for improving the capabilities of inertial sensors and robotic manipulators.

Increased sensitivity, frequency response, dynamic range, resolution and robustness can often be achieved in science sensors through the use of microtechnologies. One of the key components is the micromachined transducer. A prime example is the tunnel sensor, an ultra-sensitive new transducer based on electron tunneling between a micromachined tip positioned a few Å above an underlying surface, the entire structure fabricated from a single silicon wafer. Reconfigured as a transducer, tunneling structures can reveal changes in the tip-surface separation with accuracies of 0.1 Å or better, representing an increase in sensitivity of many orders of magnitude over conventional transducers. Nanofabrication and lithographically defined transducer structures offer large enhancements in sensitivity over conventional approaches. Microchemical sensors offer the possibility of in-situ chemical sensing. A second technology area of critical importance to future science instruments is the application of micro and nanofabrication techniques to optics and optical systems. Microactuators will play a key role in advanced optical systems. Micromachining techniques offer significant enhancements in X-ray imaging resolution, and new opportunities in electrostatic imaging and vacuum electronics for chip-level particle detection and analysis. Nanolithography of optical surface structure is another key element. Lithography on the nm scale is also required for the fabrication of high-frequency receiver components, phased-array antennas and chip-level photonic devices.

DISTRIBUTED SYSTEMS

Perhaps the most stimulating and provocative opportunities for new mission capabilities and science return emerging from the workshop fall into this category. We are at the threshold of the MEMS revolution, anticipated to have as far-reaching an impact on the miniaturization and cost reduction of components as the microelectronics revolution we have already experienced. With the availability of mass-produced, miniature instrumentation comes the opportunity to rethink our fundamental measurement paradigms. It is now possible to expand our horizons from a single instrument perspective to one involving multi-node or distributed systems. As the largest departure from conventional approaches, advances in this area are the hardest to predict, but may be the most far-reaching.

Given the possibility of launching suites of microspacecraft, it is appropriate to consider the benefits of multi-spacecraft missions. Advantages for Eos–type missions include simultaneous multi-swath mapping. Placing two or more satellites at appropriately phased intervals in the same orbit enables direct active measurements through the atmospheric layers of interest. Multiple spacecraft can also be used as nodes along an extended interferometric baseline, or as points of a gigantic linear unfilled aperture array. Distributed sensor systems offer performance advantages in health management for conventional and microspacecraft. The greatest impact is expected for fuel and propulsion systems, G&C systems and life-support systems, which will require the development and insertion of physical, chemical and biological sensors. Propulsion and fuel systems would benefit from suites of temperature, pressure and specific chemical sensors for leak detection.

One of the most exciting ideas that emerged from the workshop is the concept of utilizing distributed sensor systems for extending the scope of possible science measurements. Similar to the breakthrough in science return offered by focal-plane arrays versus discrete detector elements, distributed arrays of sensors can provide extended sets of information that lead to new levels of understanding of the underlying phenomena. Multi-node sensor systems enable both imaging/mapping activities, as well as the acquisition of time-phased/dynamic information unavailable from a single-sensor measurement mode. For example, while a single seismometer can only indicate the local ground acceleration, multiple sensors distributed across the planetary surface can lead to a detailed understanding of global seismic activity and the nature and structure of the planetary interior. Examples of science instruments where the advantages of distributed arrays are on the horizon include seismometer arrays, free-flying magnetometers, planetary surface constituent analysis, and fiber-optic-linked, free-space interferometers. Complex science instruments may also benefit from embedded arrays of microsensors to monitor their system functionality.

MICROTECHNOLOGY DEVELOPMENT RECOMMENDATIONS

An integrated assessment of the panels suggests that the predominant near-term impact of microtechnologies on NASA space missions is most likely to occur in two areas: (i) the implementation of miniature systems utilizing existing technology; and (ii) the insertion of micromachined sensors and actuators. The miniaturization of spacecraft, planetary rovers and science instruments can proceed rapidly with the incorporation of miniature technologies that have already been developed at the component level, but not yet integrated into appropriately designed miniature systems. Compact packaging technologies will also assist in this process. New miniaturization opportunities are offered by emerging micromachined sensors and actuators, selected chemical sensors, discrete photonic devices, and lithographically defined micro–optics technologies.

Further miniaturization and performance enhancement of spacecraft, planetary rovers and science instruments will be possible as the on-chip integration of micromechanical and electronic components becomes feasible. Coupled with the development of appropriate processing networks, this should enable the first distributed sensor systems for health management applications. Other important mid-term impact areas include the incorporation of binary and adaptive optics and the development of space-qualifiable high-speed electronic systems for Ka–band communications and adaptive processing networks. More fundamental advances are likely to provide additional system advantages further downstream. To ensure that areas relevant to space applications emerge in a timely manner, it is recommended that NASA consider base-program support in selected areas of long-term pay-off. These include micromachining and nanofabrication techniques of greater sophistication and in new materials including binary optics, chemical and biological microsensor development, vacuum electronics components, integrated photonic technologies, and fundamental advances in concurrent processing architectures.

CONCLUSIONS

As the first forum spanning the emerging microtechnologies and bringing together the technology and space systems experts across the country, the workshop was enthusiastically supported by all parts of the community. Over 225 people participated in this workshop, drawn from universities, industry, NASA centers, and other government laboratories and agencies. The workshop was chaired by Fred Hadaegh, Bill Kaiser and Barbara Wilson, with presentations overviewing emerging microtechnology developments coordinated by Frank Grunthaner. Following the workshop, a set of recommendations to NASA in support of the key technology development areas was generated as an interim internal report, which was subsequently incorporated into the NASA technology planning process.

Microtechnologies
and
Applications to Space Systems Workshop

APPENDIX

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MICROTECHNOLOGIES AND APPLICATIONS TO SPACE SYSTEMS WORKSHOP

AGENDA

DAY 1: May 27, 1992

WELCOME - Barbara Wilson, Session Chair

8:00 am	*Workshop Welcome*	Terry Cole, JPL
8:15 am	*Workshop Overview*	Wayne Hudson, NASA Code RS

FUTURE VISIONS - Gordon Johnston, Session Chair

8:30 am	*Future Trends in Small Missions and Need for Microtechnology*	Charles Elachi, JPL
8:50 am	*The NSF Microtechnology Program, or Robots on the Head of a Pin*	George Hazelrigg, NSF
9:20 am	*Silicon Micro-Instrumentation*	Kurt Petersen, Lucas NovaSensor

NASA MISSION & SCIENCE GOALS - Wayne Hudson, Session Chair

10:10 am	*The Solar System Exploration Program: Goals, Strategy, and Plans*	Corinne Buoni, SAIC
10:30 am	*Science Goals & Constraints of MESUR*	Arthur Lane, JPL
10:50 am	*The Fast Flyby Pluto Mission: Completing the Reconnaissance of the Solar System*	Paul Henry, JPL
11:10 am	*Space Physics Mission Needs*	Jim Randolph, NASA Code SS
11:30 am	*Mission & Science Goals of Lunar Outpost Missions*	Jeffrey Plescia, JPL

MICROTECHNOLOGY PROGRAM OVERVIEWS PART I - Frank Grunthaner, Session Chair

1:00 pm	*Micro Electro Mechanical Systems (MEMS) and Their Impact on Future Robotic Systems*	Stephen Jacobsen, Univ. of Utah
1:20 pm	*SDI Development of Miniaturized Components*	Mick Blackledge, SDI/TN
1:50 pm	*DoD Advanced Space Technology Program Challenge*	Al Wheatley, DARPA
2:10 pm	*Code R Microtechnologies*	Dave Lavery, NASA Code RS
2:30 pm	*Micromechanics Program at Sandia: Micromechanical Sensors, Actuators and Devices*	Ned Godshall, Sandia
2:50 pm	*Micromanufacturing: Recent Developments in this Country and Abroad*	Robert Warrington, Louisiana Tech Univ.
3:10 pm	*Microsensors and Microinstruments: New Measurement Principles and New Applications*	William J. Kaiser, JPL

MICROTECHNOLOGY PROGRAM OVERVIEWS PART II - William Kaiser, Session Chair

5:00 pm	*Micro-Sensors, -Actuators, -Systems: Accomplishments & Prospects*	Richard White, UC Berkeley
5:20 pm	*National Nanofabrication Facility and Nanoelectromechanics*	Noel MacDonald, Cornell Univ.
5:40 pm	*Microactuator Production via High Aspect Ratio, Edge Acuity Metal Fabrication Technology*	Henry Guckel, Univ. of Wisconsin-Madison
6:00 pm	*Overview of Microoptics: Past, Present and Future*	Wilfrid Veldkamp, Lincoln Laboratory, MIT
6:20 pm	*Microsensors, Smart Sensors, Sensor Arrays, and the Artificial Nose*	Joseph Stetter, Transducer Research Inc.

DAY 2: May 28, 1992

APPLICATIONS OVERVIEWS PART I - John DiBattista, Session Chair

8:00 am	*Micromechanical Actuators*	William Trimmer, Princeton Univ. & Belle Mead Research
8:30 am	*In Situ Meteorological Sensors for Earth and Mars Applications*	James Tillman, Univ. of Washington
8:50 am	*Silicon Flexural Microelectromechanical Devices*	Kaigham Gabriel, NRL
9:10 am	*Micromachining the Future*	Marc Madou, Teknekron
9:40 am	*Learning from Biology - Motor Systems at all Scales*	M.G. Littman, Princeton Univ.

APPLICATIONS OVERVIEWS PART II - Fred Hadaegh, Session Chair

10:20 am	*Micro-Software for Micro-Robots*	David Miller, MIT
10:40 am	*Spacecraft Telecommunications Technology for Microspacecraft*	Charles Kyriacou
11:00 am	*Microspacecraft: A Concept*	Ross Jones, JPL
11:20 am	*Micro-Guidance and Control Technology Overview*	Glen Kissel, JPL
11:40 am	*Health Management Issues for Space Systems*	Stephen Johnson, Martin Marietta Astronautics

PARALLEL SESSION ON SCIENCE INSTRUMENTS
SESSION AND PANEL CHAIRS: Benton Clark, Gregg Vane & Louis Watts

1:00 pm	*Trends in X-Ray Fluorescence Instruments*	Benton Clark, Martin Marietta
1:20 pm	*Miniaturization in X-Ray and Gamma-Ray Spectroscopy*	Jan Iwanczyk, Xsirius, Inc.
1:40 pm	*Backscatter Mossbauer Spectrometer (BaMS) for Extraterrestrial Applications*	David Agresti, Univ. of Alabama
2:00 pm	*A Sub-cm Micromachined Electron Microscope*	Alan Feinerman, Univ. of Illinois at Chicago
2:20 pm	*Differential Scanning Calorimetry for Planetary Surface Exploration*	Douglas Ming, JSC
2:40 pm	*Micro-Sensors for in-situ Meteorological Measurements*	David Crisp, JPL
3:00 pm	*A Broad-Band Microseismometer for Planetary Applications*	Bruce Banerdt, JPL
3:40 pm	*The Miniature X-Ray Telescope ALEXIS*	Bill Priedhorsky, Los Alamos
4:00 pm	*Imaging Spectrometry for the Earth and Other Solar System Bodies*	Gregg Vane, JPL
4:20 pm	*Smart Focal-Plane Technology for Micro Instruments and Micro Rovers*	Eric Fossum, JPL
4:40 pm	*Evolution of Miniature Detectors and Focal Plane Arrays for Infrared Sensors*	Louis Watts, SAIC
5:00 pm	*Photonics Devices for Microinstruments*	Robert Lang, Spectra Diode

PARALLEL SESSION ON MICROSPACECRAFT
SESSION AND PANEL CHAIRS: Denis Connolly, Ross Jones

1:00 pm	*Asteroid Investigation with Microspacecraft (AIM)*	Ross Jones & Christopher Salvo, JPL
1:20 pm	*Fundamental Limits on Earth Remote Sensing from Small Spacecraft*	David Rider, JPL
1:40 pm	*Development of MMIC Technology for SATCOM Applications*	John Berenz, TRW
2:00 pm	*Spacecraft Telecommunications Technology for Microspacecraft Applications*	Charles Kyriacou, JPL
2:20 pm	*Power Subsystem State-of-the-Art Assessment and Miniaturization Technology Needs*	Robert Detwiler, JPL
2:40 pm	*The Application of Micro Technology to Spacecraft On-Board Computing*	Leon Alkalaj, JPL
3:20 pm	*Command & Data Subsystem Technology*	Richard Grammier, JPL

3:40 pm	*Electronic Packaging for Microspacecraft Applications*	David Wasler, JPL
4:00 pm	*Microspacecraft Attitude Control*	George Sevaston, JPL
4:20 pm	*Miniaturized Propulsion Systems*	Dale Hook, TRW
4:40 pm	*Lightweight Structures and Mechanisms for Microsatellites*	Robert Wendt, Martin Marietta
5:00 pm	*SDI Flight Tests of Integrated Microsystems*	Rich Matlock, SDI/TN

PARALLEL SESSION ON SPACE STATION, SHUTTLE & PROPULSION

SESSION AND PANEL CHAIRS: W.T. Powers, Gerald Voecks

1:00 pm - 6:00 pm Roundtable Discussions and presentations

PARALLEL SESSION ON MICROROVERS

SESSION AND PANEL CHAIRS: Kaigham Gabriel and Subramani Venkataraman

1:00 pm	*Role of Microrovers in Planetary Exploration*	Corinne Buoni, SAIC
1:25 pm	*Robotic Vehicles for Planetary Exploration*	Brian Wilcox, JPL
1:50 pm	*Application of Behavior Control Technology to Planetary Rovers*	Rajiv Desai, JPL
2:15 pm	*Difficulties Inherent in Miniaturizing Current Rover Technologies for Use as Planetary Explorers*	Gerald Roston, CMU
2:40 pm	*Micromachining Technologies for Automotive Applications*	William Tang, Ford Motor
3:05 pm	*Microtechnology on Minirovers*	Donald Bickler, JPL
3:50 pm	*Silicon Flexural Microelectromechanical Devices*	Kaigham Gabriel, NRL
4:15 pm	*Micromechanical Actuators*	William Trimmer, Princeton Univ. & Belle Mead Research
4:40 pm	*Toward Milli-Newton Electro- and Magneto-Static Microactuators*	Long-Shen Fan, IBM Almaden
5:05 pm	*Micro Structures and Micro Actuators for Implementing Sub-Millimeter Robots*	Ronald Fearing, UC Berkeley
5:30 pm	*Coordinated Control of Legged Locomotion via Nonlinear Oscillators*	P. Krishnaprasad, Univ. of Maryland

PARALLEL SESSION ON MICROTECHNOLOGIES OF THE FUTURE

SESSION AND PANEL CHAIRS: Frank Grunthaner, John Hines and Brent Mott

1:00 pm - 6:00 pm Roundtable Discussions and presentations

PARALLEL SESSION ON GUIDANCE & CONTROL

SESSION AND PANEL CHAIRS: John DiBattista, Fred Hadaegh and Claude Keckler

1:00 pm	*Control of Micro-Machined Deformable Mirrors*	P.K.C. Wang, UCLA
1:25 pm	*Emerging Technologies in Microguidance and Control*	Marc Weinberg, C.S. Draper Laboratory
1:50 pm	*An Electrostatically Suspended, Micro-Mechanical Rate Gyroscope*	Timothy Hawkey, Satcon Technology Corp.
2:15 pm	*GEC Ferranti Piezo Vibratory Gyroscope*	John Nuttall, GEC Ferranti
2:55 pm	*The Application of Micromachined Sensors to Manned Space Systems*	Gary Havey, Honeywell Systems & Research
3:20 pm	*Micro Guidance and Control Synthesis: New Components, Architectures and Capabilities*	Edward Mettler, JPL
3:45 pm	*Microoptomechanical Devices & Systems using Epitaxial Lift-Off*	Mark Allen, Georgia Inst. of Technology
4:10 pm	*Miniature Wide Field-of-View Star Trackers for Spacecraft Attitude Sensing & Navigation*	William McCarty, OCA Applied Optics, Inc.
4:35 pm	*Novel Position Sensor Technologies for Micro Accelerometers*	Thomas Van Zandt, JPL

WORKSHOP PANELS

PANEL ON SCIENCE INSTRUMENTS

PANEL CHAIRS: Benton Clark, Gregg Vane & Louis Watts

PANEL MEMBERS

Arden Albee, Caltech
James Bradley, JPL
Benton Clark, Martin Marietta
Eric Fossum, JPL
Raymond Goldstein, JPL
Gordon Johnston, NASA Code RSS
William Kaiser, JPL
James Tillman, Univ. of WA
Gregg Vane, JPL
Wilfrid Veldkamp, MIT Lincoln Labs
Louis Watts, SAIC

PANEL ON MICROSPACECRAFT

PANEL CHAIRS: Denis Connolly, Ross Jones

PANEL MEMBERS

Leon Alkalaj, JPL
John Berenz, TRW
Corinne Buoni, SAIC
Richard Cheng, Hughes
Denis Connolly, LeRC
Robert Detwiler, JPL
Terry Gamber, Martin Marietta
Rick Grammier, JPL
Dale Hook, TRW
Ross Jones, JPL
Charles Kyriacou, JPL
Robert Lafferty, Motorola
Rich Matlock, SDI/TN
John McIver, Boeing
Rich Reinert, Ball Aerospace
George Sevaston, JPL
Dave Stevens, JPL
David Wasler, JPL
Robert Wendt, Martin Marietta

PANEL ON SPACE STATION, SHUTTLE & PROPULSION

PANEL CHAIRS: W.T. Powers, Gerald Voecks

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Thurman Henderson, U. of Cincinnati
Richard Higgins, GA Tech Res. Inst.
Stephen Johnson, Martin Marietta
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PANEL ON MICROROVERS

PANEL CHAIRS: Kaigham Gabriel and Subramani Venkataraman

PANEL MEMBERS

Rajiv Desai, JPL
Long-Shen Fan, IBM, Almaden
Kaigham Gabriel, NRL
Dave Lavery, NASA Code RS
Michael Sims, ARC
Bill Tang, Ford Scientific Res. Lab.
Subramani Venkataraman, JPL
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PANEL ON MICROTECHNOLOGIES OF THE FUTURE

PANEL CHAIRS: Frank Grunthaner, John Hines and Brent Mott

PANEL MEMBERS

Robert Hughes, Sandia
Stephen Jacobsen, Univ. of Utah
Seun Kahng, LaRC
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Ned Godshall, Sandia
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Harvey Moseley, GSFC
Brent Mott, GSFC
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Robert Warrington, LSU
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PANEL ON GUIDANCE & CONTROL

PANEL CHAIRS: John DiBattista, Fred Hadaegh and Claude Keckler

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15. Supplementary Notes

16. Abstract

During FY'92, the NASA Code RS System Analysis RTOP funded a study to evaluate the potential impact of emerging microtechnologies on future space missions. As part of this study, a workshop, "Microtechnologies and Applications to Space Systems" was held May 27-29th, 1992, in Pasadena, CA. This volume serves as the Proceedings of this workshop. It contains the manuscripts provided by plenary and parallel session presenters, and summary reports generated from this material and from information presented during the panel discussions. Where manuscripts were not provided, extended abstracts, if available, have been included. The order of the papers follows the original workshop agenda.

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