Intelligent Star Tracker

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ABSTRACT

We describe our Intelligent Star Tracker System. Our Intelligent Star Tracker System incorporates an adaptive optic catadioptric telescope in a silicon carbide housing. Leveraging off of our active optic technologies, the novel active pixel position sensors (APPS) enable wide dynamic range and allows simultaneous imagery of faint and bright stars in a single image. Moreover, the APPS, in conjunction with the adaptive optics technologies, offer unprecedented accuracy in altitude and navigation applications.

INTRODUCTION

Current state-of-the-art commercial star sensors typically weigh 15 pounds, attain 5 to 10 arc-second accuracy, and use roughly 10 watts of power. Unfortunately, the current state-of-the-art commercial star sensors do not meet many of NASA's "next-generation" spacecraft and instrument needs. Nor do they satisfy Air Force's need for micro/nano-satellite systems. In this paper we present a low cost, miniature Intelligent Star Tracker for spacecraft attitude determination and navigation. Our Intellgient Star Tracker incorporates adaptive optic catadioptric telescope in a single, compact, robust Silicon Carbide housing. The MOEMs micro-mirrors are used to compensate for various aberrations as well as introduce aberrations such as defocus to ensure optimal system performance.

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Leveraging off of our adaptive optics research, our active pixel position sensors enable wide dynamic range and simultaneous imaging of faint and bright stars in a single image frame. The adaptive optics telescope, using, MOEMs micro-mirrors, enables extremely accurate tracking. When coupled with our star matching scheme based on algebraic coding theory, the active optic technologies enable fast and accurate star pattern recognition to support guidance navigation and control (GN&C).

The massively parallel processing architecture designed into the Intelligent Star Tracker not only enables very high bandwidths, exceeding 40 Hz, but also enables tracking of at least 5 stars simultaneously. Moreover, the massively parallel architecture enables the star tracker to operate autonomously without burdening the spacecraft processor and may be used to supplement the onboard processor. Because our design utilizes technologies that inherently integrate well together and lend themselves to batch processing, we estimate that the Intelligent Star Tracker will have a recurring cost less than $100k. In addition to low cost, preliminary analysis indicates that our Intelligent Star Tracker will have a pointing accuracy Tracker will have a pointing accuracy exceeding 0.20 arc-sec, NEA better than 0.10 arc-sec, power consumption less than 2 W and a weight of approximately 0.20 Kg.

ATTITUDE DETERMINATION

The most obvious application for the Intelligent Star Tracker is star tracking for spacecraft attitude determination. To assess

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the true star density in the Intelligent Star Tracker FOV we will use our Space Technologies Applied Research Laboratory (AFRL StarLab) to produce accurate star patterns. AFRL has already set this up for adaptive optics purposes. The AFRL StarLab also provides a convenient method to accurately test the Intelligent Star Tracker with accurate star densities.

CATADIOPTRIC TELESOPE

Our novel Intelligent Star Tracker, shown in figure 1, incorporates a totally new optical design which consists of a high high-resolution adaptive optic telescope folded into a single low cost, Silicon Carbide structure.

We chose to use catadioptric telescope design because of their simplicity and wide field imaging capabilites. There are several catadioptic telescopes that could be used in a star tracker system. Figure 1 illustrates the Intelligent Star Tracker we designed using a Matsutov-Bouwers configuration. Other catadioptric telecopes which could also be used include Schmidt-Cassegrain, and Baker-Schmidt. In each of these catadioptric telescopes uses a full-aperture refracting element to provide the aberration correction needed to get good imagery over a wide field.
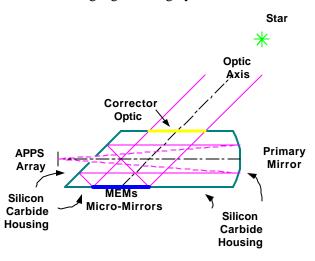

Figure 1. Intelligent Star Tracker.

SILICON CARBIDE OPTICAL HEAD

The dramatic difference in weight between conventional and Silicon Carbide optical systems has led to Silicon Carbide material being applied to a number of optical applications associated with next generation remote sensing concepts. Silicon Carbide material have a number of bulk property advantages, very high specific stiffness and outstanding thermal stability, which makes it particularly well suited for the Intelligent Star Tracker system. The superior thermal stability in conjunction with the outstanding specific stiffness, make Silicon Carbide ideally suited for star trackers. Silicon Carbide provides excellent lightweighting capabilities (approximately 80% of beryllium.), and is 50% the hardness of diamond. Historically, there are two problems associated with CVD Silicon Carbide materials: (1) the CVD process very expensive with furnacing runs costing on the order of $100k each and (2) CVD SiC cannot be produce in very lightweight geometries.

A state of the art CVD Silicon Carbide mirror can be expected to have a density on the order of 30-50 Kg/m^2. Hence, any complex geometries that are required, or any lightweighting geometries need to be machined in place. Such machining is costly and time consuming. We will have the Intelligent Star Tracker fabricated using a castable form of Silicon Carbide as a reflector substrate material. Cast Silicon Carbide parts are formed by pouring a slurry of Silicon Carbide powders and water into a reusable mold. The mold can be very complex, as is needed for the folded up catadioptric telescopes. This enables the intricate folded telescope design to be formed directly without the need for costly and time consuming machining. Finally, this Silicon Carbide technique has excellent polishability since the mirrors can be formed with a surface RMS roughnessless than lambda/20. Moreover, our analysis indicates that the optical head has a small recurring cost of approximately $15k.

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ADAPTIVE OPTICS

Assuming no distortion of the stars, the matching of unit-sphere-projected Airy patterns is simply a matter of finding the correct three dimensional rotation which causes the two sets to match. All stars can be represented with Cartesian coordinates and quaternions are used to represent the rotations. Conceptually, a quaternion is a quadruple consisting of a three-dimensional vector and rotation about that vector. The micro-mirror, in conjunction with computational techniques, can then be used to compensate for geometric and spectral aberrations and effects. Geometrical aberrations are induced by pressure, acceleration, and temperature affects.

Although silicon carbide has outstanding tolerances, there are some residual distortions that can be compensated for by the adaptive optics and intelligent processing. For enhanced robustness, accuracy, and bandwidth we plan to use algebraic coding theory techniques for star pattern recognition. AFRL has developed a novel method of using algebraic coding theory for pattern recognition. Algebraic coding theory enables better accuracy because of embedded redundancies. Moreover, our innovative algebraic coding theory techniques are inherently parallel and thus enable over a 10-fold improvement in bandwidth of conventional pattern recognition techniques.

Most pattern matching techniques used in star trackers compute the quaternion that has the smallest aggregate RMS error. Such techniques do not necessarily provide the quaternion that is best for heading determination. Errors in particular star positions may be caused by overexposed star images. They can also arise from incorrect estimation of lens focal length or optical aberrations. Our novel method uses adaptive optic techniques in conjunction with clever processing to ensure optimal accuracy.

MOEMs MICROMIRRORS

The technical objective for the micro-mirror portion of the overall design includes refinement of our current practices for producing high active-area-coverage piston mirror arrays. The Air Force Research laboratory currently has a test die containing an 8x8 piston mirror array in fabrication in the four-layer planarized SUMMiT process at Sandia National Laboratories. Testing of this and follow-on arrays will yield a final array with optical and electrical characteristics which far exceed any piston micro-mirror currently available in any laboratory. Figure 2 shows the 8x8 mirror array test die. The main array occupies the center of the die and is connected to the outside tier of bond pads.

Figure 3 shows the details of an individual mirror design. This figure captures all of the advantages of the SUMMiT process for MOEMS. SUMMiT has a combination of features not found in other MEMS fabrication processes, such as a chemical-mechanically polished upper surface, 1 micron design rules, and four releasable layers. One of these layers is only 1 micron thick, allowing extremely low drive voltages. Current 4-flexure mirrors can be designed for actuation at less than 10V, making it possible to drive them with standard CMOS circuitry. The multiple releasable layers allow all of the wiring and flexures to be completely hidden under the polished optical surface, resulting in near-optimum active mirror area coverage. This is an important consideration not only for optical efficiency, but also in applications where stray light leakage into the mechanism limits power handling capability.

The multiple layers also allows us to shield the wiring so the optical surface can be metalized after the release etch. Thus the optical surface of choice can be deposited without concern over its survival through the harsh release etch. Another advantage of post-release metalization is that the entire active area is

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covered, unlike drawn metal which requires a margin between the edge of the metal and the edge of the polysilicon upper plate. These capabilities, coupled with the hidden-flexure/post metalization design techniques, give the 8x8 test array of 100 micron square mirrors an active area coverage of 97.7%. This high active area coverage offers unprecedented to diffraction-limited imaging with minimal light loss. Referring to figure 2, Figure an array of 50 micron square mirrors. Note that only mirror surfaces are visible, and the only area lost is due to the 1 micron gaps between the mirrors, the etch holes, and the anchor posts. This array has an active area coverage of 95.3%, and there are no topological effects from the underlying layers.
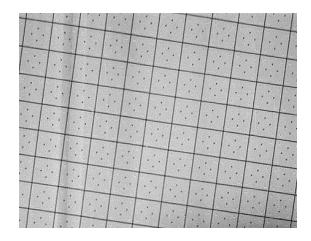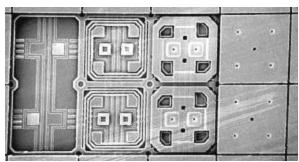

Figure 2. Array of MOEMs Micro-Mirrors

Figure 3. Details of the structure of the micro-mirrors are shown.

Referring to figure 3, the details of a typical flexure beam piston micromirror which takes full advantage of the SUMMiT capabilities. These 50 micron square mirrors achieve 95.3% active mirror surface coverage. The layers left to right are: Poly0 layer used for wiring throughout the array; Poly1 used for the flexures because it is the thinnest layer, poly1 is also used for metalization gutters (square frames surrounding the spiral flexures) to prevent post-release metalization from shorting the wiring; Poly2 is used for the lower electrode of the electrostatic actuator; Poly3 forms the upper electrode and is also the planarized surface - note the total lack of topological effects at this level.

ACTIVE PIXEL POSITION SENSORS

The Active Pixel Position Sensors (APPSs) we have developed for some of our adaptive optics research appear to be well suited for use in star trackers. Our active pixel position sensors (APPS) have several advantages over CCD and traditional Active Pixel Sensors (APS). The APPS offers the advantage over CCDs in including two orders of magnitude less power consumption and less susceptibility to radiation damage. Like APS sensors, our APPS can be directly accessed, simplifying the camera system design and enhancing its capabilities. Also like APS sensors our APPS sensors are substantially cheaper to produce (in quantity) than traditional CCDs, and allow for reduced component count.

Figure 4 illustrates one very promising APPS detector along with some experimental results that characterize its performance. As illustrated in Figure 4, the phtotodetector is a simple, planar back-to-back Schottky-barier Si position sensor of 3-80 micron gap dimensions that is sensitive to nm scale position changes. Unlike most other position sensitive detector, this device requires contacts on only one side, making it fully compatible with VLSI processing. As illustrated in Figure 4 the Schottky photodetector is not only fast (350 ps rise time) but extremely accurate. Is shown in

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Figure 4, each detector (80 microns in the ones we fabricated for an adaptive optic system) can accurately measure with sub pixel accuracy (less than 10nm) a spot displacement that is independent of spot size. We needed such characteristics for our adaptive optic systems, but our preliminary studies indicate that these position sensors are ideally suited for star trackers. For our Intelligent Star Tracker, we will investigate these (as well as other) APPS technologies and perform a trade analysis ensuring optimal overall star tracker performance.

Based on experimental results, we will perform trade studies on various architectures that are best suited to the Intelligent Star Tracker. We will then fabricate 64x64 array and a 128 x 128 pixel array. Because of the architecture of the APPS enables a single pixel to very accurately track stars, smaller arrays can be used. Moreover, since the light form a star does have to be spread over multiple pixels, our approach enables much higher signal to noise and hence more accurate position sensing at higher bandwidths. Moreover, our fixed pattern noise (FPN), temporal noise techniques enhance performance conjunction with the Silicon Carbide telescopes and algebraic coding pattern recognition (for massively parallel pattern recognition and added error correction for enhance accuracy as discussed later) we
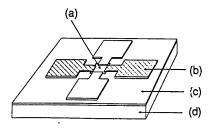

Figure 4. APPS used to accurately track a spot of light. Schematic of the detector a) active area, b) Ni-Cr,Au, c) SiO_2 and Si bulk layers.
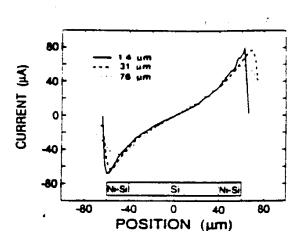

Figure 5. Experimental results showing the tracking accuracy of the active pixel position sensors.

feel our Intelligent Star Tracker is not only a factor of 10 cheaper, lighter but also will be much more accurate than the current state-of the art star trackers.

Figure 5 shows I_{sc} as a function of displacement for 1D 80 micron gap device. The incident power at 633nm and the beam diameter was approximately 2 microns. A minimum computer controlled translation stage with a step 5 nm was used over the center 1 micron of the gap. The position sensitivity of this detector was also tested for different spot diameters or 31 and 76 microns, as shown in figure 5.

The lateral photovoltaic effect is often discussed in the context of a non-uniformly illuminated junction where the large built in fields are in the longitudinal or z direction. Photo-injection results in a localized change in the diode potential and hence a transverse field and carrier transport by drift and diffusion establishing the lateral photovoltage. In contrast, the APPS incorporates transverse internal fields, limited to the depletion region near each electrode and a large filed free region, especially for the larger 80 micron devices.

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We are currently evaluating these and other APPS for use in a low-light environments such as that needed for the Intelligent Star Tracker.

INTELLIGENT SATELLITE PROCESSOR

The Intelligent Satellite Processor system, being developed at AFRL for our adaptive optic system has incredible processing and control capability. At the heart of the system is our reconfigurable vision chips which are capable of massively parallel analog processing. The smart vision chips are capable of not only centroiding and pattern recognition but also tracking and controlling devices including micro-mirrors. In addition to analog processing, our Intelligent satellite Processor system includes the Texas Instrument's TMS320C6000 series DSP chips. The 'C67 is the fastest DSP processor in the world, clocking in at over 1GFLOP. New packaging technologies like flexible flaps, chip-on-board, chip scale, and micro-fineline BGAs are paving the way for revolution in lightweight, low power systems. While recognizing the cost effectiveness of legacy implementations of multi-chip module designs, we intend to take full advantage of the newer technologies as we migrate our design from the lab to a space based application over the duration of this proposal.

Our approach allows us a multitude of high bandwidth designs with minimum of redesign of the software and hardware. We will tap the true potential by optimizing the integration of all the subsystems. For example, high-speed imagery can be stored in inexpensive RAID storage banks using Fiber channel modules. Another example is using our massively parallel analog vision chip to interface directly with the photodetectors and micro-mirrors. While arguments can be made for using COTS equipment, many program suffer short sightedness from the fact that when it is time to integrate the subsystems, the final design consumes too much power and has reduced reliability and robustness. We have effectively short-circuited this problem by choosing technologies that inherently lend themselves to integration and batch production.

PATTERN RECOGNITION USING ALGEBRAIC CODING THEORY

In order to accelerate the evolution of faster, better, cheaper spacecraft, it is evident that greatly enhances general-purpose attitude determination methods are needed. Both narrow-field and wide-field star trackers are currently being used, and each has its special advantages. Out initial analysis indicates that a 10 degree field of view optical system would capture an average of 6 or more stars of suitable magnitude, and that this number is sufficient to produce the required reliability of star pattern recognition and accuracy. A particular pixel's value is a function of the light falling on the detector, offset values, shot noise, readout noise, background noise, fixed pattern noise, bright or dead pixels, random non-uniformities.

Active pixel arrays are fundamentally different from CCD arrays. AFRL has developed propriety methods for handling the fixed pattern noise and temporal noise in both active pixel sensors and our novel active pixel position sensors. Temporal noise sets a fundamental limit on image sensor performance, especially under low light illumination. In a CCD image sensor, temporal noise is well studied and characterized. It is primarily due to photodetector shot noise and the thermal and 1/f noise of the output charge to voltage amplifier. In Active pixel sensors several additional sources contribute to temporal noise, including the noise due to pixel reset, follower, and access transistors. The analysis is further complicated by the nonlinearity of the APS charge to voltage characteristics which is becoming more

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pronounced as the technology scales and the fact that the reset transistor operates below threshold for most of the reset time. AFRL has developed some innovative techniques for the star sensor to intelligent adapt automatically to whatever quality of image it encounters thus ensuring the Star sensor to be operating optimally. While constant brightness offsets are eliminated by the nature of the algorithms, varying noise intensities require compensation. We believe our innovative techniques will be able to enhance the noise tolerance. This enables the tracker to recover should it suddenly be exposed to a few frames of extreme visual noise generated by either electromaagnetic pulses or flying debris.

CONCLUDING REMARKS

In order to accelerate the evolution of faster, better, cheaper spacecraft, it is evident that greatly enhanced general-putpose attitude determination methods are needed. There is a clear need for lightweight, accurate, reliable, and inexpensive systems for spacecraft attitude estimatation. Star Trackers are one of the several competing devices used for on-orbit attitude determination.

Current state-of-the-art commercial star sensors typically weigh 15 pounds, attain 5 to 10 arc-second accuracy, and use roughly 10 watts of power. Unfortunately, the current state-of-the-art commercial star sensors do not meet many of NASA's "next-generation" spacecraft and instrument needs. Nor do they satisfy Air Force's needs for micro/nano-satellite systems.

We built a prototype Intelligent Star Tracker system using commerical off the shelf components. Figure 5 shows an image we obtained from a Matutov-Bouwers catadioptric telescope with a 7 degree field. We are in the process of modifying the design to yield a larger field of view (estimated to be greater than 12 degrees). For the image shown in figure 6, a Starlite CCD camera was used as the photodetertor array.

Figure 6. Image obtained form a Matsutov-Bowers Star Tracker with a 7 degree field of view.

The Air Force Research Laboratory (AFRL) and New Mexico State University (NMSU) propose to develop a low cost, miniature Intelligent Star Tracker for spacecraft attitude determination and navigation, incorporating adaptive optic catadioptric telescopes in a single, compact, robust Silicon Carbide housing. Leveraging off of our adaptive optic technologies developed in-house at AFRL, our Active Pixel Position Sensor (APPS) enables a wide dynamic range and allows simultaneous imaging of faint and bright stars in a single image frame. In addition, the three widely separated, wide field of view (FOV) catadioptric telescopes, each with its own array, enable high accuracy attitude and navigation measurements with minimal mounting bias errors. The folded adaptive optics telescopes using MEMs micro-mirrors enables extremely accurate tracking and when coupled with our star matching scheme based

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on algebraic coding theory, enables fast and accurate star pattern recognition and guidance, navigation, and control (GN&C). .The massively parallel processing architecture not only enables very high bandwidths, exceeding 40 Hz, but also enables tracking of at least 5 stars simultaneously. Moreover, the massively parallel architicture enables the star tracker to operate autonomously without burdening the spacecraft processor and may be used to supplement the on-board processors. Because our design utilizes technologies that inherently integrate together well and lend themselves to batch processing, we estimate that the IntelliStar will have a recurring cost less than $100k. In addition to low cost, preliminary analysis indicates that our Intelligent Star Tracker will have a pointing accuracy exceeding 0.20 arc-sec, NEA better than 0.10 arc-sec, power consumption less than 2 W and a weight of approximately 0.20 pounds.

ACNOWLEDEMENTS

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