Lightweight, Low-Power Coarse Star Tracker

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Abstract. General industry research on spacecraft attitude determination and control components is focused on increasing accuracy to the exclusion of all else. This is contrary to the clear requirement for decreased complexity, mass, and power consumption to fit the needs of small, maneuverable, low-cost spacecraft. To address this need, AeroAstro and the Massachusetts Institute of Technology Space Systems Laboratory are developing a coarse star tracker, which strikes an appropriate balance between accuracy, power consumption, mass and cost.

The coarse star tracker is targeted for small spacecraft, addressing requirements of a wide range of applications, including orbit transfer and rendezvous missions. This market is presently inadequately served, because higher accuracy star trackers simply do not fit within the mass, power, and cost constraints of small spacecraft missions. The design described herein is a 300-gram unit that consumes less than 1 Watt of power. With a pointing accuracy of better than 100 arc-seconds, the star tracker will enable a cost-effective three-axis stabilized spacecraft to attain pointing accuracies to better than 0.25 degree, more than adequate for most low-earth orbit (LEO) missions. The team is exploiting acquisition and tracking algorithm simplification and is developing ways to further reduce mass, power consumption, complexity and cost.

Introduction

Several years ago, AeroAstro began investigating microsatellite attitude determination components for missions with coarse pointing requirements. The small satellites investigated required extremely lightweight attitude determination components, with minimal power requirements, such that they can rely solely upon body-mounted solar panels or primary batteries for its mission. In addition to these constraints, most satellites required components capable of determining attitude from a cold-start, providing information to allow the spacecraft to perform tasked adjust maneuvers.

Sun sensors, earth limb sensors, and horizon crossing indicators are capable of determining attitude from a cold-start and can achieve combined accuracies of slightly better than 0.25 degree. However, several sensors in combination are required to attain this accuracy in three axes. This leads to increased complexity, mass and power consumption. Greater or similar accuracy from a single sensor currently requires the use of a heavy, power-hungry star tracker that is out of the reach of most small satellite budgets.

During this investigation, it quickly became apparent to AeroAstro that there was a market for a coarse star tracker – something less precise than the high-end star trackers, yet more capable than a sun sensor. A low-end star tracker, even with greatly reduced update rates and roll rates, could be a viable product but must provide attitude determination in an x,y,z earth-centered inertial (ECI) frame and interface easily with typical microsatellite command and data handling subsystems.

It also became evident that there was a growing trend within the U.S. Department of Defense (DoD) toward smaller and more capable space vehicle applications, which suffered the same lack of suitable small satellite components. The lack of low-mass, low-power components was limiting the development of small spacecraft. This problem was further compounded by the fact that innovations in component technologies typically need flight heritage prior to their use on such systems – something that is usually time consuming and expensive to achieve.

Many small satellite missions require attitude sensors that have an accuracy midway between the low-end

Figure 1. Comparison of Star Trackers on Price, Power Consumption, and Mass.

devices at 1 to 0.5 degree and technology's best performing star tracker at less than 10 arc-seconds, and at a cost only slightly greater than the coarse accuracy systems, somewhere in the $50k to $75K range. The coarse star tracker now under development at AeroAstro and the Massachusetts Institute of Technology (MIT) Space Systems Laboratory (SSL), funded by the Missile Defense Agency (MDA) through the DoD Small Business Technology Transfer (STTR) program, fills this gap, as shown in Figure 1, and supports MDA and other DoD organizations' small satellite programs.

Currently, AeroAstro and the MIT SSL are continuing development of the coarse star tracker, moving to refine the design through flight prototype hardware development, integration, and testing. The performance specifications for the coarse star tracker are shown in Table 1, and a simplified functional block diagram of the star tracker is shown in Figure 2.

The mass and volume constraints imposed on the coarse star tracker are a direct result of the low mass and volume requirements of small satellite systems themselves. In an effort to significantly reduce the mass and complexity of the coarse star tracker, one of the key innovations investigated is the use of a pinhole lens as an alternative to traditional, heavy lenses.

Table 1. Star Tracker Performance Specifications.

Specification	Performance
Field of View	~30 degrees (conical)
Accuracy	< 100 arc-seconds
Roll Rate (Minimum with Above Accuracy)	0.3 degree/sec
Update Rate	1 Hz
Mass	300 grams
Power	< 1 Watt @ 5.5 VDC
Dimensions	5.1cm x 7.6cm x 7.6cm
Volume	300 cm^3
Output	x, y, z ECI frame
Limiting Star Magnitude	4th
Star Pairs Tracked Simultaneously	Maximum of 4
Interface	RS-422

The coarse star tracker being developed is a shift away from the industry trend toward increasing star tracker attitude determination accuracy to the exclusion of all

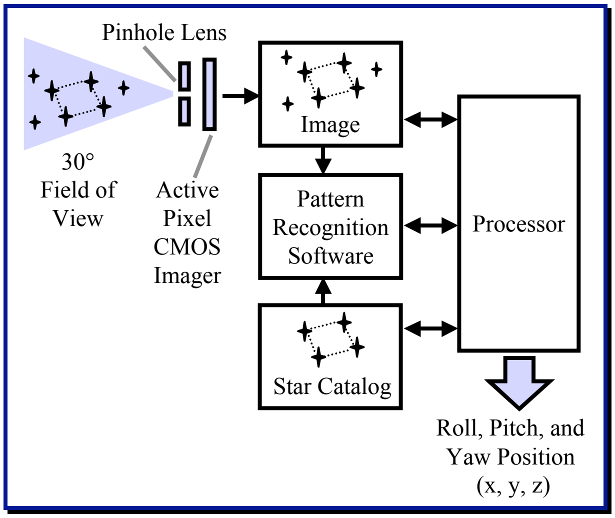


Figure 2. Simplified Functional Block Diagram.

other considerations. Current star tracker development is focused on rapid pattern recognition, widening fields of view to process many stars and star patterns simultaneously, and expanding internal star catalogs to well over 20,000 stars ranging from 0th to 6th magnitude. While these advances make for very capable systems, the penalty to the satellite is a substantial increase in size, mass, power, complexity, and expense. For small satellites, some of which are designed to simply provide on-orbit demonstration of space technologies, this is contrary to the requirement for decreases in these metrics. The coarse star tracker is, very simply, designed to provide acceptable accuracy at an affordable price, not as competition for the higher end star tracker market.

Star Identification Algorithms

As seen in Figure 2, the operation of the coarse star tracker is similar to larger, more expensive star trackers. The algorithms that are employed, however, are much leaner in terms of computation requirements. The star pair match group algorithm used in the coarse star tracker actively seeks to reduce the quantity of stars considered in a wide field of view (FOV) image for an attitude solution relying primarily on about five stars. This, in turn, limits the catalog size to the brightest stars in any given region of the sky and considers only the brighter stars for the solution.

By stripping away unneeded operations, our approach vastly reduces the operations the microprocessor unit (MPU) has to step through in order to achieve a quick attitude solution. Although using a wide-FOV identification method limits the overall accuracy of our design, it improves acquisition speed and reduces power consumption while still achieving a pointing accuracy of 70 to 100 arc-seconds, compared to higher-end star trackers with a pointing accuracy of 10 arc-seconds or less.

By relying only on magnitude 4 stars and brighter, the exposure times of the imager can be shortened while still maintaining an adequate signal-to-noise ratio between imaged stars and the imager background. Thus, a lower imager frame rate can be maintained, further minimizing power consumption, while meeting the attitude solution rate goal of once per second.

A useful item regarding the accuracy of the star tracker was found in a paper by Birnbaum.[1] It gives a rule of thumb for the accuracy improvement in using more than two stars to perform a least squares fit to obtain an attitude determination. The error of the attitude estimate improves with the number of stars used,

$$Optical\ \ axis\ \ attitude\ \ error = \frac{Error\ \ of\ \ 1\ \ star\ \ measurement}{\sqrt{Number\ \ of\ \ stars\ \ matched}} \qquad (1)$$

This is significant, in that even if the star tracker pixel accuracy is on the order of 100 arc-seconds, the attitude determination will be on average much better than this due to multiple stars being imaged. Thus, the decrease in pixel accuracy from increasing the FOV to 30 degrees to guarantee more stars in the FOV would be countered by the benefit of identifying more stars.

Further background research has uncovered an additional promising identification method – a gridded, pattern recognition approach. In contrast to a star pair or star triangle algorithm, the identification is done by what is essentially an image comparison. Using a clever method to simplify the star field into a coarse bit map, it compares the pattern of stars observed to a catalog of stored patterns. The advantages, as detailed in Padgett, are a decrease in the star identification time of two orders of magnitude and an increase in the reliability of the algorithm to inaccuracies and false stars.[2]

The grid algorithm requires enough stars in the FOV to produce a unique pattern. There is some question as to the effectiveness of this approach when the number of stars in the FOV is limited, as for very short exposures. The applicability of this gridded technique is being evaluated as an alternative for the coarse star tracker.

Roll Rate Limitations

The roll rate limitations for the coarse star tracker have been resolved and show that substantial spacecraft roll can be tolerated, as much as 3 degrees per second for a 30 degree FOV star tracker. Furthermore, it appears that larger images (3-10 pixels across) help increase the roll tolerance of the sensor. The pinhole places more severe limitations on roll rate tolerance in comparison to the use of lenses. The basic relationship for roll can be found by considering the image spot from a lens or pinhole being smeared by a spacecraft roll.

A star tracker experiencing no roll would image stars as quasi-circular patterns. Some distortion occurs at the edges of the array, so stars would appear elliptical. Pinhole optics operating in the geometrical regime would produce images of approximately uniform intensity, while a lens and focused pinhole would produce an image with a more intense central region. As roll increases, the circles become stretched into blobs, as shown in Figure 3. Now the left and right portions of the image become less intense, since the pixels in those regions are not exposed for the full exposure.

If, due to a low signal-to-noie ratio, a star is on the verge of being detected as a circle, a pixel would have to collect light for the full exposure to be considered as part of a star. Thus, as the roll increases, a limiting condition occurs when the image circles at the beginning and the end of an exposure are still touching, as shown in Figure 3. This limiting condition provides a measure of maximum tolerable roll rate as a function of the exposure time (or update rate) and the image size (diameter), where the image size is the region of the bright central peak.

$$Roll\ \ rate,\ \dot{r}\ =\ \frac{image\ \ size,\ i}{time,\ t}\ =\ Update\ \ rate\ (Hz)\bullet i \tag{2}$$

To find the update rate, the imager characteristics must be considered. Many Complementary Metal-Oxide-Semiconductor (CMOS) chips are very similar in size and capability, with notable exceptions being the logarithmic response chips, which have continuous output capability and enhanced range, as opposed to a standard integrating-type chip, which collects a signal over a given time period. Especially if a pinhole optic is used, the integrating chips are the correct choice for the low-intensity condition of star imaging.

The baseline chip for the coarse star tracker is the IBIS4 from Fillfactory.[3] It is 1280 x 1024 pixels, each 7 micrometers square, features on-board analog-to-digital conversion, quantum efficiency of greater than 50%, and a high fill factor of approximately 60%. Analytical predictions of the signal-to-noise ratio find that at 1 Hz, magnitude 4 stars should be visible in an IBIS4-type CMOS imager. This is backed up experimentally,

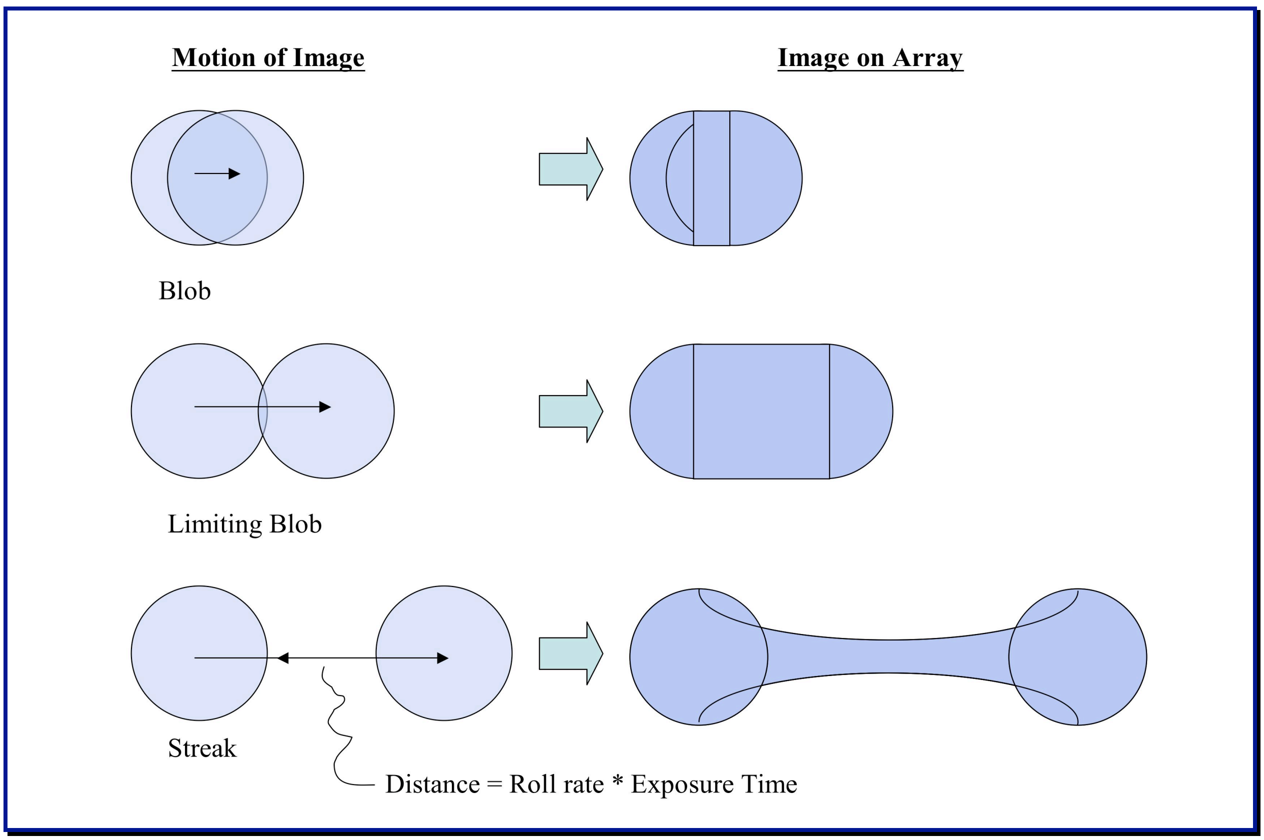


Figure 3. Affect of Roll on Image Produced on CMOS Array.

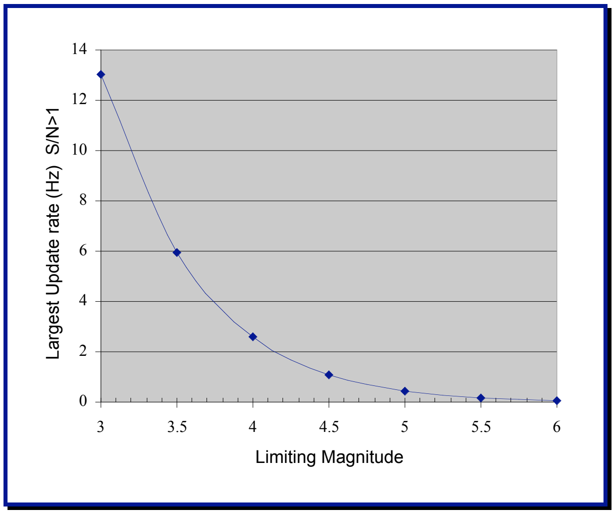


Figure 4. Largest Acceptable Update Rate vs. Limiting Stellar Magnitude.

where images show that magnitude 4 stars can be resolved adequately with a 1 Hz update rate and a 30 degree FOV on an IBIS4-type CMOS imager, which should allow a reliable star pair algorithm to succeed.

Using the IBIS4 characteristics and a limiting signal-to-noise ratio of 1, the fastest possible update rate to image a star of a particular magnitude can be found, as shown in Figure 4. For a given image size of 1000 arc-seconds, corresponding to 10 pixels, the limiting roll rate can be calculated for a given magnitude star by using the maximum update rate as given in Figure 5.

Further, if a bright star is allowed to move so much across the imager as to produce a streak, as was shown in Figure 3, the intensity of the affected pixels will be less than would be expected for a full exposure. The reduction in exposure time means that bright stars would be imaged as less intense streaks. The intensity

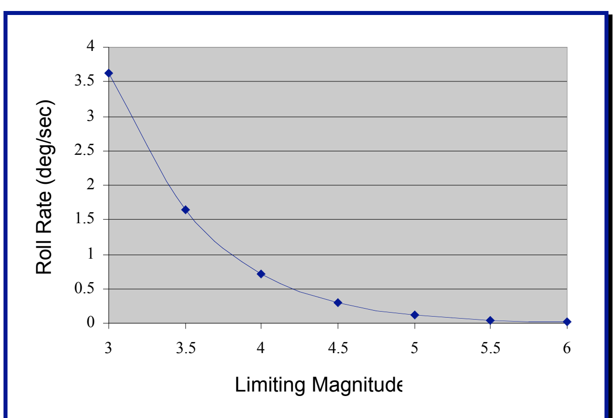


Figure 5. Limiting Roll Rate for a Corresponding Stellar Magnitude.

reduction eventually would result in that star becoming so dim that none of the streak's pixels would have a signal-to-noise ratio greater than 1. The intensity reduction is given by:

$$\frac{I_{rolling}}{I_{no\ roll}} = \frac{iU}{\dot{r}} \tag{3}$$

Figure 6 shows how a bright star can be resolved at higher roll rates as a streak in comparison to dimmer stars at given update rates. This is important, since the update rate will be somewhat fixed at slower update rates in order to image dim stars, and bright stars will show up as streaks. In the figure, for a given update rate, the brighter stars can handle higher roll rates.

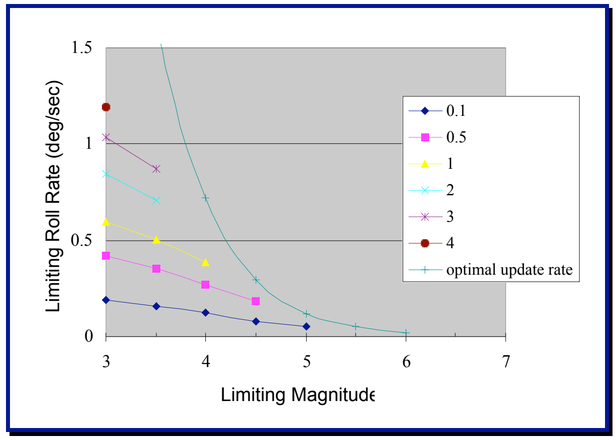


Figure 6. Roll Rate Increases from Use of Bright, Streaked Stars with Fixed Update Rates.

Already, one can see that the coarse star tracker design provides a considerable roll capability. The effect of a lens over a pinhole would be to increase the intensity of light on the pixels, which would greatly increase the fastest allowable update rate. Thus, a lens would tolerate faster roll rates by operating at these faster update rates.

Another interesting possibility is that the star tracker could be used as a crude roll sensor. The simple approach is to look at two subsequent attitude fixes finding the roll rate. An intriguing option would be to intentionally allow the star images to become streaks, and measure those streaks in order to find the roll. This technique has been implemented in the Italian FAST project.[4] This is an interesting possibility, but not within the specifications for the initial star tracker being developed by AeroAstro and the MIT SSL.

Instrument Definition

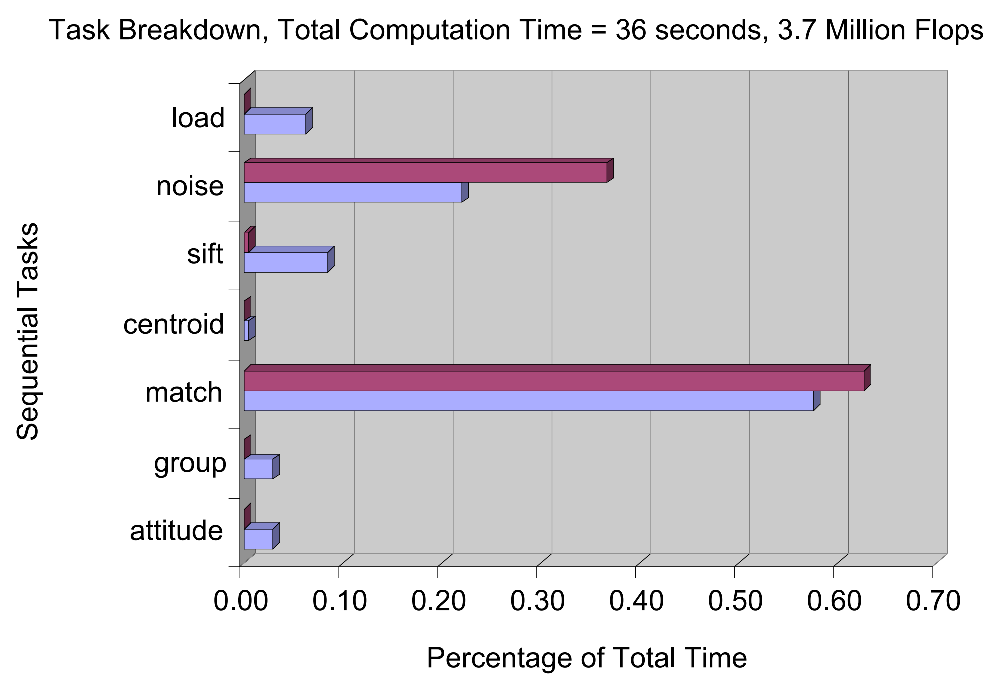
Work to date suggests that the power goal of less than 1 Watt is achievable. Even though at this time, a firm estimate of the amount of imager/MPU logic that will be required is not known, judging from the interface presently supplied on the IBIS4 evaluation board and that supplied for high-speed interface on most of the SH7065 commercial off-the-shelf developmental boards presently available on the market, we feel confident the quantity or power requirements for the amount of logic that would be required will not exceed our goal and the power consumption of the final design will remain at approximately 0.7 Watts. Footprint growth of imager/MPU logic is still well within expectation for the coarse star tracker. At the present time, the only growth not precisely accounted for is providing for the large pad count both on the MPU and imager, but this too has been roughly taken into account. Thus, based on the imager and MPU developmental boards and the application of five-layer printed circuit boards, it is anticipated that the desired dimensions can be achieved.

Table 2 shows the breakdown of mass and power by component for the baseline star tracker design.

Table 2. Component Breakdown of Mass & Power.

Component	Mass (grams)	Power (Watts)
MPU	40	0.285
Imager	80	0.430
Housing	120	0
Pinhole Aperture	35	0
Total	295	0.715

High-level processor requirements were examined. In order to enumerate the processing requirements for the algorithm as it is developed to date, the running time in the Matlab programming environment and the floating point operation count were analyzed for each task in the star pair algorithm operating an a 330K pixel test image obtained from CMOS ground observations. The results are shown below in Figure 7.



	attitude	group	match	centroid	sift	noise	load
flops (% of 3.7 Million Flops)	0.00	0.00	0.63	0.00	0.00	0.37	0.00
time (% of 36 sec)	0.03	0.03	0.58	0.00	0.08	0.22	0.06

Figure 7. Computation Requirements of each Task in Time and Flops.

One can see that the noise correction and matching routines account for the bulk of the processing effort. The total processing effort for 330K pixel image amounted to 3.7 Million floating point operations. This is well below the baseline Hitachi processor capability of 78 MIPs. Baseline images will be somewhat larger, on the order of 1 million pixels, but this will not greatly affect the match time, although it will affect the noise correction. In addition, the above simulation was carried out with a larger catalog (1140 stars) than is envisioned for the final product (~600). Still, the noise correction operation is linear with pixel count, and the total computations should be well within the processor capabilities. The code currently executes without regard for fixed point vs. floating point operations. The computation should be easily adapted to complete fixed point operation, allowing for faster operation.

Several schemes for the further reduction of the star tracker's overall power consumption have been considered. These mainly consist of reducing or economizing on the quantity of MPU operations and the selection of the MPU itself. Some of these schemes could contribute further to the reduction in the star tracker's power consumption. Among those that will receive further consideration in future work include:

- **More efficient grid algorithm –** This has the potential to greatly reduce the processor power draw by a factor of 10.
- **Keeping the star catalog as small as possible –** This is important because of the non-linear scaling for match group algorithms processing requirements with catalog size. The grid algorithm scales linearly, however, with catalog size.
- **Reduced update rate –** By reducing the update rate from 1 Hz to 0.5 Hz, the average power draw on the processor could be reduced by a factor of 2. However, this may adversely affects the ability of the star tracker to achieve its mission requirements, so this trade needs to be investigated further. Another option is to have an update rate tailored to the available power.
- **Implement a tracking mode –** A tracking mode would help to alleviate the processor load from the matching routine, but would increase the software complexity and logic.

Most of the required power savings identified to date have been in the form of lower duty cycles on the imager and processor circuitry. One other solution that may both reduce MPU operation and contribute significantly to power consumption reduction is the application of a grid algorithm rather than the pattern recognition methods explored to date. The gridded algorithm offers a significantly improved probability of acquisition and significantly reduces the active memory required of the star catalog. However, this gain comes at a cost in algorithm complexity.[2] This option has not been fully explored, and during the next phase of work, our plan is to implement and model the grid algorithm to determine if this method is preferable to the pattern recognition approach.

Conclusions and Future Objectives

AeroAstro and the MIT SSL are developing a coarse star tracker that serves a presently unserved attitude determination need of small spacecraft. This star tracker will have a mass of less than 300 grams, dimensions less than 5.1cm x 7.6cm x 7.6cm and consume 1 Watt or less of power.

Our work to date has brought the coarse star tracker from concept to a preliminary design. The design has been modeled, and its operation and dynamic ability have been verified. The team is moving toward implementing the star tracker design in a testbed star configuration. This will allow further refinement of star tracker hardware design to minimize the circuitry and power consumption in the imager and MPU. The testbed will also serve to optimize the star tracking algorithms and verify its performance through simulated and sky conditions. It is anticipated that fabrication of a proto-flight model of the coarse star tracker will be complete in mid-2004.

Acknowledgements

This material is based upon work supported by the Dahlgren Division, Naval Surface Warfare Center, under Contract No. N00178-02-C-3125.

The authors wish to thank the Missile Defense Agency and the DoD SBIR/STTR Program for their support of the Phase I contract under which this work was conducted. We especially thank Dr. Erwin Myrick and Mr. Marc Wigdor, both of the MDA, for their consideration and support.

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