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A Stellar Gyroscope for Small Satellite Attitude Determination

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ABSTRACT

A stellar gyroscope is a star based attitude propagator that is capable of propagating a spacecraft's attitude in three degrees of freedom by tracking the motion of the stars in an imager's field of view. The modeling and algorithm development has been done by the Space Systems Laboratory at the University of Kentucky. This paper discusses a realization of the stellar gyroscope concept on a CubeSat attitude determination and control system (ADCS) designed by SSBV Space & Ground Systems UK. The stellar gyroscope can be used to measure attitude changes from a known initial condition without drift while sufficient stars are common across frames, because absolute attitude changes are measured and not angular rates. Algorithms to perform the star detection, correspondence, and attitude propagation are presented in this paper. The Random Sample Consensus (RANSAC) approach is applied to the correspondence problem which is challenging due to spurious false-star detections, missed stars, stars leaving the field of view, and new stars entering the field of view. The CubeSat attitude determination and control system described in this paper uses a stellar gyroscope, implemented using inexpensive optics and sensor, to augment a MEMS gyroscope attitude propagation algorithm to minimize drift in the absence of an absolute attitude sensor. The MEMS device provides the high frequency measurement updates required by the control system, and the stellar gyroscope, at a lower update rate, resets the drift accumulated in the MEMS inertial gyroscope integrator. This in effect could allow sun-sensing satellites to maintain a high quality attitude estimate in eclipse, where the sun sensors can no longer contribute in absolute attitude estimates. This paper describes an algorithm to solve the relative attitude problem by identifying the change in attitude between two star field images. RANSAC is applied to solve the correspondence problem in the presence of false star detections and misses. The camera and attitude determination and control system are described, prototype hardware is used to generate night-sky datasets of known attitude changes to demonstrate the performance of the algorithm, and a simulation is developed to evaluate the stellar gyroscope's ability in limiting the drift of an attitude propagator based on MEMS gyroscope rates. The CubeSat ADCS system developed by SSBV is an experiment on TechDemoSat-1, to be launched in early 2013.

INTRODUCTION

SSBV Space & Ground Systems UK is developing a modular CubeSat Attitude Determination and Control solution. To support a high accuracy attitude controller, attitude knowledge must be of high accuracy as well. The design goal of the system was to address that problem and maintain a high quality attitude estimate throughout the orbit, including eclipse. The sun and magnetic field vectors can be used to find attitude estimates, along with rate gyroscopes to filter and improve the attitude estimate. However, maintaining attitude knowledge in eclipse, in the absence of the sun vector measurement, is challenging and is often addressed by propagating rate information from the rate gyroscopes at the cost of drift. In order to maintain a high quality attitude estimate in eclipse, two current alternatives are employed. A star tracker/mapper can be used to identify star constellations and retrieve absolute attitude. However, star trackers add cost and complexity requiring a star database, high update rates, and consequently high quality optics, sensors and a baffle. The second method is to use an Earth horizon sensor. For the sensor to work in eclipse, the infra-red (IR) spectrum corresponding to the H2O absorption bands is used [1]. This typically requires a specialized IR sensor, a detector cooling system, or a chopping or rotation mechanism to generate differential readings of the Earth and space temperatures. Such a system requires significant power and the mechanical systems have reliability concerns. The units tend to be physically large and need to be mounted on the nadir face which is already a scarce resource due to communications antennae and Earth observation payloads. The alternative, used in the design described in this paper, is to use a stellar gyroscope, as a relative attitude sensor, to reset the drift from the rate gyroscope propagation in eclipse [2,3]. The stellar gyroscope can be realized using low cost sensor and optics, where the algorithms can tolerate a large amount of noise, and does not require a star database.

The stellar gyroscope can be used to propagate a spacecraft's attitude from a known initial condition without drift. Normally, in the absence of an absolute attitude measurement, attitude is propagated by integrating gyroscope angular rate data (typically MEMS based for small satellites). This results in a drift in the attitude estimate, which is essentially a loss of attitude knowledge after a sufficient amount of time. The image based approach can propagate attitude without drift while sufficient stars are common across frames [2,3]. As the camera pans the sky, after sufficient time all the stars may leave the frame. In that case, some error accumulates as rotation estimates are stacked. However, this happens over a significantly longer period of time compared to a MEMS rate integrator. The image-based rotation estimates can complement a set of MEMS rate gyroscopes to maintain a high accuracy attitude estimate at low angular rates (where MEMS gyroscope drift is most severe).

For the stellar gyroscope, the star correspondence problem across frames is challenging due to spurious false-star detections (false-positives) and missed stars (false-negatives). Correspondence of stars across frames can be done with limited success by proximity for small angular changes, where for short time intervals, the stars are assumed to not have moved much. However, for large attitude changes, the star association algorithm between frames must overcome false stars, missed stars, stars leaving the field of view and new stars entering the field of view. The problem is essentially to fit a mathematical model over data with a large number of outliers, for which the Random Sample Consensus (RANSAC) approach is effective [4,5]. RANSAC is a popular algorithm in machine vision and stereo vision, and has been proposed for satellite based image registration for geographic applications [6].

This paper describes a CubeSat Attitude Determination and Control system that utilizes a stellar gyroscope to enhance its attitude estimate. The system is overviewed and the stellar gyroscope hardware and algorithms are described in detail. Prototype hardware of the camera system is used to collect star field images of the night sky to validate the algorithms and a simulation shows the expected attitude determination accuracy in eclipse.

RELATED WORK

Research by Liebe et al. from the NASA Jet Propulsion Laboratory (JPL) studies the feasibility of using a stellar gyroscope to estimate high rotation rates [7]. The basis of operation depends on a single long-exposure image of the star field and then analyzing the circular arcs caused by the stars' motion. The concept is optimized for high rotation rates outside regular gyroscope operation ranges, and with the single-exposure method results in a noisy image even for a high quality sensor. The research by JPL, despite the difference in scope, presents the concept of inferring the rotation rate and spin rate from the star streaks. The approach in this paper adopts the idea while eliminating the requirement of taking long exposure images (with very low Signal to Noise Ratio) by taking a sequence of snap shots and effectively processing a "video" instead of a single long-exposure image.

Star Trackers/Mappers are traditionally attitude determination systems carrying star catalogs that are used to identify star constellations in order to calculate the spacecraft's attitude in inertial space. Recent research efforts have been focused on improving the hardware and search algorithms of star trackers to increase the update rates to a level where the angular rates can be approximated. Such a high update rate star tracker is sometimes referred to as a Stellar Gyroscope [8]. Another effort to estimate the angular rate of a satellite using star sensors implements a Kalman filter that models the environmental torques as a random process and depends on the absolute attitude measurements of a high update rate star tracker [9]. The work in this paper aims to eliminate the need of absolute attitude measurement and a complicated star identification algorithm for attitude propagation.

In previous work on the stellar gyroscope concept and the University of Kentucky [2,3], the concept is described, the camera model is developed, and solutions for star detection, star correspondence, and the relative attitude determination problem are discussed. As well as evaluating the performance on simulated images and photos of the night sky. This paper takes the concepts and algorithms developed to integrate a stellar gyroscope onto a CubeSat attitude determination and control system.

ATTITUDE DETERMINATION AND CONTROL SYSTEM

The attitude determination and control system is designed for CubeSats on a standard PC104 board [10]. In its basic configuration, it integrates a high sensitivity magnetometer, up to 6 sun sensors, 3 axis MEMS gyroscopes, and 3 magnetic torque rods as a 3-axis magnetic attitude control system. In its full configuration for improved attitude knowledge and pointing accuracy, a GPS receiver, a stellar gyroscope and an ADCS control computer are added on a daughter board, still within the PC104 height constraints. A momentum wheel or three reaction wheels can be added from a third party supplier.

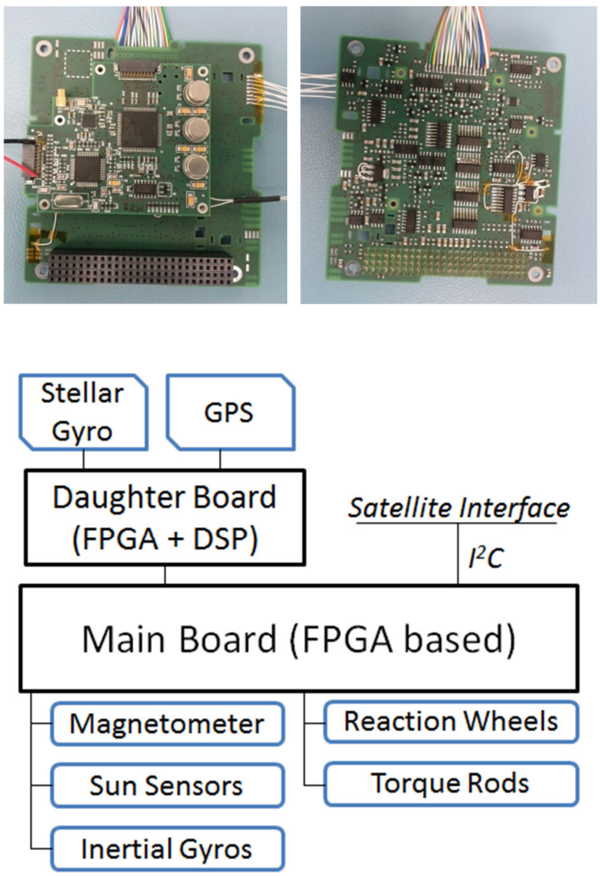

Figure 1: Top: photos of the CubeSat ADCS board of both faces with daughterboard installed (prototype hardware with test connectors). Bottom: block diagram of the overall system.

As mentioned earlier, the stellar gyroscope complements the MEMS rate gyroscopes in eclipse to maintain an accurate estimate of attitude. However, in order to benefit from accurate propagation in eclipse, accurate knowledge in sunlight is necessary. The system utilizes sun sensors accurate within 0.5 degrees developed by SSBV, as well as a high-accuracy magnetometer that produces magnetic field vector measurements to around 1 degree of accuracy in combination with an IGRF magnetic model and good knowledge of the position in orbit, which is provided by the GPS receiver. This combination results in a high quality estimate of attitude in sunlight.

Figure 2 shows the camera system and ADCS system as designed for the technology demonstration experiment on TechDemoSat-1 [11]. The experiment will take sample images and log other sensor data to tune and validate the attitude determination algorithms.

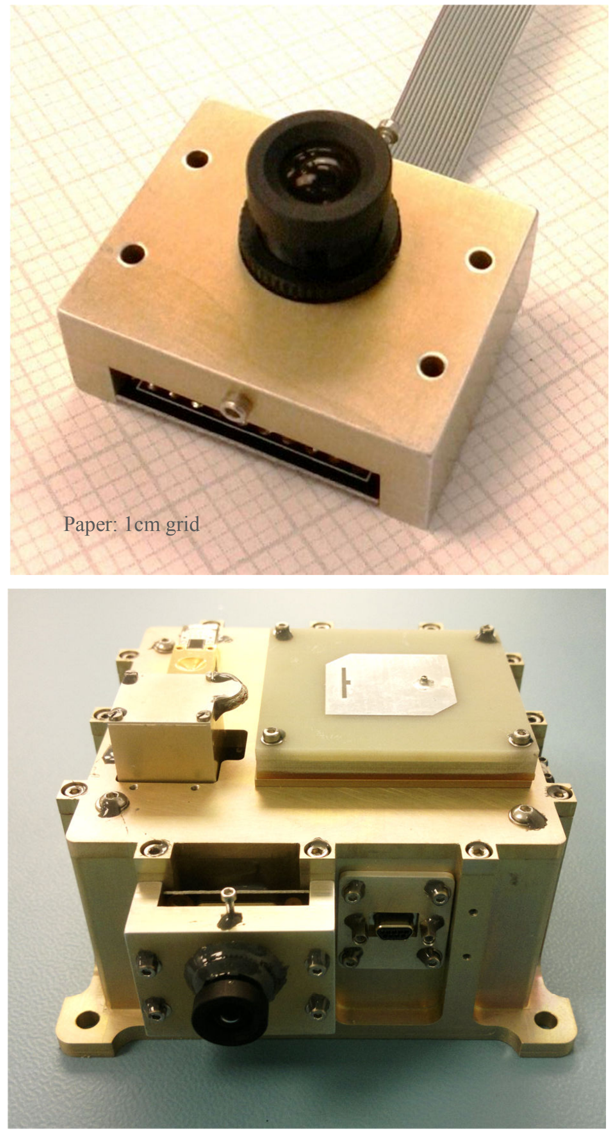

Figure 2: Camera assembly and SSBV CubeSat ADCS experiment on TechDemoSat-1.

STELLAR GYROSCOPE CAMERA SYSTEM

The stellar gyroscope on this ADCS system consists of a low-cost camera assembly and processing hardware and is designed to require little mass and volume. The camera is based on the OmniVision OV7725 VGA CMOS sensor and a miniature S-mount lens with a focal length of 6mm. This configuration results in a 27.6° by 36.7° field of view. Table 1 summarizes the camera specifications. As it is only to be used in eclipse in this application it is not required to operate in sun light and does not need a baffle.

The camera is designed to register stars of magnitude 4 and brighter. With the selected optics, field of view, and an exposure time of 800 ms, at least 4 stars are visible in 97% of the sky, and at least 3 stars are visible in 99% of the sky.

Table 1: Summary of Stellar Gyroscope CubeSat Hardware

Parameter	Value
Sensor	OmniVision OV7725 CMOS VGA Sensor (640 x 480 pixels)
Optics	6 mm focal length, Aperture F/2.0
Field of View	27.6° by 36.7°
Sensitivity	3.8 V/(Lux · s)
S/N Ratio	50 dB
Dark Current	40 mV/s
Pixel Size	6 x 6 µm

In future developments, in order to tolerate higher slew rates and improve image quality, we will replace the optics to be able to significantly reduce the exposure time by increasing the aperture. Preliminary analysis shows that slew rates up to 3 degrees/second are feasible with the improved configuration. At higher slew rates, the system uses the MEMS rate gyroscopes as they become more reliable.

STELLAR GYROSCOPE ALGORITHM

The camera modeling and star detection algorithm are discussed in detail in previous work [2]. The stellar gyroscope operation begins by detecting stars and calculating the unit vectors associated with the stars originating from the spacecraft pointing towards the stars, defined in body-fixed coordinates. The changes of these vectors are tracked and used to infer the rotation changes between frames. An ideal pinhole camera model is used where a shell of the celestial sphere is mapped onto the camera's sensor. A single star affects multiple pixels on the sensor as shown for in Figure 3. Sub-pixel resolution is achieved with a centroiding algorithm. The star location is found by first thresholding the noise to ensure that the noise values will not contribute to the expectation, then calculating the expected value of the star pixels. Figure 3 shows a star cross section to illustrate this process.

Rotation estimation can be thought of as a relative attitude determination problem, where the relative attitude between two star field images is being calculated. As a problem with 3 degrees of freedom, there are 3 unknowns and at least 3 pieces of information are required to provide an estimate. Each star/vector provides two pieces of information (with the orthogonality constraint), therefore, at least 2 stars are required to generate an estimate, and it's an over determined problem for which a statistical approach is effective.

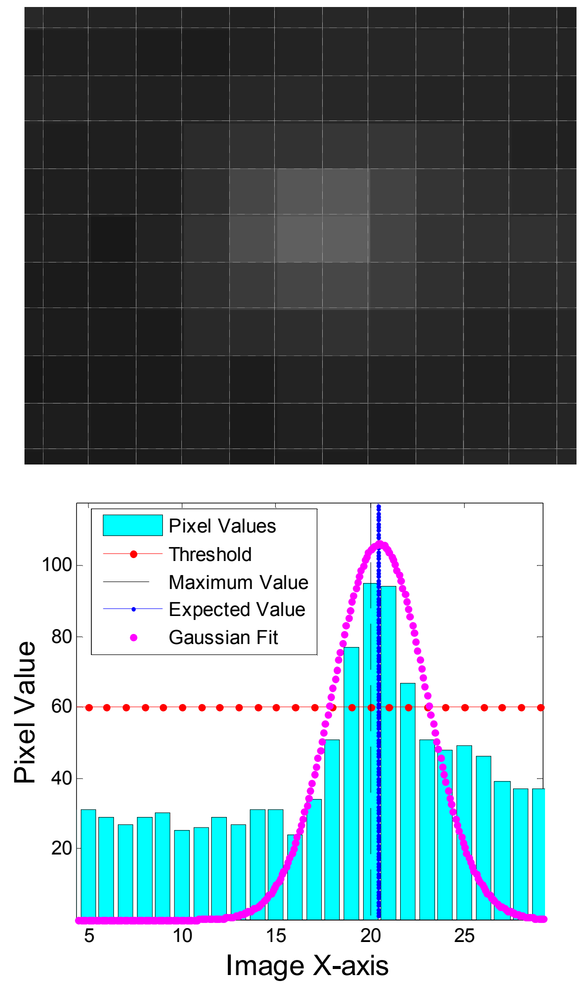

Figure 3: Top: zoomed in photograph of a star (Gamma Ursae Majoris) using the designed camera. Bottom: an illustration of one-dimentional centroiding of the star cross section to obtain sub-pixel resolution.

For this discussion, the Direction Cosine Matrix is used for attitude representation. For example, the rotation between frame a and frame b for a star represented by the vector $\vec{\mathbf{v}}$ is given by:

$$\overrightarrow{\mathbf{v}^{b}} = C^{ba}\,\overrightarrow{\mathbf{v}^{a}}$$

$$\overrightarrow{\mathbf{v^b}} = \begin{bmatrix} \mathbf{C_{11}} & \mathbf{C_{12}} & \mathbf{C_{13}} \\ \mathbf{C_{21}} & \mathbf{C_{22}} & \mathbf{C_{23}} \\ \mathbf{C_{31}} & \mathbf{C_{32}} & \mathbf{C_{33}} \end{bmatrix} \overrightarrow{\mathbf{v^a}}$$

where $\overrightarrow{\mathbf{v^\iota}}$ and $\overrightarrow{\mathbf{v^b}}$ are the unit vectors pointing at the same star in two image frames in body-fixed coordinates. The matrix $\boldsymbol{C^{ba}}$ hence defines the camera attitude change between those two frames.

Given at least two measured vector pairs across frames a and b, $\boldsymbol{C^{ba}}$ can be estimated using the q-method which minimizes the sum of the square errors of all vector pairs [12]. This error can be represented by the following cost function for L vector measurements:

$$J(\mathbf{C}^{ba}) = \sum_{k=1}^{L} w_k \left|\mathbf{v}_k^{\boldsymbol{b}} - \mathbf{C}^{ba}\,\mathbf{v}_k^{\boldsymbol{a}}\right|^2$$

where $\mathbf{v}_k^{\boldsymbol{b}}$ are the vectors in frame b, and $\mathbf{v}_k^{\boldsymbol{a}}$ are the corresponding vectors in frame a. The quantity $\mathbf{v}_k^{\boldsymbol{b}} - \mathbf{C}^{ba}\,\mathbf{v}_k^{\boldsymbol{a}}$ for a certain value of k (one pair of vectors) represents the rotation of the vector from frame a to frame b, and subtracting it from the corresponding vector in frame b, resulting in the error vector to be minimized by finding the optimal value of $\mathbf{C}^{ba}$. w_k is a weighing factor to assign relative measurement quality to individual vector pairs. Because all measurements are being made with the same sensor, this value is set to be a constant for the work in this paper.

The q-method is an analytical solution for the minimization of the cost function $J(\mathbf{C}^{ba})$. This is done by representing the rotation matrix by the attitude quaternion. The literature describes the derivation and restating of the minimization problem of the cost function with the following maximization problem of the gain function in quaternion form [12]:

$$J'(\mathbf{q}) = \mathbf{q^T}\,\mathbf{K}\,\mathbf{q}$$

where

$\mathbf{q}$ is the attitude quaternion

$$\mathbf{K} = \begin{bmatrix} \mathbf{S} - \sigma\mathbf{I} & \mathbf{Z} \\ \mathbf{Z^T} & \sigma \end{bmatrix}$$

$$\mathbf{B} = \textstyle\sum_{k=1}^{N} w_k (\mathbf{v}_k^{\boldsymbol{b}}\,\mathbf{v}_k^{\boldsymbol{a}\mathbf{T}})$$

$$\mathbf{S} = \mathbf{B} + \mathbf{B^T}$$

$$\mathbf{Z} = [\mathrm{B}_{23} - \mathrm{B}_{32},\ \mathrm{B}_{31} - \mathrm{B}_{13},\ \mathrm{B}_{12} - \mathrm{B}_{21}]$$

$$\sigma = \mathrm{tr}[\mathbf{B}]$$

The solution is shown to be, using Lagrange multipliers [12], a quaternion that is the eigenvector of $\mathbf{K}$ of the largest eigenvalue. The quaternion is next converted to its equivalent rotation matrix $\mathbf{C}^{ba}$ [13]**.** To simplify the notation in the remainder of the paper, the q-method will be referred to with the following operator that returns the optimal estimate of $\mathbf{C}^{ba}$ given two sets of vectors in frames a and b.

$$\mathbf{C}^{ba} = q\mathrm{method}\,([\mathbf{v}_1^b\ \mathbf{v}_2^b \ldots \mathbf{v}_L^b], [\mathbf{v}_1^a\ \mathbf{v}_2^a \ldots \mathbf{v}_L^a])$$

We note that the solution requires solving the Eigenvalue and Eigenvector problems for a 4x4 matrix, which is computationally expensive. There are several available approximations and optimazitations in the literature. The number of times required to solve for a quaternion will be used as a measure of computational cost for different algorithm implementations.

CORRESPONDENCE BY RANDOM SAMPLE CONSENSUS

As it can be seen in Figure 4, the data collected (using the low cost sensor and optics) and expected on orbit contains false stars and missed stars. In addition, stars entering and leaving the field of view will appear in one frame and not the other of the two frames being analyzed. It was also noticed that hot pixels appear as stars in both frames, and suggest that the satellite did not move. These challenges set the requirement of a robust algorithm that is not sensitive to these errors. Random Sample Consensus (RANSAC) is an iterative method to estimate parameters of a mathematical model from a set of observed data which is contaminated by a large number of outliers that do not fit the model [4]. The steps of RANSAC can be summarized as [14]:

1. Hypothesize: A Minimum Sample Set (MSS) is randomly selected from the input data and the model parameters (in this paper's implementation: the rotation matrix) are computed using only that randomly selected set.
2. Test: The model generated in the first step is tested against the entire dataset. The data that shows consensus, to some measurement of deviation, are counted towards the Consensus Set (CS).
3. Iterate: RANSAC iterates between the above two steps until a random hypothesis finds "enough" consensus to some selected threshold.

We investigated the implementation and evaluation of RANSAC for the stellar gyroscope problem in previous work [2]. Two different implementations for the hypothesis step were created: one that pairs stars across images in a completely random manner, and another that paired stars by proximity, specifically by randomly selecting stars in the first frame, then randomly paring it with one of the nearest two stars to its location. In this paper, we present a new approach that pairs stars by brightness. We also present an improvement on the hypothesis test step to reduce its computational cost.

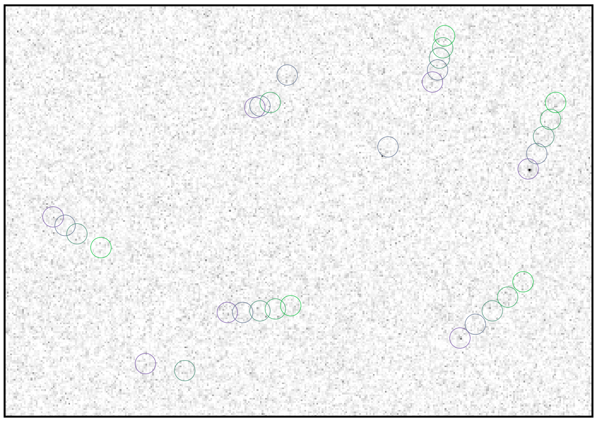

Figure 4: Star field image overlaid by star detections in 5 consecutive frames, with a 3 degree rotation between each frame. This figure illustrates the tracking challenge where the data consists of reliable stars, false positives, and false negatives. Colors are adjusted for clarity.

In order to adopt RANSAC for the relative attitude determination problem several elements had to be identified, namely the mathematical model to generate the hypothesis, a test process to evaluate the model's fitness against the entire dataset, and finally, a measure of error to determine consensus.

First, the mathematical model is the rotation matrix that is generated using the q-method described earlier. We recall that two stars are required as the minimum set. For *M* detected stars in first frame and *N* stars in second frame, to generate the hypothesis we randomly select $[\mathbf{v}_{H1}^{a}\ \mathbf{v}_{H2}^{a}]$ as two stars in frame *a* and $[\mathbf{v}_{H1}^{b}\ \mathbf{v}_{H2}^{b}]$ as two stars from frame *b*. A hypothesis rotation matrix is generated using the randomly selected pair.

$$\mathbf{C}_{Hypothesis}^{ba} = q\text{method}\left([\mathbf{v}_{H1}^{b}\ \mathbf{v}_{H2}^{b}], [\mathbf{v}_{H1}^{a}\ \mathbf{v}_{H2}^{a}]\right)$$

Second, the hypothesis is tested against all stars in the first frame and all stars in the second frame (total of M×N iterations). In previous work, we used a hypothesis test that used the q-method with every test pair and compared the resulting rotation matrix with the hypothesized matrix, where similarity counted towards consensus. A less computationally expensive approach is to test each pair the hypothesized rotation matrix by calculating an error vector as follows:

$$\overrightarrow{\mathbf{v}_{error}} = \overrightarrow{\mathbf{v}^{b}} - \mathbf{C}_{Hypothesis}^{ba}\,\overrightarrow{\mathbf{v}^{a}}$$

The magnitude of $\overrightarrow{\mathbf{v}_{error}}$ is minimal for correctly paired stars when the hypothesized rotation matrix represents the true rotation between frames *a* and *b*. Consensus is registered if $\|\overrightarrow{\mathbf{v}_{error}}\| < 0.002$.

Effectively, hypotheses will find little consensus unless they represent the actual rotation, which makes the application of RANSAC to the Stellar Gyroscope problem effective. Once a hypothesis finds consensus larger than 40% of the number of stars in the first frame, RANSAC terminates and returns the consensus set, which consists of the hypothesis stars in the first frame and their corresponding location in the second frame along with the star pairs that showed consensus. The consensus set is used to generate the relative attitude solution:

$$\mathbf{C}^{ba} = q\text{method}\left([\mathbf{v}_{c1}^{b}\ \mathbf{v}_{c2}^{b} \dots \mathbf{v}_{\boldsymbol{C}}^{b}], [\mathbf{v}_{c1}^{a}\ \mathbf{v}_{c2}^{a} \dots \mathbf{v}_{\boldsymbol{C}}^{a}]\right)$$

This concludes the implementation of the purest form of RANSAC on the stellar gyroscope problem. Random star selection in both frames to generate the hypothesis (namely $[\mathbf{v}_{H1}^{b}\ \mathbf{v}_{H2}^{b}]$ and $[\mathbf{v}_{H1}^{a}\ \mathbf{v}_{H2}^{a}]$) works for an arbitrary change in orientation whether small or large. However, in this case, RANSAC requires a significantly large number of iterations to find a hypothesis that finds consensus. This can be improved by pairing stars across frames by proximity or brightness. The number of hypotheses required to find a solution can be drastically reduced by modifying the randomization process.

Pairing by brightness has been most effective. For the improved algorithm, the two stars in the first frame are still randomly selected ($[\mathbf{v}_{\boldsymbol{H1}}^{\boldsymbol{a}}\ \mathbf{v}_{\boldsymbol{H2}}^{\boldsymbol{a}}]$), while the corresponding stars in the next frame are selected to be similar in brightness to those stars. The star brightness values are evaluated in the star detection process and are sorted. The pairing across frames is done by randomly selecting stars in the second frame ($[\mathbf{v}_{\boldsymbol{H1}}^{\boldsymbol{b}}\ \mathbf{v}_{\boldsymbol{H2}}^{\boldsymbol{b}}]$) from a pool of stars that are within a specified range of brightness to the stars in the first frame.

DISCUSSION AND RESULTS

Pictures of the night sky were collected using the OmniVision 7725 sensor. The camera, as described in the design section, was set to an exposure time of 800ms and maximum gain. The camera was set facing at a random point of the sky, where the Earth spin rate and spin axis relative to the camera angle were to be estimated. A photo was taken every 2 minutes, which corresponds to 0.5° of Earth's motion. A non-ideality in the dataset is caused by the atmosphere that is considered to attenuate and blur the stars and cause inconsistent star brightness, which is the main reason for inconsistent brightness of the stars in the dataset.

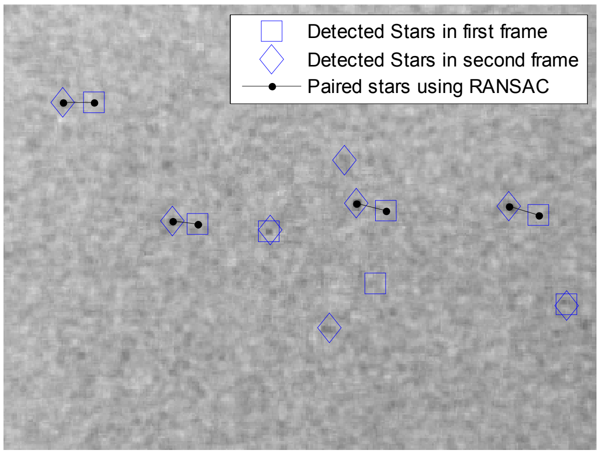

Figure 5: Processing and star pairing of two overlaid images 1.5° apart. Image is cropped and colors are adjusted for clarity.

Figure 5 illustrates the stellar gyroscope operation. Two images from the dataset are selected that are known to be 1.5° apart. The images are overlaid and the colors are inverted for clarity. The paired stars using RANSAC are highlighted. This figure illustrates the success of the implementation of RANSAC to the relative attitude determination problem. We note that despite that Figure 5 shows a single angle for its estimate, all 3 degrees-of-freedom are being estimated.

To demonstrate how the stellar gyroscope can be integrated into an attitude determination system, a simulation was developed that models an attitude determination system entering eclipse. The simulation is based on the SNAP (Smart Nanosatellite Attitude Propagator) tool [15,16], and models a CubeSat in LEO in 6 degrees-of-freedom under gravity gradient torques. These dynamics provide a test case (where the spacecraft body wobbles with a maximum rate of approximately 1.5 °/second) to model the MEMS rate gyroscopes and the stellar gyroscope and compare the computed estimates with the actual attitude.

As mentioned earlier, the main utility of the stellar gyroscope for the SSBV CubeSat ADCS system is to maintain attitude knowledge in eclipse. Attitude knowledge for the system in the illuminated part of the orbit is based on sun and magnetic field vector measurements combined with the MEMS rate gyroscope data in a Kalman Filter. In eclipse, as it is common in many CubeSat systems that lack star trackers or IR Earth sensors, the loss of the sun vector eliminates the ability to generate absolute attitude estimates and the satellite relies on integrating rate data to maintain attitude knowledge. The following figures show the drift associated with that integration process, and show how the stellar gyroscope can assist the system in resetting the drift.

The simulation models the eclipse part of the orbit, beginning with perfect knowledge of the attitude before entering eclipse, and uses the following quaternion kinematic equation to propagate the attitude [13]:

$$\dot{\boldsymbol{q}} = \frac{1}{2}(q_4\boldsymbol{\omega} - \boldsymbol{\omega} \times \boldsymbol{q})$$

$$\dot{q}_4 = -\frac{1}{2}\boldsymbol{\omega}^T \boldsymbol{q}$$

where $\boldsymbol{\omega}$ are the angular rates of the spacecraft as measured by the MEMS rate gyroscopes. The rate gyroscopes produce rate measurements at 50Hz with a noise level of 0.1 °/second RMS, sampled and quantized by a 12-bit analog to digital converter with a range of ±80 °/second.

The discretization in time and magnitude (sampling and quantization), as well as the measurement noise, cause the attitude estimate to drift with time. Figure 6 shows the attitude estimate error for the eclipse duration (for a 90-minute orbit). The plot shows the attitude difference between the estimated and actual attitudes in Euler angles representation. Attitude knowledge error increases up to 5 ° in the first 5 minutes and more than 10 ° after 35 minutes.

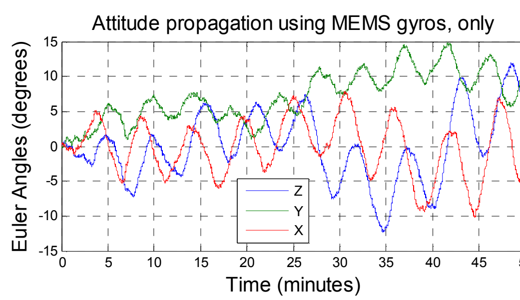

Figure 6: Euler angles representation of attitude difference between estimated and actual attitudes for an unassisted MEMS gyroscope rate integrator. Beginning with perfect knowledge, the plot illustrates attitude loss in eclipse.

Figure 7 illustrates how the stellar gyroscope can assist the rate integrator during eclipse. The system generates relative attitude estimates between photos that are taken. In this example, an attitude measurement is made every 15 seconds. A photo is taken at the beginning of the eclipse phase, and is assigned the best known absolute attitde acquired using the attitude determination filter (that uses the sun-vector). Subsequent photos are referenced against the first photo to propagate the attitude through the ecplipse cycle. It is modeled in the simulation as an imperfect reset to the attitude estimate every 15 seconds. The attitude estimate of the MEMS rate propagator is reset to the actual attitude at an error with a standard deviation of 0.1 degrees. As Figure 7 shows, when stars are in common across frames throughout the period, attitude knowledge is maintained to under 1 degree of error. This is while maintaining the update rate of 50Hz to allow the attitude controller to maintain control.

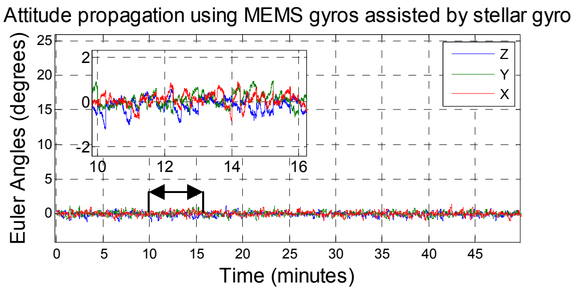

Figure 7: Euler angles representation of attitude difference between estimated and actual attitudes for a MEMS gyroscope rate integrator assisted by a stellar gyroscope. The stellar gyroscope resets the drift every 15 seconds, at least two stars common to the field of view throughout the plot duration are assumed.

FUTURE WORK

The camera interface board uses an FPGA to acquire and process the images, and uses a Digital Signal Processor to perform the attitude propagation. Algorithms will be developed on the FPGA to perfrom, in a time efficient manner, the image conditioning, star detection, centroiding, brightness measurements, and sorting. This architecture provides a good balance between processing speed and power consumption.

An algorithm to perform the relative-attitude measurement has been presented. A run-time algorithm will be developed as well. MEMS gyroscope measurements will be used to predict the view of the stellar gyroscope camera to evaluate the number of stars in common across frames. The propagator will correlate the photo taken with the oldest available image with stars in common in order to minimize the amount of error build up. Also, the RANSAC algorithm can be significantly simplified by replacing the randomized process of hypothesis generation and testing with a hypothesis rotation matrix based on the rate gyroscope output, and test it for consensus to identify the reliable stars from the noise, to then use the consesnus set to calculate the best estimate of the rotation.

CONCLUSIONS

The stellar gyroscope concept and algorithm have been discussed. By tracking the motion of stars in the camera field of view, and solving the relative attitude problem, the stellar gyroscope propagates the spacecraft attitude in 3 degrees of freedom, as long as the camera is viewing the sky.

Using low cost and small sensor and optics, star field images suffer from false star detections and missed stars. The RANSAC approach is effective in finding a rotation estimate with consensus and filter out false data.

A CubeSat attitude determination and control system has been presented. The attitude determination system was designed to maintain a high quality attitude estimate throughtout the orbit, including eclipse when the sun vector is lost. The solution does not use a complex star tracker with a baffle, nor an IR horizon sensor. A stellar gyroscope is used to assist the MEMS rate gyroscopes in eclipse by resetting the drift to preserve attitude knowledge to be within 1^{o} of error.

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