Development of a Low-Cost Multi-Camera Star Tracker for Small Satellites

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INTRODUCTION

Missions requiring precise attitude determination are starting to take advantage of CubeSat platforms for their low cost and design simplicity. Historically, magnetometers and sun sensors have been used as attitude sensors for CubeSat missions. However, these sensors cannot provide attitude information better than 0.2° , and sun sensors do not work in eclipse, hindering their utility on high performance missions. Star trackers, instead, provide attitude determination with accuracy better than 0.1° throughout the orbit, which is sufficient for the applications such as Earth observation and optical communication.

While there are several commercial star trackers that are compatible with the CubeSat formats (such as Berlin Space Technologies ST-200, Sinclair Interplanetary ST-16, and Adcole Maryland Aerospace MAI-SS), universities and other research institutes often choose to build their own star trackers for their CubeSat missions. Commercial star trackers with high accuracy and robustness tend to be costly, and lower cost star trackers, mostly developed by universities, lack the desired levels of performance.

This paper focuses on the design of a low-cost star tracker compatible with CubeSat formats by combining images from multiple low-cost commercial cameras instead of using a single expensive low-noise camera.

IMAGE STACKING AND STAR DETECTION

The sensitivity of a star tracker determines a star's detectability and sets a threshold for the dimmest stars the star tracker can detect. Improving the star detectability of a star tracker improves the attitude estimation accuracy and the robustness of the system. Combining images from multiple low-cost cameras is proposed to maintain a sensitivity similar to a single high-sensitivity camera without the attendant cost. The improvement of the star detectability through the addition of multiple cameras can be quantified to determine the optimal camera array size.

To obtain the star detectability as a function of the number of cameras added, the equation is derived and shown below.

$$m_x \leq 7.5 - 2.5log_{10}\left(\frac{{V_{th}}^2 + \sqrt{{V_{th}}^4 + 4{V_{th}}^2 \cdot (N_{dark} \cdot T + {N_{read}}^2) \cdot n}}{2n \cdot A_l \cdot T_l \cdot \Delta B \cdot T \cdot QE \cdot K_{fill} \cdot K}\right)$$

where m_x is highest star visual magnitude a star tracker can detect; An SNR threshold V_{th} is defined to determine if an SNR value is sufficient for detecting stars; $\sqrt{N_{dark} \cdot T}$ is the standard deviation of the dark current in electrons; T is the exposure time in seconds; N_{read} is the standard deviation of read noise in electrons; n is the number of image stacked; A_l is the area of light collecting surface in cm^2, $A_l = \frac{\pi}{4}d^2$ and d is the diameter of the camera's aperture; T_l is optical transmittance; ΔB is the bandwidth of the lens; QE is the general quantum efficiency; K_{fill} is the ratio of a pixel's light sensitive area to its total area; K is the energy concentrative degree. The star detectability as a function of the number of cameras added is plotted below.

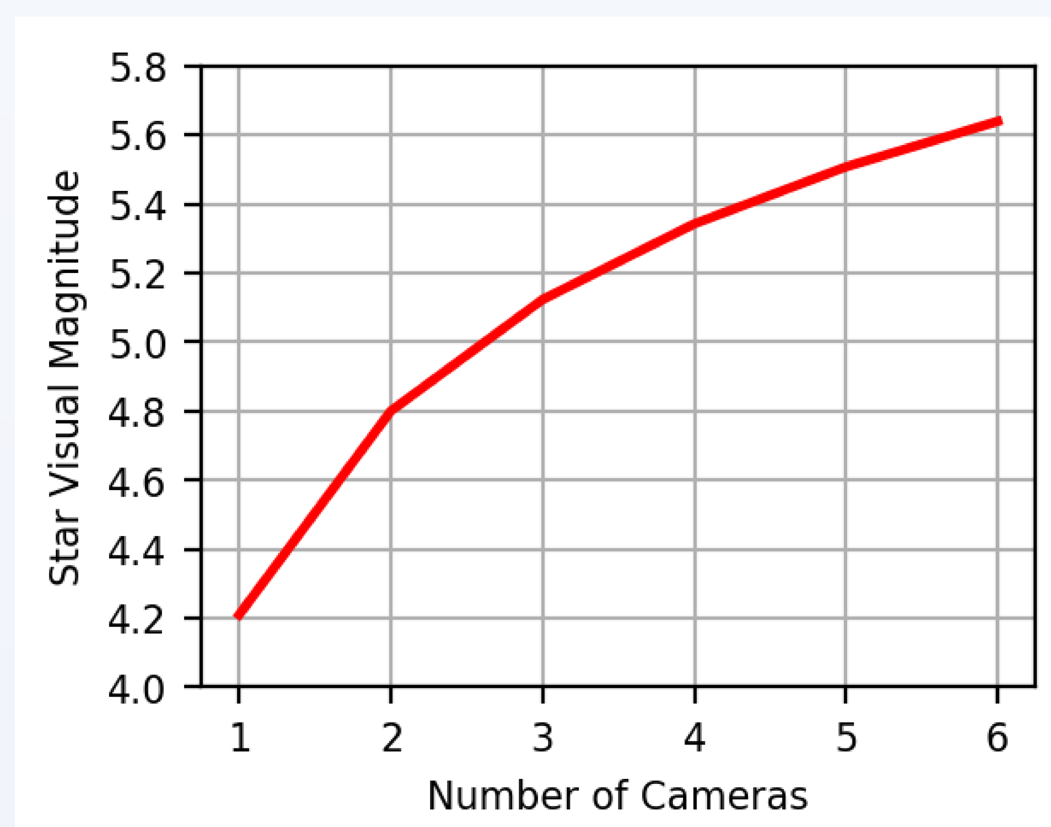

Figure 1: Star Detectability as a Function of the Number of Cameras Added

As shown in the plot, there should be more than three cameras in star tracker system to achieve adequate sky coverage. However, this analysis doesn't consider the impacts of errors in image processing algorithms, which would hinder the improvement of star detectability.

IMAGE PROCESSING ALGPRITHMS

The software system for our multi-camera star tracker consists of an image processing algorithm, a centroiding algorithm, a star identification algorithm, and an attitude determination algorithm. Due to the cameras' misalignments and different intrinsic parameters, images are processed and transformed before stacking. One camera is selected as the reference camera and its star images are defined as the reference images. The images from non-reference cameras are then mapped to the reference images. The reference images and non-reference images are processed differently.

For the reference images, the tangential and radial distortion correction is applied. A mapping is needed from the undistorted coordinates to the distorted position to obtain the image intensity at the corrected position by image interpolation. There are misalignments between the reference camera and the non-reference cameras. As a result, in addition to the distortion correction, the projective transformation is applied for the non-reference images.

An example of the image processing results for two cameras is shown below. From the top to the bottom, the first image is the raw image taken by the reference camera, the second image is the raw image taken by the non-reference camera, and the third image is the final stacked image. The X and Y axes are the pixel coordinates, and the grey scale bars represent the pixel intensities. All images are generated by a star image simulator algorithm. The locations of the stars on the second image are different from that of the first image due to the rotation between two cameras. After being processed, the stars on the second image are mapped to the first image, as can be seen in the third image. Also, the effects of distortion correction can be seen on the third image.

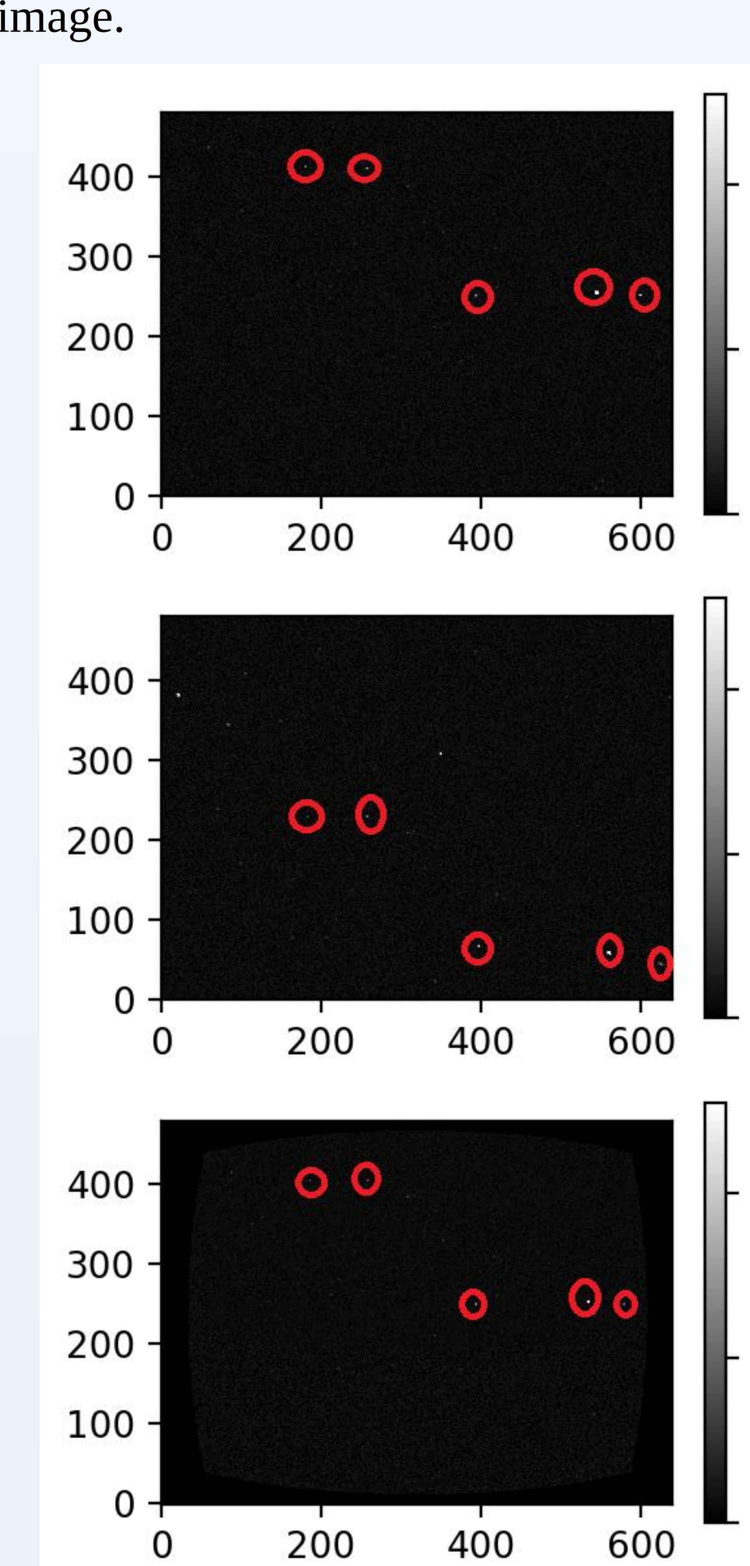

Figure 2: An Example of Image Processing Results

SIMULATION AND TEST

A star tracker software simulator is designed to test the algorithms by generating star images with sensor noises, lens defocusing, and lens distortion. Simulations at thirty different attitude orientations were run for different star tracker configurations. The average attitude estimation errors are 0.0204° for one camera, 0.0198° for three cameras, and 0.0188° for four cameras. The attitude estimation accuracy is improved when there are three or more cameras, as the noise level is reduced by the image stacking. A hardware prototype is being assembled for night sky verification testing.

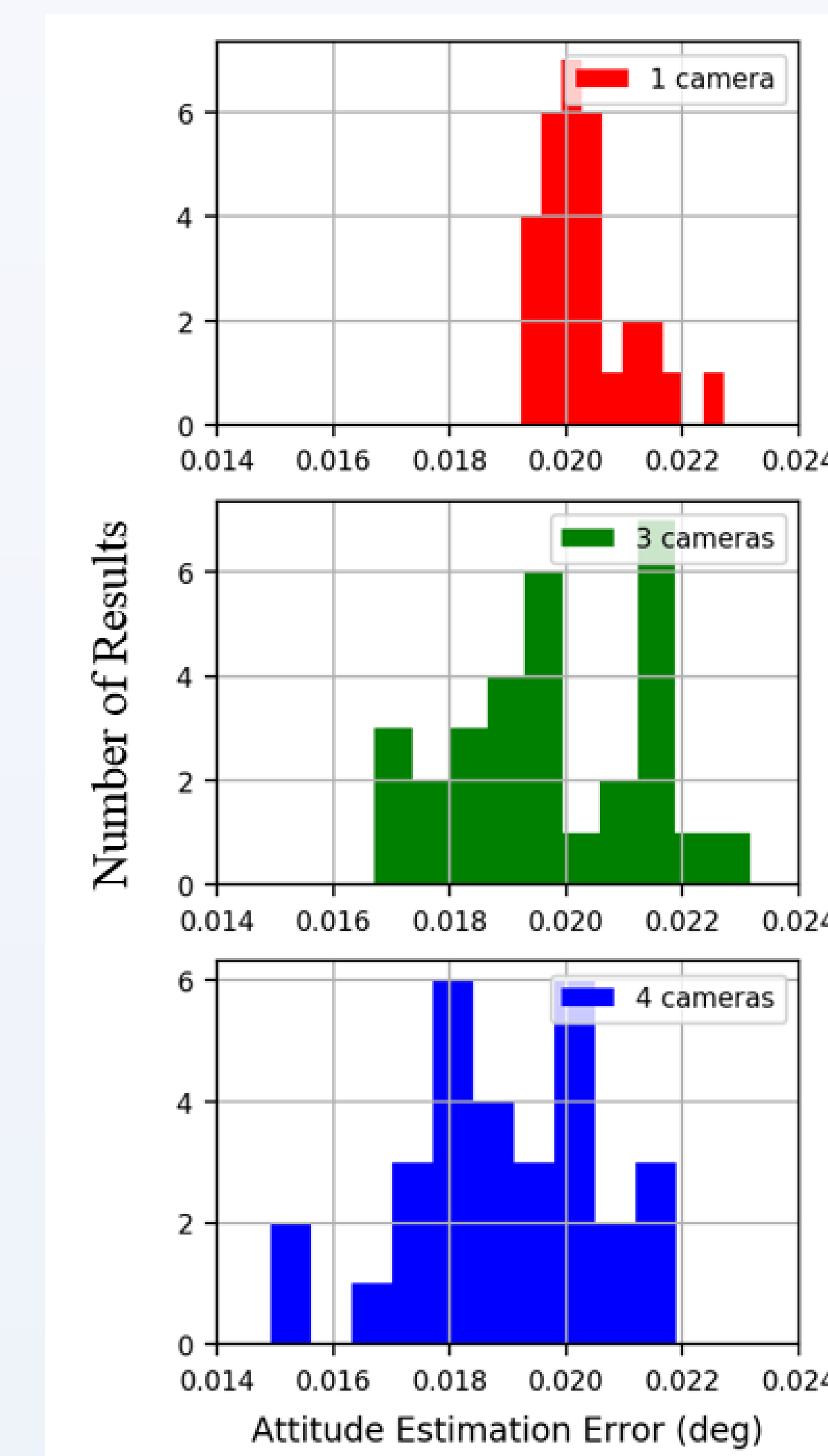

Figure 3: Attitude Estimation Error Results for Different Camera Configurations

CONCLUSION

The concept of a multi-camera star tracker is proposed to improve the sensitivity while reducing integrated system assembly and test costs. The feasibility of the concept has been verified through theoretical analysis and numerical simulation. A hardware prototype is being assembled, and preliminary night sky testing will be conducted to verify the feasibility of the selected hardware. For the future work, additional analysis and testing is planned to complete the verification of the low -cost multi-camera star tracker concept.