Image-Based Stellar Gyroscope for Small Satellites

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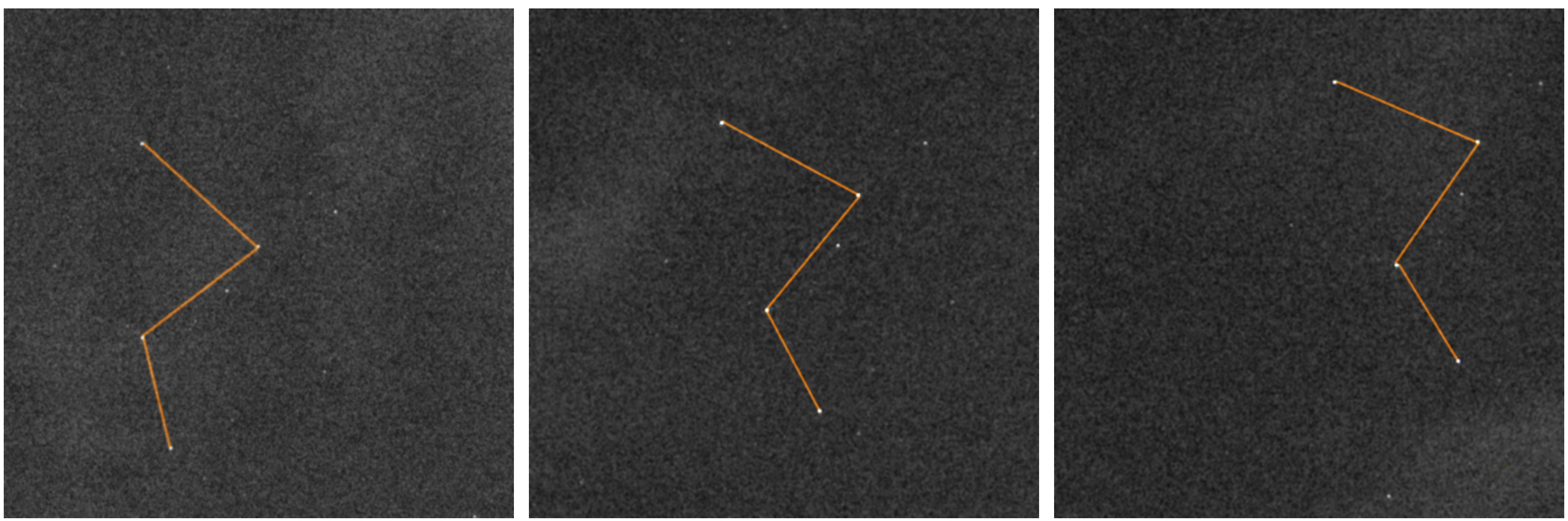
Presentation Overview

- Stellar Gyroscope
  - Concept
  - Related Work
- Current Progress and Initial Results
- Proposed Work
- Schedule

Concept of Stellar Gyroscope

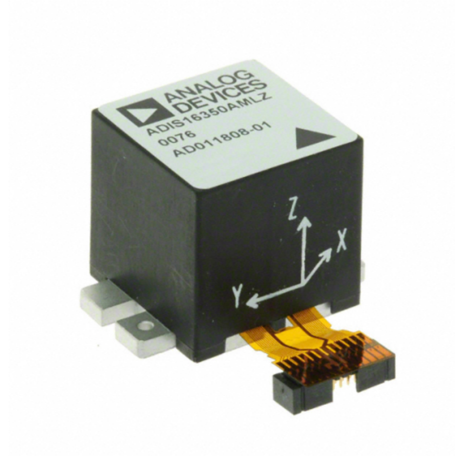
- Problem Statement:

  Observe the motion of stars in camera's field of view to infer changes in satellite's attitude.



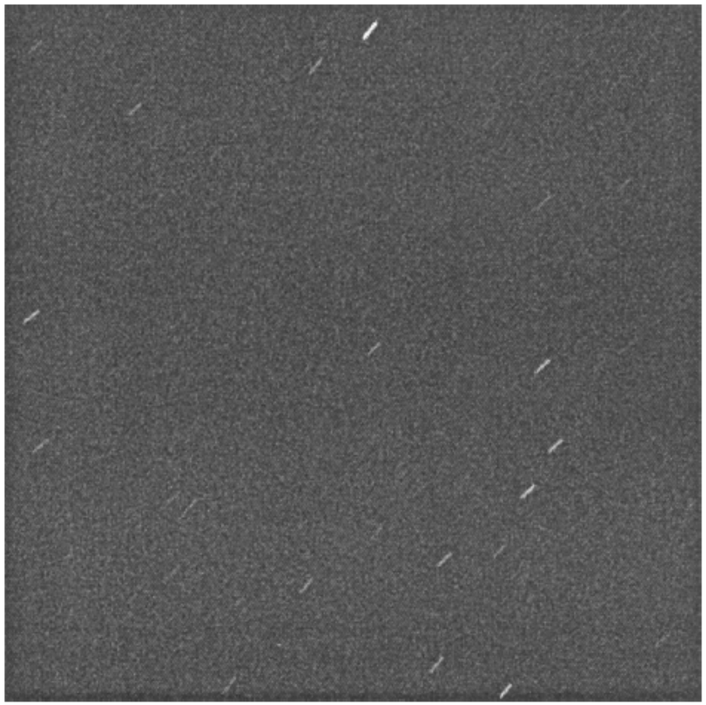
Motivation

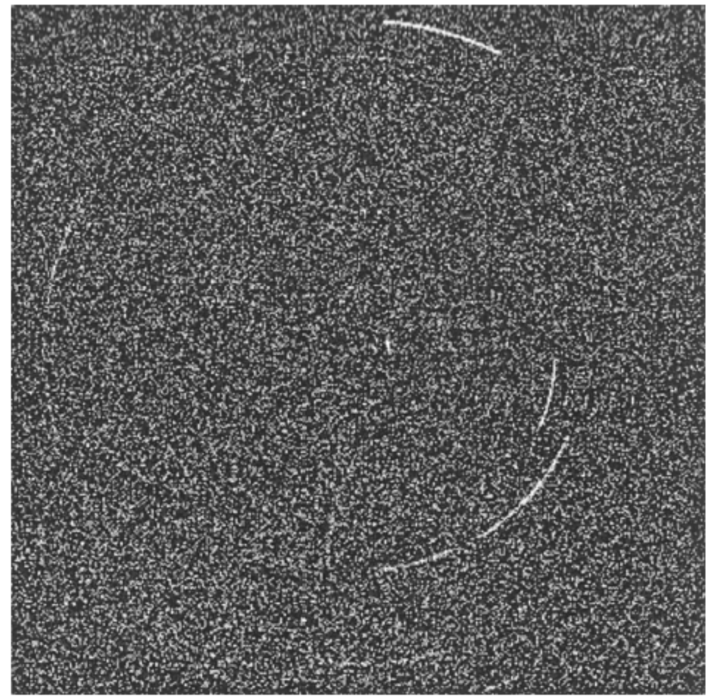
- Current Technology
  - Laser Ring Gyros: Highly accurate, Large, Expensive
  - MEMS Gyros:
    - Compact, and Affordable
    - Small Satellites almost exclusively use MEMS
    - Noisy: drift 0.5 ~ 30 degrees per minute
- Image-based Approach:
  - Comparable volume and cost
  - Added computational requirements
  - No drift



Related Work

- NASA Jet Propulsion Lab (Liebe et. al., 2004)

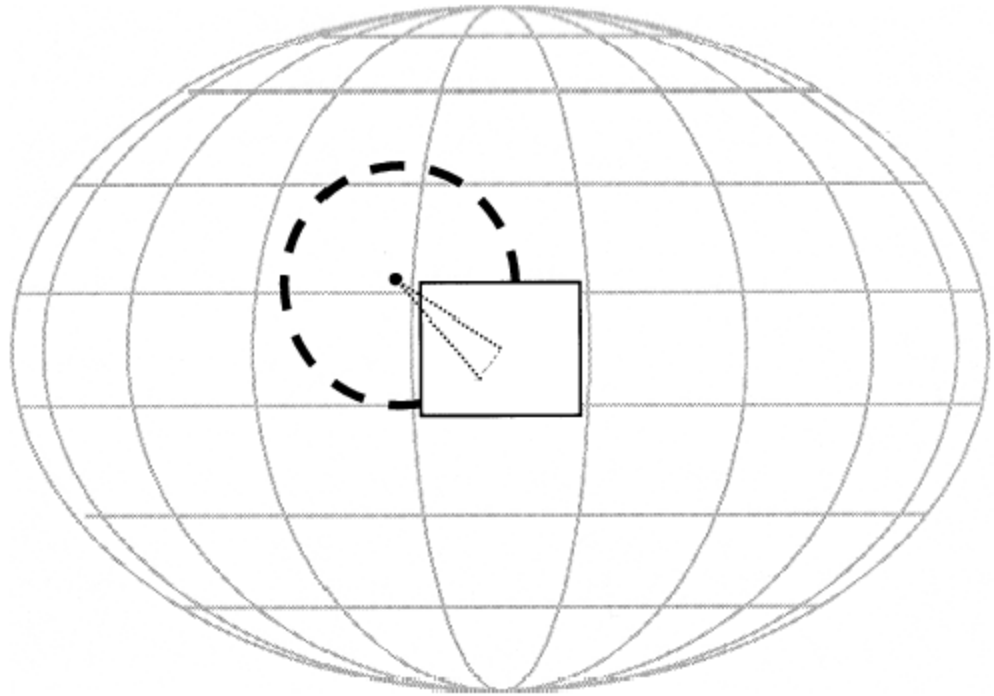




Simulated star images of 50 ms exposures of cross-boresight rotation at 28 deg/s (left) and rotation around boresight at 420 deg/s (right).

Calculating Spin Axis and Spin Rate

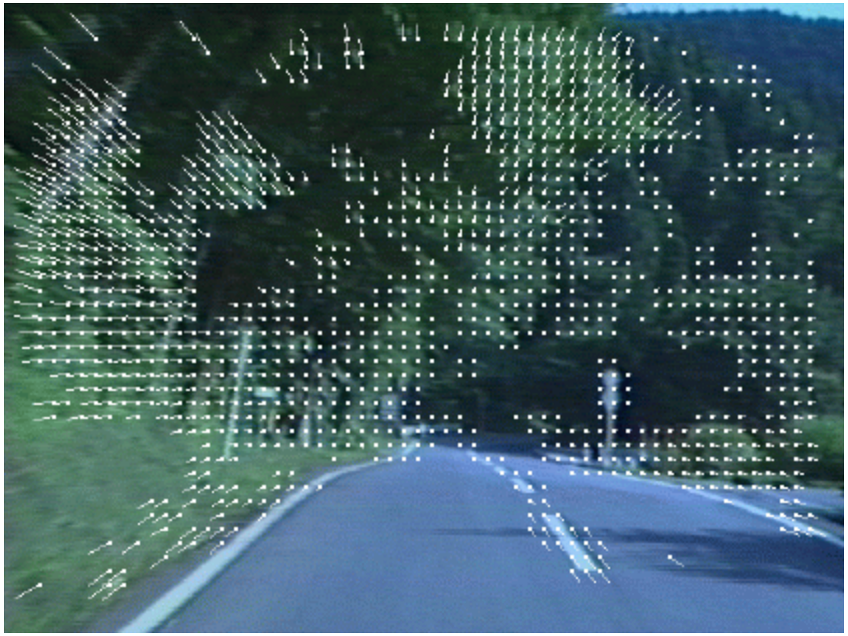
- Circle Fitting Method (JPL 2004)
- Center of the circle describes spin axis
- Spin Angle is found by calculating arc length



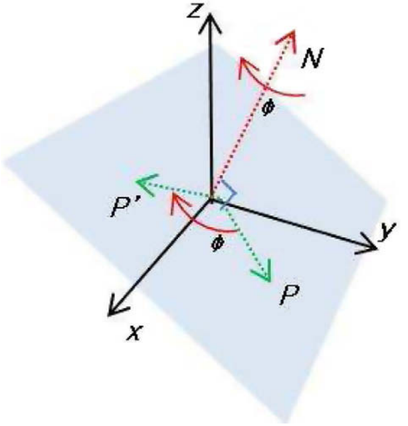
- Range of Motion Limitations
  - Stars near spin axis
  - Motion cross boresight

Egomotion Estimation (Machine Vision)

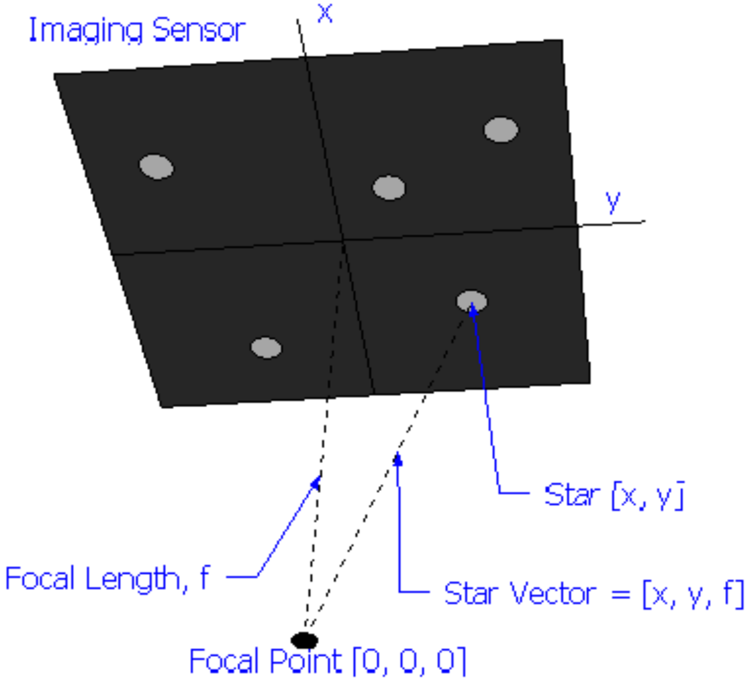
- Typically: Gradient Methods
  - Using image velocity
  - Star field images lack features to calculate optical flow

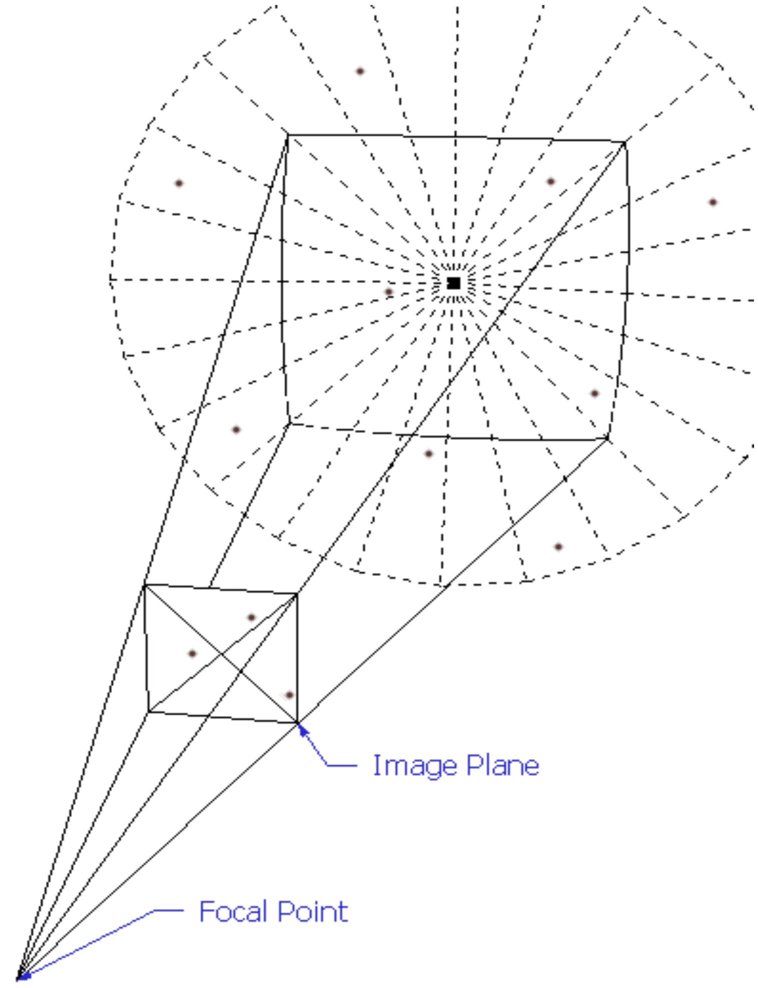


- Displacement Methods
  - Using displacement vectors associated with image features between frames
  - Apply to Stellar Gyroscope and star field images as a special case



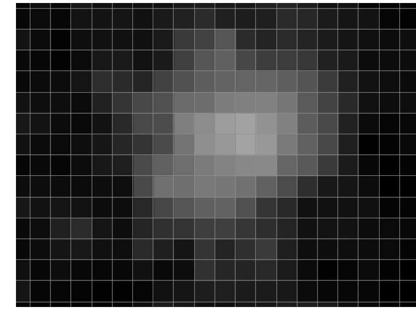
Camera Model





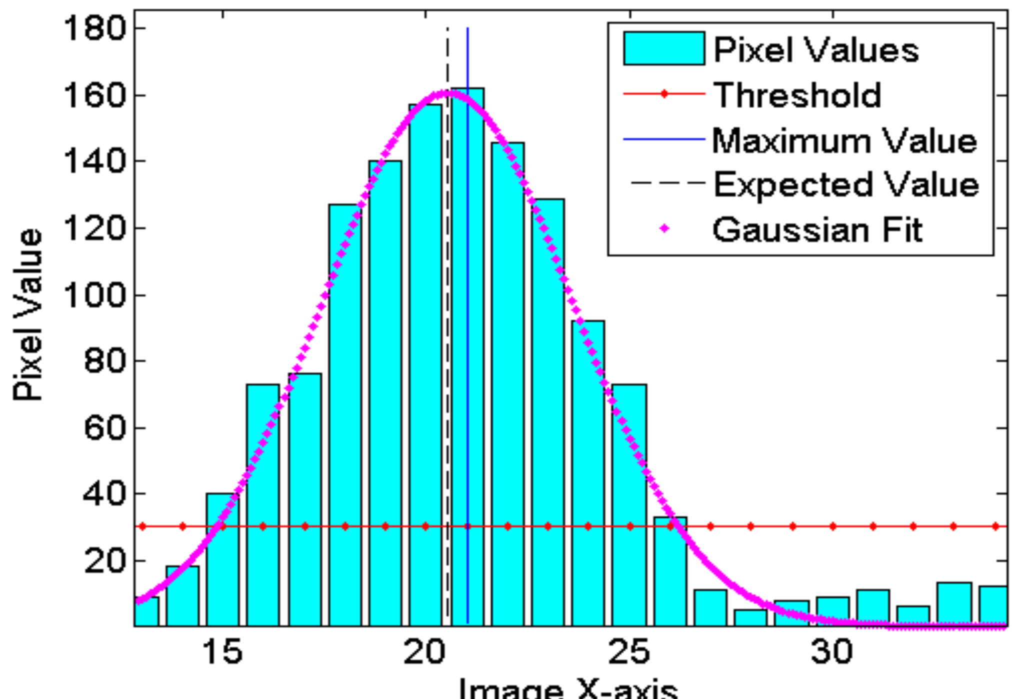
Star Detection

- "Centroiding", aka Expected Value



$$E(x) = \sum x \cdot f_x(x)$$

$$f_x(x) = \sum_y f_{xy}(x, y)$$



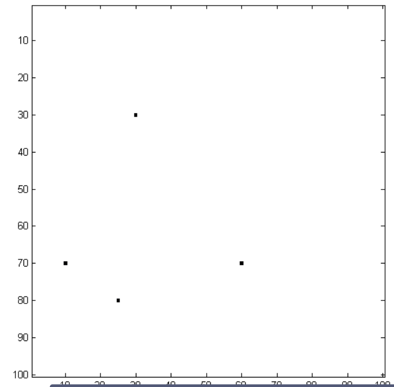
Least Squares Approach

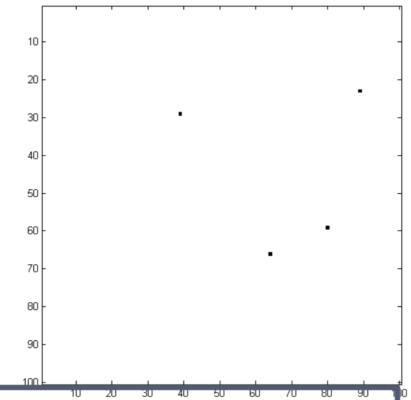
- Vector rotation:

$$\overrightarrow{u^b} = C_{ba}\, \overrightarrow{u^a}$$

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

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





- More than 3 stars:

$$S^b{}_{3\times N} = C_{ba_{3\times 3}} \cdot S^a{}_{3\times N}$$

$$C_{ba} = S^b S^{a^T} (S^a S^{a^T})^{-1}$$

- Solving for C

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} = \begin{bmatrix} u_1^b & v_1^b & w_1^b \\ u_2^b & v_2^b & w_2^b \\ u_3^b & v_3^b & w_3^b \end{bmatrix} \begin{bmatrix} u_1^a & v_1^a & w_1^a \\ u_2^a & v_2^a & w_2^a \\ u_3^a & v_3^a & w_3^a \end{bmatrix}^{-1}$$

Star Visibility

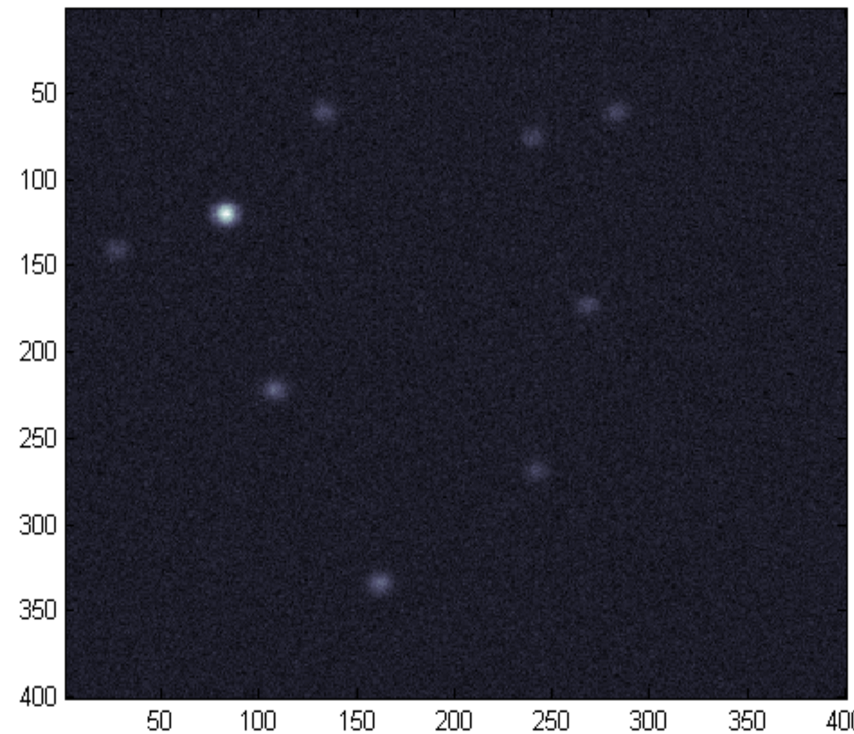
- It has been shown that with the selected sensor (5MP MT9P031), a field of view of 15x22 (16mm focal length) and an exposure time of 100 ms:
  - Star magnitudes brighter than 5.75 can be captured.
  - At least 3 stars will be visible in over 99.99% of the sky.
  - Can tolerate slew rates up to 1 °/second for star magnitudes 5.75 and brighter.

- To tolerate higher slew rates:
  - Sacrifice dim stars
  - Use wider field of view

SKY2000 Master Star Catalog

- Compiled to generate derivative mission-specific star catalogs for NASA and non-NASA spacecraft utilizing star sensors.

Virtual Camera: Using J2000 star unit vectors and magnitude values to "take picture" for any given camera attitude.



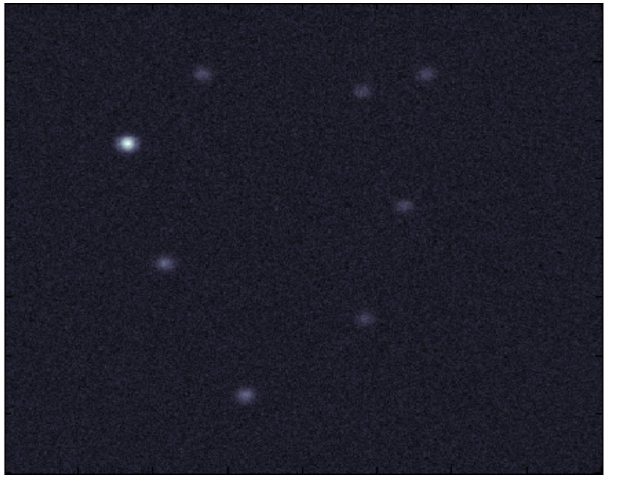
Results

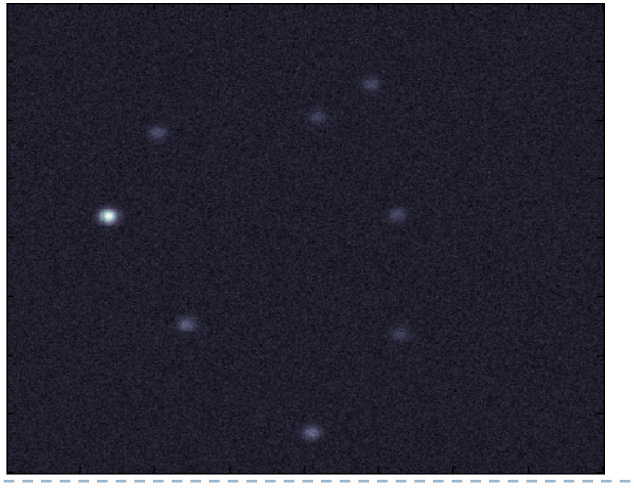
- "C" is converted to the 1-2-3 Euler Angle set
- Actual:

$$\begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} = \begin{bmatrix} 16.067487148167718\,° \\ 0.162200887147300\,° \\ 0.989417931361931\,° \end{bmatrix}$$

- Calculated:

$$\begin{bmatrix} \tilde{\theta}_1 \\ \tilde{\theta}_2 \\ \tilde{\theta}_3 \end{bmatrix} = \begin{bmatrix} 16.018860946764185\,° \\ 0.158859418630225\,° \\ 0.990416316507994\,° \end{bmatrix}$$





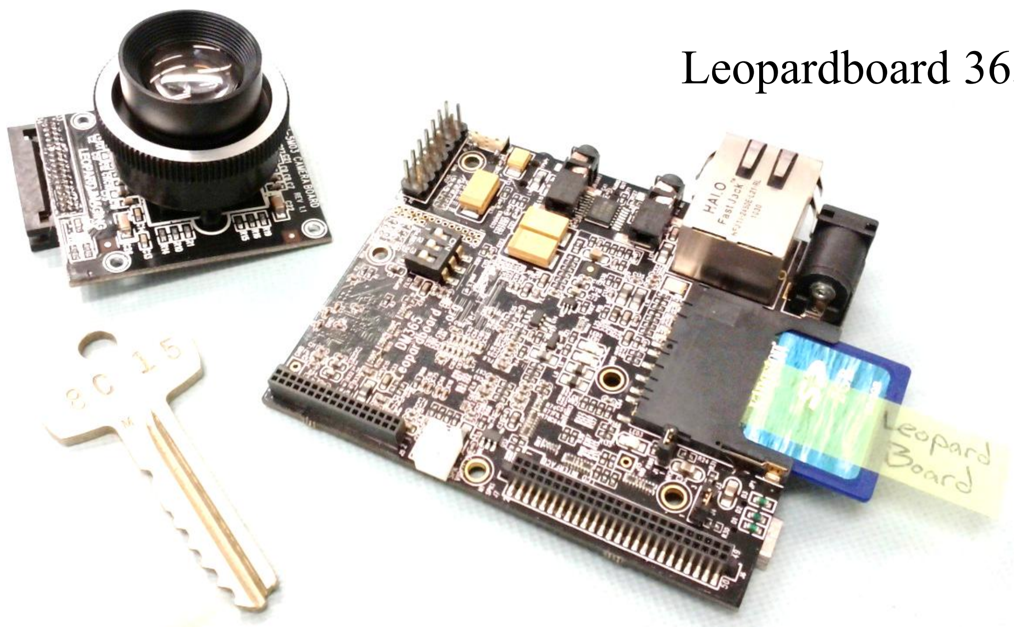
The error between the actual and the estimated orientations for the worst case (θ_1) is 0.0486, or 0° 2' 54.9594".

LeopardBoard 365

- Open Source Hardware and Software
- Community Support

5MegaPixel MT9P031 Camera Board for LeopardBoard

Leopardboard 365



Camera Features

- Texas Instruments DM365 Architecture:
  - ***ARM9***26EJ-S Core: 216, 270, 300MHz
  - Enhanced Video Processing Subsystem with Face Detection module
  - Video Processing Subsystem (VPSS)
  - HD Video Codecs: H.264, MPEG4, ***MJPEG,*** WMV9/VC1, MPEG2
  - Audio Codecs: MP3, WMA, AAC, Audio Echo Canceller (AEC)

- Variety of available Camera modules
- UART or Ethernet access to Linux Shell
- RidgeRun Linux with GStreamer and OpenCV

Conclusions

- The Stellar Gyroscopes resolves attitude changes from the motion of stars in a camera field of view, in 3 degrees-of-freedom.
- Attitude propagation is done without an integration process of a noisy signal (no drift).
- Simple: does not require a star database
- Could potentially augment Star Tracker algorithms by reducing database requirements.

Thank You

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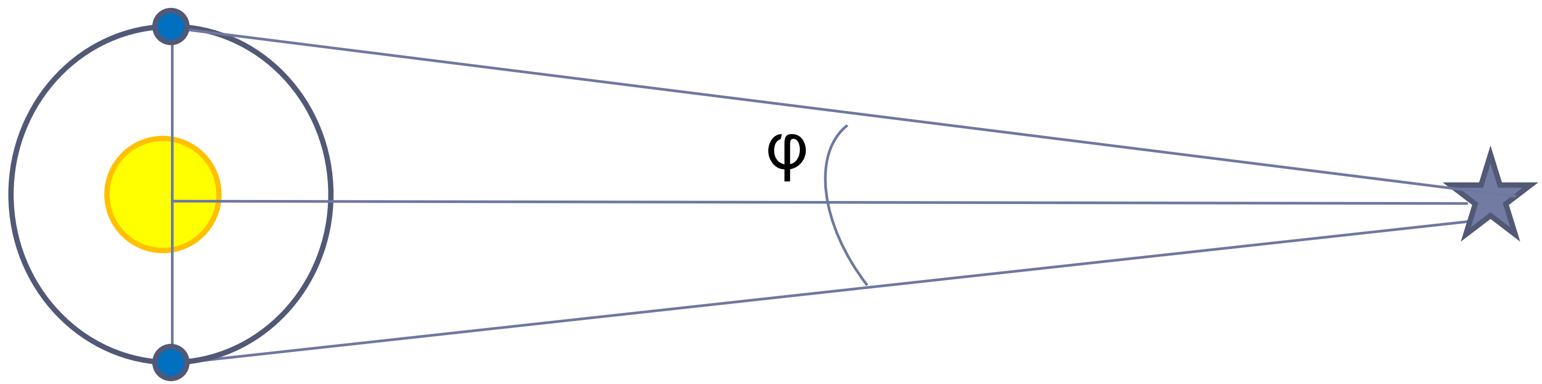
Backup Slides

Alpha Centauri

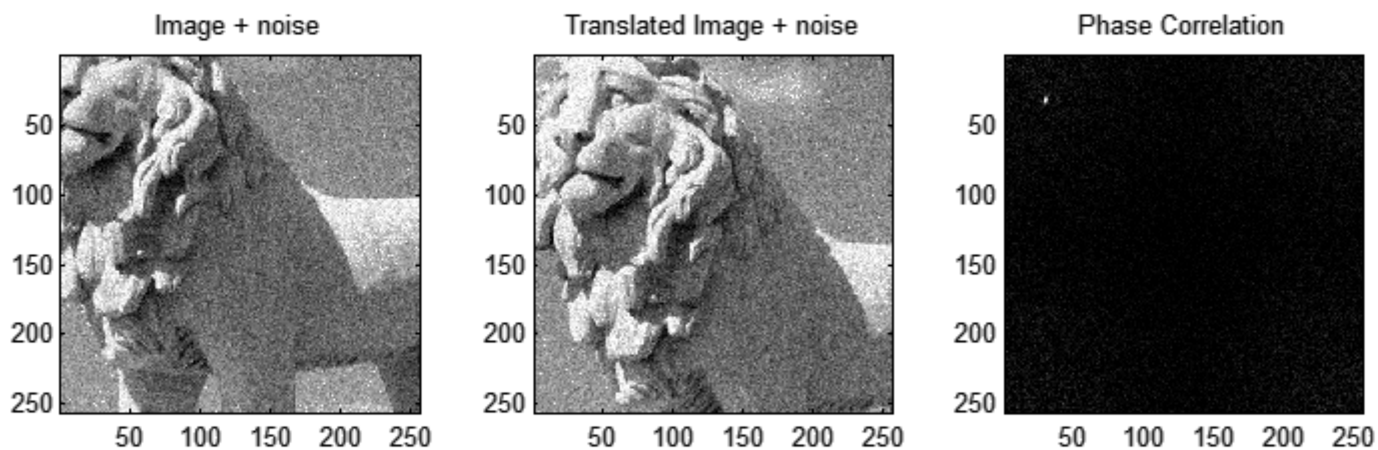
- Nearest star to Sun: 4.37 light-years away (41 trillion kilometers)
- Earth Aphelion: 152,098,232 km



$$\varphi = 2 \times \tan^{-1}(1.52\times10^{8} / 4.1343\times10^{13}) = 0.00042158\ ^{\circ}$$

Phase Correlation

Phase correlation is a method of image registration, and uses a fast frequency-domain approach to estimate the relative translative offset between two similar images



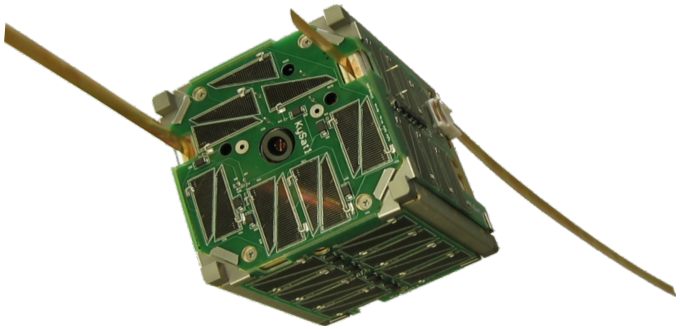
Star Magnitude

$$m_x = -2.5\log_{10}(F_x/F_x^0)$$

where F_x is the observed flux (W/m^2), and $F_x{}^0$ is a reference flux (Vega star)

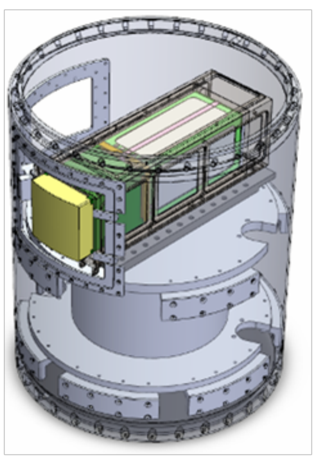
Kentucky Space

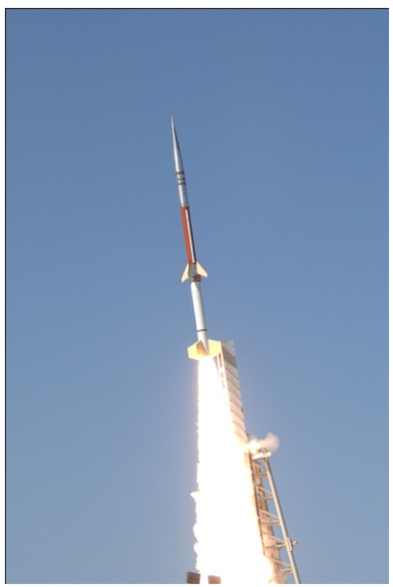
Orbital



High Altitude Balloons

Sub-Orbital





International Space Station: CubeLabs