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

Imaging Sensor

X

Y

Star [x, y]

Star Vector = [x, y, f]

Focal Length, f

Focal Point [0, 0, 0]

Image Plane

Focal Point
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:
  \[ \vec{u}^b = \mathbf{C}_{ba} \cdot \vec{u}^a \]
  \[ \vec{u}^a = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} \cdot \vec{u}^a \]
  \[ \begin{bmatrix} \vec{u}^b & \vec{v}^b & \vec{w}^b \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} \begin{bmatrix} \vec{u}^a & \vec{v}^a & \vec{w}^a \end{bmatrix} \]

- Solving for \( \mathbf{C} \)

\[ \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} = \begin{bmatrix} \vec{u}_1^b & \vec{v}_1^b & \vec{w}_1^b \\ \vec{u}_2^b & \vec{v}_2^b & \vec{w}_2^b \\ \vec{u}_3^b & \vec{v}_3^b & \vec{w}_3^b \end{bmatrix} \begin{bmatrix} \vec{u}_1^a & \vec{v}_1^a & \vec{w}_1^a \\ \vec{u}_2^a & \vec{v}_2^a & \vec{w}_2^a \\ \vec{u}_3^a & \vec{v}_3^a & \vec{w}_3^a \end{bmatrix}^{-1} \]

- More than 3 stars:
  \[ \mathbf{S}_{3 \times N}^b = \mathbf{C}_{ba} \cdot \mathbf{S}_{3 \times N}^a \]
  \[ \mathbf{C}_{ba} = \mathbf{S}_b^a \mathbf{S}_a^{T} (\mathbf{S}_a^a \mathbf{S}_a^{T})^{-1} \]
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:
  \[
  \begin{bmatrix}
  \theta_1 \\
  \theta_2 \\
  \theta_3 
  \end{bmatrix} = \begin{bmatrix}
  16.067487148167718^\circ \\
  0.16220087147300^\circ \\
  0.989417931361931^\circ 
  \end{bmatrix}
  \]
- Calculated:
  \[
  \begin{bmatrix}
  \bar{\theta}_1 \\
  \bar{\theta}_2 \\
  \bar{\theta}_3 
  \end{bmatrix} = \begin{bmatrix}
  16.018860946764185^\circ \\
  0.158859418630225^\circ \\
  0.990416316507994^\circ 
  \end{bmatrix}
  \]
  The error between the actual and the estimated orientations for the worst case (\(\theta_1\)) is 0.0486, or 0° 2' 54.9594".
LeopardBoard 365

- Open Source Hardware and Software
- Community Support

5MegaPixel MT9P031 Camera Board for LeopardBoard
Camera Features

- Texas Instruments DM365 Architecture:
  - ARM926EJ-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

\[ \varphi = 2 \times \tan^{-1}(\frac{1.52 \times 10^8}{4.1343 \times 10^{13}}) = 0.00042158 \degree \]
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)
Orbital

High Altitude Balloons

Sub-Orbital

International Space Station: CubeLabs

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2011 Summer CubeSat Developers’ Workshop