Image Processing and Attitude Estimation Performance of Star Camera with Extended Bodies in the Field of View

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Outline

- Background – Attitude Sensors
- STR Flight Software: Main Functional Modules
  - Camera Control
  - Tools of Image Processing
  - Image Centroiding
- Ground Calibration for the Bore-sight Offsets and the Focal Length
  - Ground Calibration Procedure
  - Ground Calibration Results
- Master (on-board) Star Catalog
- Lost-In-Space Algorithm (LISA)
- Attitude Estimation
- End-to-End test – Stars only
- End-to-End test – Stars and Moon
- Results and Conclusion
To determine the attitude and the position of a spacecraft its orientation and location relative to some frame of reference of well known celestial body must be defined.

- **Earth Horizon Sensor**
  - Horizon sensors are infrared devices that detect the contrast of the cold of space and the warmth of the Earth

- **Sun Sensor**
  - Measure Sun angle by measuring the energy deposited in a photocell

- **Magnetometer**
  - Measure both the direction and magnitude of the magnetic field

- **Star Sensor (Star Tracker)**
  - Measure Starlight directions
STR Flight Software: Main Functional Modules – Current Status

CAMERA CONTROL
- Image Frame
- Pixel Response Data

IMAGE PROCESSING
- CCD temperature
- exposure time
- # of dark frame
- threshold DN
- max # of stars
- min star separation

LISA
- STAR PATTERN IDENTIFICATION
- Observed Star #, RA, DEC
- Matched Star #, RA, DEC

ATTITUDE ESTIMATION
- Attitude Matrix quaternion
- Ground / On-board Calibration

TELEMETRY INTERFACE
- Main CPU

Star Catalog On-board Tables
- Observed Star #, RA, DEC

Ground / On-board Calibration
- Observed Star #, RA, DEC

Matched Star #, RA, DEC
Camera Control

- Raw Image
- Dark Subtracted Image
- Calibrated Image
- Dark Frames
- Master Dark
- Raw Flat Fields
- Master Flat
- Flat Dark
Tools of Image Processing

PSF response for a typical star.
Image Centroiding is a fundamental process in any star sensor. It’s output is the imaged star coordinates \((x, y)\).

\[
\hat{x} = x_m + \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} x_{ij} I_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{n} I_{ij}}
\]

\[
\hat{y} = y_m + \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} y_{ij} I_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{n} I_{ij}}
\]

\[
\hat{W}_i = \frac{1}{\sqrt{(x_i - x_o)^2 + (y_i - y_o)^2 + f^2}} \begin{pmatrix} -(x_i - x_o) \\ -(y_i - y_o) \end{pmatrix}
\]
• Star Camera Calibration is an important task in attitude determination of the spacecraft.

• Generally, star cameras are calibrated on the ground in high precision laboratories. However, any significant change in the instrument or the environment can result in this calibration being in-accurate on-orbit.

• The calibration process is mainly divided into two major parts:

  • Calibration of principal point offset \((x_0, y_0)\) and focal length\(f\)
  • Calibration of focal plane image distortions due to all other effects (lens distortion, misalignment, detector alignment etc.)
The ideal camera parameter calibration algorithm is used to estimate the "accurate" values for the camera focal length and the focal plane offsets.

The Attitude Independent (AID) approach is used for calibration.

\[
\cos \theta_{ij} = \hat{V}_i^T \hat{V}_j = \hat{W}_i^T \hat{W}_j + \text{meas errors}
\]

\[
\hat{W}_i = \frac{1}{\sqrt{(x_i - x_o)^2 + (y_i - y_o)^2 + f^2}} \left( \begin{array}{c} -(x_i - x_o) \\ -(y_i - y_o) \\ f \end{array} \right)
\]

\[
\hat{V}_i = \left( \begin{array}{c} \cos \alpha_i \cos \delta_i \\ \sin \alpha_i \cos \delta_i \\ \sin \delta_i \end{array} \right)
\]

\(i=1,2,\ldots,\) no. of imaged stars
Modified from Hipparcos Star Catalog

- 12,500 guide stars for Magnitude range: -1.5 to ~ 6.4
- Number of stars within mag. threshold $M_v \leq 5.4$ is about 2870 stars
- Data: Inertial direction vectors, Visual magnitude($M_v$)

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Size of FOV vs Number of Stars/FOV

Average Number of Measured Stars within given FOV

Average Number of Measured Stars vs Visual Magnitude

- 5 x 5
- 10 x 10
- 15 x 15
- 20 x 20
- 25 x 25
- 30 x 30

OpNav FOV
The key problem is to match imaged and cataloged stars and identify the imaged stars as particular catalogued stars...
Matching inter-star angles for 2 Stars to within 0.001°:
   => probability of wrong star ID is > 0.9 !!

Matching angles for 3 Stars:
   => probability of wrong star ID is ~ 10^{-4}

Matching angles for 4 or more Stars:
   => probability of wrong star ID is ~ <10^{-11}
Attitude Estimation

- Optimal Attitude Estimation
- Least squares estimation criterion
- Parameterize attitude using quaternions
- Kalman filtering to propagate and update measurements & covariance

Attitude Estimate and Covariance

Unit vectors toward ID ed measured Stars in body frame
Unit vectors toward ID ed stars in Inertial (catalog) frame

Boresight RA, Declination

To Image Processing and Star Position Measurement

\[
q = \begin{bmatrix} q_{13} \\ q_4 \end{bmatrix}
\]

\[
q_{13} = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \hat{n} \sin(\theta/2)
\]

\[
q_4 = \cos(\theta/2)
\]
### End-to-End test 1 – Stars only

#### Accuracy Cross Boresight
- 3.7 arc-sec

#### Accuracy About Boresight
- 11.2 arc-sec

#### Coordinates

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**qJ2000_Cam1** = [-0.4238 0.0858 0.8903 0.1430]

**qJ2000_ST** = [-0.4219 0.0812 0.8894 0.1560]

qErr before align = 1.5867 deg
qErr after align  = 0.0032 deg

= 11.6 arc-sec
End-to-End test 2 – Stars only

\[ qJ2000\_Cam1 = [-0.0922, -0.4168, -0.0651, 0.9020] \]
\[ qJ2000\_ST = [-0.0853, -0.4209, -0.0762, 0.8999] \]

\[ qErr \text{ before align} = 1.5883 \text{ deg} \]
\[ qErr \text{ after align} = 0.0048 \text{ deg} \]

Accuracy Cross Boresight = 4.5 arc-sec
Accuracy About Boresight = 15.5 arc-sec
End-to-End test 1 with Moon

q2000_Cam2 = [-0.3031 0.5730 0.6364 -0.4182]
q2000_ST = [-0.1911 0.3845 0.7662 -0.4781]

qErr before align = 30.0831 deg
qErr after align = 0.0025 deg = 8.86 arc-sec
Accuracy Cross Boresight = 1.7 arc-sec
Accuracy About Boresight = 8.3 arc-sec

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$q_{2000 \_Cam2} = [-0.3504 \ 0.5446 \ 0.6756 \ -0.3525 ]$
$q_{2000 \_ST} = [-0.2537 \ 0.3466 \ 0.7960 \ -0.4265 ]$

$q_{Err \ before \ align} = 30.0844 \ deg$
$q_{Err \ after \ align} = 0.0036 \ deg \ = 13.0 \ arc-sec$

Accuracy Cross Boresight = 5.6 arc-sec

Accuracy About Boresight = 12.8 arc-sec
End-to-End test 3 with Moon

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$q_{2000\_OpNav2247} = [-0.3023, 0.5734, 0.6369, -0.4173]$

$q_{2000\_ST} = [-0.1905, 0.3847, 0.7669, -0.4771]$  

$q_{Err}$ before align = 30.0830 deg  
$q_{Err}$ after align = 0.006 deg = 21.4 arc-sec  
Accuracy Cross Boresight = 9.4 arc-sec  
Accuracy About Boresight = 17.8 arc-sec
Percent SuccessID = 97.5610
Percent4StarsFound = 11.219
badImgCount = 0
quaternion error after align,
Mean = 22.44 arc-sec,
STD = 14.17 arc-sec
Cross Bore-sight = 6.42
About Bore-sight = 19.03

quat. error before align (deg), Mean = 1.5898, STD = 0.0063279

Accuracy (arc-sec) Cross-Boresight = 6.4233

quat. error after align, Mean = 22.4384

Accuracy (arc-sec) About-Boresight = 19.0344
Star ID – Att. Det. Results Cam1 1.0s exposure

Percent SuccessID = 98.5366
Percent4StarsFound = 7.3171
badImgCount = 0
quat. error before align (deg), Mean = 1.5887, STD = 0.0069389
quat. error after align, Mean = 23.23 arc-sec, STD = 15.98 arc-sec
Cross Bore-sight = 6.05
About Bore-sight = 18.17

Accuracy (arc-sec) Cross-Boresight = 6.0524

Accuracy (arc-sec) About-Boresight = 18.1078
Star ID – Att. Det. Cam2 with Moon 0.5s exposure

Percent SuccessID = 86.3415
Percent4StarsFound = 15.6098
badImgCount = 3
ImgWithMoonCount = 70
60 identified images with moon
Star ID – Att. Det. Cam2 with Moon 0.5s exposure

quat. error before align (deg), Mean = 30.0819, STD = 0.0018414

quat. error after align, Mean

Accuracy (arc-sec) Cross-Boresight = 5.6156

Accuracy (arc-sec) About-Boresight = 28.7848
• If the number of centroids < 4 object – no possible StarID- consider bad
Percent SuccessID  = 87.8537
Percent4StarsFound = 12.6829
badImgCount = 4
ImgWithMoonCount = 70
66 identified images with moon
Star ID – Att. Det. Cam2 with Moon 1s exposure

**quat. error before align (deg), Mean = 30.0818, STD = 0.0017142**

**quat. error after align, Mean**

**Accuracy (arc-sec) Cross-Boresight = 6.2052**

**Accuracy (arc-sec) About-Boresight = 31.5249**

Quaternion error after align,
Mean = **31.47** arc-sec,
STD = **23.42** arc-sec

Cross Bore-sight = **6.20**
About Bore-sight = **31.5**
Image with stars, moon and debris (plane!)
Results/Statistics

• For the Star1 Camera
  – 615 total images processed (0.5 – 1.0 sec Int. time),
  – 0 bad image (no Centroiding with at least 4 stars)
  – Success star id count = 608 = 98.9 %
  – 4 Stars identified count = 60 = 9.75 %
  – Quaternion Error (with ST quat.):
    • bias = 23 arc-sec, standard deviation = 16 arc-sec
    • Cross Boresight = 6.14 arc-sec  About Boresight = 19.56 arc-sec

• For the Moon Camera
  – 615 total images processed (0.5 – 1.0 sec Int. time),
  – 40 bad image (no Centroiding with at least 4 stars)
  – Success star id count = 530 = 92.14 %
  – 4 Stars identified count = 85 = 14.85 %
  – Images with Moon count = 210 images
  – Quaternion Error (with ST quat.):
    • bias = 34 arc-sec, standard deviation = 27 arc-sec
    • Cross Boresight = 5.71 arc-sec  About Boresight = 29.16 arc-sec