Star Tracker Astrometry Pipeline

Digantara – Image Processing Engineer (Star Tracker) Assessment

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1 Introduction

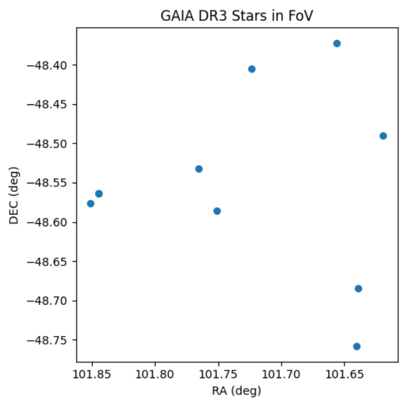
Star trackers are critical subsystems for spacecraft attitude determination and ground-based space situational awareness (SSA). They estimate the orientation of an imaging sensor by identifying stars in a captured image and matching them to a reference star catalog. The objective of this assessment is to design and implement a complete star-tracker astrometry pipeline using detected star centroids and a reference catalog.

The implemented pipeline performs catalog preparation, geometric feature creation, star matching, verification through global orientation consistency, and final export of matched star data. Special attention is given to handling *sparse star-field conditions*, which arise due to narrow sensor field-of-view and sky location.

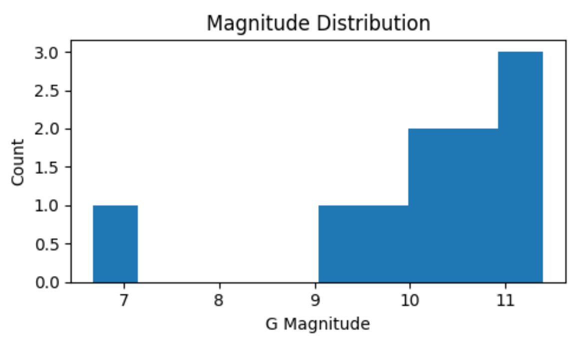
2 A1: Catalog Download

The GAIA DR3 catalog was selected as the reference catalog due to its high astrometric precision and uniform sky coverage. The catalog was queried using the provided coarse pointing metadata (RA, DEC) and a rectangular field-of-view, consistent with the geometry of a CCD/CMOS sensor. A magnitude threshold was applied to retain only stars that are realistically detectable by the sensor, reducing catalog density and false matches. The resulting catalog contains star positions (RA, DEC) and G-band magnitudes and was stored in CSV format for downstream processing.

This step is independent of the detected centroids and reflects a realistic preloaded catalog stage in star-tracker systems.



(a) Catalog stars



(b) Angular separation distributions for image and catalog stars.

3 A2: Catalog Feature Creation

Catalog star positions were converted from spherical coordinates (RA, DEC) to unit direction vectors in the celestial frame. This representation enables rotation-invariant geometric matching.

Pairwise angular separations between catalog stars were computed, and for each star a local angular-distance signature was constructed using nearest-neighbor separations. These features are invariant to translation and rotation and are well-suited for star-pattern matching.

Due to the narrow field-of-view and sky location, the catalog contained only a small number of bright stars, placing the problem in a sparse-field regime. To ensure stable features, the dimensionality of the angular signatures was adaptively reduced.

4 A3: Image Feature Creation and Star Matching

Detected star centroids were sorted by brightness, and only the brightest stars were retained to improve centroid reliability. Pixel coordinates were converted into camera-frame unit vectors using the sensor camera model, incorporating the focal length and pixel pitch.

Angular-distance features were constructed for image stars using the same methodology as for the catalog, ensuring feature compatibility. Initial matching was performed in feature space using a KD-tree search with relaxed tolerances to account for coarse pointing uncertainty.

A strict one-to-one matching constraint was enforced, ensuring that each catalog star could be matched to at most one image star and preventing degenerate many-to-one solutions.

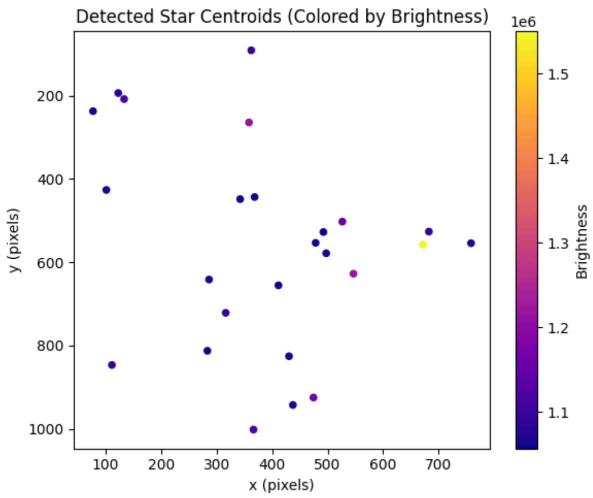


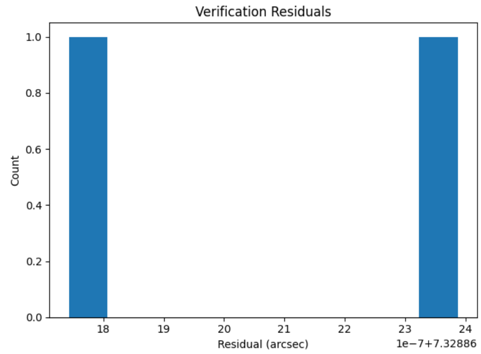
Figure 2: Detected star centroids

5 A4: Verification and Orientation Estimation

Initial matches were verified by enforcing global orientation consistency. Wahba's problem was solved using a Singular Value Decomposition (SVD)–based method to estimate the optimal rotation between catalog vectors and image vectors.

Angular residuals between rotated catalog vectors and corresponding image vectors were computed. Matches with large residuals were rejected as outliers, and the rotation was recomputed using only verified inliers. This verification step ensures that all retained matches are consistent with a single rigid-body rotation.

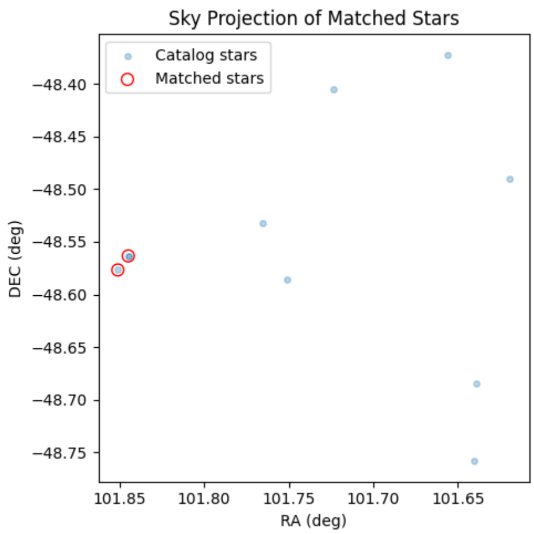
The root mean square (RMS) angular error, expressed in arcseconds, was used as the primary accuracy metric.



6 A5: Final Matched Star Output

After verification, the final inlier correspondences were used to generate the matched star catalog. Each detected centroid $(x, y, \text{brightness})$ was mapped to its corresponding catalog parameters $(\text{RA}, \text{DEC}, \text{magnitude})$.

The verified matches were exported as a CSV file, providing a direct output suitable for astrometric calibration and downstream SSA workflows.



7 Question 2: Orientation Estimation and Validation

7.1 (a) Estimation of Optimal Orientation

From Question 1, each verified match provides a unit vector in the camera frame and a corresponding unit vector in the celestial frame. The optimal orientation is obtained by solving Wahba's problem:

$$\min_{\mathbf{R}} \sum_{i=1}^{N} \left\| \mathbf{v}_i^{\text{cam}} - \mathbf{R}\,\mathbf{v}_i^{\text{cel}} \right\|^2$$

An SVD-based solution yields the optimal rotation matrix $\mathbf{R}$. From this matrix, RA and DEC are derived from the camera boresight direction, while ROLL is obtained as rotation about the boresight. The rotation can equivalently be represented as a quaternion (q_w, q_x, q_y, q_z).

7.2 (b) Mapping from (x, y) to $(\mathbf{RA}, \mathbf{DEC})$

Calibration enables image-to-sky mapping through:

1. Conversion of pixel coordinates (x, y) to camera-frame unit vectors using the intrinsic camera model
2. Application of the inverse rotation:

$$\mathbf{v}_{\text{cel}} = \mathbf{R}^{-1}\,\mathbf{v}_{\text{cam}}$$

3. Conversion of the resulting vector to spherical coordinates (RA, DEC)

7.3 (c) Importance of Verification

Initial geometric matching may include false correspondences due to centroid noise and sparse catalogs. Verification enforces global physical consistency by requiring all matches to conform to a single rigid-body rotation, eliminating degenerate solutions and ensuring robustness.

7.4 (d) Accuracy Metric

The accuracy of the estimated orientation is evaluated using the RMS angular residual:

$$\text{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \theta_i^2}$$

where θ_i is the angular separation between matched image and rotated catalog vectors. This metric directly reflects errors in RA, DEC, and ROLL.

8 Conclusion

A complete star-tracker astrometry pipeline was implemented, covering catalog preparation, feature creation, matching, verification, and final data export. Adaptive feature selection and verification-driven matching enabled robust orientation estimation under sparse star-field conditions. The resulting pipeline produces physically consistent and practically usable astrometric outputs.