Synthesis and Evaluation of an Image-Based GNSS-Redundancy System for UAV Navigation

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Background

Unmanned Aerial Vehicles (UAVs) are under attack—not by conventional weapons, but by silent, invisible forces: GNSS jamming and spoofing. These sophisticated disruptions threaten to hijack or disable navigation, placing mission-critical assets essential for national security in jeopardy. Traditional countermeasures like odometry, quantum sensing, RF communication, and LiDAR provide limited defense, often falling short in terms of cost-effectiveness, accuracy, or operational stealth.

Problem Statement

There is a need for a reliable, cost-effective redundancy system for UAV navigation when GNSS is unavailable. Image-based UAV navigation offers a promising solution but requires evaluation for practicality and effectiveness.

Aim:

Develop an image-based navigation system for UAVs to estimate position and heading using imagery, enabling return-to-base navigation when GNSS is denied.

Objectives:

- Synthesize a UAV navigation system to estimate position and heading using captured images.
position and heading using captured images.
- Find the optimal methods per stage to ensure accuracy, efficiency, and generalizability.
- Test the system across varying, challenging terrains.
- Assess the system's robustness under challenging operational conditions.
- Evaluate the practical viability of the solution.

Requirements:

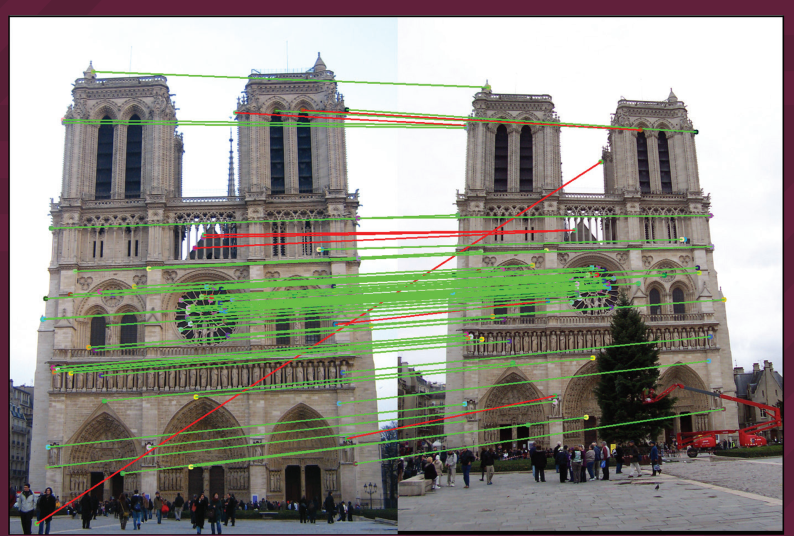
1. Accuracy: Maintain a radial location inference error below 10% of the image pair displacement.

2. Real-Time Performance: Output a position and heading estimation within 2 seconds, following GNSS loss, and process reference images at a rate of 5 seconds per frame while GNSS is available.

3. Generalizability: Sustain the required accuracy and speed across all terrains (datasets) without manual tuning.

Method Pool:

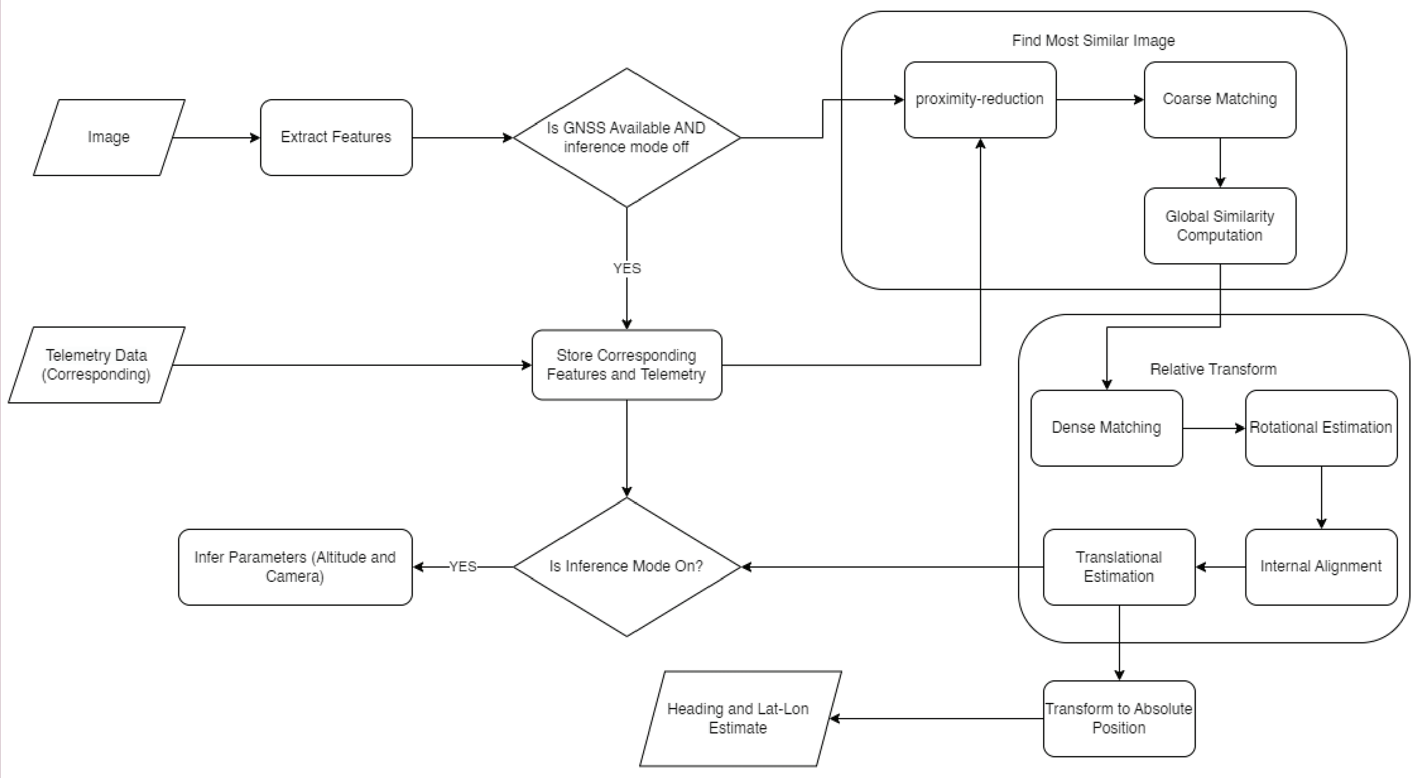
Feature Extractors: AKAZE, ORB, SuperPoint.
Feature Matchers: BFMatcher, FLANN, LightGlue.
Similarity Computation: Histogram, SSIM, cross-correlation, local retrofit.
Transformation Estimators: Rigid, Partial Affine, Affine, Homography.



Feature Matching (The System's Foundation)

Image-based navigation **safeguards** against GPS-denial attacks. The synthesized pipeline achieved **sub-1%** mean radial **error** across diverse terrains, demonstrating exceptional **generalizability**, while maintaining **real-time** performance. It further exhibited **robust** resilience to practical operational challenges.

Synthesised pipeline



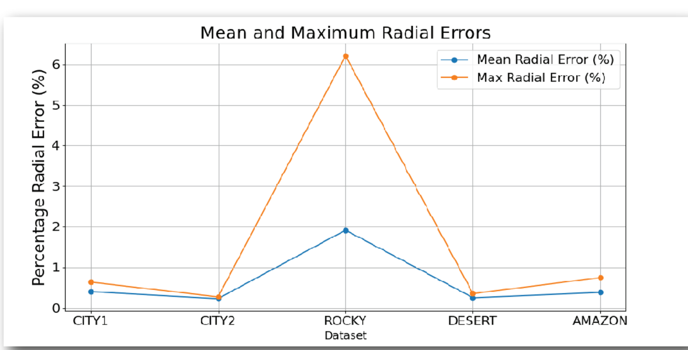
Selected Methods:

The methods below were chosen for their accuracy, efficiency, terrain generalizability, and parameter robustness. Rigorous testing (and method adaptation) was conducted on the above pool, detailed in the report.

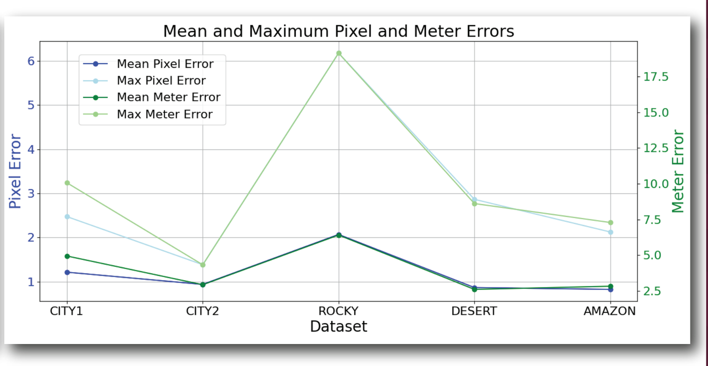
Coarse Extraction Layer: ORB with 3,000 keypoints.
Dense Extraction Layer: AKAZE with 3,000 keypoints.
Feature Matching: FLANN matcher.
Transformation Estimation: Rigid Transform using SVD.
Similarity Estimation: Histogram comparison method.

Key Results

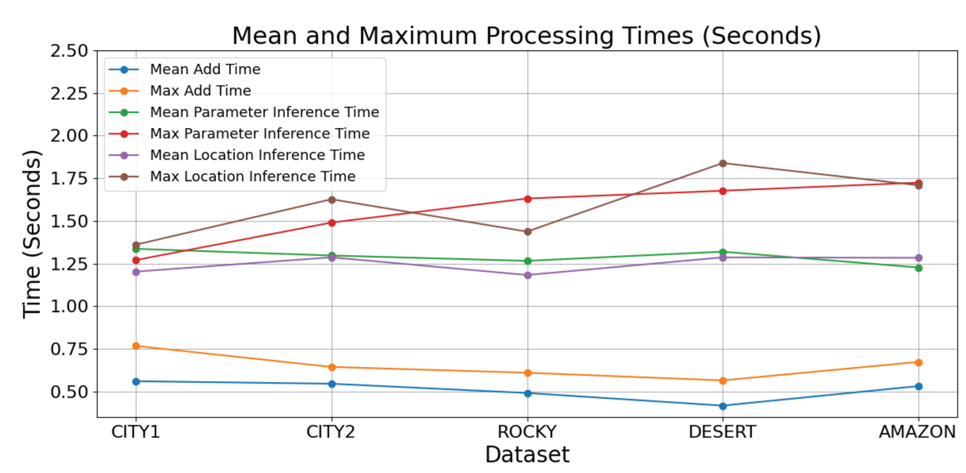
Mean Radial Error	Mean Position Response Time
0.64 % 1.18 pixels 3.94 metres	1.25 seconds



Mean and Maximum Radial Error (%) Across Datasets



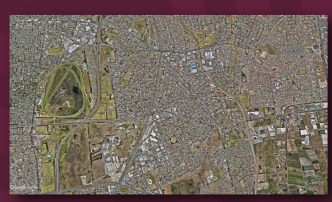
Mean and Maximum Pixel and Meter Errors Across Datasets



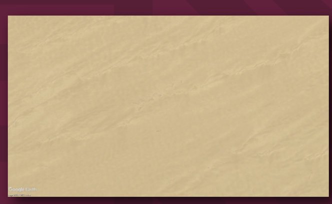
Processing Times Across Datasets

Results

Datasets Used


City Datasets


Rocky Dataset

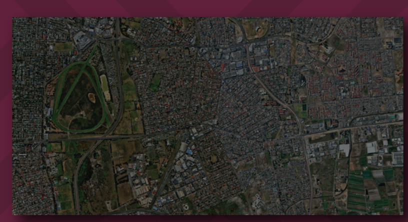

Desert Dataset

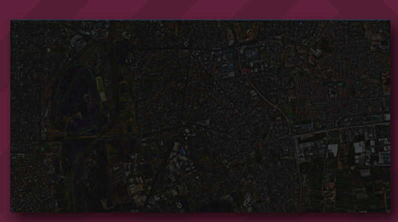

Amazon Dataset

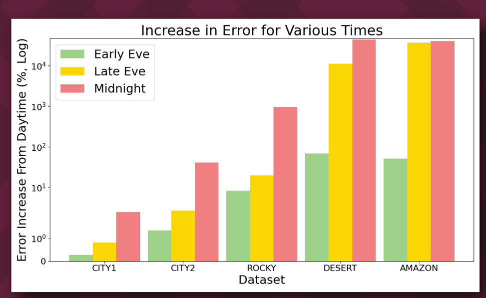
Aligned Pair Example

Lighting Effect Examples

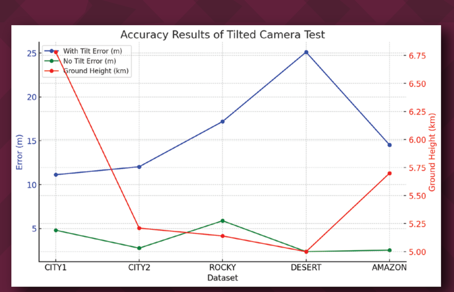

Early Evening


Late Evening

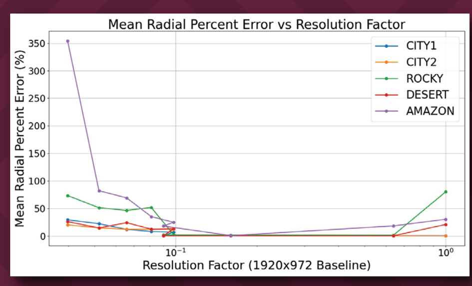

Midnight (No-Light)



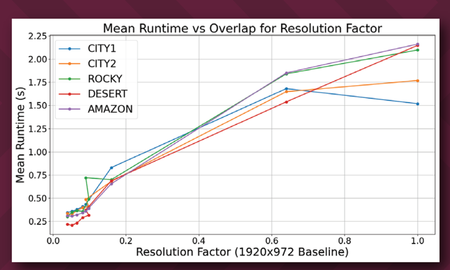
Error Increase vs Light



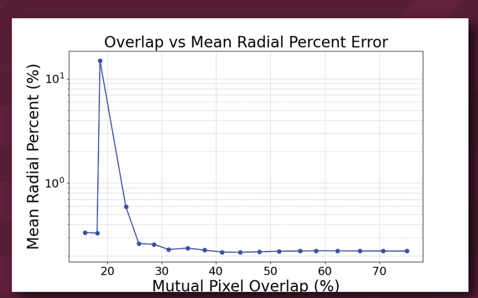
Error Comparison w/ Tilt



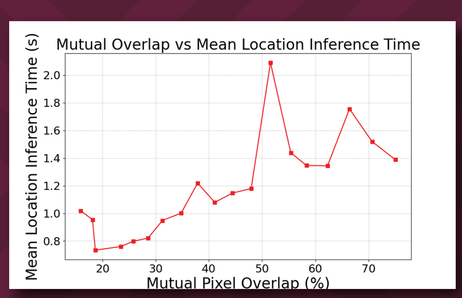
Error vs Resolution



Runtime vs Resolution



Error vs Overlap



Runtime vs Overlap

Conclusion

GNSS vulnerabilities pose critical risks to UAV navigation. This project detailed the development of an image-based navigation pipeline tailored for UAV use, with rigorous comparison and adaptation of methods to meet key requirements. The pipeline achieved sub-1% mean radial error across diverse datasets, exceeding accuracy requirements and demonstrating exceptional generalizability. It maintained real-time performance as required. Additionally, it was shown to be robust to practical operational challenges like low resolution (resource limitations), limited overlap (path loss), varying lighting conditions, and camera tilt. Performance degraded in extreme conditions including large lighting variations, under 30% image overlap, and distortions beyond the scope (non-planar distortion in the ROCKY dataset). Overall, the results validate image-based navigation as a viable GNSS redundancy, providing a promising solution to enhance UAV flight safety and national security.

Future Work

The next step is ensuring the full practicality of the solution. This involves accounting for more types of distortion, non-planar grounds, dynamic occlusions or landscapes, and navigation integration.

Feel free to contact me (samshabz13@gmail.com), or consult the report, for any further questions or references