Trajectory Reconstruction of the ST-9 Sounding Rocket Experiment Using IMU and Landmark Data

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Introduction

- The ST-9 sounding rocket experiment, also known as 41.068, was launched on April 5, 2006 from White Sands Missile Range, New Mexico.
- It was a part of NASA's space technology program which was intended to demonstrate the pin-point landing capability at distant bodies.
- The launch vehicle was a two-stage rocket system (Terrier-Orion) and the payload was equipped with an Inertial Measurement Unit (IMU), a GPS receiver, and two digital video recorders.
Mission Scenario

- Launch Complex 36
- 1st Stage Burn
- 2nd Stage Burn
- Nose Cone Jettison
- 2nd Stage Separation
- Velocity Vector Tracking (RCS)
- Re-Entry
- Parachute Deployment
- Start Imaging
- Landing & Recovery
Previous Work / Motivation

- The ST-9 trajectory was first analyzed by Mourikis et al. where the IMU data and descent images were sequentially processed using the extended Kalman filter (EKF) algorithm.
  - Provides a detailed experiment profile and thorough analysis on the expected estimation performance.

- The purpose of this paper is to demonstrate that both IMU data and images can be processed using a batch filter algorithm, which is fundamentally different from the sequential algorithm and has been used in trajectory navigation for many decades.
  - In practice, navigators favor a batch filter over a sequential filter due to easier data editing, mapping, smoothing, etc.
  - In this study, we show that the 100-meter pin-point landing requirement can be achieved using IMU and landmark data with a batch filter algorithm.
IMU Data Calibration

- The raw IMU accelerometer data is stored at 50 Hz and is provided in the spacecraft frame.
- The onboard IMU outputs the data at a higher rate, but the 41.068 flight system implementation did not allow rates higher than 50 Hz.
- The accelerometer data is first rotated into the inertial EME2000 frame using the dead-reckoned IMU gyro data and a high-precision Earth orientation model.
The integration model is based on an 8x8 Earth gravity field and IMU acceleration data, and the JPL's legacy software Orbit Determination Program (ODP) is used to integrate the trajectory.

The trajectory is integrated starting 90 seconds after launch, which is after the Terrier and Orion separations, and is initialized with the corresponding GPS state.

The comparison shows that the dead-reckoned trajectory using IMU data yields errors of ~2.3 km and ~11 m/s for position and velocity, respectively.

This high error is mainly due to the noisy IMU data, and in actual missions, the noise level can be reduced and calibrated depending on the choice of an IMU payload.

Position and velocity differences between the dead-reckoned and GPS trajectories
The ST-9 image data are processed using the Map And Image Alignment (MAIA) algorithm. The MAIA algorithm aims to match landmarks between descent images and a base map, which is an orbital image. Because of large uncertainty of initial horizontal position and relatively small attitude and altitude error, a rough horizontal correction is needed in order to speed up the data process. The FFT-base map matching is used to provide a rough horizontal position estimate. Then a descent image can be warped roughly to its correspondent location on the base map. Due to several factors the warped descent image does not always match perfectly to the base map. Map landmark matching is used to correct the small error. Multiple landmarks are selected in the descent image and then they are warped to the base map. An image spatial correlation is used to determine their correspondents in the base map.
Mapped Landmark Algorithm

- The base map used here is a USGS Ortho-photo Quadrangles (DOQs) map named “Lumley Lake”.
- The landmark elevation is obtained using Shuttle Radar Topography Mission (SRTM) elevation data of the same area.
- This Digital Elevation Map (DEM) is stored in simple latitude and longitude grids with roughly 3-arc-second grid-size.
- In order to retrieve the elevation data, the landmark position in the base map is converted from UTM coordinate to geographic coordinate and its elevation is interpolated from the DEM data.
- A small elevation correction (-22.3 meters) is applied to each elevation due to difference between the NGA EGM96 and WGS 84.
- Finally, the landmark locations are converted into Earth body-fixed 3D positions.
Kinematic-Fix

- Landmark tracking is a powerful data type which provides body-relative positional and angular information about the trajectory.
- Typically, tens of landmarks are provided per image, but in theory, only three landmarks are needed in determining the position and attitude at the time of measurement.
  - More landmarks basically improve the measurement accuracy by $O(\sigma)$.
- The process of determining the position and attitude given landmarks is called kinematic-fix.
  - It is based on the least-squares principle, and depending on the accuracy of the landmarks, a high-precision body-relative estimate can be obtained.

\[
\tilde{z} = \Lambda_0 \cdot \delta x_0 \\
\Lambda_0 = \sum_{k=1}^{N} h_k^T W_k h_k, \\
\hat{z} = \sum_{k=1}^{N} h_k^T W_k [z_k^* - z_k(r^B, \alpha, \delta, \phi)]
\]

Least-Squares Normal Equation
In this study, total of 93 images (taken approximately every 1s) are processed and the number of landmarks per image ranged from 65 to 77.

The position vector was initialized by using the first two landmark vectors, and the camera orientation was initialized from the dead-reckoned attitude using the IMU gyro data.

Each pixel/line set is assigned 1 pixel accuracy (1-σ) and the a priori position and attitude uncertainties are assumed to be 10 km and 0.5 degrees.

Overall, the position error agrees pretty well with the GPS data and the formal uncertainty is within the pin-point landing requirement.

**Position estimate (3-σ)**

**Attitude estimate (3-σ)**
Full Trajectory Reconstruction

- The full simulation is carried out using the JPL's legacy software ODP and is iterated until convergence is obtained.
  - ODP uses a pseudo-epoch state batch filter formulation.
- In the full simulation, the converted 50-Hz IMU accelerometer data is used in trajectory integration and the mapped landmark data is used to update the trajectory estimate.
- The estimation epoch was set at 649 seconds after launch and ended at 780 seconds after launch.
  - All landmarks are assumed to have 1 pixel accuracy (1-σ).
  - The first image was taken at 653 seconds after launch (~1.5 km) and the last image was taken at 751 seconds after launch (~0.6 km).
- The estimated parameters are the initial position and velocity, camera orientation of each image, and stochastic acceleration.
  - The a priori position and velocity are initialized with a corresponding GPS state and the a priori camera orientations are initialized with the dead-reckoned attitude.
- In this study, the camera orientation angles are estimated as white stochastic parameters for each measurement point and the stochastic acceleration is estimated as colored stochastic parameter with 10 minute correlation time and 20 second batch update time.
Position and velocity errors when compared with the GPS data in the EME2000 frame.

- The result shows better than 10 meter position and 0.5 m/s velocity errors (3-σ) for the interval with available landmark data, which satisfies the pin-point landing requirement.
- The discontinuities shown in the position difference are due to errors in the GPS data which can be improved by smoothing the GPS data, but was not considered in this study.
Full Trajectory Reconstruction

- Camera orientation and stochastic acceleration estimates:
  - The estimated camera orientation accuracy was on the order of 0.1 degrees, which indicates fairly accurate nominal camera orientations.
  - The estimated stochastic acceleration accuracy was on the order of 1 mm/s² when landmark measurements are available.

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**Camera Orientation Estimates (3-σ)**

**Stochastic Acceleration Estimates (3-σ)**
Full Trajectory Reconstruction (20-second)

- The position and velocity errors when images are taken at every 20 seconds.
  - The reconstructed position accuracy is better than 100 meters.

[Position Difference with 3-σ Bound diagrams]

[Velocity Difference with 3-σ Bound diagrams]
Conclusions

- The purpose of the 41.068 ST-9 sounding rocket experiment was to demonstrate the pin-point landing capability for future space missions.
- The raw ST-9 IMU accelerometer data were first converted into EME2000 inertial acceleration and were used in trajectory integration.
- The dead-reckoned trajectory using the IMU data only resulted in a large deviation (~2.3 km) at landing, which was not sufficient for pin-point landing requirement.
- The descent images were pre-processed using the map-matching algorithm and landmarks were computed for each image.
- The kinematic-fix alone of the landmark measurements showed ~10 meter accuracy for the position estimates.
  - This result indicated that trajectory reconstruction using both IMU data and descent images would satisfy the pin-point landing requirement.
Conclusions

- In the full batch simulation, the estimated parameters were the spacecraft state, camera orientation angles, and stochastic accelerations.
  - The reconstruction showed that the accuracy of the estimated position and velocity were on the order of few meters for the position and sub-meters per second for the velocity.
  - Different landmark tracking update showed that imaging at a lower frequency (20 seconds) can also satisfy the pin-point landing requirement.
- Overall, the reconstruction of the ST-9 sounding rocket trajectory showed that IMU accelerometer data and descent imagery can be processed using a batch filter and can obtain the trajectory accuracy required for a pin-point landing at distant bodies.
Questions?