Integrated Navigation System

Adhika Lie
adhika@aem.umn.edu

AEM 5333: Design, Build, Model, Simulate, Test and Fly Small Uninhabited Aerial Vehicles

Feb 14, 2013
Navigation System

- Where am I?
  - Position, velocity, and attitude (navigation state vector)
- Sensor system, but generally an estimation (a filtering) problem
- Example:
Integrated Navigation System

- Stochastic
  - No perfect model
  - No perfect sensor: random biases, random noises, etc.
- Statistical notion of the quality of the estimates
- An integrated navigation system blends information from different sensors to generate an optimal estimate of the navigation states
- Optimal: Minimize mean square error

\[
\hat{x} = \arg \min \text{Tr} \left\{ \mathbb{E} \left[ (x - \hat{x})(x - \hat{x})^T \right] \right\}
\]
Kalman Filter

- Kalman filter and its variants are the workhorse behind almost all navigation systems.

- Property of the Kalman Filter
  - Optimal estimator for linear systems corrupted by Gaussian noise (Gauss-Markov systems)
    - It is the minimum variance unbiased estimator, the least square estimator, and the maximum likelihood estimator.
  - Best **linear** unbiased estimator for Markov systems

- A series of prediction – correction based on the statistical nature of the information.
Working Principle

Real World

Input

Noise on Input Measurements

INS

What we thought the state should be

MODEL

Update our model

FUSION

Imperfect information from the "real world"

Sensor

GPS, Magnetometer, Altimeter, etc.

Noise
INS vs. GPS

• Inertial Navigation System (INS)
  – High bandwidth: up to 1.6 kHz
  – Self-contained
  – Solution drifts with time (stochastic)

• Global Positioning System (GPS)
  – Low bandwidth: 1 – 10 Hz
  – Depends on external signal
  – Stable solution over time
Inertial Navigation System

- Sensors are accelerometers and rate gyros
- Sensor outputs are corrupted by systematic and stochastic error:
  - Misalignment and Nonorthogonality, Random bias, Scale factor, Random noise, Discretization error
- Integration algorithm and update rate matters for accuracy

\[
\begin{align*}
\dot{V}_{EB}^N &= C_B^N f^B - (2\Omega_{IE}^N + \Omega_{EN}^N) V_{EB}^N + g^N \\
\dot{C}_B^N &= C_B^N \Omega_{IB}^N - (\Omega_{IE}^N + \Omega_{EN}^N) C_B^N
\end{align*}
\]
INS Error

- Basic INS error model

\[ a(t) = 0 + b + w(t) \quad \rightarrow \quad v(t) = \int_{t_0}^{t_f} a(t) dt \]

\[ = v(t_0) + b\Delta t + \int_{t_0}^{t_f} w(t) dt \]

\[ x(t) = x(t_0) + v(t_0)\Delta t + \frac{1}{2} b\Delta t^2 + \int_{t_0}^{t_f} \int_{t_0}^{\tau} w(t) d\eta d\tau \]
Global Positioning System

- United States' Global Navigation Satellite System (GNSS)
- A system that consists of:
  - User segment (i.e. the receivers)
  - Space segment (i.e. the satellites)
  - Control segment (i.e. satellite control station)
- Single receiver estimates position and velocity based on multilateration techniques and Doppler effect
GPS Error: Range Error

- GPS works based on timing signal
- Distance measured is distance traveled by the signal – *pseudorange*
- Propagation delay error:
  - Atmospheric error
  - Multipath
- Noise error
  - Radio Frequency Interference
  - Signal jamming, etc.
GPS Error: Dilution of Precision

Range accuracy maps into user position's accuracy as a function of satellite geometry.

\[
\begin{bmatrix}
X \\
Y \\
Z \\
b
\end{bmatrix} = (G^T G)^{-1} G^T
\begin{bmatrix}
\rho_1 \\
\rho_2 \\
\rho_3 \\
\rho_4
\end{bmatrix}
\]
GPS-aided Inertial Navigation System (INS/GPS)

- Error characteristics of INS and GPS are different
  - Stable vs. drifting, High bandwidth vs. low bandwidth, Self-contained vs. signal dependent

- Combine the good qualities of INS with good qualities of GPS

- Results in solution that is
  - Not drifting, stable solution
  - High bandwidth
  - Robust* towards signal interference

* The degree of robustness highly depends on quality of IMU used.
INS/GPS Architecture

Accel Triad
IMU
Gyro Triad

Bias Compensation

GPS

Extended Kalman Filter

Earth rate and Transport Rate Compensation
Coriolis Force Compensation

Sensor Signal
INS Signal
Error Reset Signal
Flight Test Results
(Position & Velocity)

Trajectory in North–East Plane

Ground Speed

FASER Flight 04
Flight Test Results
(Attitude & Bias)

Euler Angles

Accel Bias

Gyro Bias

FASER Flight 04
Implementation Challenges

- Sensor synchronization
- Data dropouts
- Bad GPS measurements
- Lever arm effects
- Convergence
- Filter tuning and accuracy
- Alternative/backup mode
Convergence

- The use of automotive grade IMU degrades the stochastic observability of yaw rate gyro bias

- Heading angle is poorly observable when aircraft is not accelerating

- Improve using magnetometer
Filter Tuning

• Automotive grade IMU does not have good sensor error characterization
  – Large output error, non-Gaussian, colored noise, unstable bias, misalignment, etc.

• Filter tuning allows the filter to account this unmodeled error and thus improve accuracy of the filter

• Requires truth reference system in order to tune the filter
What to expect from Filter Tuning

Alternative Navigation

• GPS is well-known to be very prone of interference, signal jamming, and spoofing

• Low-cost automotive grade INS requires constant online calibration because of the large output error

• Example of backup navigation mode:
  – Reversion to Attitude mode
  – Camera-aided INS
Summary

- Robust navigation hinges on the capability of fusing information from multiple sensors to generate the optimal estimate of the navigation state vector
- The error in the navigation system is stochastic
- INS/GPS is one example of integrated navigation system commonly used for UAV application
- Proper implementation of INS/GPS system requires careful examination of the system's robustness and accuracy.