Robust Navigation and Attitude Determination Systems for Unmanned and Micro Aerial Vehicle Applications

Demoz Gebre-Egziabher

Department of Aerospace Engineering and Mechanics
University of Minnesota, Twin Cities

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Motivation of using UAV/MAV

• An Unmanned/Uninhabited Aerial Vehicles (UAV) is defined to be an aircraft which flies without a human operator onboard.
  – Micro Aerial Vehicles (MAV) are a subset of UAVs.
  – Maximum dimension < 15 cm (DARPA definition)
• Ideal for performing Dull, Dirty and Dangerous operations.
  – Overcome errors that are caused by operator fatigue
  – Remove the human element from operations that are potentially hazardous
• Reduced direct and life cycle costs.


http://en.itek.norut.no/norut_it/nyheter/nyhetsarkiv/h_ytsvevende_teknologi
UAV/MAV in ITS Application

- Planned future uses in Intelligent Transportation Systems (ITS) sensor platforms:
  - Evacuation coordination
  - Nodes for communication & navigation networks
  - Delivery of emergency supplies.

- Recent examples of such use includes:
  - Hurricane Katrina recovery effort
    - 5 Silver Fox UAVs used during hurricane Katrina search rescue operation.
  - Remotely piloted helicopters used for structural inspection
  - Utah Highway Patrol – Accident scene documentation/reconstruction

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Ghostnet Problem

• Airborne Technologies' *Malolo I*: Being evaluated for autonomous Ghostnet searching missions (ATI/NOAA)
  • [http://www.highseasghost.net](http://www.highseasghost.net)
Indoor Flyer (Yard Stick)

- RC Receiver
- Data Modem
- MPC 555 Computer
- MNAV Sensor
- Brushless motor
- Yardstik RC Plane
Avionics Functional Block Diagram

Control Algorithms → Sensors

Guidance Algorithms

Navigation Algorithms

Command/Data Up- & Down-Link

Data Link

Operator Interface

Avionics Suite
(Navigation, Guidance & Flight Control)

Ground Operating Station
Issues with COTS Avionics

- While some off-the-shelf technology to support remote operation of aerial vehicles exists, inexpensive, provably safe (reliable) and easily reconfigurable systems are scarce.
  - Cost, power, size, weight, etc. constraints are not easy to satisfy.
  - Many avionics or sensor suites do not provide meaningful metrics/guarantees of performance.
  - Difficult to assess performance without any insight into algorithms.
- When it comes to avionics, the “one size fits all” philosophy does not work.
  - Off the shelf avionics solutions are “tuned” or “tailored” to specific vehicle/application.
  - For robustness, close coupling between mission, navigation, guidance and control must be considered (especially at the small size of the spectrum).
Example: Heading vs. Ground Track

\[ \psi_G = \tan^{-1}\left(\frac{V_{\text{East}}}{V_{\text{North}}}\right) \]

\[ \psi = \psi_G + \zeta \]

\( \psi \) = Heading

\( \psi_g \) = Ground track angle

\( \zeta \) = Crab angle
The Multi-Sensor Avionics Suite

- LIDAR
- Vehicle Dynamic Model
- Air Data/Baro

RF Signals of Opportunity
- IMU
- Data Link
- Doppler Radar

GPS RF Front End
- EO/IR Camera

Doppler Velocity Log (Acoustic)

Multi-Sensor Fusion Algorithms (Linear/Non-Linear Filters)

Clock

Navigation State Vector and Time

- Hardware
- Software
Our Approach: Community of Avionics Developers/Researchers

- Developing an open source navigation, guidance and control software.
  - Hardware used is the Crossbow MicroNav.
  - Software leverages FlightGear (open source flight simulator).
    - Link for MicroGear can be found at http://sourceforge.net/projects/microgear/
Simulation Environment

- Generate GPS Data
- Navigation, Guidance & Control Algorithms
- Sensor Error Models
- Package Data
- Playback

Generate Vehicle Trajectory → Inverse Navigation → User’s Algorithm

- Flightgear
- Constell™
- Simulink™ (Aerospace Blockset)
- Inertial Navigation Toolbox (U of M Developed)

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Architecture of COTS Low Cost Avionics

- GPS Receiver
- Magnetometer Triad
- Air Data Sensors

Extended Kalman Filter

Inertial Navigation Algorithms

Inertial Measurement Unit

Attitude/Navigation Solution

Inertial Sensor Error Feedback Path
Loose INS/GPS Integration

- Most COTS INS/GPS navigators for low-end UAV applications use variants of the “loose” integration scheme shown here.
  - In the absence of GPS system must rely on INS or another form of navigation.
Flight Test Trajectory
Roll Angle Estimation History

- Roll angle data from MIDG sensor
- MNAV data (INS/GPS algorithm)
- MNAV data (Modified AHRS algorithm)

Time (s) vs. Roll angle (deg)
Pitch Angle Estimation History

- MIDG sensor data
- MNAV data (INS/GPS algorithm)
- MNAV data (Modified AHRS algorithm)
Sensor Output Error Estimation History
Open Loop Attitude Estimation Errors

- Covariance analysis using the Euler angle kinematics equations.

- Models for gyro residuals developed from laboratory data.

- Separate contribution of the various errors is shown:
  - Even the wide band noise contributes to the attitude error.

- **Conclusion**: Cannot use these MEMS-based gyros in a stand-alone fashion for attitude estimation.
Case Study: 2-D Observability Analysis

- Airplane Flying/Car Traveling level with a 2-D INS
  - 2 Accelerometers
  - 1 Rate Gyro
  - A Magnetometer Triad
- Along trajectory B, airplane is moving at a constant speed.
- Loose integration with Feedback
  - 8 States (position, velocity, heading, accelerometer biases and rate gyro biases)
- Variation on estimator architecture
  - GPS Position only (P)
  - GPS Position and Velocity (PV)
  - GPS Position and Magnetometer Heading (PH)
  - GPS Position and Velocity and Magnetometer Heading (PVH)
Heading Error Estimates (GPS P and V aiding Only)
Observability of Heading Errors

Given Error-Free Accelerometers

\[ a_N = f_x \cos(\psi) - f_y \sin(\psi) \]
\[ a_E = f_x \sin(\psi) + f_y \cos(\psi) \]

\[ \psi_{INS} = \psi + \delta\psi \]

\[ [a_N]_{INS} = a_N - (f_x \sin(\psi) + f_y \cos(\psi)) \delta\psi \]
\[ [a_E]_{INS} = a_E + (f_x \cos(\psi) - f_y \sin(\psi)) \delta\psi \]

Given Error-Free Accelerometers

True Acceleration

\[ \psi_{INS} = \psi + \delta\psi \]
Pictorial Depiction of Vector Matching

- Pictorially the vector matching problem is as shown in the figure on the left.

- The two sides of the triangle defining the $u-v$ plane is known (or expressed) in two separate coordinate systems.
Using Earth Magnetic and Gravity Vectors

• An attitude determination system can be mechanized using measurements of Earth’s magnetic and gravity field vectors.

  – Magnetometer triad measures Earth’s magnetic field vector (vector $\mathbf{u}$)
  – Accelerometer/GPS measures gravity vector (vector $\mathbf{v}$).

  • GPS required because an accelerometer measures the combined effect of gravity and acceleration. That is,

\[
\begin{align*}
\vec{f} &= \vec{a} + \vec{g} \\
\vec{g} &= \vec{f} - \vec{a} = \vec{f} - \frac{d}{dt}(V_{GPS})
\end{align*}
\]
VM Measurement Model

- The relation on the last page can be used to write the following measurement model:

\[
\begin{bmatrix}
\delta \hat{u}^b \\
\delta \hat{v}^b
\end{bmatrix} \equiv \begin{bmatrix}
\hat{u}^b - \hat{\hat{u}}^b \\
\hat{v}^b - \hat{\hat{v}}^b
\end{bmatrix} = -\begin{bmatrix}
\hat{u}^b \\
\hat{v}^b
\end{bmatrix} \times \begin{bmatrix}
\delta \phi \\
\delta \theta \\
\delta \psi
\end{bmatrix}, \quad \begin{bmatrix}
\hat{u}^b \\
\hat{v}^b
\end{bmatrix} \times = \begin{bmatrix}
\begin{array}{ccc}
0 & -u_3^b & u_2^b \\
u_1^b & 0 & u_3^b \\
-u_1^b & u_2^b & 0
\end{array}
\end{bmatrix}
\]

- Magnetometer measurements are u and accelerometer measurements v.

\[
\delta \hat{z} = \begin{bmatrix}
\delta \hat{u}^b \\
\delta \hat{v}^b
\end{bmatrix} = H \delta \hat{x} = \begin{bmatrix}
\hat{u}^b \\
\hat{v}^b
\end{bmatrix} \times \begin{bmatrix}
\delta \phi \\
\delta \theta \\
\delta \psi
\end{bmatrix}, \quad \begin{bmatrix}
\hat{u}^b \\
\hat{v}^b
\end{bmatrix} \times = \begin{bmatrix}
\begin{array}{ccc}
0 & -u_3^b & u_2^b \\
u_1^b & 0 & u_3^b \\
-u_1^b & u_2^b & 0
\end{array}
\end{bmatrix}
\]

\[
\delta \hat{x} = \begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix}
\]
Flight Test Trajectory

Longitude (West) vs. Latitude (North) plot showing the trajectory of an aircraft. Key points marked with 't' indicate the time (in minutes) at which certain positions were reached.

- t = 20 min
- t = 21 min
- t = 22 min
- t = 23 min
- t = 24 min
- t = 25 min
- t = 26 min
- t = 27 min
- t = 28 min
- t = 29 min
Flight Test Data Playback

Navigation Frame Linearization

- Vector Matching Algorithm
- Truth Reference

- θ (deg)
- φ (deg)
- Time (min)
Computed Gravity Vector

Computed $|| g ||$ (Normalized) vs. Time (min)
Indoor Flyer (Yard Stick)

- RC Receiver
- Data Modem
- MPC 555 Computer
- MNAV Sensor
- Brushless motor

Yardstik RC Plane
Issues for Mag Use on MAVs
(Effect of Power Transients #1)
Issues for Mag Use on MAVs
(Effect of Power Transients #2)
The Multi-Sensor Avionics Suite

- LIDAR
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- IMU
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- Clock

Multi-Sensor Fusion Algorithms (Linear/Non-Linear Filters)

Navigation State Vector and Time

Hardware
Software

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Blade CX Miniature Helicopter
Blade CX Miniature Helicopter (2)

- stabilizer bar
- upper rotor
- lower rotor
- 2 E-motors
- receiver
- 2 servos
- battery
- reflective markers
Sensor Fusion Architecture
MEMS Gyro Open Loop Performance
MEMS Gyro Open Loop Performance
Integrated Navigation System Integrity

\( I_H = \text{Integrity Risk (Pre-defined)} = \text{Maximum Acceptable Hazard Risk} \)

\( P_H = \text{Probability of Hazard} \)

O.K. as long as \( P_H < I_H \)

Hazardously Misleading Information
Calculating Protection Levels

- Estimators such as Kalman Filter (KF) or Extended Kalman Filter (EKF) assume:
  - Input or sensor noise, \( \nu \) is known or characterized perfectly
  - First moment (mean) and second moment (variance) of noise with uncertainties are sufficient for characterization

- In many applications neither of these assumptions is valid.
  - Faults can alter or change the statistics of noise pdf, \( P_\nu \)
  - \( P_\nu \) may be Non-Gaussian (e.g. heavy tailed distribution)

\[ y = Hx + \nu, \quad \delta x = \hat{x} - x \]
\[ p_\nu = N(0, R) \quad P = (H^T R^{-1} H)^{-1} \]
\[ R = E\{\nu \nu^T\} \quad p_{\delta x} = N(0, P) \]
\[ P(\delta x > \delta x_{\text{max}} \cup \delta x < \delta x_{\text{min}}) = P_H \leq I_H \]
Sensor errors smaller than the minimum detectable fault can cause dangerous bias shifts (Left Figure).

Some sensor measurement errors exhibit heavy tails (Right Figure).

How do we protect against these uncertainties?

- How do we ensure that $P_H$ is ALWAYS less than $I_H$?
Guarantees for Integrity: Overbounding

• For problems that are linear (quasi-linear), time invariant and input noised are uncorrelated, the method of Gaussian overbounding can be used to calculate integrity bounds (DeCleene 2000)
  − Successfully applied to FAA’s GPS/WAAS
• Integrated navigation systems violate one or more of the above assumption
  − Require new tests for integrity to be developed.
• Developing methods for providing some level of guarantee on performance:
  − Symmetric Overbounding (Rife & Gebre-Egziabher, 2007): Deals with correlated errors
  − SO Test (Bageshwar & Gebre-Egziabher, 2008): Deals with a class of time varying systems.