Course 557: Inertial Systems, Kalman Filtering and GPS/INS Integration (3.0 CEUs)

DAY 1	DAY 2	DAY 3	DAY 4	DAY 5
Dr. Alan Pue, Johns Hopkins, Navigation & Defense Consultant			Mr. Michael Vaujin, Aerospace, Navigation & Defense Consultant	
Introduction to INS/GPS integration • Inertial navigation • Integration architectures • Example applications **Vectors, Matrices, and State Space** • Vectors and matrices • State-space description • Examples **Random Processes** • Random variables • Covariance matrices • Random process descriptions	**Inertial Navigation Mechanization** • Gravity model • Navigation equations • Implementation options **Inertial Sensor Technologies** • Accelerometer technologies • Optical gyros • MEMS technologies • Technology survey **Strapdown Systems** • Quaternions • Orientation vector • Coning and sculling compensation	**INS Aiding of Receiver Tracking** • Code and carrier tracking • Track loop design trades • Interference suppression • Deep integration **Tightly-Coupled INS/GPS Design** • Measurement processing • Filter parameter selection • Pseudo-range and delta pseudo-range measurement models **Multi-Sensor Integration** • Terrain aiding and relative GPS • Carrier phase differential integration • GPS interferometer/INS integration	**Aided Psi-Angle Navigator** • Description and demonstration of an aided Psi-angle wander azimuth navigator flying an aircraft type trajectory **Aided Phi-Angle Navigator** • Description and demonstration of an aided Phi-angle north-slaved navigator flying and aircraft type trajectory • Modeling position error as latitude/ longitude error • Modeling position error as navigation frame tilt error • Comparison of popular state dynamics matrix elements **Partials of Measurement Equations** • Techniques and tricks for taking partials, examples • Psi-angle and Phi-angle feedback to strapdown • Pros and cons of the 3 different navigator types	**Square Root Filtering** • Square root covariance filtering and smoothing • Information filter derivation • Square root information filters • UD factorization & filtering **Suboptimal Covariance Analysis** • Effects of mis-modeling errors • Optimal and sub-optimal (two pass) covariance analysis • Error budget and reduced state analysis **Unscented Kalman Filters** • Sigma points and the Unscented Transform • Performance against the EKF • Augmentation and application to navigation • Spherical Simplex Sigma Points • Square Root UKFs
Lunch				
Kalman Filter • Filtering principles • Least squares estimation • Kalman filter derivation **Filter Implementation** • Filter processing example • Off-line analysis • Filter tuning **Navigation Coordinate Systems** • Earth model • Navigation coordinates • Earth relative kinematics	**Navigation System Errors** • Tilt angle definitions • Navigation error dynamics • Simplified error characteristics **System Initialization** • INS static alignment • Transfer alignment • Simplified error analysis **Loosely-Coupled INS/ GPS Design** • Measurement processing • Filter design and tuning • Navigation system update	**Mr. Michael Vaujin, Aerospace, Navigation & Defense Consultant** **Building Extended Kalman Filter** • Linearized & Extended Kalman Filters • Radar tracking of vertical body motion with non-linear dynamics • Radar tracking of an accelerating body with non-linear measurements **Numerical Preliminaries & Considerations** • Keeping a covariance matrix well-conditioned, symmetric, & positive definite • Sequential vs batch measurement processing • Methods of measurement de-correlation **Discreet Time Strapdown Implementation** • Attitude updates and TOV of the acceleration • Propagating the position DCM • High rate vs low rate routines • Effects of errors in initialization & IMU data	**Initialization & Process Noise** • Strapdown and covariance matrix initialization • Process noise for gravity and random walk • Common sensor error models: random constant, random walk and Gauss Markov **Measurement Editing & Adaptive Filters** • Online and offline residual analysis • Advanced methods of outlier detection and rejection • Multiple Model Adaptive Estimation • Application to carrier phase integer ambiguity resolution **Methods of Smoothing** • Optimal prediction and fixed interval smoothing • Fixed point and fixed lag smoothing • Applications to navigation testing	**Ground Alignment & Integrated Velocity** • Gyro-Compassing, zero velocity and zero earth rate observations • Large azimuth static alignment, advanced methods • Small azimuth static alignment & leveling • Ground alignment observability examples • Integrated true velocity error, mapping into delta-range **Attitude Matching & Use of Inexpensive IMUs** • Attitude matching & boresight error states • Considerations for use of very inexpensive IMUs • Non-holonomic motion constraints • Magnetometer aiding • In class measurement equation exercise • Matrix partitioning for computational efficiency **Particle Filtering** • Bootstrap particle filter (PF) • Multi-modal position solutions • Particle filter example • Applications to navigation

Course Objectives

This course on GNSS-aided navigation will immerse the student in the fundamental concepts and practical implementations of the various types of Kalman filters that optimally fuse GPS receiver measurements with a strapdown inertial navigation solution. The course includes the fundamentals of inertial navigation, inertial instrument technologies, technology surveys and trends, integration architectures, practical Kalman filter design techniques, case studies, and illustrative demonstrations using MATLAB®. The full five days allow for a fuller, detailed development of the design of an aided navigation system, including a detailed discussion of the use of lower quality IMUs, and advanced filtering techniques.

Who Should Attend?

- GPS/GNSS engineers, scientists, systems analysts, program specialists and others concerned with the integration of inertial sensors and systems.
- Those needing a working knowledge of Kalman filtering, or those who work in the fields of either navigation or target tracking.

Prerequisites

- Familiarity with principles of engineering analysis, including matrix algebra and linear systems.
- A basic understanding of probability, random variables, and stochastic processes.
- An understanding of GPS operational principles in Course 346, or equivalent experience.

Equipment Recommendation

- Recommended, but not required: A computer (PC or Mac) with full version of MATLAB 5.0 (or later) installed. This will allow you to work the problems in class and do the practice "homework" problems. However, ALL of the problems will also be worked in class by the instructor.
- These course notes are searchable and you can take electronic notes with the Adobe Acrobat Reader we will provide you.

Materials You Will Keep

- A color electronic copy of all course notes provided in advance on a USB drive or CD-ROM.
- Ability to use Adobe Acrobat sticky notes on electronic course notes.
- NavtechGPS Glossary of GNSS Acronyms.
- A black and white hard copy of the course notes.
- Textbook: I*ntroduction to Random Signals and Applied Kalman Filtering,* 3rd edition, by R. Grover Brown and Patrick Hwang, John Wiley & Sons, Inc., 1996. (Note: This does not apply to private group contracts. Any books for group contracts are negotiated on a case by case basis.)

What Attendees Have Said

"As a practicing engineer in integrated navigation, I came to the class to explore the boundaries of my knowledge. The course greatly exceeded my expectations. Mr. Vaujin's mastery of each topic helped me to synthesize prior knowledge and attain new fundamental understanding of the psi and phi navigators.

— Andrew Harmon, Signal Quest, May 2018

"I have recently become interested in learning about strapdown navigation. My objective was to increase my exposure to the topic and gain a more solid overview. This course met and exceeded my objectives."

— Kenneth Bentley, USAF, July 2020

Instructors

Dr. Alan Pue, Instructor

Mr. Michael Vaujin, Instructor