COURSE 457 (3.0 CEUs)

Applied Kalman Filtering with Emphasis on GPS-Aided Systems

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
	Mr. Michael Vaujin, Raytheon				
8:30	**Random Process Review** • Random variables, probability densities, Gaussian and multivariate • Expectation, covariance matrix, random process, autocorrelation, power spectral density, stationary and nonstationary • Linear response, shaping filters **State Space Modeling** • Models derived from differential equations, PSDs and block diagrams • Discrete time solution • Mean and covariance response • Markov and integrated Markov examples • Transition and process covariance **Random Process Simulation and Analysis** • Vector random process simulation • Autocorrelation and PSD from data • Computer demo	**Practical KF Implementation Issues** • Divergence detection and causes, no observability, round-off, mismodel • Residual analysis • Numerically robust KF • Suboptimal KF analysis due to mismodeling **KF Application to GPS Navigation** • GPS measurement and error models • 2 state clock models • 9 state inertial, 11 state, 8 state, 5 state, 8 state with correlated acceleration **More on GPS Navigation** • Carrier phase measurements • Use of Doppler measurements, delayed states • Carrier smoothing of range measurements • Integrated velocity states	**Building Extended KF** • Radar tracking of vertical body motion (nonlinear dynamics) • Sled tracking of horizontal motion (nonlinear measurements) • Computer demo **Phi Angle Strapdown Navigation Error Equations** • Phi angle development • Small angle psi *vs.* phi • Large angle, computing phi in real time • Feedback methods to strapdown **Measurement Processing and Matrix Partitioning** • Care and Feeding of **P** • Residual analysis, on-line, off-line • Sequential *vs.* batch measurement processing • LU decorrelation • Matrix partitioning for efficiency • Pseudorange bias states	**Smoothing and Prediction** • Prediction recursive equations • Smoothing, fixed point, fixed lag, fixed interval derivations • Computer demo **Square Root Filtering** • Motivation • Square root filtering (SRCF) • Square root smoothing (SRCS) • UD filtering • Computer demo **Adaptive Filtering** • Advanced residual analysis (iterative) • Computer demo • Residual tuning for Q & R • MMAE (Magill) • Computer demo	**Integrity Monitoring and Schmidt Filtering** • Parity space techniques • Solution separation using master and subfilters • Schmidt (consider state) development **Nonlinear Dynamics and Particle Filters** • Nonlinear dynamics and error model • Linearized, extended & unscented filter comparisons • Particle filters and example • Computer demo **Model Aiding and Higher-Order KFs** • Pseudo measurements and vehicle dynamics model • 2nd and 3rd order EKF and performance on tracking problem
	LUNCH IS ON YOUR OWN 12:00-1:30 PM				Dr. James Sennott (Friday Afternoon)
5:00	**KF System Integration** • Integration with complementary filtering • Integration examples • State space modeling • Simplified KF derivation **The Kalman Filter** • Simplified algorithm description • Bias, random walk and Markov examples • Off-line error (covariance) analysis **Linearization and Nonlinearity in KFs** • Taylor series *vs.* perturbation • Linearized and extended KF • KF combined with reference • Linearization examples in GPS and inertial (9 state) • Simplest integration	**More KF Examples** • State augmentation • Markov random process modeling and design • Measurement prefiltering • Cycle slip detection and multipath mitigation • Computer demo **GPS Orbit Determination** • Inverse GPS navigation perspective • Computer demo • Observability • Computer demo **GPS-Aided Inertial Design** • Basis for inertial navigation • Inertial system error models • Observability analysis • Computer demo	**Measurement Sensor Error Models** • Odometer Loran and magnetometer error models • Random walk and Allan variances • Detailed inertial sensor error models • Compensation for unmodeled errors **Advanced Suboptimal Analysis and KF Design** • "Dual state" covariance analysis • Error budget design analysis for aided inertial navigation design • Computer demo **Software Review** • Detailed review of software involving an aircraft trajectory flown by strapdown navigator aided by a 32 state EKF • Computer demo	**Information Filters, Decentralized and Federated Filters** • Information filters and information summing in decentralized and federated filters • Optimal *vs.* efficient configurations **Square Root Information Filtering (SRIF)** • Motivation for SRIF • Information filtering concepts • SRIF derivation **Unscented KFs** • Augmented and non-augmented • Application to navigation • Performance *vs.* EKF • Computer demo	**Ultra-Tight, Deep Integration of GPS/INS (Dr. James Sennott)** **Nonlinear Estimation Perspective** • Nonlinear waveform estimation and the MAP estimator • Estimation bounds • GPS waveform mapping and correlator observation model • GPS line-of-sight dynamics innovation model **Extended Kalman Filter Mechanizations** • Integration hierarchy • Sub-components and interfaces • Filter formulations • Latency and clock effects • Jamming adaptation **Case Studies** • Modeling and simulation techniques • Stand-alone high accuracy applications • High-accuracy tactical applications, including landing guidance • Anti-jamming applications

Course Objectives

This is a highly intensive, 5-day short course on Kalman filtering theory and Kalman filtering applications. The student will receive a thorough understanding of linear, extended, unscented, and square root Kalman filters and their practical applications to real time strapdown navigation and target tracking. The student will also be exposed to Information filters, 2nd and 3rd order extended Kalman filters, particle filters, integrity monitoring, and methods of smoothing.

Emphasis is on practical applications, but sufficient supporting theory is provided to give attendees the necessary tools for meaningful research and development work in the field. Considerable time is devoted to modeling, the most difficult aspect of Kalman filtering, in an application setting.

There will be a high level of instructor/attendee interaction, designed to provide hands-on problem solving and solution discussions.

Who Should Attend?

Engineers who need a working knowledge of Kalman filtering or who work in the fields of either navigation or target tracking.

Equipment Recommendation

- A laptop (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 each evening. All of the problems will also be worked in class by the instructor, so this equipment is *not required*, but is ***recommended***.
- These course notes are searchable and you can take electronic notes with the Adobe® Acrobat®9 Reader we will provide you.

Prerequisites

- A basic understanding of linear systems
- A basic understanding of probability, random variables, and stochastic processes
- A thorough familiarity with matrix algebra principles.

Materials You Will Keep

- A color electronic copy of all course notes will be provided on a USB Drive or CD-ROM. Bringing a laptop to this class is highly recommended; power access will be provided.
- A black and white hard copy of the course notes will also be provided.
- Public Venue Attendees: *Introduction to Random Signals and Applied Kalman Filtering, 3rd edition,* by R. Grover Brown and Patrick Hwang, John Wiley & Sons, Inc., 1996. (Note: Book arrangement does not apply to on-site group contracts.)

Mr. Michael Vaujin