Multi-Sensor Integrated Navigation Systems

Dr. Aboelmagd Noureldin, Professor, Tier - I CRC, P. Eng.
Director, NavINST - Navigation and Instrumentation Research Lab

This tutorial provides a comprehensive overview of modern multi-sensor navigation systems, focusing on the integration of inertial navigation systems (INS), global navigation satellite systems (GNSS), and perception systems such as LiDAR, cameras, and radar. It begins with the foundational principles of INS and GNSS, exploring dynamic motion modelling and sensor error sources and their stochastic modelling as well as the computation of a moving platform's position, velocity, and attitude in three-dimensional space. The course then introduces the theory and practical implementation of INS/GNSS integration, including Kalman filtering, loosely and tightly coupled architectures, and real-world case studies. A significant portion of the tutorial is dedicated to perception-based navigation, emphasizing the use of LiDAR, radar, and camera systems in GNSS-challenged environments. Topics include sensor characteristics, calibration, and synchronization, as well as techniques for odometry and map-based localization. The tutorial further explores registration of real-time perception systems' point-cloud data with prior 3D maps using the Iterative Closest Point (ICP) algorithm, and demonstrates how tightly coupled ICP/INS/GNSS fusion can enhance positioning accuracy. Application examples, performance evaluation metrics, and insights drawn from the NavINST dataset provide attendees with a practical understanding of integrated navigation in real-world scenarios. This tutorial is ideal for engineers, researchers, and graduate students working in robotics, autonomous systems, and resilient navigation technologies.

Course Outlines:

Overview: inertial navigation, satellite-based positioning, different GNSS systems, perception systems and the benefits of integration.

Introduction to inertial navigation: Fundamentals of inertial navigation systems (INS), inertial sensors (gyroscopes and accelerometers), reference frames, inertial sensor measurements and performance characteristics, inertial sensor errors and their impact on positioning accuracy, computation of position, velocity and attitude of a moving platform from inertial sensor measurements.

Introduction to GNSS: GNSS fundamentals with a focus on global positioning system (GPS), GPS signal structure, GPS observables, GPS errors, Differential GPS (DGPS), GPS Real-Time Kinematics (GPS-RTK), GPS augmentation systems, including wide area augmentation system (WAAS), and GPS precise point positioning (GPS-PPP).

INS/GPS Integration: Introduction to Kalman filtering (KF), understanding the influence of the covariance matrices of the dynamic, measurement and estimation error. Measurement update models for ZUPT, CUPT and GNSS position and velocity. Loosely coupled (De-Centralized) and tightly coupled (Centralized) modes of integration. Closed-loop versus open-loop realization schemes. Discussion of practical implementation issues and demonstration of real road–test results.

Multi-Sensor Perception Systems for Navigation: Overview of Lidar, Cameras, and Radar for navigation. Field of view, resolution, and environmental robustness. Timing and synchronization challenges. Integration with prior 3D LiDAr maps, sensor-to-map registration, map matching and position estimation. Tightly coupled ICP/GNSS/INS fusion for high precision positioning. Case studies and use of NavINST dataset, evaluation metrics for map-based positioning performance.