Introduction and Overview

George T. Schmidt
Consultant
10 Goffe Road
Lexington, MA 02421
USA

gtschmidt@alum.mit.edu

ABSTRACT

Position, velocity, and timing (PVT) signals from Global Navigation Satellite Systems (GNSS) is used throughout the NATO forces but the availability and reliability of these signals in conflicts or other difficult environments has become a subject of concern for both military and civilian applications. Indeed, there have been numerous study groups, symposia, and recommendations presented during the last 20 years. This is a difficult problem that still requires new and innovative ideas to fill the PVT gap when GNSS data are degraded or unavailable. This Lecture Series will present the state-of-the-art technologies used in addressing these challenges and provide a forum for discussions with technical experts. Through this Lecture Series the technical community will be updated on current application techniques and possible near-term and future solutions. This Introduction and Overview will give the Agenda for the Lecture Series and the biographies of the experts who are lecturing. Then more technical details summarizing each of the lectures will be provided.

1.0 AGENDA

	FIRST DAY	
0830-0900	Registration	
0900-0915	Opening Ceremony and STO Overview	National Authorities
0915-0930	Introduction and Overview	G. Schmidt
0930-1030	Navigation Sensors and Systems in GNSS Degraded and Denied Environments	G. Schmidt
1030-1100	BREAK	
1100-1200	High-Sensitivity GNSS Limitations in RF Perturbed Environments	G. Lachapelle
1200-1330	LUNCH	
1330-1430	Contemporary and Emerging Inertial Sensor Technologies	R. Hopkins
1430-1530	Determining Absolute Position Using 3-Axis Magnetometers and the Need for Self-Building World Models	J. Raquet
1530-1600	BREAK	
1600-1700	Nonlinear Estimation Techniques for Navigation	M. Veth

Figure 1. Agenda Day 1.

	SECOND DAY	
0900-1000	Miniature Augmentation Sensors in GNSS-Denied Navigation Applications	R. Hopkins
1000-1030	BREAK	
1030-1130	High Precision GNSS RTK Navigation for Soldiers and Other Military Assets	G. Lachapelle
1130-1230	Navigation Using Pseudolites, Beacons, and Signals of Opportunity	J. Raquet
1230-1400	LUNCH	
1400-1500	Statistical Predictive Rendering for Robust Passive Relative Navigation	M. Veth
1500-1530	BREAK	
1530-1615	Round Table Discussion	All Delegates
1615-1630	Concluding Remarks	G. Schmidt

Figure 2. Agenda Day 2.

2.0 BIOGRAPHIES OF THE LECTURERS

The biographies of the presenting lecturers are given next in the order of their presentations.

George T. Schmidt is a Distinguished Lecturer for the Institute of Electrical and Electronics Engineers (IEEE), Aerospace and Electronic Systems Society and a member of the Board of Governors of that society. In 2013, he retired after 17 years as Editor-in-Chief of the American Institute of Aeronautics and Astronautics (AIAA) Journal of Guidance, Control, and Dynamics. In 2007, he retired after 46 years at the MIT Instrumentation Laboratory and the Draper Laboratory, Cambridge, Massachusetts. His final position was as the Draper Director of Education. Prior to that position he was the Leader of the Guidance and Navigation Division and Director of the Draper Guidance Technology Center. For many years he was a Lecturer in Aeronautics and Astronautics at MIT, retiring in 2011. He has received several awards including the AIAA International Cooperation Award in 2001 and the NATO Science and Technology Organization’s highest technical award, the von Kármán Medal in 2005. He is an AIAA Fellow and a Life Fellow of the IEEE. He is author or contributing author of numerous technical papers, reports, encyclopedia articles, and books. He received his S.B. and S.M. degrees in Aeronautics and Astronautics from MIT and his Sc.D. in Instrumentation from MIT.

Gérard Lachapelle holds a Canada Research Chair in wireless location in the Department of Geomatics Engineering, University of Calgary, where he has been a professor since 1988 and Department Head from 1995 to 2003. He held an iCORE Chair from 2001 to 2011. From 1980 to 1988, he was in industry where he directed GPS R&D programs. Between 1975 and 1980, he conducted research related to physical geodesy at Natural Resources Canada. Since joining the University of Calgary, he and his colleagues in the PLAN (Position, Location And Navigation) Group have developed numerous novel algorithms, processes, software and patents related to Global Navigation Satellite Systems (GNSS) that have been licensed worldwide. His research has focused on GNSS RTK techniques, pedestrian location and navigation, integrated navigation and, more recently, on electronic interference countermeasures. He has been active in numerous professional societies in his career. He holds degrees for Laval University, the University of Oxford, the University of Helsinki and the Technical University at Graz. Professor Lachapelle has received scores of awards for his work, including the Institute of Navigation Johannes Kepler Award in 1997 and fellowship in the Royal Society of Canada, the Institute of Navigation, the Canadian Academy of Engineering and the Royal Institute of Navigation.

Ralph Hopkins is a Distinguished Member of the Technical Staff and Group Leader in the Guidance Hardware Division at Draper Laboratory where he is responsible for the design and development of inertial instruments and sensors. Ralph has served as technical director of advanced inertial instrument development programs including high performance strategic grade gyros and accelerometers, and navigation and tactical grade MEMS instruments. He holds four patents, has authored several papers and is an invited speaker for short course tutorials on inertial instruments and inertial technology. He has also presented in the NATO Science and Technology Organization sponsored lecture series "Low Cost Navigation Sensors and Integration Technologies". Ralph holds s a BS and ME in Mechanical Engineering from Rensselaer Polytechnic Institute, an ME in Engineering Mechanics from Columbia University, and an MS in Engineering Management from The Gordon Institute of Tufts University.

John F. Raquet is the Director of the Advanced Navigation Technology (ANT) Center at the Air Force Institute of Technology (AFIT), where he is also an Associate Professor of Electrical Engineering. The ANT Center consists of 27 faculty members, 7 staff members, and over 40 students working to solve a wide variety of navigation problems. Dr. Raquet directly supervises the research of 6-10 MS and PhD students. He has degrees in geomatics engineering (Ph.D., University of Calgary, 1998), aero/astro engineering (SM, Massachusetts Institute of Technology, 1991), and astronautical engineering (BS, US Air Force Academy Distinguished Graduate, 1989). He also served as an active-duty US Air Force officer for 14 years. He has published over 130 navigation-related conference and journal papers and taught 46 navigation-related short courses to over 1,600 students in many different organizations. Dr. Raquet is a Fellow of the Institute of Navigation (ION), **-** has served as a session chair, program chair, track chair, and general chair of ION conferences, and recently completed his term as Chair of the Satellite Division of the ION. In 2010, Dr. Raquet was a Fulbright Scholar at the Tampere University of Technology in Finland.

Michael J. Veth is currently the Lead Engineer and Co-founder of Veth Research Associates where he provides expert consulting and training in estimation theory and alternative navigation techniques. Previously, he served as an Assistant Professor of Electrical Engineering at the Air Force Institute of Technology and continues to serve as an Adjunct Assistant Professor. His research focus is on applying advanced estimation theory to combine inertial sensors with non-traditional, bio-inspired sensors for non-GPS navigation and control applications. He received his Ph.D. and M.S. in Electrical Engineering from the Air Force Institute of Technology and a B.S. in Electrical Engineering from Purdue University. He has authored over 40 technical articles, presentations, and book chapters in areas relating to computer vision, navigation, and control theory. Dr. Veth is active in the Institute of Navigation (ION) and is currently serving as the Program Chair for the co-sponsored ION-Institute of Electrical and Electronics Engineers (IEEE) PLANS2014 conference. He is a member of the ION and a Senior Member of the IEEE. In addition, Dr. Veth is a graduate of the US Air Force Test Pilot School.

3.0 PRESENTATIONS

The first day begins with this short introduction and overview of the Lecture Series. This is followed by a paper that provides a system level overview and rationale for the remaining papers. The third paper deals with GNSS signal acquisition and tracking difficulties in radio frequency (RF) perturbed environments. Methods that have been developed and tested to somewhat overcome these difficulties will be discussed. The fourth paper will emphasize the miniaturization of inertial instruments that leads to low cost integrated navigation systems. Micro-electro-mechanical (MEMS) inertial sensors will be discussed, as well as, developments in nanotechnology. The fifth paper will discuss the use of magnetometers to determine absolute position. This approach would allow navigation in a GNSS denied environment. The sixth paper and final paper of the first day presents an overview of estimation techniques suitable for navigation systems with nonlinearities which are not well-suited to traditional linear or extended Kalman filter algorithms.

The second day starts with a paper discussing ongoing activities in the technology developments of miniature augmentation sensors that could be used to improve performance in applications with little or no GNSS signal. It concludes with test results demonstrating a prototype miniature navigation system for personal land navigation applications. The second paper describes the use of real-time kinematic methods that can be used to obtain sub-decimeter accuracy real-time positioning and navigation for soldiers and other military assets. GNSS is the only system capable of delivering this level of performance world-wide with limited local ground infrastructure. The third paper will describe the use of RF signals for navigation designed for this purpose (pseudolites and beacons), as well as signals, that are not intended for navigation (signals of opportunity). The fourth paper deals with statistical predicative rendering techniques (SPR) that can be used in extracting navigation information from a sequence of images. The Lecture Series concludes with a Round Table Discussion with the lecturers and the audience. Abstracts of the 9 detailed technical presentations follow.

3.1 Navigation Sensors and Systems in GNSS Degraded and Denied Environments

Position, velocity, and timing (PVT) signals from the Global Positioning System (GPS) are used throughout the world but the availability and reliability of these signals in all environments has become a subject of concern for both military and civilian applications. International news reports about a successful spoofing attack on a civilian UAV at the White Sands Missile Range in New Mexico, USA have increased concerns over the planned use of UAVs in the national airspace and safety of flight in general. Other examples of the effects of GPS interference and jamming are illustrated in this presentation. This is a particularly difficult problem that requires new and innovative ideas to fill the PVT gap when the data are degraded or unavailable. One solution is to use inertial and/ or other sensors to bridge the gap in navigation information. This presentation summarizes recent advances in navigation sensor technology, including GPS, inertial, and other navigation aids. This presentation also describes recent advances in sensor integration technology and the synergistic benefits are explored. Expected technology improvements to system robustness are also described. Applications being made possible by this advanced performance include personal navigation systems, robotic navigation, and autonomous systems with unprecedented low-cost and accuracy.

3.2 High-Sensitivity GNSS Limitations in RF Perturbed Environments

Low signal power and frequency shifts make stable GNSS signal acquisition and tracking difficult under RF perturbed conditions such as in signal shaded environments and in the indoors. These difficulties result in higher measurement noise, multipath (signal reflection) and, in some cases, signal denials and associated poor geometry. Starting in the mid 90s, methods have been developed and tested to somewhat overcome these difficulties. A review of these, which consist mainly of longer signal integration, assisted GNSS (AGNSS) techniques, aiding with self-contained sensors and advanced signal processing methods such as vector-based tracking, is presented. Associated limitations such as non-coherent signal issues, thermal noise, receiver oscillator limitations, signal reflections and RF interference are discussed. Positioning capabilities and limitations are illustrated with examples in various outdoor and indoor environments as a function of signal attenuation and shading. These include natural and urban canyons, and residential and commercial buildings. New developments to further enhance performance such as multi-GNSS utilization, characteristics of new signal structures, signal diversity and enhanced aiding with other sensors are introduced and some examples are given.

3.3 Contemporary and Emerging Inertial Sensor Technologies

Recent developments in the miniaturization of inertial instruments and GPS receiver hardware have led to the introduction of small, low cost integrated navigation systems which furnish better than 10 m position accuracy. This development has revolutionized the GN&C industry by enabling GN&C functionality in vehicles where it was previously impractical because of size, weight, power and cost limitations. The development of low cost micro-electro-mechanical (MEMS) inertial instruments is largely responsible for this development, and this paper will present an overview of current MEMS gyro and accelerometer technology.

Emphasizing miniature architectures, contemporary coriolis vibrating gyro (CVG) designs will be discussed along with the key features of electro-statically sensed translational and vibrating beam accelerometers. Examples of commercially available systems employing MEMS inertial sensors will be discussed.

This paper will also show how new developments in solid state optical component developments and atomic physics based sensing approaches are being exploited in the next generation of precision gyro and accelerometer designs. This includes advances in fiber optic gyro designs enabled by the availability of photonic-crystal fibers and advanced (integrated optic chip) integration approaches. Likewise, the extension of MEMS fabrication processes beyond silicon wafer-scale planar geometries is enabling the development of novel, miniature CVG gyro concepts. Also sensing methods based on nuclear magnetic resonance, and cold atom interferometry will be shown as having the potential for dramatically improving the state-of-the-art performance accuracy of miniature gyros and accelerometers. Finally, the paper concludes with thoughts on possible future directions of inertial sensor development and system integration.

3.4 Determining Absolute Position Using 3-Axis Magnetometers and the Need for Self-Building World Models

Magnetic compasses have been used for many years to determine heading for the purpose of dead reckoning. This paper describes a more recently developed method for using 3-axis magnetometers to determine absolute position that is based on taking advantage of local magnetic field variation. The fundamental approach is to compare calibrated 3-axis magnetometer measurements with a previously collected map of the magnetic field (including local variations), and to use this information to estimate the user’s current position. This approach has been demonstrated in an indoor environment and in a ground-based vehicle application, showing promise for military navigation in environments in which GPS is not available. Development of a magnetic field map for navigation is one of the challenges of realistic implementation of such an approach, highlighting the need for developing “self-building world models”, i.e., using the magnetometer measurement data to continually improve the magnetic field map, possibly in a collaborative manner with multiple sensors. This paper describes the magnetic field modeling approach and gives case studies of its use, and it also describes the more general challenge to develop self-building world models that will be increasingly important as the military attempts to leverage natural signals for navigation in GPS-denied environments.

3.5 Nonlinear Estimation Techniques for Navigation

Optimal estimation techniques have revolutionized the integration of multiple sensors for navigation applications. These estimation techniques typically make assumptions about the sensor measurements, namely the sensor measurements and errors are well modeled as linear, Gaussian systems. Unfortunately, there is a large class of potential navigation sources which are non-linear, non-Gaussian or both. This motivates the development and exploration of nonlinear estimation techniques suitable for integrated navigation systems.

This paper presents an overview of estimation techniques suitable for systems with nonlinearities which are not well-suited to traditional linear or extended Kalman filter algorithms. The paper begins with a description of the generalized recursive estimation problem and associated notation and conventions. Next, the limitations of applying linear theory to nonlinear problems are addressed, along with techniques for compensating for these adverse effects, including a brief overview of the traditional extended Kalman filter. In addition, the mathematical effects of system nonlinearities on random processes are presented along with computational techniques for efficiently capturing this information, which serves as the foundation for the development of many nonlinear estimators. Next, the unscented Kalman filter and particle filters are presented and analyzed. Common limitations of nonlinear estimators are addressed and hybrid solutions are discussed. The paper concludes with a discussion and qualitative comparison of the strengths and weaknesses of various recursive estimation techniques from linear Kalman filtering to particle filtering, and their applicability to various problem spaces related to military navigation requirements.

3.6 Miniature Augmentation Sensors in GNSS-Denied Navigation Applications

Recent developments in the miniaturization of inertial instruments and GPS receiver hardware have led to the introduction of small, low cost integrated navigation systems which furnish better than 10 m position accuracy under circumstances where GPS remains available. Under situations where GPS is unavailable or intermittent such as urban, indoor or subterranean environments, navigation performance is limited by inertial sensor performance. Given the size, power and cost constraints of miniature systems, currently only tactical grade MEMS gyros and accelerometers (performing at around 1 deg/h and 1 milli-g bias stabilities, respectively) are suitable for use in these applications. Consequently position accuracy rapidly degrades in a tactical grade inertial/GPS system when GPS is denied. To recover navigation accuracy in miniature systems then, it is necessary to use additional sensors (e.g., velocity meters, magnetometers, barometers) and algorithms to augment the inertial system.

This paper discusses some of the ongoing activities in the technology development of miniature augmentation sensors that could be used to improve performance in applications with little or no GPS signal. Current developments in miniature magnetometers, velocity meter technologies and MEMS precision clocks and MEMS barometers are discussed with emphasis on suitability for navigation system integration. Recent advances in optical sensors, in particular 3D cameras, are also discussed with some references to advanced inertial aiding approaches. Simulations of position error over time are compared for certain GPS-unavailable missions based on hypothetical IMU performance expected from these inertial sensors, with and without a velocity meter, and with/without barometer and magnetometer. Algorithms used to implement integration of barometers and magnetometers into the INS navigation solution are also presented.

The paper concludes with test results demonstrating a prototype miniature navigation system developed by Draper Laboratory for personal, land navigation applications. The Draper Personal Navigation System, an integration of a MEMS tactical grade IMU, P(Y)-Code GPS, magnetometer, barometer and Doppler velocity meter, demonstrated better than 5 m position accuracy in urban canyon and GPS-denied indoor testing.

3.7 High Precision GNSS Real-Time Kinematic Navigation for Soldiers and Other Military Assets

Sub-decimetre accuracy real-time positioning and navigation for soldiers and other military assets is becoming increasingly important for a variety of missions, including relative positioning between individuals and assets. GNSS is the only system that can deliver this level of performance worldwide with limited local ground infrastructure. Methods available to achieve the above are called real-time kinematic (RTK) methods. In order for these methods to achieve sub-decimetre accuracy, some conditions are necessary, namely access to line-of-sight signals, the absence of electronic interference, the use of phase measurements made on carrier frequencies and the use of the differential or relative mode of operation to reduce or eliminate propagation, orbital and timing errors. Carrier phase measurements are used as they have mm-level noise and cm-level multipath. Differential or relative operation involves the use of two simultaneous receivers with the aim of accurately positioning one relative to the other, as opposed to positioning them accurately with respect to a global reference frame; the two receivers can be static or moving. Differential carrier phase measurements are ambiguous and these ambiguities must be resolved either as real or integer numbers, the latter providing the higher level of accuracy due to enhanced position observability. When the distance between the two receivers increases substantially, the residual effect of the atmosphere becomes a limiting factor, although dual-frequency measurements can somewhat mitigate this effect. Applications of high accuracy positioning include trajectory determination, vehicle-to-vehicle for collision avoidance and soldier-to-soldier positioning to name a few. The dominant GNSS used for the above is GPS. The use of other emerging systems such as GLONASS, Galileo and Beidou to supplement GPS in order to enhance performance is beginning to take place. The above concepts are discussed and are illustrated with examples.

3.8 Navigation Using Pseudolites, Beacons, and Signals of Opportunity

This paper describes the use of RF signals for navigation, using signals designed for this purpose (pseudolites and beacons), as well as, the use of signals that are not intended for navigation (signals of opportunity). Common challenges faced, as well as solutions, for these types of systems are covered, including the near/far problem, transmitter synchronization, atmospheric delay compensation, multipath, methods for solving for position, and geometry effects. Additionally, some of the unique challenges of navigating using signals of opportunity are described. Cases studies of navigation using pseudolites, beacons, and signals of opportunity will also be presented. The opportunities and challenges of these types of systems for a military environment are also described.

3.9 Statistical Predictive Rendering for Robust Passive Relative Navigation

Recent advances in nonlinear feature extraction algorithms have led to significant research contributions in the area of feature aided navigation techniques (e.g., simultaneous localization and mapping), most notably in the image-aided navigation application. These feature extraction and tracking algorithms are attractive due to their ability to extract a collection of interest points in a autonomous or semi-autonomous fashion. The location of these extracted features in a sequence of images can easily be exploited to solve for pose using the principles of multiple-view geometry.

One of the limitations inherent in feature tracking approaches is the requirement for the signal-processing algorithm to make hard decisions regarding the information remaining in the observation during the signal pre-processing stages. Because these decisions are made without incorporating a priori knowledge, they result in a loss of information and, as a result, sub-optimal performance. For these reasons, a more holistic approach to extracting navigation information from a sequence of images is motivated.

In this paper, the statistical predictive rendering (SPR) technique is explored. SPR techniques seek to minimize the deleterious effects of sub-optimal pre-processing stages by using the entire observation to improve the navigation state estimate. The paper begins with an overview of the SPR algorithm, highlighting the importance of properly modelling the time-varying error statistics. The algorithm is then applied to the passive relative navigation problem encountered in autonomous air-to-air refuelling. Conclusions are presented regarding the accuracy and stability of the SPR algorithm and future research directions.