Technical Evaluation Report

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ABSTRACT

Accurate knowledge of the location of all friendly forces is fundamental to maintaining situational awareness, locating threats, identifying and protecting own forces, and optimally deploying assets. However, currently deployed systems do not have the precise location determination capability required to support such requirements in these environments. This is a particularly difficult problem and one that requires new and innovative ideas and improvements in navigation sensors of all kinds. The purpose of this symposium was to bring together experts to present advances in the field of navigation sensors, system integration techniques, and applications for the NATO community. This symposium had special emphasis on indoor and urban navigation, and many techniques to navigate in these environments were presented. The symposium was organized into five topic areas, addressing: 1) Non-GNSS (Global Navigation Satellite Systems) Systems and Concepts; 2) Sensors and Enabling Technologies; 3) Simulation and Testing; 4) Military Systems and Applications; and 5) Robust GNSS Integration Techniques. A total of twenty seven papers and one keynote address were presented. Enabling technologies presented in the symposium indicated that, while there are continuing advances in navigation sensors, most of the effort is currently being spent on sensor integration and algorithmic and software development.

1.0 INTRODUCTION

In October, 2002 the Sensors and Electronics Technology (SET) Panel sponsored a successful symposium on “Emerging Military Capabilities Enabled by Advances in Navigation Sensors”. Several important issues were reported at that symposium. Advances in inertial sensor technology and improvements in GPS accuracy would make possible totally new opportunities and military operational concepts. GPS was in widespread use, but receiver limitations, jamming, and possibility of system denial were areas of concern. In particular, urban, indoor and subterranean navigation, and navigation in environments where GPS is denied or not available, were identified as areas requiring more development. Integration with other available sensors and new integration techniques were seen as necessary to provide a robust navigation and guidance solution. Therefore, because of the rapid advances being reported at that symposium, it was recommended that progress in navigation sensors and applications be reviewed in five years. Accordingly, the Program Committee set up the current symposium to report on further developments in these areas.

The Program Committee consisted of the following SET Panel members

Program Chairs:	Dr. Mikel Miller, USA
	Dr. Murate Eren, TUR

Technical Members:	Mr. J. Bird, CAN	Dr. J. Kim, USA
	Mr. S. Davison, GBR	Mr. C. McMillan, CAN
	Dr. G. Duckworth, USA	Dr. J. Raquet, USA
	Mr. S. Hernandez Arino, ESP	Dr. G. Schmidt, USA

The Program Committee was very successful in soliciting excellent papers for the 2007 symposium. The opening and welcoming remarks set the expectations for the symposium. In the introduction Dr. Mikel Miller stated that the symposium would have special emphasis on indoor and urban navigation, and that many techniques to navigate in these environments would be presented during the Symposium. Col. Nasibek (TUR), Chief of Communications and Electronics on the Turkish General Staff, and a member of the SET panel, gave the opening remarks. He stated that the goal was to bring together all the experts in navigation from military, industry, and academia and to extract developments and dispense them to other countries under NATO collaboration and cooperation. He noted the importance of Turkey as a growing industrial power and membership in NATO was part of that development. Finally, for the benefit of the attendees, Maj. Enrico Guadalupi (IT), SET Panel Executive, provided an overview of RTO's place in NATO and its mission, objectives, strategy, and the scope and importance of the SET Panels in RTO.

2.0 THEME

In light of current asymmetric threats, a need for robust navigation systems for urban, indoor, subterranean or other difficult environments is critical to maximize combat effectiveness, and minimize casualties and collateral effects. Accurate knowledge of the location of all friendly forces is fundamental to maintaining situational awareness, locating threats, identifying and protecting own forces, and optimally deploying assets. However, currently deployed systems do not have the precise location determination capability required to support such requirements in these environments. This is a particularly difficult problem and one that requires new and innovative ideas and improvements in navigation sensors of all kinds.

The symposium presentations will identify new uses of these improvements and the potential benefits to military operations and future operational concepts for difficult GNSS-degraded environments, such as those experienced in urban, indoor, and subterranean operations. Furthermore, these improvements will enhance other military capabilities, such as personal navigation, situational awareness, collaborative operation, and precision targeting.

3.0 PURPOSE AND SCOPE

The purpose of this symposium was to bring together experts to present advances in the field of navigation sensors, system integration techniques, and applications for the NATO community. They were to identify new uses of these advances and potential benefits of these innovative ideas to military operations and operational concepts. The symposium was also to provide useful information to the related Research Technology Groups (RTG), and was to set the future technical emphasis for NATO and the SET panel to consider.

The scope of the symposium was broad and was organized into five topic areas, addressing: 1) Non-GNSS (Global Navigation Satellite Systems) Systems and Concepts; 2) Sensors and Enabling Technologies; 3) Simulation and Testing; 4) Military Systems and Applications; and 5) Robust GNSS Integration Techniques. A total of twenty seven papers and one keynote address were presented over the two-day symposium; only one paper was withdrawn from the original program.

4.0 EVALUATION

4.1 Overall Summary

This symposium on military capabilities enabled by advances in navigation sensors concentrated on navigation in GPS-unavailable environments. This is an important topic, especially for NATO coalition forces. Combat forces of the future will rely much more on situational awareness, unmanned or autonomous vehicles and will need to retain this capability while operating in buildings, or underground, or in urban canyons, or when GPS is jammed. Also, the need for personal navigation systems will lead the drive for accurate, small, low cost sensors. There will therefore be reliance on a multitude of information. There have been significant efforts in recent years towards the ultimate goal of knowing position to 1 meter or better for several hours, if not indefinitely. As was stated in the keynote address GPS remains on track to provide 1 meter accuracy by around 2010, but without GPS the Inertial Navigation System (INS) position errors grow extremely rapidly, especially with low cost sensors. Therefore, this symposium was timely in covering this important area.

In the topic area of non-GNSS systems and concepts two papers were presented on signals of opportunity (SoOP), four papers on what could be loosely connected under navigation using terrain or building architecture information, one paper on a prototype backpack personal navigator, and one on a magnetometer aided INS. Navigation using SoOP is in its early stages and the papers were overview type. One of the major problems that needs to be overcome is that of timing. Also, certain battlefield scenarios may render SoOPs unavailable (eg, taking out radio and TV stations). However, progress has been made in transponders for first responders, and these may ultimately find their way into military applications with further development. The papers on navigation using land or sea terrain or building architectures presented results from early stage studies and analyses. Further development is required, but all require prior knowledge of the terrain being covered to be accurate. Honeywell’s prototype personal navigator has integrated the large suite of augmentation sensors, plus motion algorithms, required to make up for the relatively poor performance of the MEMS Inertial Measurement Unit (IMU). Results are promising. Improved MEMS inertial performance will help, but will not get to the level at which the reliance on augmentation sensors and algorithms can be significantly relaxed. Personal navigation is a very active area and several companies are pursuing the goal of wearable systems, but are likely to be some years away.

In the topic area of sensors and enabling technologies there were three papers on MEMS inertial, one on Fiber Optic Gyros (FOGs), one on general inertial technology, and one on precise time transfer concepts. Tactical grade MEMS IMUs are now Commercial Off the Shelf (COTS) items with around 4 cu in (65 cc) volume and 10 deg/h drift. MEMS gyros will have difficulty getting below 1 deg/h, but a 1 deg/h IMU is expected in the next couple of years. FOG systems are mature COTS up to 0.01 deg/h. There are ongoing efforts to develop miniature FOGs, but the major gain will be achieving equivalent performance at smaller size. There are no new breakthrough technologies on the near horizon, although cold atom bears watching. The message is that effort needs to be put into developing augmentation sensors for GPS unavailable navigation. The paper on precise timing transfer concepts brought out the point of how important this is for military (and commercial) applications. Current timing locally and world-wide relies on GPS. Chip scale atomic clocks are under development, but these won’t solve theater and world-wide timing concerns for military operations in GPS-unavailable situations.

In the topic area of simulation and testing there was one paper on optimum sensor configuration for a robust personal navigator, one on GPS signal characterization in urban environments, and one on testing military systems using GPS and IMU simulators. The first two papers presented results from relatively preliminary efforts in these important areas. There are several organizations involved in similar activities, but more work is required in these areas. The availability of GPS and IMU simulators is very important to the development and evaluation of military systems. Several companies provide this capability which is in widespread use today.

In the topic area of military systems and applications there were two papers on soldier wayfinding tests, one on a vest mounted navigation and mapping system, and one on adaptive networks for situational awareness and cooperative tracking. The importance of sensor integration, understanding user motion dynamics, human engineering factors for user satisfaction, and accurate mapping capabilities are critical to the success of any system that will be used by the military These papers presented some advances in these areas, but much development remains to be done. There was also a paper on next generation surveying and gun laying systems, which are currently available to the military.

In the final topic area of robust GNSS integration techniques the five papers covered various modeling and filtering techniques to improve robustness such as advanced signal processing, improved IMU error modeling, improved Kalman filtering, carrier phase tracking, correct gait modeling, sensor fusion, and ultra-tightly coupled INS/GPS integration. This is an important area that can extend the positioning capability in GPS outages and/or allow the use of poorer performing, lower cost IMUs. Promising results were demonstrated, but reliability of the navigation solution remains a major concern.

4.2 Summary of the individual presentations

4.2.1 Keynote Address

The keynote address ‘Future Navigation Systems: INS/GPS Technology Trends’ was presented by Dr. George Schmidt, USA. This address was an update of Dr. Schmidt’s keynote address at the SET 054 symposium in 2002. Dr. Schmidt discussed the roadmap, originated in 1995, of technology trends towards improving accuracy, lowering cost, and reducing vulnerability. On inertial sensor trends it was stated that, even though the 3 cu in (50 cu cm), 1 deg/h INS/GPS, originally projected for 2006, has been delayed we are well on the way to meeting improved performance at lower cost and smaller size. MEMS IMUs are currently available, and in the very near term a 4 cu in (65 cu cm), 10 deg/h IMU will be commercially available. Further miniaturization of GPS receivers continues. Improved non-linear filtering techniques in which multiple GPS measurements are stored to update the INS have been developed. GPS accuracy has also continued to improve, with the integration of the NIMA and AF monitoring sites enabling improved updates to the GPS satellites. Within a year the entire GPS ground station upgrades will be complete, and it is expected that (without interference) INS/GPS systems will provide 1 meter navigation accuracy. In situations where GPS is jammed or periodically unavailable, deep integration has been shown to provide up to 15 dB improvement in Anti-Jam (A/J) capability. Deep integration is an optimum non-linear filter software implementation, so it is expected to be widely incorporated into military systems. MSpot remains on track to be implemented by about 2016, and this will provide another 15 – 20 dB improvement in A/J capability. In conclusion Dr Schmidt emphasized that to increase system robustness of military platforms, continued effort was required to: reduce cost and improve accuracy of the INS; improve receivers including deep integration; improve signals in space; and develop higher performance, lower cost adaptive antennas.

4.2.2 Topic 1. Non-GNSS Systems and Concepts

This topic area contained 8 papers.

The first paper (Duckworth and Baranoski) provided a useful overview of the user needs and advantages and disadvantages of potential approaches (direct measurements, beacons, signals of opportunity (SoOP)), inertial/dead reckoning, local environment disturbances/changes) to navigating in GNSS-denied environments. Reference was made to activities on ongoing DARPA programs in which the user could start navigating anywhere independent of the environment or any prior knowledge of it – highly important for military missions. Results were discussed on combating multipath and exploitation of SoOP, using TV signals with a fielded system by Rosum Corporation. Exploitation of multipath, rather than mitigation, showed future promise.

The second paper (Soloviev, Bates, van Graas) described a relative navigation solution for indoor and outdoor urban environments using a 2-D laser scanner and a tactical grade IMU. The laser scan relies on the availability of lines or surfaces from the surroundings to make relative measurements to update the IMU periodically. Position errors at the meter level were demonstrated after 200 meters of travel outdoors.

The next paper (Soehren and Hawkinson) presented Honeywell's prototype personal navigation system (PNS). System components include a MEMS IMU, 3-axis MEMS magnetometer, MEMS barometric pressure sensor, Selective Availability Anti-Spoofing Module (SAASM) GPS receiver, and innovative human -motion algorithms. Testing with GPS disabled for various time periods on the DARPA iPINS program showed that the system mostly met the goal of position error at <1% of distance traveled. Further studies showed that, in certain cases, terrain correlation may be a useful position aid.

Papers four (Sonmez and Bingol) and six (Ekutekin) presented simulations of the application of terrain aided navigation (TAN) in the absence of GPS. Sonmez and Bingol applied TAN to land vehicles; the advantage for land vehicles is that the height above the terrain is constant (ie zero clearance). While the results appear promising further study of the effects of terrain roughness and vehicle type are required. Ekutekin implemented Track Splitting Filtering (TSF) as a new TAN algorithm for a cruise missile navigation application. TSF has a lower probability of false fixes, but requires significantly longer calculation time.

The fifth paper (Cousins) described a model based investigation into fusing precision sonar sensing of the sea floor, including enhanced acoustic environment (sound speed) estimation, with INS measurements to improve both bathymetry and navigation performance. This is still in the early stages of modeling development.

The seventh paper (Raquet and Miller) discussed the benefits and drawbacks of navigation using signals of opportunity (SoOP) and identified typical SoOP system configurations. The presentation was quite tutorial in nature, and is a useful and fairly comprehensive reference.

The last paper (Erer, Kaysal, Semerci) in this topic area described a magnetometer aided INS in a rolling airframe. Simulation and laboratory testing showed that the magnetometer aided INS had significant improvement over the INS alone. However, in practice the usual concerns remain about acquisition and interpretation of magnetic data, and susceptibility to magnetic disturbances.

4.2.3 Topic 2. Sensors and Enabling Technologies

This topic area contained 6 papers.

The first paper (Barbour, Gustafson, Hopkins) reviewed ongoing developments in small inertial sensor technology and simulated their use in random trajectory GPS-unavailable environments when augmented with a velocity meter. The ongoing developments are expected to provide relatively near term performance improvements in miniature FOGs and MEMS and possibly in the longer term with cold atom sensors. However, the simulations showed that only marginal improvements in position error would be gained, except in situations where the velocity meter has a low probability of providing accurate measurements.

The second paper (Waters and Jones) described a MEMS navigation grade accelerometer with a novel electro-optical displacement detection (readout) scheme comprising a Fabry-Perot cavity integrated with a photodiode. The device, which is in its third generation, provides very high scale factor and negligible cross axis sensitivity and offers the potential for very high performance (~10 micro g).

The next paper (Alper and Akin) discussed a MEMS gyroscope with improved drive and sense mode decoupling to minimize mechanical cross talk, and hence quadrature coupling. Although there are several ways to compensate for quadrature or reduce it after build (e.g., laser trimming) the best approach is to minimize it through design as attempted in this paper. This gyro offers the potential for 10 deg/h performance or better.

The fourth paper (Sheard et al) described Atlantic Inertial Systems (formerly parts of BAE SYSTEMS) gun hard MEMS IMU/GPS Integrated Navigation System called the SiNAV02. The IMU is the SIIMU02, which uses the well known ring resonator MEMS gyroscope developed by BAE SYSTEMS. The SiIMU02 is in large scale production and the SiNav02 is undergoing customer air and gun launched firing trials. Stated performance is around 10 deg/h and 1 milli g, which makes it useful for a large number of military applications.

The fifth paper (Dink and Stevens) presented an overview of precise time transfer concepts and discussed the operation principles of several time transfer methods currently implemented in military and commercial systems. This paper was tutorial in nature, but raised the important point that an absolute synchronization to a universal time reference is essential for military (and commercial) operations theater wide and world-wide. Currently GPS is the primary reference, but what will be the reference if GPS is unavailable?

The final paper in this section (Tazartes et al) presented Northrop Grumman's family of fiber optic based INSs which are highly reliable and widely used in military and commercial systems. FOG technology is mature so system performance improvements are being developed using system advances such as transfer alignment techniques to reduce SAR targeting errors and differential GPS corrections to achieve sub-meter positional accuracies.

4.2.4 Topic 3. Simulation and Testing

This topic area contained 3 papers.

The first paper (Arden and Bird) described test and analysis results conducted at DRDC-Ottawa towards determining an optimum sensor configuration for a robust personal navigator that would be most likely to provide precise position data in the absence of GPS. This effort is at the early development stage, so only very preliminary data were available and ongoing work to evaluate different configurations and integrated equipment needs to be completed. However, the effort is on the right track. An interesting finding while trying to characterize behavior with GPS data was that a modern commercial receiver performed better than a keyed military one.

The second paper (Soloviev, Bruckner, van Graas) discussed GPS signal characterization in urban environments using a deeply integrated GPS/IMU. Measurements indicated that direct and indirect path signals from 5 or 6 satellites are available for processing even in dense urban canyons. The quality of the IMU was shown to affect carrier phase tracking capability thus allowing for 1 to 2 meter accuracy in relative position determination.

The final paper (Fisher, Pottle, Denjean) presented techniques and benefits for testing military positioning and navigation systems under controlled laboratory conditions using simulation techniques. This paper was tutorial in nature, and gave a good outline of the benefits of simulating GNSS signals in an Embedded GPS Inertial (EGI) system with an RF generator (e.g., extend performance over and above flight test, insert controlled errors (interference and jamming), repeatability, security, low cost). Also, the actual IMU in the EGI system can be bypassed and position changes and errors simulated. GPS simulators for antenna testing are also available. These simulation techniques clearly are important during development and fielding of military systems.

4.2.5 Topic 4. Military Systems and Applications

This topic area contained 5 papers.

The first two papers (Bossi, Tack, Frim) and (Frim, Bossi, Tack) presented findings from soldier tests using an improved navigation device (GPS receiver, magnetic compass, laptop computer, stored maps) developed from the Soldier Information Requirements Technology Demonstration (SIREQ TD) in support of soldier wayfinding. The first paper covered the pros and cons of alternative display and directional modalities for soldiers traversing wooded terrain over preplanned routes while receiving either visual, auditory, or tactile cues in 1-D or 2-D. The second paper discussed alternate and improved ways the navigation information cues were presented to the soldier individually and in platoon formation. In all cases navigation was improved over the standard method, but soldier feedback showed distinct preferences. This highlights the importance of keeping the user, as well as the mission, in mind when developing new equipment.

The third paper (Eren, Atesoglu, Guner) described ASELSAN Inc's family of new generation Tactical Artillery Surveying and gun laying Systems (TARSUS). TARSUS integrates a GPS/odometer aided INS and an angle/distance measuring theodolite to produce a family of systems that are highly accurate and faster than current ones. Artillery survey teams still have a very important role to provide timely and accurate position and azimuth information for ground based fire support to military elements, so this is a useful product.

The fourth paper (Lithopoulos, Lalumiere, Beyeler) described the basic design, operation and future development of Applanix Corporations GPS-denied navigation and mapping system. The system is vest mounted and, after alignment, navigates based on measurements of motion dynamics with periodic ZUPTs. For high accuracy indoor navigation a prototype mapping system with an eleven sensor camera was described. Navigation with facility maps is a very important capability for determining precise in-building locations for military and first responders.

The final paper (Labbe, Lamant, Ge, Arden) discussed how adaptive networks can be used to build up a map of the relative locations of mobile and stationary units to improve cooperative blue force tracking (BFT) and shared situational awareness (SA) in complex terrains. The paper explored the potential synergy by integrating technologies such that the probability of failure in one will have minimal effect on the overall performance. The conclusion drawn is that the approach supports the hypothesis of improved shared SA and BFT, but that more research and development is required to make this complicated problem a practicality.

4.2.6 Topic 5. Robust GNSS Integration Techniques

This topic area contained 5 papers.

The first paper (Olson et al) described test results from an integrated sensor suite developed under the US Army's Advanced Navigation and Tracking the Future Force program. The sensor suite comprised a MEMS IMU, soldier motion detector, RF ranging, and network assisted GPS packaged in a backpack. Promising results were demonstrated with sensor fusion using correct step modeling and screens to detect false measurements. Indoor and outdoor position error was within 6 – 8 meters over various test conditions and gaits. The sensor suite appears to be compatible with future packaging in a form factor that might meet Army requirements for (dismounted) soldiers.

The second paper (Sotak,Sopata, Berezny) compared the advantages of sigma point Kalman filters (SPKF) and particle filters (PF) over traditional Kalman filters (such as linearized and extended) for merging information in an integrated INS/GPS. Both the SPKF and PF are approximate non-linear estimation techniques expected to improve performance over traditional extended Kalman filters for various applications at the price of increased complexity and computational requirements. It is not clear what improvements will be achieved when compared with a complete optimal nonlinear filter such as is implemented in "deep integration" of a GPS and INS.

The third paper (Lewis) discussed enhanced tracking performance using ultra-tightly coupled GPS/INS. Two IMUs (a Ring Laser Gyro (RLG) IMU (<1 deg/h) and a MEMS IMU (30 deg/h)) as well as two clocks (TCXO and OCXO) were integrated with a GPS receiver. For all configurations the improvement with ultra tightly coupled ranged from 5 – 15 dB. Clock performance appeared to be more critical than IMU performance and this should be evaluated further.

The fourth paper (Noureldin et al) presented analyses and results from techniques for accuracy enhancement of MEMS based IMUs, namely the impact of de-noising (pre-filtering) MEMS sensor output, a segmented Kalman filter, closed loop IMU/GPS, and stochastic modeling of MEMS inertial sensor errors. Potential for improving MEMS INS/GPS navigation performance was demonstrated. Although improving MEMS navigation performance is important, it was not clear whether significant improvement will actually be accomplished for military MEMS with these techniques.

The final paper (Petovello, O'Driscoll, Lachapelle) discussed the benefits of using an ultra-tightly integrated GPS/INS to extend the carrier phase tracking capability and hence improve Real Time Kinematic (RTK) positioning accuracy. Results from a pedestrian based field test showed that the ultra-tight integrated receiver had ~7dB sensitivity improvement over a standard one. This study was performed in an open sky environment with simulated GPS signal attenuation. Further work in a real environment is required.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The symposium achieved its purpose of bringing together leading experts in the field of navigation sensors and integration technology to present emerging system concepts to the NATO community. The Program Committee and the Turkish National hosts are to be congratulated for their efforts in arranging this technical symposium. The topics covered a broad range of activities for navigation in GPS-unavailable environments and provided substantial information to the community.

Enabling technologies presented in the symposium indicated that, while there are continuing advances in navigation sensors, most of the effort is being spent on sensor integration and algorithmic and software development . This is to be expected because the desire to use low cost, small size and hence limited accuracy (around 1 deg/h) INSs drives the need for the integration of a large number of other sensors to aid/augment the INS for accurate position determination. Furthermore, military applications are continuing to expand the role of navigation beyond the basic ‘where am I going and how do I get there’ to include situational awareness, interoperability, cooperative navigation, and the impacts of command and control possibly from remote sites. Ability to operate in these modes is essential for NATO forces of the future. However, the information presented in the symposium indicated that these emerging military capabilities are still several years away.

GPS-unavailable navigation is a difficult problem and many of the papers described results from simulations and tests that were in the early development stages. It was thus difficult to determine which technologies may be the most promising. However, clear enabling technology advances were reported in the following areas: significantly improved GPS A/J capability by 2016; prototype personal navigation systems (PNSs); sensor fusion/integration; MEMS IMUs and sensors; FOG systems; GNSS simulation hardware; artillery surveying and gun laying; and improved robustness. A very high level of interoperability in the future combat system between soldiers and soldier groups and the surrounding platforms is expected starting around 2010. NATO personnel must be ready to incorporate these technology advances into their training and operational activities.

Nearly all of the personal navigation systems (PNSs) presented are currently packaged in backpacks and are too cumbersome, too heavy, and not consistently accurate enough for the soldier in the field to use. Even with the expected availability of a 4 cu in (65 cu cm) MEMS IMU in the very near term, a significant size and power reduction for a wearable, accurate PNS will require MEMS-like packaging of all components. Typical goals have been set at 4 – 10 cu in, 1 – 3 lbs, less than 5 W power, and with position knowledge of 1 -3 meters. Rapid initialization of the system is also a problem. NATO personnel should be involved in testing, evaluating, and providing feedback on these systems.

It is clear that much effort and investment will continue to be spent on improving navigation in GPS-unavailable situations, and that this is a rapidly moving field. The SET panel should maintain expertise on the panel in this area and should review progress in another 3 – 5 years by holding a similar symposium. Some of the current presenters might be requested to provide an update of their technology developments. In particular the next symposium could be broadened to provide sessions on the enabling technologies identified herein, such as: precise timing concepts; miniature integrated PNSs; accurate, very low power, small sensors (e.g., inertial and augmentation); signals of opportunity; targeting and mapping. Papers should be encouraged to emphasize recent tests results rather than academic analyses.